Present-day and future precipitation in the Baltic Sea region as simulated in a suite of regional climate models.

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Abstract

Here we investigate simulated changes in the precipitation climate over the Baltic Sea and surrounding land areas for the period 2071-2100 as compared to 1961-1990. We analyze precipitation in ten regional climate models taking part in the European PRUDENCE project. Forced by the same global driving climate model, the mean of the regional climate model simulations captures the observed climatological precipitation over the Baltic Sea runoff land area to within 15% in each month, while single regional models have errors up to 25%. In the future climate, the precipitation is projected to increase in the Baltic Sea area, especially during winter. During summer increased precipitation in the north is contrasted with a decrease in the south of this region. Over the Baltic Sea itself the future change in the seasonal cycle of precipitation is markedly different in the regional climate model simulations. We show that the sea surface temperatures have a profound impact on the simulated hydrological cycle over the Baltic Sea. The driving global climate model used in the common experiment projects a very strong regional increase in summertime sea surface temperature, leading to a significant increase in precipitation. In addition to the common experiment some regional models have been forced by either a different set of Baltic sea surface temperatures, lateral boundary conditions from another global climate model, a different emission scenario, or different initial conditions. We make use of the large number of experiments in the PRUDENCE project, providing an ensemble consisting of more than 25 realizations of climate change, to illustrate sources of uncertainties in climate change projections.

Keywords: Precipitation climate, Baltic Sea, Climate change, Regional climate modeling, Sea surface temperature

1. Introduction

The Baltic Sea region is a region with complex geography regarding both land-sea distribution and orographic features. Together with large differences in the precipitation pattern between the various seasons this makes the region a suitable area for regional climate model evaluation. The interactions between energy and water cycles and the geography of this area have been investigated in several studies, in particular in the context of the WCRP/GEWEX CSE BALTEX (e.g. Raschke et al., 2001). Coupled regional climate models have been used to investigate these interactions in the Baltic Sea region (Jacob et al. 2001; Döscher et al. 2002). Features of the hydrological cycle in these models have been evaluated against observations in experiments with so called perfect boundary conditions (i.e. reanalysis data; cf. Hagemann et al., 2004, Jones et al., 2004a). The models are able to simulate, for instance, the main features of the seasonal cycle of precipitation. In addition to process studies, the models complement existing observational networks, in particular over the Baltic Sea where stations are few (e.g. Rutgersson et al. 2001). Precipitation in the Baltic Sea runoff area determines, together with the other components of the water budget, the river runoff to the Baltic Sea with implications for salinity and water quality. Electricity power production and risk of damage by flooding are other important topics with high societal and natural impact in this area. River runoff to the Baltic Sea within the framework of the PRUDENCE project is discussed in Graham et al. (2006).

Within the European PRUDENCE project (Christensen et al., 2006) an ensemble of regional climate change simulations, covering Europe, has been produced with various regional climate models (RCM) driven by a few global climate models (GCM) and two emission scenarios. In the present study, we investigate the simulated precipitation in the Baltic Sea area in the different PRUDENCE RCMs. In a first part of this work the model-simulated present-day (1961-1990) climate is compared to the observed climate. Secondly, simulated climate change signals at the end of this century (2071-2100) are compared to each other. Uncertainties resulting from choices of RCMs, GCMs, emission scenarios, and internal variability for Europe and subregions based on the PRUDENCE experiments are addressed in Déqué et al. (2006) and Rowell (2006). Here, we specifically study these uncertainties in projections of precipitation for the Baltic Sea region. The results are put into a wider perspective by comparing RCM-simulated precipitation changes with those from a set of GCMs forced by four emission scenarios (cf. Ruosteenoja et al., 2006).

2. Methods

We use data sets from ten RCMs that cover the entire Baltic Sea runoff area. In addition to the eight PRUDENCE RCMs described in Christensen and Christensen (2006), HadRM3P (Jones et al., 2004b) and a version of HIRHAM operated at MetNo (Hanssen-Bauer et al., 2003; in the following this is called HIRHAM-NO to distinguish from HIRHAM-DK operated at DMI) has been used. We consider Arpège as being a RCM even if it is a global model. Due to its stretched grid it has about the same horizontal resolution as the other RCMs in large parts of Europe. All model results have been interpolated onto a common regular latitude/longitude grid with 0.5 degree horizontal resolution. For a comprehensive description of the models and their ability of simulating the present-day climate and uncertainties in climate projections, see Christensen and Christensen (2006), Jacob et al. (2006) and Déqué et al. (2006).

There is one common experiment performed with nine RCMs, in which the models have been run with lateral boundary conditions from the Hadley Centre climate modeling system HadCM3/HadAM3H (Pope et al. 2000; Gordon et al. 2000) for one control period (1961-1990) and one future time period (2071-2100) under the IPCC SRES A2 emission scenario (Nakićenović et al. 2000). In addition to the common experiment, some RCMs have been run with the B2 emission scenario. Also, some experiments have been made in which the RCMs have been forced by boundary conditions from other GCMs (HadCM3/HadAM3P, Arpège/OPA, ECHAM4/OPYC3). Finally, some of the models have been run with the same boundary conditions and emission scenarios but starting from different initial conditions. Taken together there are 28 realizations of climate change including the entire Baltic Sea runoff area.

The common experiment is not strictly identical across the RCMs. First, the horizontal domain of the RCMs varies. Second and more importantly, the SSTs and sea ice conditions for the Baltic Sea and Kattegat are not identical in all RCMs. RCAO includes a regional ocean model (RCO) covering this area, thus providing its own SSTs and sea-ice distributions to the atmospheric part of the model. RACMO has also been forced with SSTs taken from the RCO in the A2 simulation. Arpège uses SSTs and sea-ice distribution either from observations (Smith et al., 1996) or, for the future period, directly from HadCM3 or Arpège/OPA. In the HIRHAM-DK simulations with lateral boundary conditions from ECHAM4/OPYC3, SSTs and sea-ice distributions have been taken from the oceanic part (OPYC3) of that model. In all other RCM simulations the SST and sea-ice distributions have been taken from the Hadley Centre modeling system. In the control run their SST and sea-ice distribution consists of the HadISST1 sea surface observations (Rayner et al.. 2003). In the A2 scenario runs, the SST and sea ice distribution are obtained by adding to HadISST1 the change projected by the coupled HadCM3 model, with the trend over the 30-year time slice included in the change. In the following the Hadley Centre SST and sea-ice data will be referred to as HCSST.

Present-day climate simulations from the RCMs are compared with existing climatologies for precipitation. For land-areas surrounding the Baltic Sea we use the CRU TS1.0 climatology (New et al., 2000). This is a high-resolution (0.5^{o}) gridded data set with monthly mean precipitation inferred from surface-based observations. In addition, we use the GPCPV2 data set (Huffman, et al., 1997) consisting of gridded monthly means at low resolution (2.5^{o}) constructed from both surface-based and satellite observations. Correction factors based on a detailed analysis of the precipitation for the years 1996-1998 by Rubel and Hantel (2001) have been used to correct the GPCPV2 product for its entire period. The GPCPV2 data only cover the time period 1979-1995. We have used the observed precipitation from CRU to bridge the gap in time by dividing the original GPCPV2 data with the total precipitation from CRU for 1979-1995 and then multiplying it with the CRU precipitation for 1961-1990. For the Baltic Sea itself there are not many surface observations, and there we rely solely on the GPCPV2 data which, in this case, have not been corrected in any way.

3. Results and discussion

3.1. THE CONTROL CLIMATE

Figure 1 shows the RCM-simulated seasonal cycle of precipitation in the Baltic Sea and in the runoff land area in the common control experiment together with the observations and the simulated precipitation from the driving GCM. It can be seen that in the land areas HadAM3H tends to overestimate the precipitation during the winter half of the year. The land-based uncorrected rain-gauge data used by CRU have a problem with undercatch especially during the winter half of the year (Rubel and Rudolf, 2001, Rutgersson et al., 2001). In the corrected and time-adjusted GPCPV2 data set this problem is reduced, and compared to this dataset the simulated precipitation is much closer to the observations. The fact that the simulated precipitation is too high in winter may be related to the somewhat too strong westerly flow in the HadAM3H control climate, importing too much moisture to northern Europe (cf. Jacob et al., 2006). During summer the agreement is better; consequently the amplitude of the seasonal cycle is underestimated. The timing of the seasonal cycle is in good agreement with the observations.

Estimates of precipitation over the Baltic Sea are problematic due to the lack of observations in open sea areas; coastal stations are often more representative for land areas (Rutgersson et al., 2001). Keeping this limitation in mind we use the combined GPCP data, for depicting the seasonal cycle of precipitation over the Baltic Sea (Fig. 1).

The observed seasonal cycle over the Baltic Sea lags that over the surrounding land areas with minimum precipitation in April/May and maximum in late summer and autumn (Figure 1 and Table 1). The HadAM3H generally catches this behavior, although the precipitation particularly during summer is too weak compared to the observations. Part of the underestimation may be spurious, due to the influence of land-based stations observing more precipitation during summer than what actually falls over the sea (Rutgersson et al., 2001). A minor part of the underestimation may be related to the relatively short observational record (1979-1995). According to the CRU data that period was about 5% wetter than the period 1961-1990 during summer and winter, at least in the surrounding Baltic Sea runoff land area.

The ensemble mean of the RCM simulations closely resembles the result from HadAM3H, indicating the importance of the boundary conditions. The difference between the two is smaller than 5% for all months over land and somewhat larger over the Baltic Sea with a maximum difference of 15% in May. Differences between the highest and lowest simulated monthly precipitation in the individual RCM experiments are in the range 25-40%. During winter, precipitation over land is too high in several RCMs, an error inherited from HadAM3H, Figure 1. HIRHAM-DK, CHRM and CLM all give less precipitation than the other RCMs, more in line with the observations. On the other hand, these models are too dry during the summer months, while the other RCMs are closer to the observations (and HadAM3H). These differences between models and observations imply that the amplitude of the seasonal cycle is underestimated in all of the RCMs. The amplitude, here defined as the ratio of the maximum to minimum monthly precipitation, lies in the range 1.3-1.6 for the individual RCMs, 1.5 for HadAM3H, the corresponding observed ratio being almost 1.9 (2.6) in GPCP (CRU). In simulations with perfect boundary conditions the agreement between RCMs and observed climatology is better (cf. Hagemann et al., 2004; Jones et al., 2004a), especially when employing the corrected GPCPV2 data. Over the Baltic Sea the simulated amplitude of the seasonal cycle varies between 1.7 and 2.4 among the RCMs, being 1.6 for HadAM3H, while the observed amplitude is 1.9 (Table 1). All RCMs tend to simulate less precipitation than observed during summer over the sea.

The bias of the simulated annual mean precipitation, as well as its seasonal cycle, in the Baltic Sea runoff area is geographically variable (Christensen and Christensen, 2006, Jacob et al., 2006). In all models there is a wet bias in the entire region during winter. In spring the wet bias gets smaller, especially south of the Baltic Sea. In summer there is a dry bias to the south and east of the Baltic Sea, while most models still show a wet bias over much of Scandinavia. In autumn the overall bias is small but positive in northern Scandinavia and negative along the east coast of the Baltic proper.

3.2. THE SIMULATED FUTURE CLIMATE

In the common experiment, the RCMs project increased precipitation over the Baltic Sea during winter and on average only small changes during spring (Figure 2 and Table 1). In summer the difference between the climate change responses is very large. In the majority of models precipitation increases by 40-90%, while in the remaining two there is only a small increase, 6% (RACMO), or a decrease, 10% (RCAO). The reason for the large increases in most models lies in the large increase (around 6K) in the HCSSTs during summer (JJA). RCAO simulates a more modest increase in summertime

SSTs, around 3K. The same SST is also used in RACMO. Kjellström et al. (2005) compares the simulation with RCAO used here to an experiment in which RCA2 (the atmospheric component of RCAO) is forced by the HCSSTs used by the other RCMs in this study. They show that the large increase in SSTs during JJA leads, not only to increased precipitation, but also to unrealistic energy fluxes between the Baltic Sea and the atmosphere in the uncoupled experiment with HCSSTs. Particularly they find that the Baltic Sea acts as a net heat source to the atmosphere during summers that are relatively cold. The largest increase of projected precipitation in most models is confined to the same areas of the Baltic Sea (Figure 3) coinciding with the largest increase in SSTs (Kjellström et al., 2005). Five other GCMs (see Table 1 of Ruosteenoja et al., 2006), forced by the SRES A2 scenario, show an increase in the Baltic Sea average near-surface air temperature of 2.2-4.6 K, the corresponding figure for HadCM3 being 5.6K.

In the common experiment all RCMs simulate increased precipitation over the Baltic Sea runoff land area (Figure 2). Increases in annual precipitation are in the range 5-15%. Wintertime precipitation increases by 20-35%. During summer precipitation is either decreased or increased by at most 10% except in REMO were it increases by 20%. The large increase in summertime precipitation in REMO is due to the fact that this model also uses the HCSSTs for lakes. The resulting large increase in lake temperatures leads to large increases in precipitation particularly in lake-rich areas in Finland (Figure 3). Kjellström et al. (2005) show that in the uncoupled RCA2 experiment the very high SSTs also lead to higher precipitation in the land areas surrounding the Baltic Sea. In that study differences are less than 5% in the entire runoff area but locally, along the coastal regions, differences of more than 20% were found. Similar features in precipitation along the coastal regions are also seen in the other RCMs (Figure 3).

3.3. INTERANNUAL VARIABILITY OF PRECIPITATION AND SSTs

The interannual variability of precipitation is considerable. In the various RCMs the standard deviation of the 30 seasonal averages in the common CTRL experiment expressed in percent lies in the range 10-25% for the Baltic Sea and its runoff land area. In the common experiment the interannual variability is found to increase with climate change. The variability reaches 25-40% during summer and autumn, except in RCAO and RACMO where it remains close to 20%. The increase in variability in precipitation in the other RCMs coincides with the large increase in SST and the increase in the interannual variability of the SST. Further, the correlation between the interannual variability in SST and the interannual variability in precipitation differs between the RCMs (Figure 4). In HIRHAM-DK and CHRM it is relatively high; indicating that in these models precipitation over the Baltic Sea is sensitive to SSTs. In the other models the degree of correlation is lower and in the Hadley Centre models non-existing. Interestingly, HIRHAM-DK and CHRM are the two models that predict the largest increases in precipitation, whereas the Hadley Centre models show the smallest increase among the models forced by the high SSTs (Figure 4). In the common experiment the degree of correlation between the interannual variability in SST and precipitation is in most models higher in A2 than in CTRL. In the Hadley Centre models, the degree of correlation is still small indicating that precipitation in these models is less sensitive to SST forcing, at least for the Baltic Sea.

3.4. ASSESSING UNCERTAINTIES IN THE CLIMATE CHANGE SIMULATIONS

Even though PRUDENCE has provided a large matrix of experiments, only some models have been employed to perform both A2 and B2 simulations, used boundary conditions from more than one driving GCM, and addressed the sampling uncertainty. But, even if the matrix were to be filled by additional simulations, uncertainty ranges would still be limited. The three GCMs used in PRUDENCE constitute only a small subset of existing GCMs. While GCMs correspond rather well in terms of global mean temperature change (Cubasch et al., 2001), the regional responses in the global models are sometimes very different (e.g. Räisänen, 2001). Also, the uncertainty in the radiative forcing is not fully covered by the A2 and B2 scenarios. To put the present RCM results into perspective, we study responses of a wider set of GCMs to four emission scenarios. Figure 5 shows the change in precipitation in four experiments with HadCM3 forced by the emission scenarios A1FI, A2, B2 and B1, and with six GCMs forced by the A2 emission scenario (cf. Ruosteenoja et al., 2006). In addition, we present ranges based on the common experiment performed with nine RCMs.

The uncertainty due to choice of GCM is large in all seasons, most notably in winter when the six GCMs predict precipitation increases between 10 and 40% but also in summer with changes in the range of ±12%. The difference in radiative forcing also contributes to the uncertainty, but in general less than the GCM uncertainty, except during fall. The HadAM3H and HadCM3 responses are fairly different. One reason for this could the different SSTs used (HadAM3H use observed SST plus the simulated change between scenario and control runs of HadCM3), particularly during summer.

Other possible explanations for the differences could be different horizontal resolution and/or different parameterizations in the two models. Given the lateral boundaries from HadAM3H, the RCMs project a range of precipitation changes. This range is smaller than that from the six GCMs in winter, about equal in spring, and larger in summer and autumn. The very large range in summer and autumn is due to the fact that the treatment of SST is different in the various models, as discussed above. One group of RCMs (RCAO and RACMO) employing lower SSTs simulate small precipitation change, in line with most GCMs under different emission scenarios. The other group consists of the RCMs that are forced by the high SSTs, resulting in substantial increase of precipitation. Figure 5 also shows how the sampling uncertainty is manifested in this region. For two models, HIRHAM-DK and Arpège, there are three ensemble members differing only in initial conditions. In general, the inter-RCM ranges between the three members are smaller than the ranges due to choice of GCMs and RCMs. However, in summer there is a rather large scatter between the three HIRHAM-DK ensemble members. This is probably caused by the fact that Baltic Sea precipitation in this model is very sensitive to the SSTs which differ between the three ensemble members.

4. Summary and conclusions

The simulated seasonal cycle of precipitation in the Baltic Sea runoff area has been compared to observations. HadAM3H employed to drive RCMs in the common experiment overestimates precipitation in winter, a bias that is also seen in the RCMs. In the land areas studied, however, the RCM mean precipitation differs from observations by less than 15% for any individual month. Even if the agreement between the ensemble mean and the driving GCM is good, there is a considerable spread among different RCMs; when studying seasonal averages, the wettest RCMs simulate about 40% more precipitation compared to the driest one.

In the common experiment, the precipitation in the Baltic Sea runoff land area increases by 5-15% annually in the different RCMs. Most RCMs project increases in each month between October and May with the largest increases during the winter months. In summer the overall climate change signal is more complex with increasing precipitation in the north and decreasing precipitation in the south. Since these increases and decreases differ between the models, as does the borderline between increase and decrease, some RCMs project area-integrated increases in precipitation while others project decreases.

For the future climate, it is shown that the SST of the Baltic Sea has an impact on projections of precipitation change. In particular, the SSTs derived from the driving global model in the common experiment are very high during summer and fall and induce a very large increase in precipitation (30-80%) in the RCMs. Moreover, it is shown that these models respond differently to the increased SSTs. Some models are more sensitive and show a high degree of correlation between interannual variability in SSTs and precipitation already in the control climate. In the A2 scenario these are the models projecting the largest increase in precipitation. In contrast to this, some models show almost no correlation between the SST and precipitation variability and likewise simulate a smaller increase in precipitation in the scenario run. Two RCMs have been forced with much lower SSTs, which have previously been shown to be more in balance with the atmosphere. These two models show either a very small increase or a decrease in summer precipitation over the Baltic Sea.

We have also investigated uncertainties in the projections of precipitation change in the Baltic Sea region due to other sources than differences in RCMs. We have found that the uncertainty due to the choice of GCM is high particularly in winter. The uncertainty in the future radiative forcing is found to be most important in the autumn when it coincidentally is comparable to the GCM uncertainty. The sampling uncertainty, albeit not negligible, is not dominating during any season.

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Figure captions

Figure 1. Seasonal cycle of precipitation over the Baltic Sea runoff land area (left) and over the Baltic Sea (right). The shaded area and full line represent the maximum, minimum and mean of the common CTRL experiments. The dashed line shows the HadAM3H simulation. The dash-dotted line depicts the CRU and the dotted line the GPCP observations. Unit: mm/month.

Figure 2. Change in the seasonal cycle of precipitation over the Baltic Sea runoff land area (left) and over the Baltic Sea (right) in the common A2 experiment. The shaded area and full line show the maximum, minimum and mean of the ensemble. The dashed line shows the HadAM3H simulation. Unit: %.

Figure 3. Relative changes in summer (JJA) precipitation from CTRL to A2 in the common experiment in the various RCMs. Changes in the gray areas are less than 5%. Unit: %.

Figure 4. Annual increase in precipitation over the Baltic Sea for the seven RCMs using HCSST. The increase is plotted against the correlation between interannual variability in SST and precipitation over the Baltic Sea in CTRL.

Figure 5. Area-averaged seasonal precipitation projections for the Baltic Sea. From left to right, the columns of symbols present: i) precipitation responses to A1FI, A2, B2 and

B1 scenarios simulated by HadCM3, ii) precipitation responses to A2 scenario simulated by six GCMs, iii) precipitation responses to A2 scenario in the various RCM simulations driven by HadAM3H and iv) the three HIRHAM-DK and Arpège ensemble responses to A2 scenario, driven by HadAM3H. To facilitate interpretation, all GCM projections are denoted by black, RCM projections by red symbol. (o) Refers to the A2-forced HadCM3, (*) to the corresponding HadAM3H experiment, (Δ) to HIRHAM-DK and (∇) to Arpège. All other model projections are denoted by (+). Unit: %.