Atmospheric response to different sea surface temperatures in the Baltic Sea: coupled versus uncoupled regional climate model experiments*

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Abstract A climate change experiment with a fully coupled high resolution regional atmosphere–ocean model for the Baltic Sea is compared to an experiment with a stand-alone regional atmospheric model. Both experiments simulate 30-yr periods with boundary data from the same global climate model system. This particular global model system simulates very high sea surface temperatures during summer for the Baltic Sea at the end of this century under the investigated emission scenario. We show that the sea surface temperatures are less warm in the coupled regional model compared to the global model system and that this difference is dependent on the atmospheric circulation. In summers with a high NAO index and thereby relatively strong westerly flow over the North Atlantic the differences between the two models are small, while in summers with a weaker, more northerly flow over the Baltic Sea the differences are very large. The higher sea surface temperatures in the uncoupled experiment lead to an intensified hydrological cycle over the Baltic Sea, with more than 30% additional precipitation in summer taken as an average over the full 30-yr period and over the entire Baltic Sea. The differences are mostly local, over the sea, but there are differences in surrounding land areas.

Keywords Atmosphere–ocean coupling; Baltic Sea; climate change; NAO index; regional climate modelling; sea surface temperature

Introduction

The energy and water cycles over the Baltic Sea basin have been the focus in the European continental-scale Baltic Sea Experiment (BALTEX) during its first phase (see, for example, Raschke *et al.* 2001). Among other items, how the complex topography of the surrounding land areas together with properties of the Baltic Sea influences these cycles has been investigated. Several regional atmospheric model systems have been used to investigate these influences (e.g. Jacob *et al.* 2001). The ability of the model used in this study, given realistic lateral boundary conditions and SSTs, to simulate the hydrological cycle over the Baltic Sea has been tested by Jones *et al.* (2004). They compare the simulated seasonal cycles of precipitation (P), evaporation (E) and P-E to observations for a large part of the time period 1981–2000 and find that "the agreement between model and observations is encouraging". 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.* 2002). During the first phase of BALTEX the first coupled regional climate models, including atmosphere, land, and ocean, have been developed (Döscher *et al.* 2002; Jacob *et al.* 2003). In particular, such models have been tested in the present climate during observational intensive campaigns such as the PIDCAP (Pilot study for Intensive Data

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Collection and Analysis of Precipitation) period from August to October 1995 (Hagedorn *et al.* 2000). They show that fluxes between coupled and uncoupled models can be very different. Coupled and uncoupled models have been used, not only to study present-day conditions, but also to provide climate scenarios for the end of this century under changing emissions of greenhouse gases (e.g. Räisänen *et al.* 2004; Christensen and Christensen, 2003).

Within the European project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, see Christensen *et al.* (2002)) an ensemble of climate change simulations have been made with different regional climate models driven by different global climate models and different emission scenarios. In PRUDENCE there is one common experiment among others, in which all regional climate models (RCM) are run with lateral boundary conditions from the Hadley Centre global climate model (HadAM3H/HadCM3; Pope *et al.* 2000; Gordon *et al.* 2000) driven by the A2 emission scenario from IPCCs special report on emission scenarios (Nakićenović *et al.* 2000). In the simulated future climate that particular combination of global model and emission scenario predicts very high sea surface temperatures (SSTs) in the Baltic Sea for the summer months (+6 K, taken as an area average, compared to the control climate). This very large change in SST is an outlier as compared to other global climate models under the same emission scenario (less than or at most +4 K, K. Ruosteenoja, FMI, personal communication). An extensive use of the PRUDENCE results with the RCMs driven by the very high SSTs from HadAM3H/HadCM3 is foreseen. Parallel to PRUDENCE the two EU projects MICE (Modelling the Impact of Climate Extremes (Palutikof, 2002)) and STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions (Goodess *et al.* 2003)) are running, which focus on impacts and extreme events. These two projects rely heavily on this one realization of climate change.

In addition, the coupled regional climate model RCAO, which describes the Baltic Sea in a much more detailed manner than the HadCM3 ocean model component, simulates a more modest change in Baltic Sea SST (+3 K) forced by the atmospheric large-scale circulation taken from HadAM3H (Döscher and Meier, 2004). As described here, the large difference in SSTs between the regional coupled RCAO model and the regional atmosphere-only RCA2 (forced by SSTs resulting from a combination of observations and HadCM3 results, see below for details) have a profound impact on the hydrological cycle in the simulated future climate over the Baltic Sea.

Methods

In the present work we use results from the Rossby Centre regional atmosphere–ocean model RCAO (Döscher *et al.* 2002; Döscher and Meier, 2004) (see Table 1 for a list of models used here). The model consists of an atmospheric part RCA2 (Jones, 2001; Jones *et al.* 2004), and an oceanic part RCO (Meier *et al.* 1999, 2003) representing the Baltic Sea. In these experiments RCA2 is run with 50 km horizontal resolution while RCO is run at 6 nmile (approximately 11 km). RCAO is forced with boundary conditions from the Hadley Centre global climate model HadAM3H/HadCM3 (Pope *et al.* 2000; Gordon *et al.* 2000). We investigate one control experiment for the time period 1961–1990, and one simulation of a future climate for the time period 2071–2100. For the future time period we use the emission scenario A2 from the IPCC special report on emission scenarios (Nakićenović *et al.* 2000). These experiments will be referred to as RCAO-CTL and RCAO-A2 in the following. The results of these experiments with RCAO are described in more detail in Räisänen *et al.* (2003, 2004) and Kjellström (2004) for RCA2;

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Table 1 A compilation of the models discussed in the text. Type of model indicates if the model is an atmosphere-only model (A) or a coupled atmosphere–ocean model (AO)

Model name	Horizontal resolution		Type of model	SSTs and sea ice
	Atmosphere	Ocean		
HadCM3	3.75°lat × 2.5°lon	1.25° × 1.25°	AO	Internal
HadAM3H	1.875°lat × 1.25°lon	–	A	HadISST1 and HadISSTscen*
RCA2	0.44° × 0.44°	–	A	As in HadAM3H
RCAO	0.44° × 0.44°	6 nmile (~11 km)	AO (Baltic Sea and Kattegat)	Internal

*See text.

Döscher and Meier (2004) and Meier *et al.* (2004*b*) for RCO; Andréasson *et al.* (2004) and Graham (2004) for hydrological applications; and Meier *et al.* (2004*a*) for sea level changes.

In the experiments at the Hadley Centre, the oceanic component of HadCM3 simulates SST and sea-ice explicitly. The atmospheric model HadAM3H is forced by HadISST1 sea surface observations (Rayner *et al.* 2003) in the control period and by HadISST1 plus a change given by the difference of the HadCM3 scenario and HadCM3 control including a trend over the 30-yr time slice. In the following we refer to this future SST product as HadISSTscen. In RCAO, the boundary conditions from HadAM3H include initial conditions and lateral boundaries every 6 h for the atmosphere. For the ocean, sea surface temperatures and sea ice are the HadISST1/HadISSTscen except for the Baltic Sea and Kattegat where RCO calculates them. To illustrate the geographical configuration in the models Figure 1 shows the land–sea mask of the atmospheric part of the models. It can be noted that, even if the oceanic component of HadCM3 runs on a 1.25° × 1.25° degree grid, the coastlines are taken from the coarser atmospheric model component as seen in Figure 1. This implies that the Baltic Sea has no exchange of water with the North Sea through the straits in HadCM3. Figure 1 also shows the Baltic Sea mask used in the different models. The whole area, including ice-covered parts of the sea, defined by these masks is referred to as the Baltic Sea in the following.

In addition to the experiments with RCAO, one experiment with RCA2 (i.e. only the atmospheric model component) has been performed driven by boundary conditions (now including also SST and sea ice from the HadISSTscen in the Baltic Sea) from the HadAM3H, also under the same emission scenario. This experiment will be referred to as RCA2-A2 in the following. By comparing RCAO-A2 and RCA2-A2 we investigate the influence of coupling of the atmosphere–ocean on the regional scale.

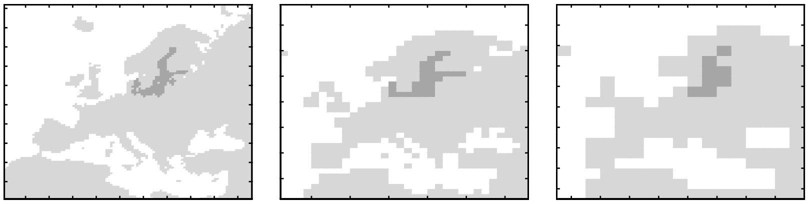

Figure 1 Land–sea masks in the atmospheric part of (a) RCAO, (b) HadAM3H, (c) HadCM3. The dark shaded areas show how the Baltic Sea is defined here

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Results and discussion

Control climate

In the control climate RCAO simulates SSTs that are in close agreement with observations, Figure 2. As discussed in Döscher and Meier (2004) a bias of less than 0.6°C in the annual average is detected in comparison with the climatological observations of Janssen *et al.* (1999). This bias is largest during summer due to a too warm atmosphere at this time of the year. The difference between HadISST1 and the climatological data of Janssen *et al.* (1999) for the considered period might be due to the different resolutions (1° compared to 0.1°) in combination with different observational input and extrapolation techniques. Also other variables in RCAO have been tested against observations. Räisänen *et al.* (2003) compared mean sea level pressure (MSLP), 2 m temperature, cloud cover, wind speed and precipitation of the simulated control climate in RCAO to observations. They found that many aspects of the simulated climate compare well with observations. The main biases for the Baltic Sea runoff area are overestimations of cloudiness (all year) and precipitation (in the winter half of the year). For the Baltic Sea Meier *et al.* (2004*b*) have shown that sea ice, which is strongly dependent on realistic heat fluxes, is realistically simulated in the control climate.

While RCAO simulates SSTs in close agreement with observations HadCM3 is too cold in the control climate during a large part of the year, Figure 2. Compared to the HadISST1 observations HadCM3 SSTs are about 3 K too low as an annual average. The low SSTs in the HadCM3 control period may be related to errors in the large-scale circulation over northern Europe. The Icelandic low is too weak, as illustrated by the summertime MSLP distributions of the two global models in Figure 3. The circulation over the Nordic region differs between HadCM3 and HadAM3H, the latter being close to the observed climate (not shown). The high pressure ridge centred over the Baltic Sea in HadCM3 prohibits warm air from the southwest from entering the region, leading to a cold bias of 2–3 K in near-surface temperature in the entire Nordic area including the Baltic Sea (not shown). This widespread bias in air temperature indicates that the very low SST in the HadCM3 control is a result of the atmospheric forcing and not a result of the oceanic part of the HadCM3. We also looked at the thermocline depths of the Baltic Sea and found them to be in qualitative agreement with recent climate observations and with RCAO in a way that does not allow explaining the large SST biases as a result of flawed mixing depths in HadCM3. Mixing depth is a robust feature. Meier (2002) showed that even an unrealistic density stratification only weakly affects the SST as long as a vertical gradient is present.

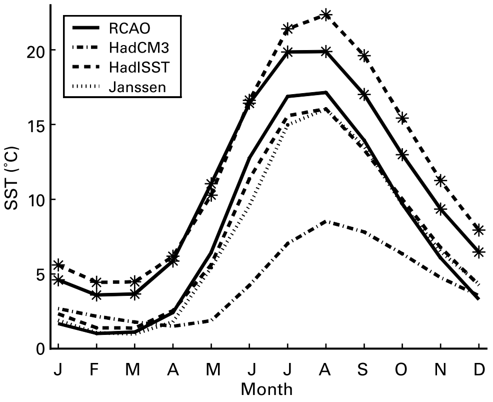

Figure 2 Seasonal cycle of area averaged sea surface temperature over the entire Baltic Sea as defined in Fig. 1. RCAO, HadCM3, HadISST1/HadISSTscen and observations from Janssen *et al.* (1999). (*) denotes the scenario period

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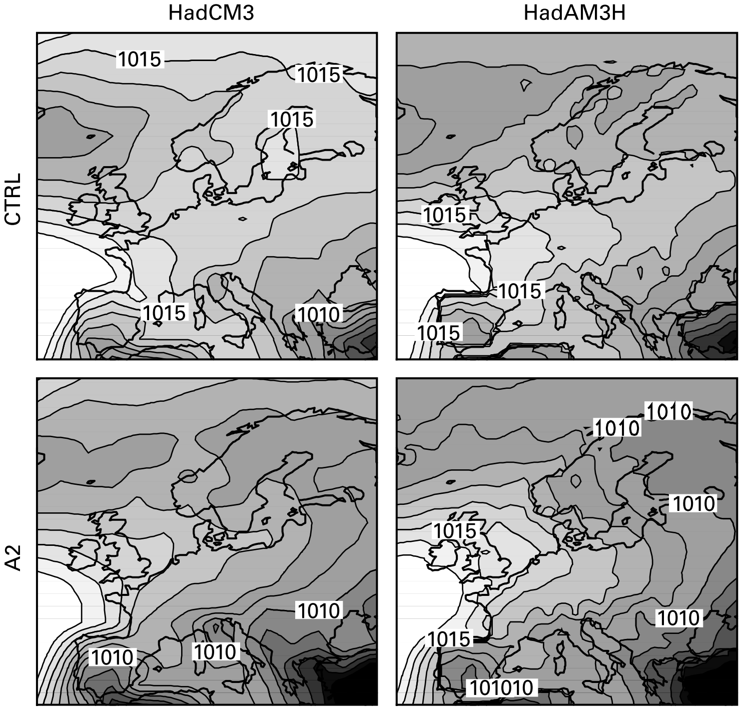

Figure 3 Seasonal average MSLP distribution for summer (JJA). Upper panels shows the control period (1961–1990) and the lower panels the A2 scenario period (2071–2100). Contours at every 1 hPa

Future climate

The simulated annual cycle of SSTs in the future climate is also shown in Figure 2. In RCAO-A2 the increase in SST compared to the control climate is more or less uniform throughout the year, resulting in SSTs being approximately 3 K higher in the future climate, Figure 4(a). This almost uniform increase is very different from what is given by HadCM3. In that model the SST increase has a pronounced maximum in summer, leading to much higher SSTs in HadISSTscen than in RCAO-A2. The SSTs are also higher in the subsequent months throughout the fall and winter, until the two models show similar temperatures in spring, Figure 2. The average increase in SST during June, July and August (JJA) is about 6 K in HadCM3 while it is about 3 K in RCAO-A2, Figure 4(a). As the SSTs differ also the heat fluxes at the surface differ. Shown in Figure 4(b) is the seasonal cycle of the total heat flux (i.e. the net heat exchange between the atmosphere and the ocean) in the two experiments. The largest difference between the two experiments is in August when the SSTs are highest. The differences in SSTs and heat fluxes are evident also in fall and winter, with a stronger heating of the atmosphere by the ocean in RCA2-A2.

The large increase in SSTs in HadCM3 seems to be a result of the too cold control period as described above. HadCM3 is also colder than RCAO in the future climate. But for this period the difference is smaller compared to the difference in the control period leading to a stronger climate change signal in HadCM3, 4.5 K versus 3 K in RCAO for annual mean conditions. Again a look at the large-scale circulation can give some insight into the differences between the models. Figure 3 reveals that the large-scale circulation in the two global models is much closer to each other in the future climate than in the control period. Also, the large-scale circulation resembles the large-scale circulation of the control period in HadAM3H. Thus, advection of warm air masses from the southwest over the Nordic region

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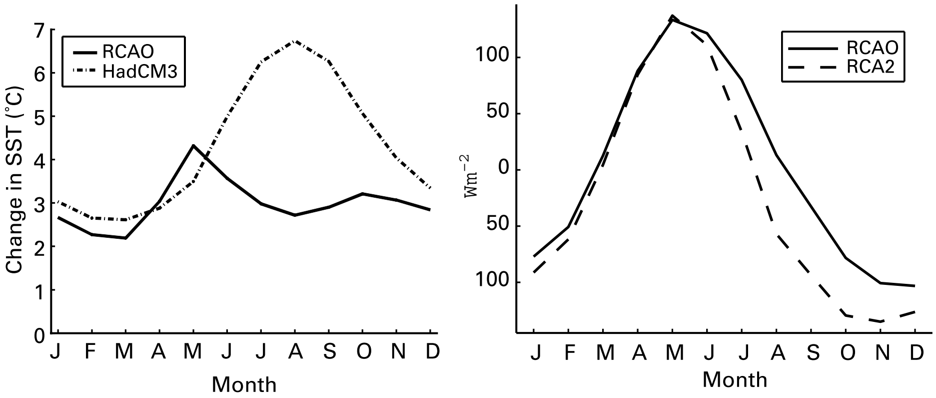

Figure 4 (a) Change in the seasonal cycle of SST. (b) Seasonal cycle of total heat flux at the surface (positive flux is downward) in the A2 experiments. Both (a) and (b) show area averaged conditions over the entire Baltic Sea as defined in Figure 1.

is also possible in HadCM3. It seems that the larger climate change signal in summer in HadCM3 than in HadAM3H for the Nordic region is related to the changes in atmospheric circulation. In the other seasons there are also some differences in the future large-scale circulation between HadCM3 and HadAM3H (not shown) but they do not have the same strong effect on the Baltic Sea SSTs.

The summer air temperature increase between the HadCM3 control and A2 scenario periods indicates a strong local positive anomaly over the Baltic area, a pattern which is confirmed in HadAM3H (forced with HadISSTscen). The pattern, though weaker than in HadAM3H, is also seen in RCA and again but even weaker in RCAO (not shown). Possible reasons for the differences between RCA and HadAM3H are different horizontal resolutions and/or different parametrisations. At this point, we can only state these differences. However we might speculate that, since RCA is better adjusted to regional conditions and resolves orographical effects better, it is more suitable to represent the Baltic region. In the following we will focus on differences between RCA and RCAO that are related to the treatment of the Baltic Sea.

Focusing on the very large difference in SSTs during summer we look into the interannual variability of the SST in the two experiments. Figure 5 shows how the JJA SST varies between the different years in the A2 simulations. The overall long term trend seen in the global model is more or less absent in the RCAO-A2. Figure 5 reveals large differences, of almost 4 K, between the two experiments during some years while in others the differences are small. The degree of correlation between the SSTs is low (0.25). In order to explain the different behaviour between the different years we plot the normalised difference between the two different sets of SSTs against the NAO index taken as the north–south pressure gradient between Iceland and Portugal during summer (Figure 5). The figure clearly illustrates that in summers with a high NAO index (strong N–S pressure gradient) the difference in SST between the two model runs is small. The opposite, i.e. large differences in SST, is true for summers with a low NAO index (weak N–S pressure gradient). The largest NAO signal and its consequent influence on temperature and precipitation is usually found in the winter season (Hurrel, 1995). But also during the rest of the year there exists a clear signal in monthly mean data as illustrated here for the summer and shown earlier by Barnston and Livezey (1987). Next, we select the summers with the most pronounced differences (as illustrated in Figure 5) and make composites for these summers, i.e. one when the NAO index is high and one when it is low. In Figure 6 the mean sea-level pressure (MSLP) in JJA is shown for these composites in

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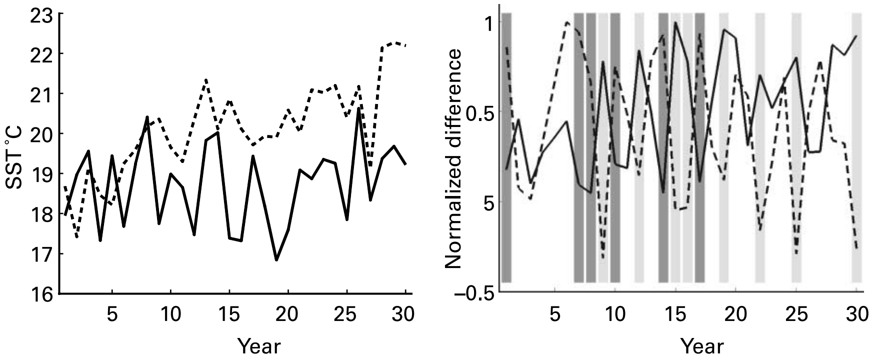

Figure 5 (a) JJA area averaged SST of the Baltic Sea in RCAO-A2 (full line) and in HadISSTscen (dashed). (b) Absolute difference between the SST in RCAO-A2 and HadISSTscen (full line) and NAO index (dashed line). The NAO index is taken as the North–South pressure gradient between one gridbox in southern Iceland and one in central Portugal. Both curves have been normalised so that their respective maximum is equal to one. The light (dark) grey shaded vertical bars group summers with a large (small) difference in SST and low (high) NAO index

RCAO-A2. It is clearly seen how the westerly winds bring air from the North Atlantic towards northern Europe in summers when the NAO index is high. In summers with a low NAO index the circulation over the Baltic Sea region is determined by a weaker and more northerly flow. Figure 6 shows that the MSLP fields in RCAO-A2 and RCA2-A2 are very similar. This is not unexpected since RCA2 preserves the large-scale patterns in MSLP in the model domain as inherited from the global model on the boundaries (Jones *et al.* 2004). However, there are some regional differences in the low NAO-index situation when the average MSLP over the Baltic Sea is more than 0.5 hPa lower in RCA2-A2 than in RCAO-A2. This is an effect of the regional atmospheric response to different SST forcing. Smaller differences between uncoupled and coupled simulations in situations with strong forcing from the boundaries compared to situations with more stationary conditions were also found by Hagedorn *et al.* (2000). They investigated a three-month period during late summer and fall 1995 and found episodes

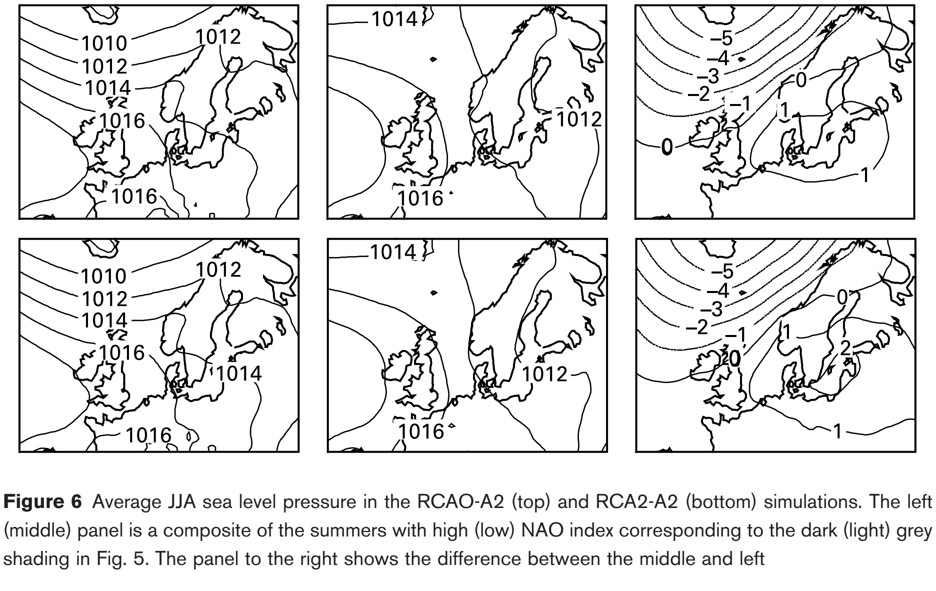

Figure 6 Average JJA sea level pressure in the RCAO-A2 (top) and RCA2-A2 (bottom) simulations. The left (middle) panel is a composite of the summers with high (low) NAO index corresponding to the dark (light) grey shading in Fig. 5. The panel to the right shows the difference between the middle and left

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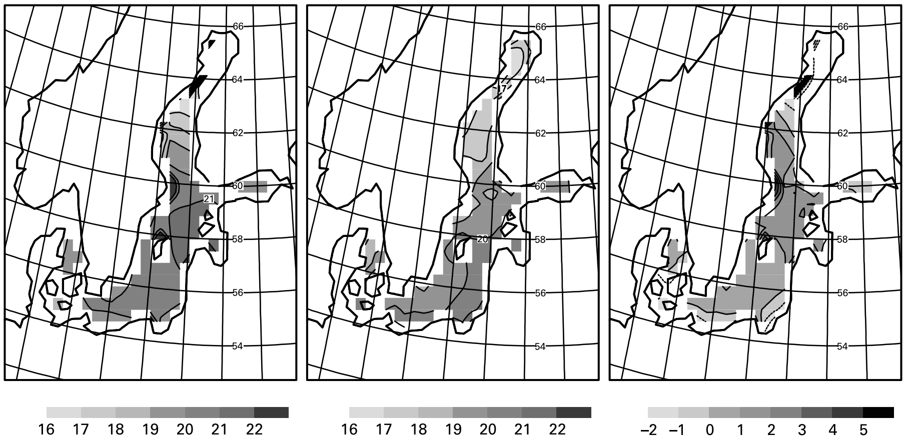

Figure 7 Average JJA SST in summers with high NAO index (dark grey shading in Fig. 5). To the left is the SST used in the uncoupled run RCA2-A2 (HadISSTscen), in the middle is the SST from the coupled RCAO-A2, and to the right is the difference between the two

when the dynamical structure of the atmosphere is influenced on a regional scale by the coupling. Here, we also find a similar response in a climatological sense for the summer months.

Figures 7 and 8 illustrate how the SST in the two experiments differs between these two circulation types. In years with a high NAO index the SSTs in the two experiments are relatively similar in most of the Baltic Sea, Figure 7. The very large difference between the experiments in years with a low NAO index is seen in Figure 8. The SSTs in RCAO-A2 in this circulation type are lower than in the high NAO-index type while the reverse is true in RCA2-A2. Apart from the very different behaviour of the models in the different circulation types there are some common features of the models in both circulation types. One is that in the Bothnian Bay the RCAO-A2 is warmer than HadISSTscen in both circulation types. Another common feature in both circulation types is that the SSTs from RCAO-A2 are lower than those from HadISSTscen in the northern part of the Baltic proper and in the southern part of the Bothnian Sea.

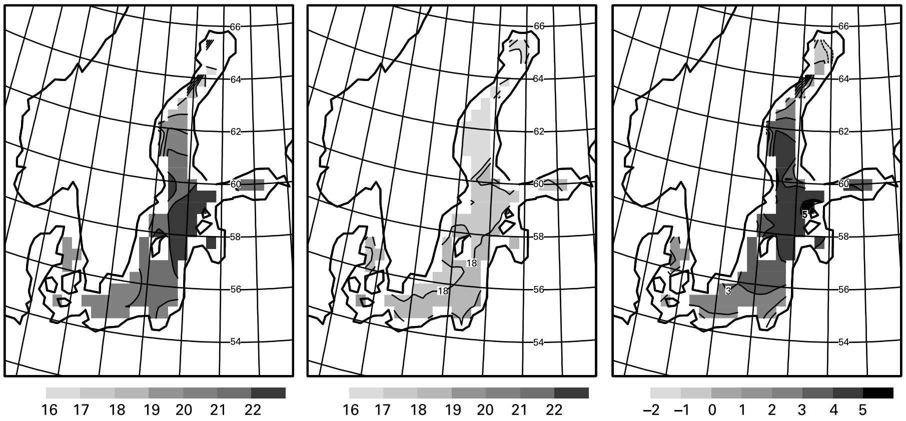

Figure 8 As Fig. 7 but for low NAO index (light grey shading in Fig. 5)

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In the control period there is a link between the summertime SSTs in the Baltic Sea and the regional hydrological cycle in terms of the evaporation but not for precipitation. The data for 1961–1990 (not shown here) have been taken from the Forty-Year European Re-Analysis (ERA40; Kållberg *et al.* 2004). The interannual variability of summertime SSTs from the observational product HadISST1 and evaporation from ERA40, taken as Baltic Sea averages, are positively correlated ($r = 0.62$). For precipitation there is no such correlation. This indicates that, while evaporation is largely determined by the Baltic Sea SSTs, precipitation is determined by other factors. The very high SSTs used in RCA2-A2 give rise to an enhanced hydrological cycle over the Baltic Sea. Table 2 lists area averages of some variables over the Baltic Sea in the latitude band between 58°N and 62°N, where the differences in SST between the two experiments are largest (cf Figure 7 and 8). In the case of a high NAO index the two experiments give relatively similar results even though there is a difference in SST of about 1 K and a difference in the total heat flux of about 60%. The low NAO-index situation, on the other hand, gives rise to large discrepancies between the two experiments. The evaporation is more than twice as large in RCA2-A2 as in RCAO-A2. At the same time the amount of clouds is higher (about 8%), particularly due to more low clouds (15%, not shown). There is also about 50% more precipitation. The difference in precipitation is due to the much larger amount of convective precipitation in this experiment (RCA2-A2) which is triggered by the high SSTs. This implies that the precipitation is more controlled by local conditions in the RCA2-A2 experiment compared to both the control and the RCAO-A2 experiments. The heat fluxes for this area are also very different between the two experiments. In RCAO-A2 the total heat flux from the atmosphere to the ocean is almost the same in the two circulation types due to compensating differences in the different heat flux components enabled by coupled interaction, see Table 2. In RCA2-A2, on the other hand, the differences are very large. In the low NAO-index situation the Baltic Sea is actually losing heat in this area, a clear indication that the A2 scenario SSTs given from HadISSTscen constitute a considerable shift in the climate in the Baltic Sea domain.

The atmospheric difference between the two experiments is mostly confined to the boundary layer over the Baltic Sea. Figure 9 shows differences in temperature and humidity in the lower atmosphere in the area between 58°N and 62°N during JJA in RCA2-A2 and RCAO-A2. First, it can be noted that the atmosphere in this region is colder and drier in the low NAO-index situation. This is true both in the lower free troposphere and the boundary layer except at the 2 m level in the RCA2-A2 simulation where the opposite is true. Further,

Table 2 Area average conditions in JJA over the Baltic Sea between 58°N and 62°N. Shown are averages from the two A2 simulations under the two different circulation types as discussed in the text. The heat fluxes are all net fluxes at the sea surface; positive numbers implies a heat flux from the atmosphere to the ocean

	High NAO index		**Low NAO index**	
	RCA2-A2	**RCAO-A2**	**RCA2-A2**	**RCAO-A2**
SST (°C)	20.2	19.1	21.5	17.5
T_{2m} (°C)	19.9	19.7	20.1	19.2
Evaporation (mm/month)	85.9	64.6	133.7	55.5
Cloud cover (%)	59.5	58.8	71.7	66.3
Precipitation (mm/month)	48.7	45.4	91.4	61.3
Latent heat flux (W m^{-2})	−83.1	−62.4	−129.0	−53.6
Sensible heat flux (W m^{-2})	−10.4	−6.2	−19.6	−4.7
Shortwave heat flux (W m^{-2})	194.4	196.0	167.7	178.8
Longwave heat flux (W m^{-2})	−53.4	−51.4	−53.6	−45.6
Total heat flux (W m^{-2})	47.5	76.0	−34.5	74.9

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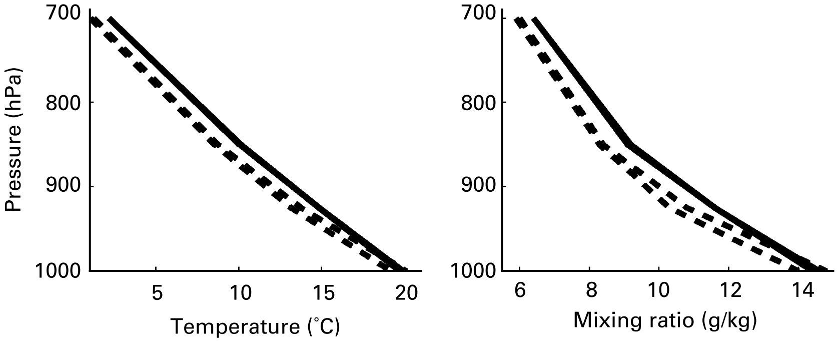

Figure 9 Vertical profiles of temperature and mixing ratio in JJA. The profiles are Baltic Sea averages in the area between 58°N and 62°N. Data are from 700, 850, 925 and 1000 hPa. At 1000 hPa we use the conditions at 2 m above the surface. Full (dashed) line shows a composite of summers with high (low) NAO index. Both RCAO-A2 and RCA2-A2 are shown: when there are differences RCAO-A2 is the colder and drier

the small differences seen at the surface at high NAO-index summers is also seen at higher altitudes (the full lines in Figure 9 are almost indistinguishable from each other). Finally, it can be noted that the larger differences seen at the surface in the low NAO-index situation are also present at higher altitudes.

The geographical differences in precipitation for summers with high NAO index are shown in Figure 10. In RCAO-A2 there is a minimum in precipitation over the entire Baltic Sea while there are local maxima over the surrounding land areas. In RCA2-A2 the pattern follows the SST with the maximum in the eastern part of the central Baltic Sea. It can be seen from Figure 10 that the largest differences in precipitation between the two models are over the Baltic Sea. But there are also differences in surrounding land areas. All coastal areas surrounding the Baltic proper, the Bothnian Sea and the Gulf of Finland receive more than 10% additional precipitation in RCA2-A2 as compared to RCAO-A2 as a mean over the full 30-yr period during JJA. The largest differences are especially east of the Baltic Sea in the vicinity of the area with the largest SST differences, i.e. coastal areas in southern Finland, Estonia and Latvia. In these areas the difference is more than 20%. The impact from the

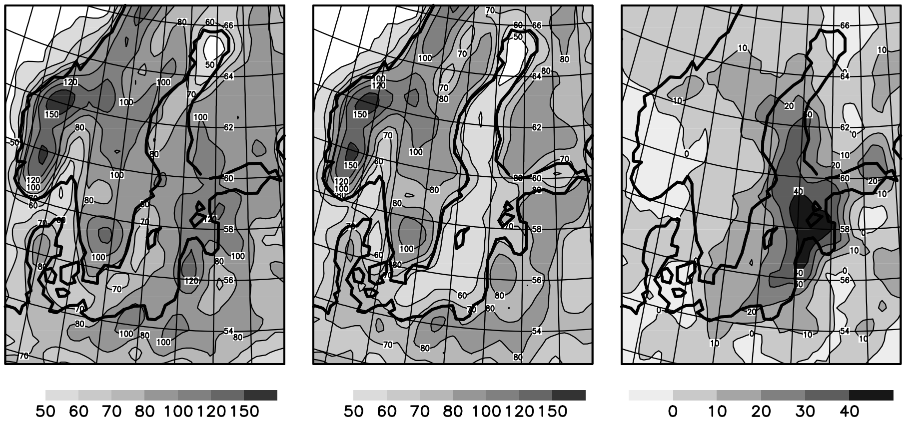

Figure 10 Average JJA precipitation in summers with a low NAO index over the Atlantic (light grey shading in Fig. 5). To the left is the precipitation from the uncoupled run RCA2-A2, in the middle is the precipitation from the coupled RCAO-A2, and to the right is the difference between the two. Unit: mm/month

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choice of model version on a larger area is smaller. For the entire Baltic Sea runoff area the differences in summer is about 5%. In other seasons the differences are smaller.

Summary

In the present study we investigate the impact of different SSTs on the climate in the Baltic Sea region. In particular, we have studied the influence of coupling atmosphere and ocean in a regional climate model.

In the control climate the RCAO model produces SSTs that are similar to those observed, both in terms of absolute numbers and seasonal cycle. SST observations are directly used to force the global atmospheric model HadAM3H, which in turn supplies RCAO with lateral boundary data. In the future climate, on the other hand, the regional and global models differ significantly in the Baltic Sea region. The SSTs used by the global atmospheric model are much higher than those calculated in RCAO, mostly during the summer and to some extent also during fall. We show that these differences are especially pronounced in summers when the NAO index is low. During these years the total heat flux in the uncoupled model is negative over the Baltic Sea in summer, implying that the sea is losing energy to the atmosphere, while the opposite is true in the coupled model. During years when the NAO index is high the difference between the coupled and uncoupled model is much smaller.

HadCM3, which is the underlying global climate model, simulates too low SSTs in summer in the control climate. This bias is shown to be related to errors in the large-scale circulation. SSTs in HadCM3 are lower than those simulated by RCAO, distinctly in the control period and to a smaller extent also in the scenario period. These differences lead to the very strong climate change signal which is later added to the observed climate and imposed in the HadAM3H future scenario simulation. Small SST differences during high NAO situations indicate that differences in atmosphere-to-ocean forcing between the regional and global models involved are less severe when there is a strong atmospheric forcing from the lateral boundaries. Generally, a well validated high-resolution regional model such as RCAO appears to better represent the Baltic Sea than either a relatively coarse resolution global coupled model, which must be adjusted to the regional scale, or a higher resolution global atmosphere model forced by prescribed SSTs. Differences between coupled and uncoupled atmosphere–ocean models must be more pronounced during low NAO years. This is due to an enhanced dynamic freedom for the internal solution in the regional model in response to different representations of the Baltic Sea surface. Regional feedbacks between ocean and atmosphere in the coupled system are not to be expected, neither on the inter-seasonal scale (due to seasonal memory of the Baltic Sea) nor on the shorter scale (as investigated in non-published sensitivity experiments).

The impact of the choice of coupled versus uncoupled model on the atmosphere is shown to be mostly confined to the Baltic Sea area itself. We also show that there are also notable differences in the surrounding land areas. Finally we note that, for the Baltic Sea runoff area, it would be preferable to use results from the high-resolution regional coupled model than regional atmosphere-only models with prescribed SSTs. In particular, atmosphere-only models should be treated with care, at least for the summer months in the Baltic Sea runoff area.

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