Papers

doi:10.5697/oc.56-2.167
OCEANOLOGIA, 56 (2), 2014.
pp. 167–189.

New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas

KEYWORDS
Coupled model
Atmosphere
ocean-sea-ice interaction
Baltic Sea
North Sea
COSMO-CLM
NEMO
OASIS3

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Received 25 October 2013, revised 12 February 2014, accepted 26 February 2014.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Abstract

This paper introduces a newly established coupled atmosphere-ocean-ice system with the regional climate model COSMO-CLM and the ocean-sea-ice model NEMO for the North and Baltic Seas. These two models are linked via the OASIS3 coupler. Experiments with the new coupled system and with the stand-alone COSMO-CLM model forced by ERA-Interim re-analysis data over the period from 1985 to 1994 for the CORDEX Europe domain are carried out. The evaluation results of the coupled system show 2-m temperature biases in the range from −2.5 to 3 K. Simulated 2-m temperatures are generally colder in the coupled than in the uncoupled system, and temperature differences vary by season and space. The coupled model shows an improvement compared with the stand-alone COSMO-CLM in terms of simulating 2-m temperature. The difference in 2-m temperature between the two experiments are explained as downwind cooling by the colder North and Baltic Seas in the coupled system.

1. Introduction

According to the description in IPCC (2001) the climate system is an interactive system which contains different components such as the atmosphere, hydrosphere (the oceans and river systems), different ice forms on the Earth's surface, land surface and all ecosystems. All of these components interact with each other. In order to simulate the climate system, all of them, therefore, need to be taken into account.

Beside global climate models, regional climate models are, in general, used to describe the state of the atmosphere in a limited area on a regional scale with higher resolution. In practice, the interactive feedback of the atmosphere and the ocean at that scale is often neglected. The necessary ocean surface data is taken from an external data set, for example, a global climate simulation or a sea surface data analysis. However, examining the atmosphere separately would yield an incomplete picture of the real climate system, because the links between the different climate system components would be missing.

The use of prescribed surface ocean data might lead to an inaccuracy of the model results. For instance, Kothe et al. (2011) studied the radiation budget in the COSMO-CLM regional climate model for Europe and North Africa using ERA40 reanalysis data (Uppala et al. 2005) as the lower boundary forcing. The authors evaluated the model outputs against re-analysis and satellite-based data. The results show an underestimation of the net short wave radiation over Europe, and more considerable errors over the ocean. Because the lower boundary condition was prescribed with ERA40, these errors in radiation over the ocean could be due to wrongly assumed albedo values over ocean and sea ice grids.

In the same way, ocean models often use atmospheric forcing datasets without active feedback from the atmosphere. Griffies et al. (2009) investigated the behaviour of an ocean-sea-ice model with an atmospheric data set as the upper boundary condition. In that study, the difficulties in using a prescribed atmosphere to force ocean-sea-ice models are recognised. First of all, it is very often the case that atmospheric forcing datasets may not be 'tuned' specifically for the purpose of an ocean-sea-ice model experiment. For example, the above study used global atmospheric forcing data for the ocean and sea-ice model from Large & Yeager (2004). However, this dataset was originally evaluated over the ocean, not over sea ice and, thus, gives better results over open water. Moreover, the authors also demonstrated that the error consequent upon decoupling the ocean and sea ice from the interactive atmosphere could be large. One problem that is very likely to crop up is the error in the ocean salinity, due to the fresh water inflow, especially precipitation. The prescribed precipitation can cause a dramatic drift in ocean salinity. The second problem is the error in sea-ice area, which can lead to a wrong balance of the Earth's radiation and an unrealistic heat transfer between atmosphere and ocean. The findings from this paper show the necessity of giving an active atmosphere feedback to the ocean instead of using a forcing dataset.

The ocean-atmosphere interaction has been taken into account in many AOGCMs (Atmosphere-Ocean General Circulation Models), as shown in Giorgi (2006). However, on a global scale, the local characteristics of marginal seas cannot be resolved (Li et al. 2006) and these seas are, in fact, not well represented by AOGCMs (Somot et al. 2008).

On the regional scale, there are a few coupled atmosphere-ocean-ice model systems available for different European domains. In 2003, Schrum et al. 2003 studied a coupled atmosphere-ice-ocean model for the North and Baltic Seas. The regional atmospheric model REMO (REgional MOdel) was coupled to the ocean model HAMSOM (HAMburg Shelf Ocean Model), including sea ice, for the North and Baltic Seas. The domain of the atmospheric model covers the northern part of Europe. Simulations were done for one seasonal cycle. Their study demonstrated that this coupled system could run in a stable manner and showed some improvements compared to the uncoupled model HAMSOM. However, when high-quality atmospheric re-analysis data was used, this coupled system did not have any added value compared with the HAMSOM experiment using global atmospheric forcing. Taking into account the fact that, high quality re-analysis data, like ERA40 as mentioned above, is widely utilised in state-of-the-art model coupling, coupled atmosphere-ocean models must be improved to give better results. In addition, the experiments were done for a period of only one year in 1988, with only three months of spin-up time, which is too short to yield a firm conclusion on the performance of the coupled system. Moreover, for a slow system like the ocean, a long spin-up time is crucial, especially for the Baltic Sea, where there is not much dynamic mixing between the surface sea layer and the deeper layer owing to the existence of a permanent haline stratification (Meier et al. 2006).

Kjellstroem et al. (2005) introduced the regional atmospheric ocean model RCAO with the atmospheric model component RCA and the oceanic component RCO for the Baltic Sea, coupled via OASIS3. The coupled model was compared to the stand-alone model RCA for a period of 30 years. The authors focused on the comparison of sea surface temperature (SST). In 2010, Doescher et al. (2010) also applied the coupled ocean-atmosphere model RCAO but to the Arctic, to study the changes in the ice extent over the ocean. In the coupling literature, the main focus is often on the oceanic variables; air temperature has not been a main topic in assessments of coupled atmosphere-ocean-ice system for the North and Baltic Seas.

Ho et al. (2012) discussed the technical issue of coupling the regional climate model COSMO-CLM with the ocean model TRIMNP (Kapitza 2008) and the sea ice model CICE (http://oceans11.lanl.gov/trac/CICE); these three models were coupled via the coupler OASIS3 for the North and Baltic Seas. The authors carried out an experiment for the year 1997 with a three-hourly frequency of data exchange between the atmosphere, ocean and ice models. The first month of 1997 was used as the spin-up time. In their coupled run, SST shows an improvement compared with the stand-alone TRIMNP. However, one year is a too short time for initiating and testing a coupled system in which the ocean is involved.

Another coupled system for the North and Baltic Seas is the atmospheric model RCA4 and the ocean model NEMO, coupled via OASIS3, from the Swedish Meteorological and Hydrological Institute (SMHI). This system was evaluated for the period from 1970 to 1999 in a report by Dieterich et al. (2013). The authors revealed that heat fluxes and near surface temperatures of the seas were in good agreement with the satellite-based estimates. However, in this study, horizontal transports in the North Sea were seriously underestimated, and as a result, the salinities were not well simulated.

Our aim is to look at the impact of the North and Baltic Seas on the climate of central Europe. We want to look at the climate system in a more complete way with an active atmosphere-ocean-ice interaction in order to obtain a model system that is physically more consistent with reality. For the first time we couple the regional climate model COSMO-CLM and the ocean-ice model NEMO for the North and Baltic Seas. COSMO-CLM and

NEMO were chosen because they are both open-source community models, and they have been extensively used in the European domain. Moreover, NEMO has the possibility to simulate sea ice, which is important for North and Baltic Seas. In addition, NEMO has also been successfully coupled to COSMO-CLM for the Mediterranean Sea (Akhtar et al. 2014, submitted). In this paper, we have evaluated this new coupled system, focusing on the influence of the active ocean on air temperature.

Firstly, we give a brief description of the model components in section 2 along with the modifications necessary to adapt them to the coupled system. Section 3 introduces the experiment set-ups. In section 4, we describe the evaluation data and the method for determining the main wind direction that we use in this work. The results are given in section 5, including an evaluation of our coupled system against observational data and a comparison of the coupled and uncoupled results. We discuss the results in section 6, compare our results with other studies and explain the differences between the two experiments. We bring the paper to a close with the conclusions in section 7.

2. Model description

A regional atmosphere-ocean-ice coupled system was established based on the regional atmospheric model COSMO-CLM version cosmo4.8_clm17 (Boehm et al. 2006, Rockel et al. 2008) and the regional ocean model NEMO version 3.3 (Nucleus for European Modelling of the Ocean) including the sea-ice module named LIM3 (Louvain-la-Neuve Ice Model version 3; Madec 2011). The two models have differences in domain areas, grid sizes, and time steps; therefore, in order to couple them we use the Ocean Atmosphere Sea Ice Soil Simulation Software (OASIS3) coupler (Valcke 2006). It acts as an interface model which interpolates temporally and spatially and exchanges the data between COSMO-CLM and NEMO. The exchanged fields from COSMO-CLM to NEMO are the flux densities of water, momentum, solar radiation, non-solar energy and of sea level pressure; and from NEMO to COSMO-CLM they are SST and the fraction of sea ice.

2.1. The atmospheric model COSMO-CLM

The atmospheric model COSMO-CLM is a non-hydrostatic regional climate model. The model setup complies with CORDEX-EU in the CORDEX framework (Coordinated Regional climate Downscaling Experiment) (Giorgi et al. 2006). The domain covers the whole of Europe, North Africa, the Atlantic Ocean and the Mediterranean Sea (Figure 1a). The horizontal resolution is 0.44° (approximately 50 km) and the time step is 240 seconds; it has 40 vertical levels. COSMO-CLM applies a 'mixed' advection

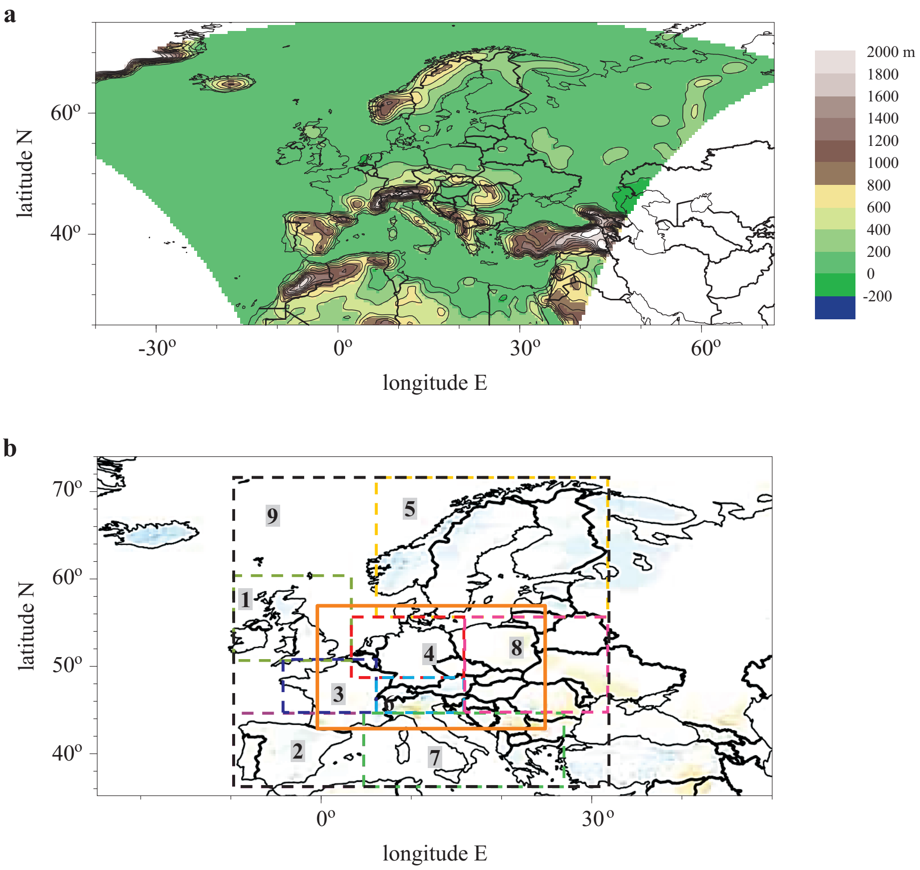

Figure 1. a) COSMO-CLM model domain (topography with contours every 200 metres from ERA-Interim re-analysis data). b) Nine PRUDENCE evaluation areas within the COSMO-CLM domain; the solid orange box is the weather classification area)

scheme, in which a positive-definite advection scheme is used to approximate the horizontal advection while vertical advection and diffusion are calculated with a partially implicit Crank-Nicholson scheme. In COSMO-CLM, several turbulence schemes are available; in our experiments, we used the so-called 1-D TKE-based diagnostic closure, which is a prognostic turbulent kinetic energy (TKE) scheme. It includes the interaction of air with solid objects at the surface (roughness elements).

We modified the model code to adapt it to the coupled mode. Originally, COSMO-CLM did not have sub-grid scale ice; a grid over the ocean is either fully covered with ice or fully open-water. Thus, a grid size of 50×50 km^2 implies a rather coarse approximation of real ocean conditions. In addition, COSMO-CLM does not have an ice mask over the ocean; an ocean grid is handled as sea ice or open water depending on the SST. If the temperature is below the freezing point of water, which is −1.7°C in COSMO-CLM, the surface is considered to be sea ice. When the temperature is equal to or higher than the freezing point, COSMO-CLM handles the surface as open water. However, a freezing point of water of −1.7°C is applicable to sea water with a salinity of approximately 35 PSU (Practical Salinity Units). In contrast, brackish sea water like the Baltic Sea has a much lower salinity than the average salinity of the World Ocean. At the centre of the Baltic Sea, the Baltic Proper, the salinity is only 7–8 PSU, and this decreases even further northwards to the Bothnian Sea, Bothnian Bay and Gulf of Riga (Gustafsson 1997). The freezing point of this brackish water should therefore be higher than −1.7°C. When the freezing point is so low, the sea ice cover in the Baltic Sea in COSMO-CLM will be substantially underestimated. Therefore, when coupling COSMO-CLM with the ocean model NEMO, the sea ice treatment is modified in the surface roughness and surface albedo schemes. In the current albedo calculation scheme, COSMO-CLM attributes fixed albedo values to the water surface (0.07) and the sea ice surface (0.7) for the whole grid cell. In the coupled mode, as COSMO-CLM receives the ice mask from NEMO, it can now calculate the weighted average of the albedo based on the fraction of ice and open water in a grid cell.

The surface roughness length of the sea ice and open-water grid is calculated in the turbulence scheme of COSMO-CLM. The roughness length of sea ice surface is fixed at the value of 0.001 m. But unlike sea ice, water roughness varies strongly with the wind speed; therefore, the Charnock formula $z_0 = \alpha_0 u^2/g$ is used, where $\alpha_0 = 0.0123$, u is the wind speed and g is the acceleration due to gravity.

As in the surface albedo scheme, when COSMO-CLM is coupled to NEMO, the grid-cell roughness length is the weighted average of sea ice-covered and water-covered areas.

2.2. The ocean model NEMO

We used the NEMO ocean model version 3.3 adapted to the North and Baltic Sea region. This model setup is described by Hordoir et al. (2013) in a technical report in 2013. The horizontal resolution is 2 minutes (about 3 km), and the time step is 300 seconds. There are 56 depth levels of the ocean. The flux correction for the ocean surface was not applied in our experiments.

The domain covers the Baltic Sea and a part of the North Sea with two open boundaries to the Atlantic Ocean; the western boundary lies in the English Channel and the northern boundary is the cross section between

Scotland and Norway. The model domain of NEMO can be seen on Figure 6 (see p. 183).

For the Baltic Sea, the fresh water inflow from the river basins plays a crucial role in the salinity budget. Meier & Kauker (2003) found that the accumulated fresh water inflow caused half of the decadal variability in the Baltic salinity. It is, therefore, very important to take the rivers into consideration when modelling Baltic Sea salinity. In this paper, we use the daily time series from E-HYPE model outputs for the North and Baltic Seas (Lindström et al. 2010). The input for the E-HYPE model is the result from the atmospheric model RCA3 (Samuelsson et al. 2011) forced by ERA-Interim re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011).

2.3. The coupled system COSMO-CLM/NEMO

The atmospheric and ocean models are coupled by the coupler OASIS3. The results from Meier & Kauker (2003) show that half the variability of salinity in the Baltic Sea is caused by fresh water inflow and the other half is related to the exchange of sea water between the North and Baltic Seas through the Kattegat. This water exchange process is determined by the wind stress and the sea level pressure difference between the two seas. Therefore, when coupling the atmosphere to the ocean, we send the wind fluxes and the sea level pressure from COSMO-CLM to NEMO to get an appropriate inflow of water from the North Sea to the Baltic Sea. On the atmospheric side, the exchanged fields are the flux densities of water (Precipitation-Evaporation), momentum, solar radiation, non-solar energy and sea level pressure.

On the ocean side, we send SST and the fraction of sea ice to COSMO-CLM. This exchange process is done every 3 hours. The fields are gathered by OASIS3 and then interpolated to the other model's grid. Apart from the coupled ocean area, COSMO-CLM takes the lower boundary from ERA-Interim data for other sea surface areas.

3. Experiment setup

In order to test and evaluate the coupled model, we set up two experiments:

COSMO-CLM stand-alone: The atmospheric model was run in the uncoupled mode. In this case, the initial and lateral boundary conditions including the lower boundary were taken from ERA-Interim re-analysis. This experiment is later referred to as the 'uncoupled run'.

Coupled COSMO-CLM and NEMO: The atmospheric and ocean models were run together in the coupled mode and exchanged information. At the two lateral boundaries of NEMO, temperature and salinity were prescribed by Levitus climatology data (Levitus et al. 1994, Levitus & Boyer 1994). At the upper boundary of the ocean model, atmospheric forcing was taken from COSMO-CLM. The COSMO-CLM model, on the other hand, received forcing from NEMO at its lower boundary. This experiment is later referred to as the 'coupled run'.

The ocean and sea-ice model was spun up in stand-alone mode from January 1961 to December 1978. After that, both atmospheric and ocean-sea-ice models were spun up from 1979 to 1984 in the coupled mode. The simulations which were used for evaluation start from 1985.

4. Evaluation data and method

Since the COSMO-CLM and NEMO models were coupled for the North and the Baltic Seas for the first time, we assessed the coupled system by comparing its results with the uncoupled COSMO-CLM run. In addition, we also evaluated the coupled model performance by using E-OBS data (Ensembles daily gridded observational dataset for temperature in Europe, version 8.0) (Haylock et al. 2008). The dataset was available daily on a 0.50° regular latitude-longitude grid, covering the whole domain of our coupled model. The period of evaluation is from 1985 to 1994 within the available period of E-OBS data (1950–2012) and of ERA-Interim (1979–2012).

Results are considered for eight sub-regions as already used in the PRUDENCE projects and described by Christensen & Christensen (2007). Region 9 encompasses all eight sub-regions as shown in Figure 1b.

The coupled model's SST was evaluated against SST data from Advanced Very High Resolution Radiometer (AVHRR) (Reynolds et al. 2007). This gridded SST analysis is provided on a daily base with a resolution of 0.25° using satellite data and in situ data from ships and buoys.

When comparing the coupled and uncoupled systems, we expected differences in the results due to the active interaction between atmosphere and ocean-ice in the coupled model. To examine the cause of the possible differences, we determined the main wind direction over the study period by adapting the weather classification method from Bissolli & Dittmann (2001).

Bissolli & Dittmann (2001) presented an objective weather type classification for the German Meteorological Service. Their study area was an extended central European area (Figure 1 in Bissolli & Dittmann (2001)). Since those authors focused on Germany, the area of Germany was given higher weighting (factor three), compared to the surroundings (weighting factor two) and the rest of the area (weighting factor one). However, in the present study, we did not focus on weather conditions in Germany but a broader area of Europe. Thus, here equal weights were used. It should be emphasised that if the area is too large, different weather conditions could occur at once such that no main wind direction could be determined. Therefore, we classified the wind direction in the area as chosen in Bissolli & Dittmann (2001) (Figure 1b).

Bissolli & Dittmann (2001) classified the weather types based on four meteorological elements: geopotential height, temperature, relative humidity at different pressure levels and horizontal wind components; this yielded a total of 40 different weather types. However, in this paper, we only looked at the main wind direction; therefore we did not take aspects of temperature and relative humidity into consideration. In addition, we only look at the wind direction at the 950 hPa level to avoid the influence of local topography.

5. Results

5.1. Evaluation of the coupled COSMO-CLM/NEMO model

Firstly, we looked at the areal mean 2-m temperature for the PRUDENCE sub-regions during the period 1985–1994. Figure 2 shows the biases of 2-m temperature from the coupled and uncoupled runs compared with E-OBS data for sub-region 1 (British Isles) and sub-region 8 (eastern Europe). It can be noticed that the temperature deviation of the coupled run from the E-OBS data is, most of the time, smaller than the uncoupled run's biases, especially for eastern Europe. It is a general finding for all sub-regions (not shown in Figure 2), that the coupled run has improvements compared to the uncoupled run.

We also examined the areal distribution of the temperature biases. The daily differences of 2-m temperature between the coupled run and the E-OBS data ($T_{COUP}–T_{E-OBS}$) were averaged for the yearly and multi-yearly seasons in the period between 1985 and 1994. Figure 3 shows the yearly and four seasonal means of temperature biases over the whole of Europe (region 9 on Figure 1b). Overall, temperature biases range from −2.5 to 3 K; biases vary in time and space, and among sub-regions and seasons. When it comes to the annual mean, the temperature bias is small; a large part of the domain has biases within −0.5 and 0.5 K. Only in some small areas in southern Europe do biases range from −1.5 to 1.5 K. Among all seasons, the most pronounced biases occur in winter with a higher temperature simulated over the east of the Scandinavian mountain range. Apart from that warm bias, there is a cold bias up to −2.5 K in winter over the rest of the domain. The spatial distribution of temperature biases in spring, summer and autumn

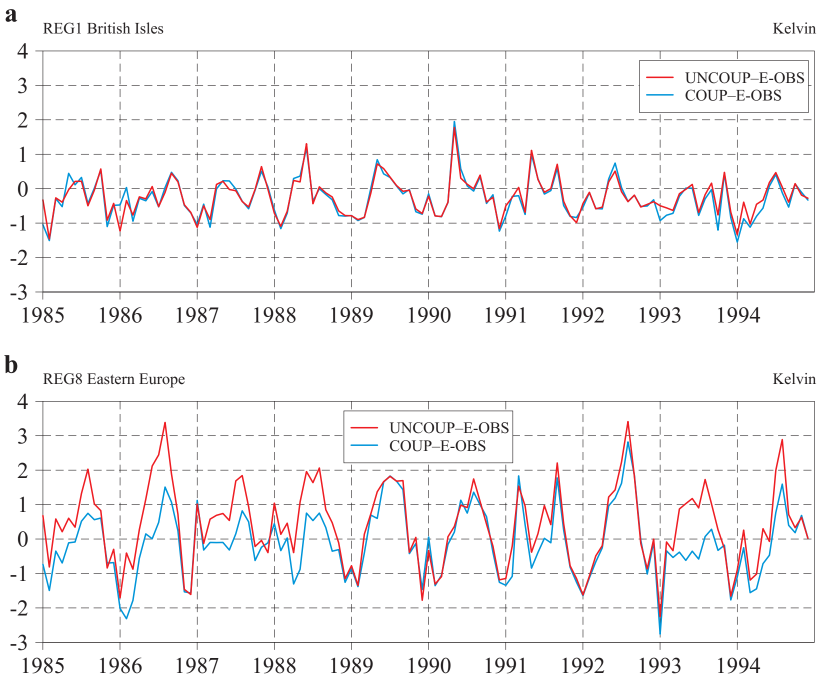

Figure 2. Monthly means of the difference in 2-m temperature between the coupled, uncoupled runs and E-OBS data over land in the period 1985–1994. Temperature is averaged for: a) sub-region 1, the British Isles; b) sub-region 8, eastern Europe)

resembles the yearly mean distribution; the temperature of the coupled run is colder in the north and warmer in the south compared with E-OBS data. However, the bias magnitudes vary among those three seasons, with summer showing the largest warm bias among the three seasons, up to 3 K in southern Europe.

Figure 4 shows the differences in the multi-year mean and multi-year seasonal mean between the coupled model's SST and AVHRR SST. It should be emphasised once again that only the North and Baltic Seas are coupled to the atmosphere; over the other oceans, COSMO-CLM is forced by ERA-Interim SST as in the uncoupled experiment. Therefore, the biases on sea areas other than the North and Baltic Seas are actually the biases of ERA-Interim compared with AVHRR data. Overall, the SST produced by the coupled model is not largely different from the AVHRR SST; biases range from −0.6 K to 0.6 K. Over the southern Baltic Sea, the biases are sometimes larger than the rest of the North and Baltic Seas. However, these biases lie within much the same range as those of ERA-Interim over the Atlantic Ocean or Mediterranean Sea. Notice that the biases seem to be

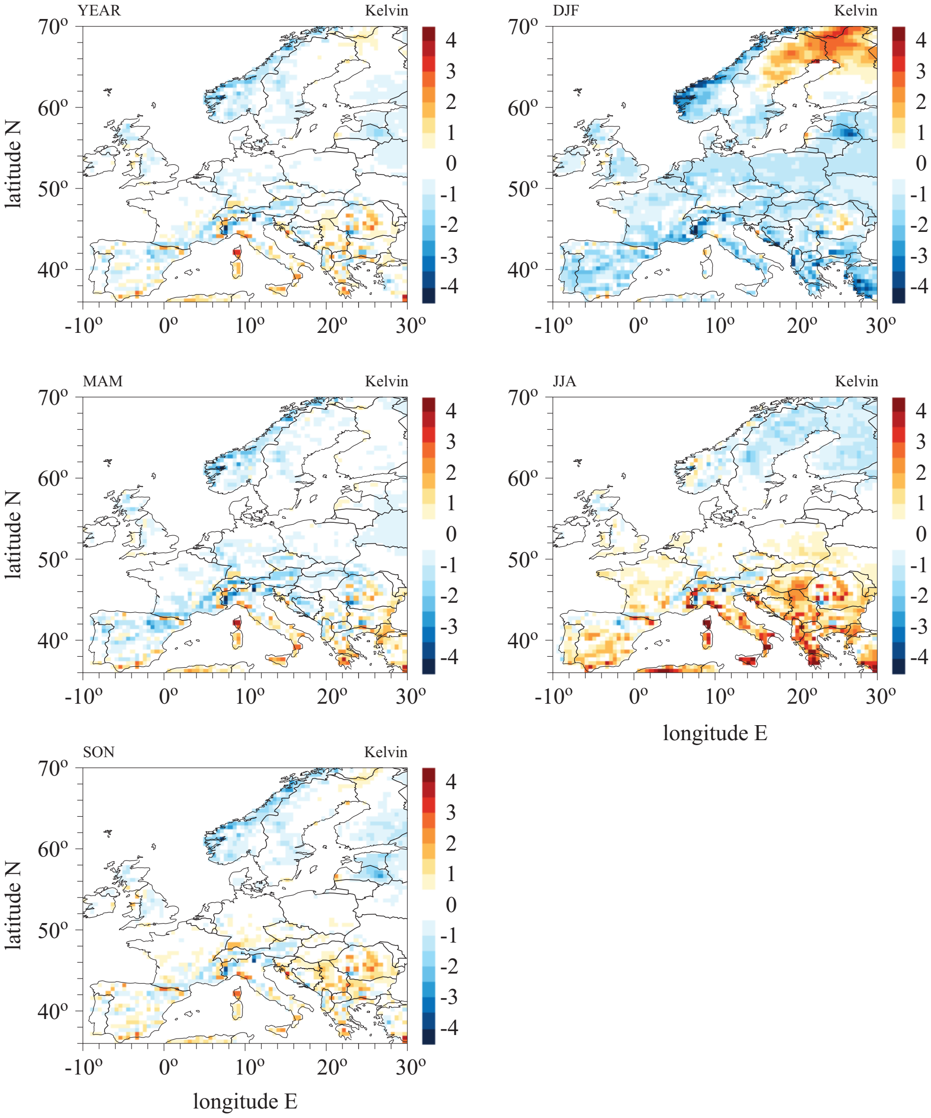

Figure 3. Yearly and seasonal means of the differences in 2-m temperature over land between the coupled run and E-OBS data, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{E-OBS}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

larger along coastlines. This can be explained by the difference in spatial resolution between the reference data and the model's output (AVHRR SST has a resolution of 0.25° while NEMO has a resolution of 2 minutes). Different resolutions result in different land-sea masks and therefore larger biases along coastlines.

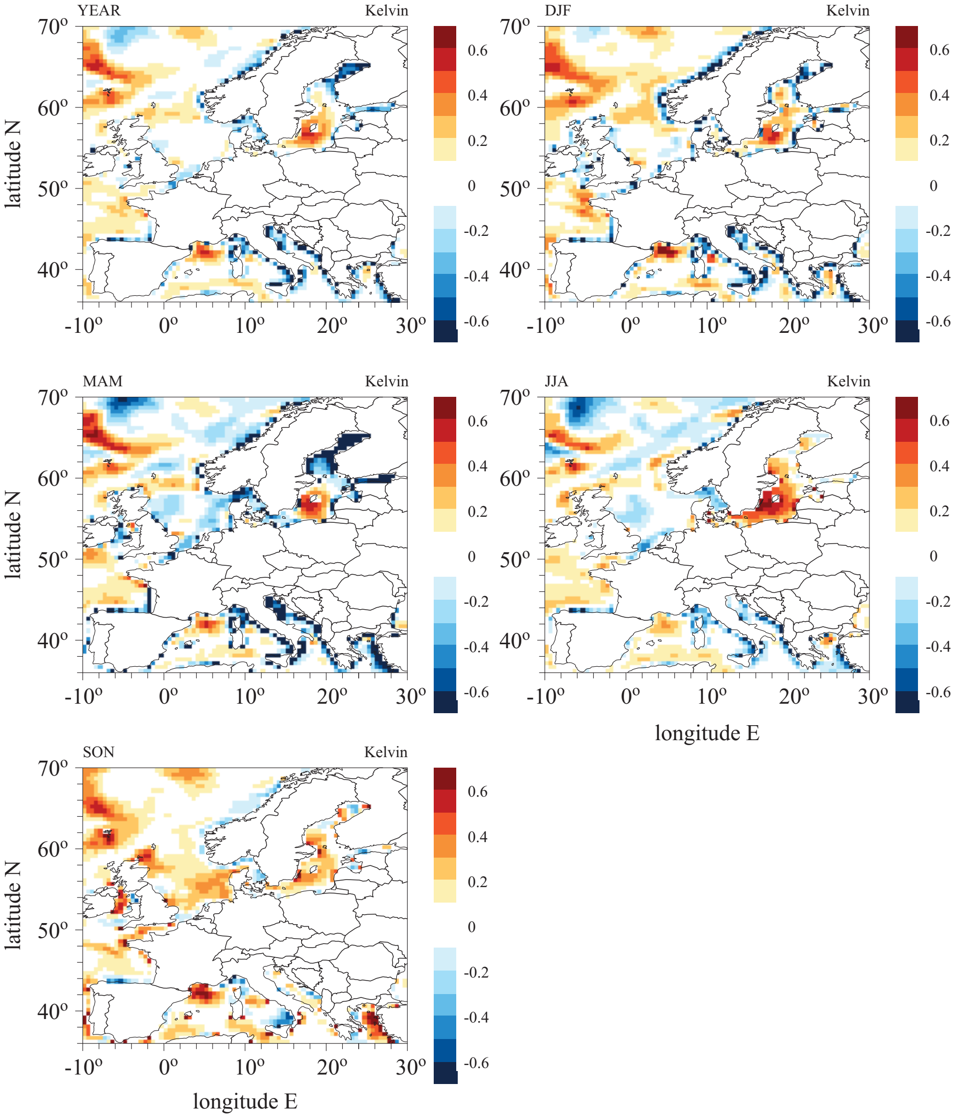

Figure 4. Yearly and seasonal means of the differences in SST between the coupled run and AVHRR data, averaged over the period 1985–1994 (SST_{COUP}–SST_{AVHRR}). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

5.2. Comparison between the coupled and uncoupled experiments

To compare the coupled atmosphere-ocean-ice system and the atmospheric stand-alone model after a 10-year simulation, the multi-year annual

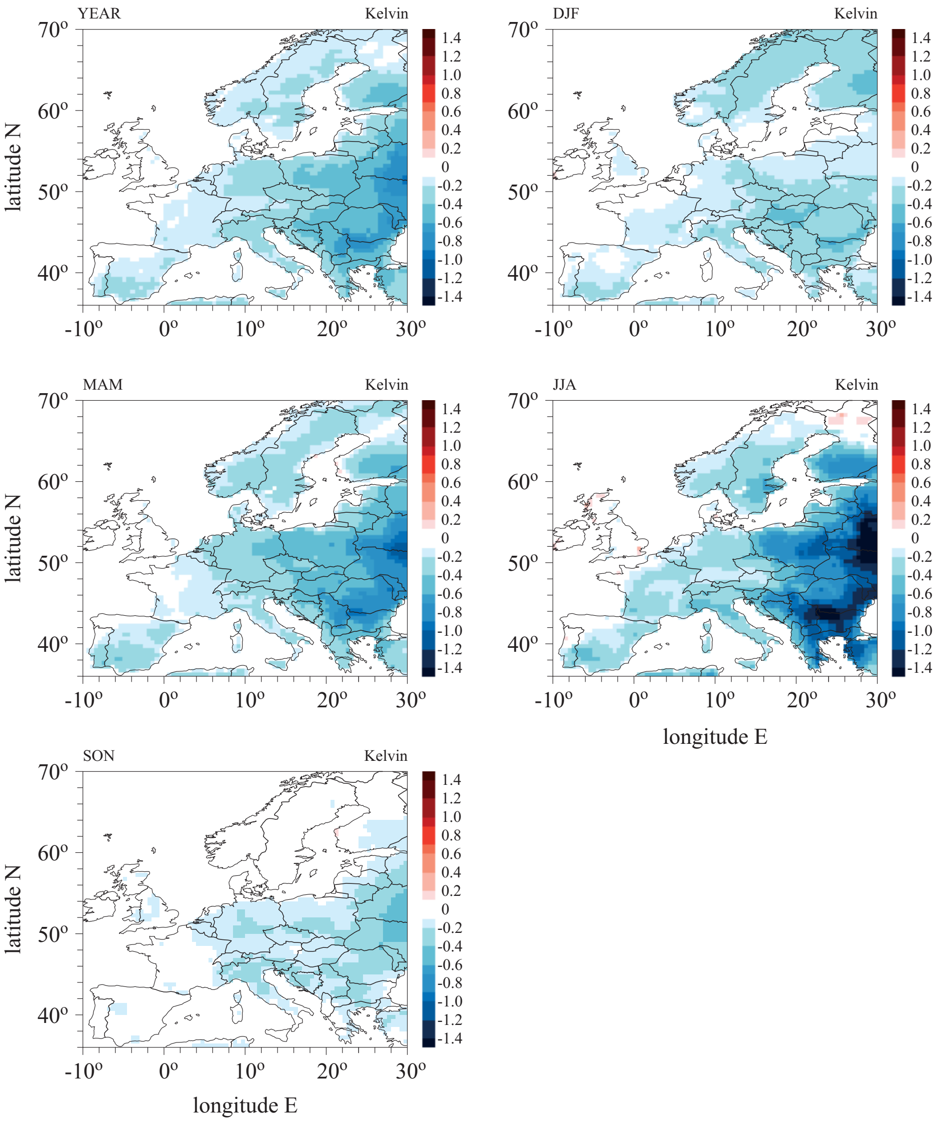

Figure 5. Yearly and seasonal means of the differences in 2-m temperature over land between the coupled and uncoupled runs, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{UNCOUP}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

and multi-year seasonal mean of the difference between the two runs are calculated for all sub-regions. Figure 5 shows the differences in 2-m temperature (T_{COUP}–T_{UNCOUP}) over Europe. It can be seen that there are obvious differences between the two experiments. Looking broadly at the yearly and all seasonal means, we see that the coupled run generates a lower

2-m temperature than the uncoupled run, leading to the negative differences in Figure 5. For the 10-year mean, the differences in 2-m temperature between two runs are as much as −1 K. Of the four seasons, summer shows the largest differences: the maximum deviation in the average summer temperature is up to −1.5 K. The spring temperature does not vary so much: the coupled 2-m temperature departs by ca −1 K from the uncoupled one. Apart from that, winter and autumn exhibit only minor differences in mean temperature, up to −0.4 K. The differences are pronounced over eastern Europe, but rather small over western and southern Europe. Eastern Europe is situated a long way from the North and Baltic Seas, so the large differences there cannot be explained by the impact of these two seas. They could be due to this region's sensitivity to some change in the domain. Another possibility might be that the 10-year simulation time is not long enough. But this feature is not well understood and needs to be tested in a climate run for over 100 years; we anticipate that the differences over eastern Europe will then not be so pronounced.

Besides looking at the whole of Europe, we also examined sub-regions to see what influence coupling had in different areas. The monthly temperature differences between the two runs and E-OBS data were averaged for each sub-region during the period 1985–1994. The biases of the coupled and uncoupled runs were quite different over the sub-regions. Some sub-regions, like the British Isles, the Iberian Peninsula and France (sub-regions 1, 2 and 3 respectively), showed only small differences. On the other hand, over central and eastern Europe (sub-regions 4 and 8 respectively), the differences were much larger. Figure 2 shows that the biases between the coupled and uncoupled runs are different by up to 2 K in sub-region 8, but minor in sub-region 1.

The two runs, coupled and uncoupled, reveal noticeable differences; and the temperature deviations are different for different sub-regions. This indicates that the air-sea interaction in the coupled system is actively working and does indeed impact on the air temperature in a large part of the domain.

6. Discussion

The COSMO-CLM model was evaluated for the European domain in many earlier studies. For example, Boehm et al. (2004) produced a mean bias of the 2-m temperature over land ranging from −4 to 1.5 K; a large part in the east of their domain had the bias from −2 K. Another work by Boehm et al. (2006) showed a cold bias from −6 to −1 K over the whole domain. Going southward of the domain, the biases became larger. The COSMO-CLM simulation carried out in these two studies had a cold bias, too. Our coupled model results are clearly an improvement in comparison with this cold bias.

Many earlier COSMO-CLM evaluation studies show biases and bias patterns similar to those revealed here. Roesch et al. (2008) showed that the 2-m temperature from a COSMO-CLM simulation had biases from −3 to 3 K. A noticeably warm bias appeared to the east of the Scandinavian mountain range; in spring and summer, the general bias pattern was a cold bias in the north and a warm bias towards the south of the domain. This is in good agreement with our results as shown in Figure 3; the distribution of warm and cold bias is similar.

Jaeger et al. (2008) found a warm bias in south-eastern and southern Europe in summer; this agrees closely with our results in Figure 3. The results from Jacob et al. (2007) have a warm bias (~ 3 K) compared with observations over the Scandinavian sub-region in winter: this is also in good agreement with our results.

Overall, it can be seen that other studies evaluating the COSMO-CLM model show similar distributions and bias magnitudes. Therefore, we conclude that, compared with the observational data of our coupled COSMO-CLM and NEMO system, shown from −2.5 to 3 K in Figure 3, the biases are within those reported for the stand-alone COSMO-CLM model.

As can be seen in Figure 5, the coupled system produces lower 2-m temperatures than the uncoupled model COSMO-CLM, but the differences vary substantially from one sub-region to another. One question that arises here is whether cold air is actually the result of air-sea feedback and whether we can attribute the changes in the coupled system to the impact of the North and Baltic Seas. In order to answer this question, we examined the SST in the North and Baltic Seas and the impact of the main wind direction on the temperature differences.

In stand-alone mode, COSMO-CLM receives SST from ERA-Interim reanalysis data, whereas in coupled mode, it is forced by SST from the NEMO model over the North and Baltic Seas (over other sea areas, COSMO-CLM receives the ERA-Interim SST). Figure 6 shows the differences between SST of the coupled run and of ERA-Interim as used in the uncoupled run. These differences are given over the North and Baltic Seas only because over other seas and oceans, both experiments use the same ERA-Interim SST and thus the difference is zero. As can be seen, the SST values produced by NEMO are lower than those from ERA-Interim data; the differences in the annual average over most parts of the North and Baltic Seas are between −0.2 and −0.6 K. the most pronounced differences occur in summer with NEMO SSTs up to about −1 K colder in the far north of the Gulf of Bothnia. Winter and autumn show weaker differences. This result of SSTs

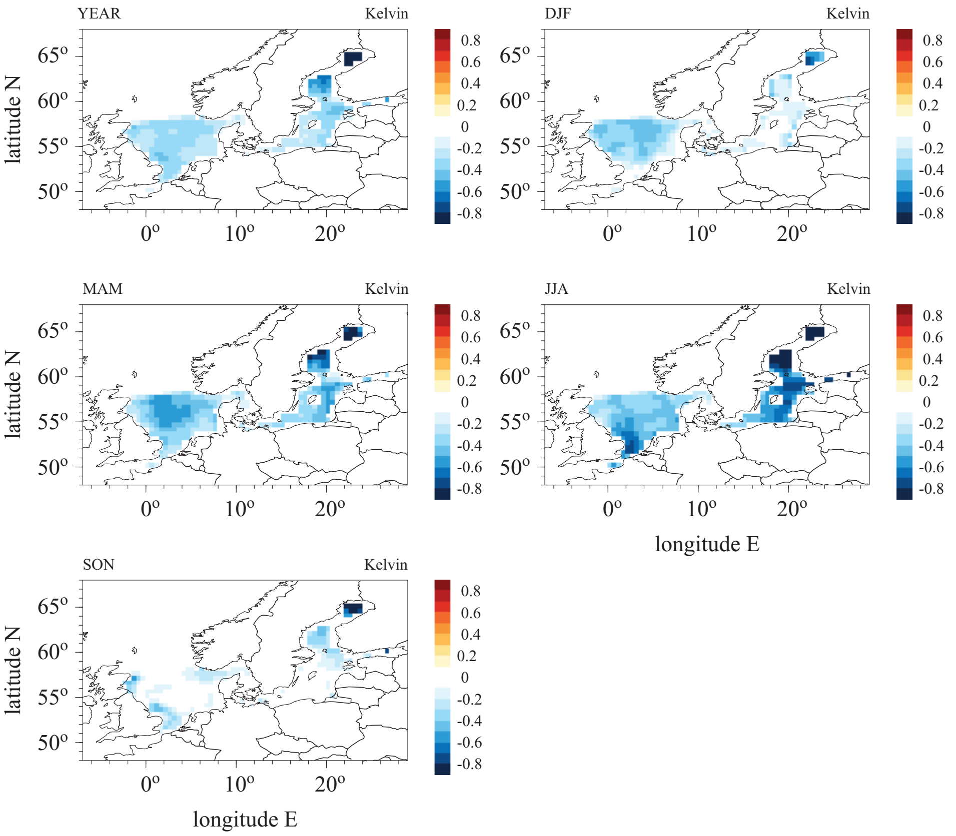

Figure 6. Yearly and seasonal means of the differences in sea surface temperature between the coupled run and the ERA-Interim re-analysis data, averaged over the period 1985–1994 for the North and Baltic Seas (SST_{COUP}–$SST_{ERA-Interim}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

from the coupled model is in good agreement with the results reported by Dieterich et al. (2013). In that work, the authors compared SSTs from their coupled RCA4 and NEMO models with a satellite-derived record (Loewe 1996, Høyer & She 2011). They also found that the SSTs from their coupled model were low compared with observations, especially in summer.

Looking at Figures 5 and 6, one sees that the 2-m air temperature and SST from the coupled experiment are both lower than those of the uncoupled experiment. Furthermore, the seasonal differences in SST follow those in 2-m temperature: the large difference in SST corresponds to the large difference in 2-m temperature and vice versa. That implies a link between the SST of the North and Baltic Seas and the 2-m temperature as well as the impact of these marginal seas on the European climate. The low 2-m temperatures in the coupled experiment lead to a shallower mixed-layer depth; as a result, the heat capacity of the ocean's upper layer falls and the SSTs remain lower than the ERA-Interim data. As a feedback, reduced heat loss from the ocean to the atmosphere results in lower air temperatures.

We classified the main wind direction over the 10-year period from 1985 to 1994 for both coupled and uncoupled experiments. The results show that the two model systems agree well on the average wind classification; therefore, only the wind rose from the coupled experiment is shown here. On Figure 7, the lines illustrate the direction where the wind comes from, the circles show the frequency of wind direction, and the colours show the wind speed corresponding to each direction and each frequency. The dominant wind direction over the 10 years is north-west with the highest frequency of about 22%; winds blowing directly from the north and west also occur for more than 10% of the time. South-westerly winds blow $>10\%$ of the time but have a relatively low speed. In 50% of the cases, south-west winds occur at speeds <5 m s^{-1} and in most cases <10 m s^{-1}. Meanwhile, the maximum speed of north-westerly winds is 20 m s^{-1}. This dominant wind direction and the colder sea surface have a cooling effect, resulting in colder air over the continent.

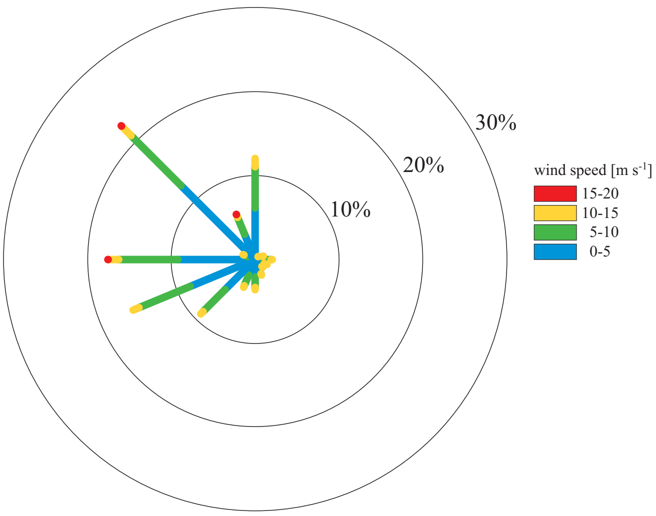

Figure 7. Wind directions from the coupled run over the period 1985–1994 in the weather classification area. The colours show the areal average wind speed at 950 hPa. The percentages show the frequency of wind direction occurrence

To separate the impact of the North and Baltic Seas from other factors, we calculated the 2-m temperature differences when the wind comes from two directions: north-west and south-west. Over 10 years, the days on which the main wind direction was from the north-west or south-west were separated and the average temperature differences on those days were calculated for the two wind directions respectively. Figure 8 shows the difference of the 2-m temperature between the coupled and uncoupled runs when the dominant wind direction was a) north-west and b) south-west. It is obvious that the difference between two runs is higher in case of north-westerly winds, temperatures being noticeably colder in the coupled run. The lower air temperature is the consequence of air masses cooling over colder SSTs in the coupled run, where the wind is blowing from the North and Baltic Seas.

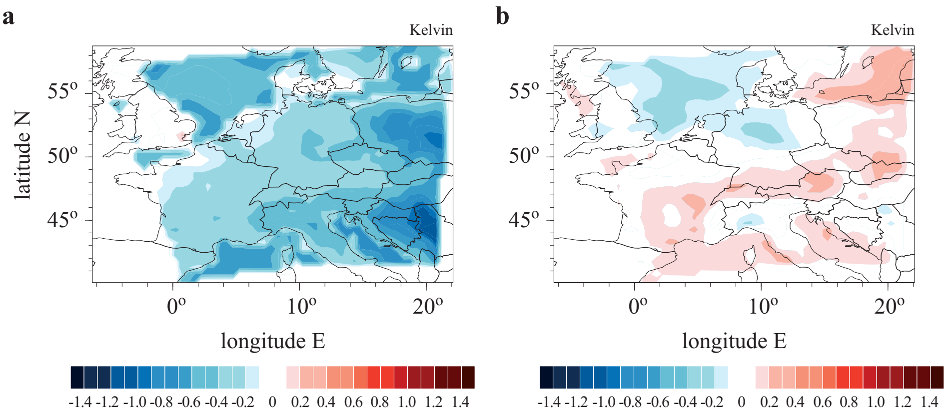

Figure 8. Mean 2-m temperature differences between the coupled and uncoupled runs, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{UNCOUP}$) for the weather classification area, for the dominant wind directions: a) North-West, or b) South-West

7. Conclusion

In this work, we have presented an atmosphere-ocean-ice model system COSMO-CLM/NEMO for the CORDEX Europe domain with the North and Baltic Seas actively coupled to the atmosphere via the coupler OASIS3. The results from this new coupled system were evaluated with observational data and compared with the results from the stand-alone COSMO-CLM model focusing on the 2-m temperature. We also examined the differences between the coupled and uncoupled model runs.

The coupled run has large biases compared with the E-OBS reference data. However, we showed that these biases are in the usual range of biases found in other COSMO-CLM studies. Compared with observations, the coupled model in this study has, most of the time, smaller biases than the uncoupled atmospheric model. These improvements are more pronounced in sub-regions that are more strongly influenced by the North and Baltic Seas than in others.

It has to be kept in mind that the uncoupled run was forced by SSTs from the ERA-Interim re-analysis, which are already of very high quality and better than SSTs from global coupled climate model runs, which have to be resorted to if regional climate projection runs are done.

An evaluation stratified with mean wind direction revealed the impact of the coupled North and Baltic Seas on the simulated air temperatures. Differences between coupled and uncoupled simulations are larger downwind of the seas (especially in central and eastern Europe). In any case, the new coupled regional climate model system COSMO-CLM/NEMO performs well and is a more complete and physically consistent model system than the stand-alone COSMO-CLM.

This paper is a first look at the impact of the North and Baltic Seas on the climate of the European continent. In our next studies, we would like to carry out experiments for longer periods in order to gain a deeper insight into the influence of these seas on the climate of Europe.

Acknowledgements

We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu).

The authors thank the Centre for Scientific Computing (CSC) of the Goethe University Frankfurt and the German High Performance Computing Centre for Climate and Earth System Research (DKRZ) for supporting parts of the calculations. We acknowledge support from the German Federal Ministry of Education and Research (BMBF) under grant MiKliP: DECREG/01LP1118B.

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