The consideration of North and Baltic Seas in regional climate modelling with the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO

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Abstract

The main objective of this PhD work is to assess the impact of fine-scale air-sea interaction on the performance of a regional climate prediction model in marginal sea regions. Focus is on the North and Baltic Seas, the largest marginal sea area in the mid-latitudes. Motivation for this work is to better understand the interaction between the different components of the climate system, namely atmosphere, ocean and sea-ice. In addition to that, the sea regions of interest, the North and Baltic Seas, are orographically complex and cannot be resolved by a global ocean model. The ice coverage on the Baltic Sea is underestimated in the stand-alone atmospheric model COSMO-CLM due to the low water freezing temperature value assumed, which is not applicable for such brackish water body. To fulfil the thesis goal, a new regional coupled atmosphere-ocean-ice system was developed for these two seas, named COSMO-CLM/NEMO. The two-way coupling system involves active feedback from both component models: the limited-area climate model COSMO-CLM and the regional ocean model NEMO-NORDIC.

The coupled system COSMO-CLM/NEMO for the North and Baltic Seas was used to study the impact of sea surface temperature and sea ice on the atmosphere on different topics. The long term impact of the North and Baltic Seas was studied through 15-year long simulations driven by European Center for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (ERA-Interim) data. Furthermore, to see whether the marginal sea modelling can advance the simulation of extreme climate events, the coupled model was used to reproduce six extreme snowband phenomena over the Baltic Sea in simulations driven by ERA-interim data. Last but not least, the role of the North and Baltic Sea model in improving long-term regional climate prediction was examined. Two sets of experiments with coupled and uncoupled models, each set has five independent decadal hindcasts forced by global climate model, were carried out.

All results were compared with observations and the stand-alone atmospheric model COSMO-CLM results. In all experiments, COSMO-CLM/NEMO showed good agreement with observations. Improvements compared with the uncoupled COSMO-CLM were also found. Coupling was found to affect the air temperature not only around the coupled sea region but also inland. The convective snowbands over the Baltic Sea were successfully reproduced by the coupled model. The high contrast of temperature in the air column, as well as considerably high amounts of surface heat fluxes exchanged between air and sea could not be simulated by COSMO-CLM without the help of reanalysis data. The coupled model also provided better forecasts in decadal scales compared with the uncoupled model and the global model. The added predictability came from the initialized regional seas and better simulated sea surface temperatures by the ocean model.

The impact of the North and Baltic Seas on the climate of the surrounding regions is in certain phases dominated by the North Atlantic Oscillation (NAO) activity. In this thesis, the relation between the NAO and the marginal sea influences was studied. It is confirmed by this study that, in strong phases, the NAO can overpower the impact of the local seas. During dominant phases of NAO, the European climate is mainly governed by large-scale circulation. On the other hand, the local seas play an important role in determining the European climate when NAO is in weak phases.

The added value of the coupled model raises promising perspectives for research in this field. It points to a potential benefit of using the coupled atmosphere-ocean-ice system for climate prediction in the region surrounding the North and Baltic Seas. Along with that, it is still a challenge to complete the model representation of the climate system by adding more climate components (such as a hydrological model). Further improvement of the coupled system can be achieved by coupling for a larger sea region, or by trying to reduce remaining low performance of the coupled model in some areas with a better configuration of the current system.

Kurzfassung

Hauptziel dieser Doktorarbeit ist die Untersuchung des Einflusses der Randmeere auf das regionale Klima, mit dem Schwerpunkt auf Nord- und Ostsee, den beiden größten Randmeeren in den mittleren Breiten. Zu diesem Zweck wurde ein regionales Atmosphäre-Ozean-Eis-System für diese beiden Meere entwickelt, das sogenannte COSMO-CLM/NEMO. Es handelt sich dabei um eine Zweiwege-Kopplung mit aktiver Rückmeldung zweier Komponentenmodellen: einerseits dem regionalen Klimamodell COSMO-CLM und andererseits dem Ozeanmodell NEMO-NORDIC. Motivation dieser Studie ist ein besseres Verständnis zu gewinnen hinsichtlich des Zusammenspiels verschiedener Komponenten des Klimasystems, nämlich der Atmosphäre, dem Ozean und dem Meereis. Zudem besitzt die untersuchte Meeresregion, die Nord- und Ostsee, eine komplexe Topografie, die von Globalmodellen oftmals nur unzureichend aufgelöst werden kann. Darüber hinaus wird Meereis über der Ostsee vom eigenständigen Atmosphärenmodell nicht gut simuliert.

Mit Hilfe des Kopplungssystems COSMO-CLM/NEMO für Nord- und Ostsee wurde der klimatische Effekt der Oberflachenwassertemperatur sowie des Meereises in verschiedenen Fallstudien untersucht. Langfristige Auswirkungen von Nord- und Ostsee wurden basierend auf fünfzehnjährlichen Simulationen mittels ERA-Interim-Reanlysedaten angetriebener Simulationen untersucht. Ebenfalls betrachtet wurde der Einfluss der Randmeere auf extreme Wetterereignisse, die jeweils nur von kurzer Dauer sind. Das gekoppelte Modell wurde durch ERA-Interim-Daten angetrieben, um das Verhalten von Schneedbändern über der Ostsee zu simulieren. Nicht zuletzt wurde dabei die Rolle von Nord- und Ostsee in langfristigen regionalen Klimavorhersagen bewertet. Insgesamt wurden für das gekoppelte sowie das ungekoppelte (mittels des Globalmodells angetrieben) Modell jeweils fünf Experimente dekadischer Vorhersagen durchgeführt.

Sämtliche Ergebnisse wurden sowohl mit Beobachtungen als auch mit Ergebnissen des eigenständigen COSMO-CLM Modells verglichen. COSMO-CLM/NEMO zeigte eine generell gute Übereinstimmung mit den Beobachtungsdaten. Daneben wurden Verbesserungen im Vergleich mit dem ungekoppelten COSMO-CLM detektiert.

Die Kopplung beeinflusste die Lufttemperatur nicht nur in der Nähe der Randmeere sondern auch im Binnenlandbereich. Das gekoppelte Modell reproduzierte die konvektiven Schneebänder über der Ostsee deutlich besser als das ungekoppelte Modell. Sowohl der hohe Kontrast der Lufttemperaturen als auch die großen Wärmeflüsse an der Meeresoberfläche konnten mit dem COSMO-CLM ohne Reanalysedaten nicht simuliert werden. Verglichen mit dem ungekoppelten Modell und dem Globalmodell

waren die dekadischen Vorhersagen des gekoppelten Modells verbessert. Dies kann einerseits auf die Initialisierung und andererseits auf im Ozeanmodell realistischer simulierte Oberflächenwassertemperaturen zurückgeführt werden. Nord- und Ostsee beeinflussen das regionale Klima unter gewissen Umständen entscheidend. In dieser Arbeit wurde die Intensität der Auswirkungen der nordatlantischen Oszillation (NAO) mit jener der Randmeere ins Verhältnis gesetzt. Es konnte dabei gezeigt werden, dass eine hohe Aktivität der NAO die Auswirkung der Randmeere deutlich überwiegen kann. Befindet sich die NAO jedoch in einer schwachen Phase befindet, spielen die lokalen Meere eine wichtige Rolle für das europäische Klima. Die Ergebnisse für das gekoppelte Modell sind vielversprechend und bieten eine erfolgversprechende Perspektive für weitere Untersuchungen auf diesem Gebiet. Weitere Verbesserungen des gekoppelten Systems könnten mittels der Kopplung einer größeren Meeresregion oder durch eine verbesserte Konfiguration des aktuellen Systems erzielt werden. Die Kopplung mit anderen Klimakomponenten wie beispielsweise dem Wasserabfluss durch Flüsse stellt für zukünftige Entwicklungen in der Klimaforschung eine weitere Herausforderung dar.

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Contents

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To my parents Pham Huu Giao and Cao Thi Thai Van

Chapter 1

Introduction

With the rapid development of computer technology, climate models have become a powerful tool for studying the complex physics of the climate system. Especially for climate change studies and in the extreme weather prone areas where climate evolution can have associated consequences for human lives and the environment, climate modelling provides one of the most important sources of information not only for scientists, but also for policy makers and the public in general. Climate models, nowadays, offer a wide range of forecasts from monthly to decadal, and climate projections with estimations for hundreds of years into the future.

Information on the development of the climate is often required in some specific regions of interest. Hence, climate studies often need to deal with small-scale atmospheric circulations affected by local orography or land surface. Regional climate modelling is a solution to produce detailed climate simulations for selected regions (McGregor, 1997). In European region, many studies have been carried out to improve the understanding of the processes in the North and Baltic Seas (Feistel et al., 2008; Jaagus et al., 2010; Jeworrek et al., 2017; Vihma and Haapala, 2009; Quante and Colijn, 2016). These studies show that the European climate is highly influenced by these two marginal seas. In order to properly present the marginal sea climate system, we need to understand the interaction between the atmosphere and the ocean. In this chapter, this interaction and the important characteristics of the North and Baltic Seas are highlighted. The difficulties and challenges in climate modelling are also discussed with focus on the European region, considering the roles of the North and Baltic Seas. Some concerns and questions, which could help to advance the understanding of the North and Baltic Seas' impact on the European climate, are addressed in this thesis.

1.1 The atmosphere-ocean interaction and feedbacks

The atmosphere and ocean are parts of the climate system, which consists of the atmosphere, hydrosphere (oceans, rivers, lakes), cryosphere (snow, ice), lithosphere (land surface) and biosphere. All of these climate components are connected to and influence each other. The oceans and atmosphere, in particular, interact with each other in many different ways via exchanging fluxes such as heat fluxes, moisture fluxes and momentum fluxes. The oceans are the largest reservoir of water on Earth, they can absorb and store heat more efficiently than land or ice surface. Oceans act as an effective heat storage as the heat stored in the deep layers of the oceans is released very slowly to the atmosphere, much more slowly than over land. The heat that oceans absorb in summer, for example, allows the air temperature not to decrease dramatically in winter. As a result, the maritime climate is often mild and moist. Due to their capacity of storing large quantities of heat and moisture, oceans play a very important role in regulating the climate in time scales from months to decades. It should be noted here that local seas can also potentially affect the atmosphere in shorter time scales starting from several days due to reasons, such as, rapid sea ice changes in the Baltic Sea.

There are many feedback mechanisms between the oceans and the atmosphere. The momentum from the atmosphere acts as forcing field for the ocean to generate surface waves. Ocean surface waves, in turn, slow down the atmosphere movements, weakening the intensity of the momentum. That is a negative feedback, in which, one activity tends to reduce another activity. An example of a positive feedback is the atmosphere-sea-ice feedback. When the atmosphere gets warmer, sea ice melts to water. Since sea water has lower reflectivity than sea ice, less solar radiation gets reflected and more is absorbed by the earth. As a result, the atmosphere gets warmer and amplifies the change in sea ice.

The total heat exchange between the oceans and the atmosphere is the sum of different heat fluxes: short wave (solar) radiation, incoming and outgoing long wave radiation to/from the oceans, latent and sensible heat fluxes. Due to its low surface reflectivity (low albedo), the solar radiation can easily penetrate the sea water; and therefore, a large portion of solar short wave reaching the sea surface is absorbed by the ocean. This energy can heat the sea water column till the depth of 100 to 200 m. The ocean transmits the energy back to the atmosphere in form of long-wave radiation (Fig. 1.1). This process increases the air temperature and subsequently the air humidity. The water content, in turn, emits the radiation back to the ocean, reducing the total loss by long wave radiating. The largest heat loss for the ocean comes from the latent heat loss because of the evaporation of sea water into the air.

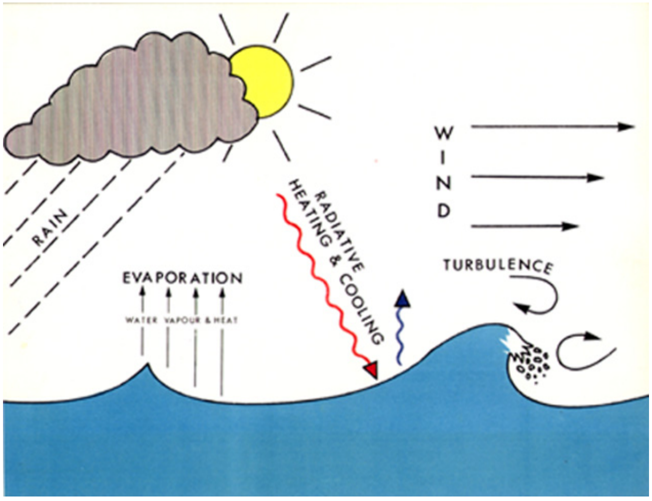

FIGURE 1.1: Air-Sea heat flux exchange [source: `https://noc.ac.uk`].

Like any other oceans, the North and Baltic Seas also strongly interact with the atmosphere, contributing to determine the climate of European region (Gröger et al., 2015; Jaagus et al., 2010). The differences in the water mixing condition and the existence of haloclines in the North and the Baltic Seas, resulting in the different influences of these two seas on the regional climate system, are discussed in detail in Section 1.2.

1.2 The marginal North and Baltic Seas

The North and Baltic Seas are the largest mid-latitude marginal seas (Backhaus, 1996). These two seas are significantly influenced by, and in turn, also influence the surrounding areas. They are, therefore, very important component of the climate system in European region. For Germany, which is located directly south of the two seas and has coastlines with both, the North and Baltic Seas are crucial factor that determine its climate. Although nearby and connected to each other, the two have very distinguished characteristics. The North Sea has strong vertical mixing during winter, but forms a thermal stratification during summer. Meanwhile, in the Baltic Sea, a strong persistent halocline exists throughout the year. The Baltic Sea, hence, has much more limited exchange with the atmosphere than the well-mixed North Sea. The heat hindered in the Baltic Sea makes it important for the long-term climate in European region. The depth of the halocline in the Baltic Sea varies during the year, making the available heat capacity change accordingly. This leads to a stronger annual cycle of sea surface temperatures (SSTs) over the Baltic Sea compared with the North Sea. Another reason for the damped SSTs of the North Sea includes the large inflow from the Atlantic ocean. The Baltic Sea, in contrast, is only connected to the open North Sea via relatively narrow straits, the Skagerrak and Kattegat. This geographical characteristic limits not only the heat exchange but also the exchange of water between the two seas (Gustafsson, 1997; Gustafsson and Andersson, 2001). Due to this semi-enclosed basin characteristic and the abundant fresh water inflow from the surrounding rivers, a large area of the Baltic Sea is brackish water, with a wide salinity gradient from north-east to south-west. The salinity starts reducing from about 20 PSU (Practical Salinity Unit) at the straits of Kattegat and Skaggerak. At the center of the Baltic Sea, the Baltic Proper, the salinity is only 7–8 PSU; this decreases even further northwards to the Bothnian Sea, Bothnian Bay and Gulf of Riga (Gustafsson, 1997). This well-known brackish water body has salinities far below the typical ocean salinity of 35 PSU, which strongly affects the freezing over the water surface. The temperature, at which Baltic sea water gets frozen, is subsequently higher than typical oceans. Thus, the application of typical sea water's freezing point for the Baltic Sea in many climate models will eventually lead to insufficient amounts of sea ice simulated in the models.

Sea ice is an important factor that influences the climate system in the Baltic Sea region. Over a good portion of the year, sea ice presents over the Baltic Sea. The sea-ice season normally starts in November; the first ice forms typically in the far north of the Baltic Sea at Bothnia Bay. Ice gradually extends through the winter and reaches its maximum usually in February or March. The ice in Bothnia Bay can last till May (Vihma and Haapala, 2009). Over the ice-covered area of the Baltic Sea, there is a high spatial variability of the surface conditions. This variability strongly affects the radiation and turbulence fluxes. Sea ice has much higher albedo than sea water, about 0.7 compared with 0.07; the distribution of the sea ice, therefore, can alter the net solar radiation dramatically. Likewise, the sea surface is much smoother if ice presents; the surface roughness of sea water is typically ten times larger than that of sea ice. A small difference in ice/open-water distribution can associate with a large change in momentum fluxes. Because of this large influence of sea-ice spatial variability on the atmospheric fluxes, it is inadequate to simulate the Baltic Sea with a coarse horizontal resolution global ocean model. In many regional climate models (RCMs) like COSMO-CLM (Böhm et al. (2006), Rockel et al. (2008)), although the spatial resolution is higher, sub-grid ice is not considered. Hence they still result in large biases in ice estimation.

Furthermore, the complex topography of the North and Baltic Seas with narrow straits and long narrow gulfs (Gulfs of Bothnia and Finland) (Fig. 1.2) cannot be resolved on the coarse grid of driving global climate models (GCMs). In addition to that, Cheng (2002) shows the importance of vertical resolution and time step of sea-ice modelling. He demonstrated that ocean-ice models with large vertical layers cannot describe the penetration of solar radiation into Baltic sea ice properly. Not absorbing enough solar radiation can lead to surface heat unbalance of the ocean, and thus to large diurnal cycle of

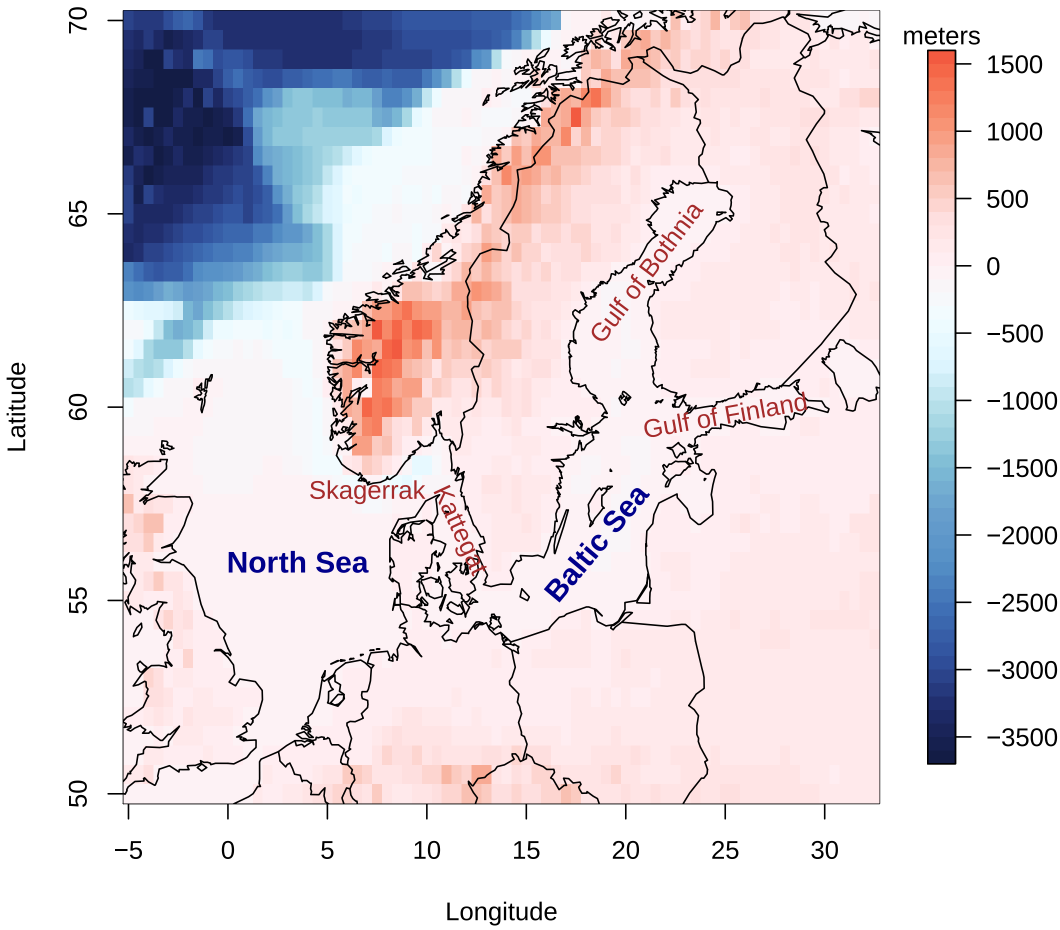

FIGURE 1.2: Topography of the North and Baltic Seas.

SST. It shows the importance of simulating the ocean in climate system with sufficiently high resolution in order to capture coast topography and vertical inhomogeneity.

The coastal orography, the brackish water, presence of sea ice, and strong vertical inhomogeneity, all of those are elements that add to the complexity of the climate system in the North and Baltic Sea area. That raises a need for a high resolution climate model which includes ocean and ice components when studying the climate of European region.

1.3 Climate models at global and regional scales

Climate models have been utilized for various scientific purposes such as to study the dynamics of the climate system, to re-create the climate of the past, or to create projections of future climate. Climate models help scientists to improve their understandings of complicated climate processes, for example: the impact of incoming solar radiation on near surface air temperature, the link between moisture content of the soil and the precipitation, or the favourable condition for a certain extreme weather event to occur. Furthermore, we also want to know how the climate has changed in the past, how it is changing now, and how it would likely change in the future. That is when climate models come into play to recreate paleoclimate or to carry out climate scenarios and climate projections.

The idea of climate modelling, or earlier weather forecasting, dates back to the beginning of twentieth century when a set of equations to describe the weather situation and numerical technique to solve these equations were developed. However, without the help of computers, the solutions, of course, could not be retrieved faster than the actual weather situation; thus are not useful. Only until the middle of twentieth century, thanks to the neck-breaking development of computer power, weather forecast and climate modelling were made possible. Along with increasing computer capability, meteorologists were able to simulate the climate with more complexity, high resolution and higher accuracy (Edwards, 2011).

Nowadays, there exist different types of climate models. One is GCMs; they are based on mathematical formulations that describe the climate processes such as radiation, wind, cloud formation, precipitation, water evaporation, and heat transportation, etc. There are different types of GCMs, the most common used nowadays which has the largest potential is the three dimensional global atmosphere-ocean model, for example MPI-ESM (Giorgetta et al., 2013), CCSM4 (Gent et al., 2011), MIROC5 (Watanabe et al., 2010). They provide good indicators of how the global climate varies by time and space (Smith et al., 2007; Hagemann et al., 2013). The knowledge gained from GCMs, for example climate changes in the future (Cox et al., 2000; Giorgetta et al., 2013), could support the policy decision making related to climate.

However, people often concern more about how the climate is at a certain region of their interest. This kind of information cannot be provided by GCMs because they are limited by their coarse resolution, thus, cannot calculate the detailed local distribution of climate variable quantities (Somot et al., 2006). The grid mesh of a GCM, on which the computation of the physical variables is done, is typically around 200 km (Sillmann et al., 2013). In the IPCC report (AR5), the CMIP5 experiment provided an ensemble of GCM scenarios with horizontal resolution of 150 km. This is too coarse to capture local development of the atmosphere. Low resolutions of GCMs also mean that the topography is smoothed out, and real landscapes, especially the mountainous areas, are not well resolved. For regions, which include seas with complex coastlines, the near-coastal issues are missed in GCMs.

There are several ways to tackle the resolution problem of GCMs. First is to run a GCM with finer resolution over a limited area. However, this method is technically expensive, and therefore, requires powerful computers and long computation time. Downscaling is a method of obtaining high-resolution climate or climate change information from relatively coarse-resolution GCMs. Many impact models require information at scales of 50 km or less, thus some methods are needed to estimate the smaller-scale information. Statistical downscaling is one of the methods to achieve finer resolution (Wilby et al., 1998; Busuioc et al., 2001; Emanuel, 2013). It first derives statistical relationships between observed small-scale (often station level) variables and larger (GCM) scale variables, using either analogue methods (circulation typing), regression analysis, or neural network methods. Future values of the large-scale variables obtained from GCM projections of future climate are then used to drive the statistical relationships and estimate the smaller-scale details of future climate. Second method to avoid the high cost of computation with GCMs is to downscale GCM results to a finer but limited area grid. This downscaling technique using an RCM; is called "regionalization".

RCMs are climate models with higher resolutions than GCMs but limited to a given area, hence cheaper than GCMs at the same resolution. RCM simulations are normally performed on the grid mesh of around 25-50 km or even finer. These high resolutions are crucial to resolve the local climate, especially the climate variation in mountainous or coastal areas, where a distance of 50 km could mean a large difference. A better representation of topography, rivers, coast-lines, or complex and heterogeneous land use allows the orography-induced or small-scaled climate features such as precipitation, snowfall, land-sea contrast to be better presented in RCMs' fine grids (Déqué and Somot, 2008; Somot et al., 2008). Gao et al. (2008) show the necessity of using a high resolution model to simulate the climate in complex topography region.

Due to their limited area, at the edges, RCMs need information such as wind, temperature, which normally comes from re-analysis data or driving GCMs. And because RCMs typically consist of atmosphere and land components, at the lower boundary, they need oceanic forcings such as SST and sea ice data. These are normally prescribed by using the same re-analysis or driving GCM data as for the lateral boundary conditions. Re-analysis data are produced by data assimilation schemes which incorporate a huge amount of observations. The advantage of re-analysis data is that they are consistent throughout time and often available at pretty high spatial resolution (e.g. ERA-Interim has spatial resolution of 80 km). However, re-analysis is not available for the future; that limits the use of re-analysis as forcings for climate predictions and climate projections. In those cases, an ocean model is needed to provide the future states of the oceanic variables. GCMs, which normally contain a global ocean model, are often used to force RCMs in climate projections. However, Li et al. (2012) show cases when fine-scale atmosphere-ocean feedbacks can largely affect the spatial and temporal variation of the regional climate. Additionally, as discussed in Section 1.2, due to the coastline complexity and small scale of the North and Baltic Seas, these marginal seas cannot be resolved on the coarse grid of GCMs. It further increases the need of using a high-resolution ocean and ice model for this particular area. In climate studies recently, efforts have been taken to include ocean, sea-ice components into climate modelling systems.

1.4 Coupled regional atmosphere-ocean-ice model

Many researches have been done recently to couple the ocean and sea-ice models to RCMs worldwide, for example: Europe (Akhtar et al., 2014; Pham et al., 2014; Wang et al., 2015; Ho et al., 2012), Africa (Paxian et al., 2016), Arctic (Paquin et al., 2013), Indonesia (Aldrian et al., 2005). These studies attempted to gain more completed climate system simulations by adding ocean and sea-ice models into the regional climate modelling systems.

The coupling of atmospheric models with ocean models showed good results with respect to the stand-alone atmospheric models in many areas of climate studies. Long-term simulations carried by Pham et al. (2014) over the North and Baltic Seas and Akhtar et al. (2017) over the Mediterranean Sea demonstrated that the coupled atmosphere-ocean model simulated some climate variables, such as 2-m temperature, 10-m wind speed, sea surface heat fluxes comparable to the stand-alone atmospheric model forced by high resolution re-analysis data. Coupled atmosphere-ocean models showed clear improvements with respect to the uncoupled RCM in terms of predicting different types of extreme weather events. The strong convective snowbands over the Baltic Sea, that could cause large damages in the surrounding regions, were successfully recreated by the coupled system from Pham et al. (2017). The medicanes (or Mediterranean tropical-like cyclones) were simulated by Akhtar et al. (2014). Heavy rainfalls causing floods in Europe were well simulated by the coupled system in Ho-Hagemann et al. (2015). Long-term climate simulation for the future were also studied with coupled models such as climate change scenarios for the Mediterranean Sea by Somot et al. (2008) or the consequences of sea-ice loss over the Arctic by Paquin et al. (2013). There are different strategies to couple atmospheric and ocean models. One strategy is to couple an RCM to a global ocean model with variable ocean resolution focused on an area of interest as done by Sein et al. (2015) and Aldrian et al. (2005) (fully coupled the regional atmospheric model REMO with global ocean model MPI-OM). Somot et al. (2008) implemented a coupling system with a global atmospheric model, with a maximum resolution of 50 km, locally coupled with a regional ocean model over the Mediterranean Sea. The limited area ocean model OPAMED was used in this study at resolutions varied from 9 to 12 km.

The resolutions of both atmosphere and ocean models were reasonably high, but time steps for the climate model and the coupling process are quite coarse, with 30 minutes and one day respectively.

A recent way of coupling strategy is to use a regional atmospheric model and a regional ocean model. Many authors have applied this method (Akhtar et al., 2017; Wang et al., 2015; Ho-Hagemann et al., 2015; Pham et al., 2014). The regional ocean models are coupled to the RCMs only over a limited sea area of the domain, other areas are driven by data (either from re-analysis or global model).

It should be noted that "coupling" here refers to two-way coupling. Which means the two components of the model system, in this case the atmosphere and the ocean models, send and receive information to and from the other. One way to enable the communication between the two component models are via files. The two models calculate till a certain time when exchanges are required; they then write the necessary information for the other side to files. The files are read by the corresponding models as input boundary data. This method is simple as it does not require any extra software, and no or limited implementation in the model source codes. But computationally, it is very inefficient because at each coupling time step, the models need to write/read files. With high coupling frequency and without parallelized input/output, the coupling could potentially add enormous computing time. Another method to exchange data between component models is to run a model as a subroutine from the other model. This is more time-efficient than the first method, but would result in extensive modifications in the model source codes (Will et al., 2017).

A better way to not disturb much the model source codes is using an external software. In this case, the two component models are often synchronized via an interface software called the coupler. There are also different way of using the coupler. The authors Akhtar et al. (2017); Wang et al. (2015); Ho-Hagemann et al. (2015); Pham et al. (2014) used it to interpolate the exchanged variables to the different times and spatial grids of the two models. Aldrian et al. (2005), however, applied the coupler only for synchronizing the coupling time, the grid interpolation was done within one of the component models. The Ocean Atmosphere Sea Ice Soil Simulation Software (OASIS) was developed specifically, as stated in the name, for the coupling of atmosphere, ocean and sea-ice models. This coupler has been widely used to couple RCMs not only with ocean, sea-ice models, but also with land, soil-vegetation, hydrological and global earth system models. Will et al. (2017) gives an overview of the RCM COSMO-CLM coupled with various models using OASIS.

An overview of some coupled model systems is given in Table 1.1. As can be seen, there are currently a handful of coupled model systems developed for the European domain. Two main interest areas for coupling studies are the marginal North-Baltic Seas, and the Mediterranean Sea. The coupling systems from these authors normally consist of an atmospheric model and an ocean model with much finer grid mesh. Besides, some systems have also additional components such as river-runoff or sea-ice. There exists a wider range of coupled models for different regions around the globe, but is not mentioned in the list.

Table 1.1: Overview of existing coupled atmosphere-ocean model systems

Coupled system	Atmospheric component	Oceanic component	Other component	Coupled area	Coupling frequency	Coupler	References
RCA4/NEMO	RCA4 0.22°/40 layers	NEMO-NORDIC 3.7km/56 layers	sea-ice model LIM3 runoff model CaMa-Flood	North & Baltic Seas	atmosphere-ocean: 3hours ocean-river: 1 day	OASIS3	Wang et al. (2015)
COSTRICE	COSMO-CLM 50 km/32 layers	TRIMNP	sea-ice model CICE	extended North & Baltic Seas	1 hour	OASIS-MCT	Ho-Hagemann et al. (2015)
RCAO	RCA 24 layers	RCO 59layers		centered around Arctic	3 hours	OASIS4	Paquin et al. (2013)
REMO/MPI-OM	REMO 0.5°/20 layers	MPI-OM global ocean model Low resolution: 40 km/20 layers High resolution: 20 km/30 layers		Maritime continent (Indonesia)	6 hours	OASIS2.4	Aldrian et al. (2005)
REMO/MPI-OM	REMO 7-65 km/40 layers	MPI-OM 1.5°/40 layers		Mediterranean Sea			Paxian et al. (2016)
SAMM	global spectral AGCM ARPEGE-Climate model variable resolution horizontal resolution: 4.5°/-0.5° 31layers timestep: 30 minutes	OGCM OPAMED 9-12 km/43 layers		Mediterranean Sea	1 day	OASIS2.4	Somot et al. (2008)
MORCE	WRF 20 km/28 layers	3D-NEMO-MED12 7 km/50layers		Mediterranean Sea	3 hours	OASIS3	Lebeaupin Brossier et al. (2013)
COSMO-CLM/NEMO	COSMO-CLM 0.44°/32 layers 0.22°/32 layers 0.08°/40 layers	1D-NEMO-MED12 5.5-8 km/50 layers		Mediterranean Sea	1 hour	OASIS3	Akhtar et al. (2014)
COSMO-CLM/NEMO	COSMO-CLM 9-50 km/32 layers	3D-NEMO-MED12 5.5-8 km/50 layers		Mediterranean Sea	3 hours	OASIS-MCT	Akhtar et al. (2017)

1.5 Climate prediction

The atmosphere is a chaotic system, some small perturbation in the initial state can cause large changes in the development of the weather. For that reason, predictability of the atmosphere is tightly dependent on the initial conditions, and therefore are limited to approximately 10 days. However, beyond that limit of weather forecasts, the mean state of the atmosphere and the statistics of weather events can be still predicted. This climate predictability emerges from other components of the climate system. These vary at much slower time scales as the atmosphere, hence control its evolution. These "slow" components are SST, sea-ice, soil moisture and snow cover. With an aid of coupled atmosphere-ocean-ice models, the gradual variation of the SST and sea ice is better simulated, and therefore, is expected to contribute to better climate predictions. In addition, coupled atmosphere-ocean-ice models could potentially also provide better statistics of extreme weather events that involve the small-scaled processes over the ocean.

1.5.1 Predicting climate on decadal scale

Predictions of the future climate on long-time scales might not be possible to provide accurate values of climate variables. However, they can bring useful information on the average states of important parameters such as temperature, precipitation, wind, etc. Nowadays, climate predictions can be carried out by climate models on different time scales from seasonal to decadal and centennial. Seasonal climate prediction depends strongly on the model initialization which would require considerable efforts to get a proper start for the climate model. Meanwhile, centennial prediction, with much longer forecast time, is less dependant on the initial state of the climate system, but can be very expensive computationally due to the lengthy simulations. In between these two time scales, decadal forecasts are the problem of both initial and boundary conditions. In order to produce good decadal forecasts, one should acquire proper initial and boundary data for the climate model.

Decadal predictions pose one of the biggest challenges to the climate community (Murphy et al., 2010). As stated by Swingedouw et al. (2013), "One of the key hypothesis underlying decadal climate predictability involves ocean memory at this time scale". They stressed the important role of the ocean in decadal predictions. It is also found in Griffies and Bryan (1997) that the coupling of the atmosphere and the ocean makes the climate variation predictable over a long period. Each prediction system has a certain level of predictability, which is the extent to which informative prediction could be pursued (Doblas-Reyes et al., 2013). High predictability requires foremost accurate initial states of the climate system. Beside the predictability loss along with forecast time (as the forecasts go further from the initial state), the loss of predictability is also caused by model formulation (Palmer, 2000). Climate models are of course not the perfect representation of the climate system, therefore they contain always uncertainties. For long climate forecast, the model physics is particularly important. These two sources of predictability uncertainties are difficult to separate (Vidale et al., 2003).

Decadal European climate is strongly governed by North Atlantic Oscillation (NAO), which is characterized by an atmospheric mass oscillation between Arctic and subtropical Atlantic. This weather condition is the fluctuations in the difference of the Azores high pressure system and the Icelandic low pressure system. Through the strength of the Icelandic low and the Azores high, NAO controls the strength and direction of the westerlies over Europe. Depending on the relative strength of these two pressure systems, NAO can be in strong or weak phases (corresponding with large and small pressure differences). Strong phases of NAO lead to increased westerlies, which bring more moist air to continental Europe. The weather during strong NAO period is often seen as mild and wet. On the other hand, westerlies are suppressed when NAO is in weak phase. More extreme weather situations like cold dry winters or storms happen. During the months from November to April especially, the NAO determines most of the weather condition in Europe.

Beside the significant impact of the large scale atmospheric oscillation, the climate variability in Europe is, of course, also influenced by the local characteristics. The local physical processes are more pronounced when the large scale driver has less influence (Vidale et al., 2003). As discussed in Section 1.2, the North and Baltic Seas with long memory of heat storage are big contributors to shape the regional climate. The extent of these marginal seas' impact changes with the strength of the NAO. When NAO index, which is basically the difference between the two pressures at Azores and Iceland, is positive, the strong westerlies could inhibit the local air-sea effect. Vice versa, the role of the North and Baltic Seas in the regional climate system is more pronounced, if NAO index is negative. Studying the climate impact of these seas should involve considering the strength of the NAO.

1.5.2 Predicting extreme weather events on climate time scale

Extreme weather is when a weather event is significantly different from the average or usual weather pattern. Extreme weather events do not occur often but once do can cause enormous damages in terms of economy and human lives to our society. In the USA, in 2011 alone, extreme weather claimed more than 1000 lives; in 2017, weather and climate disasters produced almost $90 billion financial losses (source: `http://www.nws.`

noaa.gov/om/hazstats.shtml). In Europe, from 1980 to 2010, the economic burden has been considerable, with an estimated loss of €415 billion. An estimated number of 140 000 lives lost in Europe since 1980 was also caused by weather events (Øystein et al., 2013).

Extreme weather events are not easy to define and sometimes also regarded as severe, rare, high-impact (Diaz and Murnane, 2008), they recur at irregular times. The timing of the occurrences is therefore unknown. Climate prediction often attempts to predict the estimated numbers of certain event that might occur in the future.

One of the extreme weather events that often occurs in the basin-like water bodies (i.e. large lakes, typically wider than 100 km, and marginal seas) is lake-effect snow or snowband. This phenomena has been widely studied over Lake of Michigan (Barthold and Kristovich, 2011; Carpenter, 1993), Lake Erie (Cordeira and Laird, 2008) and the Baltic Sea (Andersson and Nilsson, 1990; Andersson and Gustafsson, 1994; Jeworrek et al., 2017). The Baltic Sea, with narrow gulfs and occasionally high contrast between air temperature and SST, is a favourable location for the snowband formation. During late autumn or early winter, the Baltic sea surface is still relatively warm, meanwhile cold air mass already forms in the continent. When this cold air mass outbreaks over the open water surface of the Baltic, parallel bands of convective snow, as can be seen on Fig. 1.3, could develop (Jeworrek et al., 2017).

During a snowband event, an enormous amount of snow depositing in coastal areas could cause large damages and severe problems for traffic, transportation, communication and so on. Due to its hazardous impacts, it is helpful to predict such extreme event climate to better prepare and limit the extent of damages. Simulating the snowbands over the Baltic Sea would require climate models with relatively fine-scale air-sea interaction. Usual RCMs forced by coarse SSTs from GCMs have disadvantage in resolving the snowband locations and extensions. To overcome this disadvantage of the coarse SSTs in RCM system, coupled regional atmosphere-ocean models could be a solution to increase the resolution of the ocean fluxes.

1.6 Research questions and Objectives

As discussed above, due to the different mixing condition and the existence of haloclines, the North Sea plays more important role in regulating the regional climate in time scale of months; meanwhile, the Baltic Sea affects the climate in time scales from year to decade. Exception is the extreme snowband events, where the Baltic Sea could alter the weather within 48 hours (Andersson and Gustafsson, 1994).

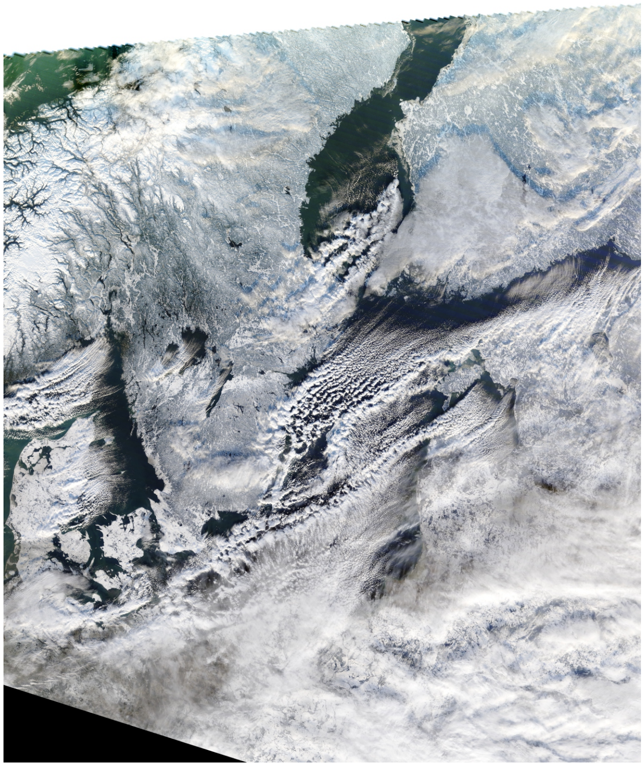

Figure 1.3: A satellite image of parallel snowbands over the Baltic Sea captured by Terra MODIS at 1015 UTC 30.11.2010.

Because of the importance of the North and Baltic Seas, the European climate system should be presented as thoroughly as possible, taking into account the ocean and sea ice, in order to understand the feedbacks among climate components and how they affect the climate at the end. A coupled atmosphere-ocean-ice model is required for climate simulations in this region. Also due to the complexity of the local topography, high resolution ocean-ice model is needed.

In this thesis, a high-resolution regional atmosphere-ocean-ice model was developed for the European region with the ocean model covering the North and Baltic Seas. This is later referred to as "coupled model". The stand-alone RCM without coupling is referred to as "uncoupled model". These two models were used to perform several experiments to address a number of questions:

1. What are the benefits of coupling the marginal North and Baltic Seas to an RCM in terms of air temperature and SST simulating? What are the impacts of the North and Baltic Seas in relation with the main wind direction over Europe?

2. What are the impacts of fine-scale air-sea interaction over the Baltic Sea in simulating the parallel snowbands? Does the high-resolution ocean-ice improve the representation of the snowbands?

3. Does coupling with an ocean-ice model increase the decadal predictability of an RCM? How does the added predictability from the coupled model change in different phases of the NAO?

The main aim of this research is to study the added values of coupling the North and Baltic Seas to the regional climate modelling system on different time scales with the help of a newly developed coupled atmosphere-ocean-ice model for the North and Baltic Seas. The detailed objectives are:

- To set up a regional coupled atmosphere-ocean-ice model system which has an ice scheme and therefore is suitable for the area of interest (the Baltic Sea); to evaluate the performance of the coupled system against observations and the uncoupled atmospheric model.
- To study a typical extreme event in the area of interest, more precisely, the convective snowbands over the Baltic Sea in early winter. To compare the results from the coupled and uncoupled with respect to reference data and to investigate the necessity of using coupled model in forecasting extreme climate.
- To carry out decadal climate predictions with the coupled and uncoupled models. To seek for improvements in decadal predictions from the coupled model in different phases of the NAO, and to search for the potential sources of added forecast skills by the coupled model.

1.7 Outline

The center piece of this thesis consists of three chapters and a conclusion, at the end there is an extended summary in German. Each chapter is a scientific paper which was published in peer-review journals. Short summaries of the three chapters are given below:

1.7.1 Chapter 2: New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas

This chapter is an introduction to a newly established coupled atmosphere-ocean-ice model system with the RCM COSMO-CLM and the regional ocean-sea-ice model

NEMO. COSMO-CLM was set up for the CORDEX-Europe domain at the resolution of 0.44° (approximately 50 km) and 40 vertical layers. The setup of NEMO, called NEMO-NORDIC, has about 3 km resolution, 56 vertical levels and covers the North and Baltic Seas. These two model components were fully coupled via the interface coupler OASIS3; the structure of the coupled system is illustrated on Fig.1.4; the coupling was done every 3 hours. The atmospheric model passed flux densities of water (precipitation - evaporation), momentum, solar radiation, non-solar energy and sea level pressure to the ocean model. NEMO, in turn, fed SST and the fraction of sea ice back to COSMO-CLM. The radiation and turbulence schemes in COSMO-CLM were altered so that they could

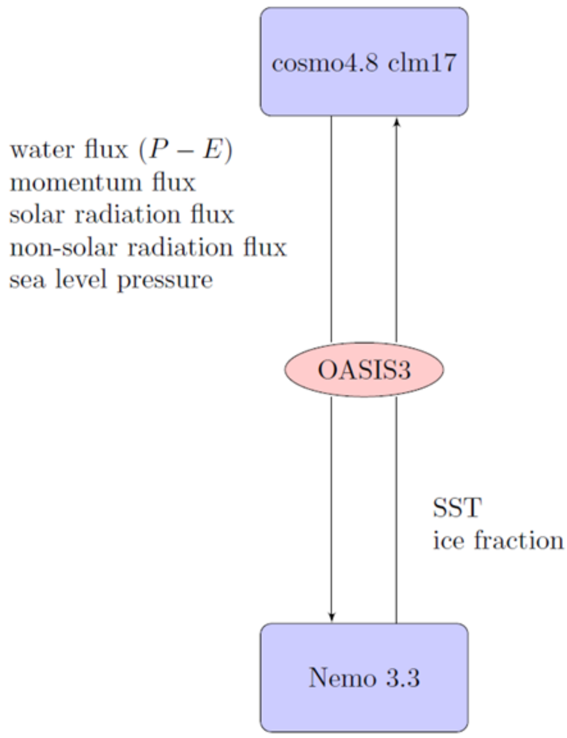

FIGURE 1.4: Coupled atmospheric-ocean-ice system COSMO-CLM/NEMO with the RCM COSMO-CLM coupled to the regional ocean-sea-ice model NEMO via the coupler OASIS3. The exchanged fields between the two component models are shown.

handle sub-grid ice (original COSMO-CLM does not have sub-grid ice) over the coupled seas. COSMO-CLM in the coupled mode calculates the weighted sea surface albedo and roughness based on the ice-water fraction that it gets from NEMO.

Two experiments with the stand-alone atmospheric model and the coupled model were done, both were forced by ERA-Interim re-analysis data over the period from 1979 to 1994; in coupled model experiment, COSMO-CLM got the lower boundary condition from NEMO over the North and Baltic Seas. Temperature and salinity at the two open boundaries of NEMO were prescribed by the Levitus climatology data.

The resulted 2-m temperature values from coupled model were compared with the E-OBS data which are a 50 km-gridded dataset available over the domain land area. Furthermore, the coupled model's results were also compared with those from the uncoupled. It should be noted that uncoupled model was driven by high resolution re-analysis data over the North and Baltic Seas. Hence, it can be a reference to judge the performance of the coupled model. To see the impact of coupling on different regions, analysis for nine PRUDENCE sub-regions was done.

The evaluation showed coupled model's monthly averaged 2-m temperature biases in the range from −2.5 to 3 K, most of the time smaller than the uncoupled model's biases. The temperature differences varied by season and sub-region. Looking at the biases over the domain, the coupled model showed comparable results with the stand-alone COSMO-CLM in terms of simulating 2-m temperature. The ranges and distribution of the biases agreed with previous studies using COSMO-CLM model. The good presentation for air temperature by the coupled model came from the ocean model's fine-scale SSTs. When comparing with ERA-interim SST data, SST values simulated by NEMO showed annual averaged differences from −0.2 to −0.6 K. The differences in 2-m temperature values between the two experiments were explained by the wind coming from the West flowing over the North and the Baltic Seas (the coupled area) to the continent.

1.7.2 Chapter 3: Simulation of snowbands in the Baltic Sea area with the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO

This chapter attempts to study the extreme snowband events over the Baltic Sea with the coupled model COSMO-CLM/NEMO. This phenomenon occurs when cold air flows over the warm water surface, enhancing strong convection and leading to heavy snow fall. In this chapter, six snowband events during the period from 1985 to 2010 were simulated in three sets of experiments: (1) COSMO-CLM forced by ERA-Interim reanalysis data; (2) COSMO-CLM/NEMO forced by ERA-Interim; (3) COSMO-CLM forced by monthly averaged ERA-Interim data over the coupled North and Baltic Seas. The third experiment set was done to simulate the case when both coupled model and reanalysis data are not available so that the atmospheric model would need to be driven by GCMs which surely have coarser SST fields than those from an ocean model or re-analysis data. The model resolutions were reasonably high to capture the snowbands; COSMO-CLM had a horizontal grid-spacing of approximately 25 km and NEMO had a horizontal grid-spacing of approximately 3 km. Experiment results showed that the coupled system COSMO-CLM/NEMO successfully reproduced the snowband events with a high contrast of temperatures between the surface and the atmosphere (at 850 hPa). The temperature contrast exceeded the threshold at which snowbands occur (13 K). Furthermore, there were sharp bands of precipitation over the sea, as well as the enormous heat fluxes released by the ocean to the atmosphere during the days when snowbands occurred. In the two cases when radar data are available, the model precipitation was shown to be in satisfactory agreement. The cloud images from satellite were used for qualitative comparison; it showed that the precipitation patterns closely followed the snowband shapes on satellite images. When COSMO-CLM was not coupled with the ocean model, the atmospheric stand-alone model provided acceptable results if forced by high-quality SSTs from reanalysis data. However, COSMO-CLM forced with lower quality SSTs, as in the third experiment set, could not recreate the snowbands. The results indicate a need of an atmospheric model with high SST skill or a coupled atmosphere-ocean model in order to simulate climate of extreme events over the Baltic Sea or marginal seas in general.

1.7.3 Chapter 4: Added decadal prediction skill with the coupled regional climate model COSMO-CLM/NEMO

This chapter presents a study on long-term climate prediction with the coupled model system. Two sets of experiments were carried out with the stand-alone COSMO-CLM and with the coupled COSMO-CLM/NEMO model. The stand-alone model was forced by MPI-ESM-LR global forecasts; while the coupled model was driven by NEMO over the North and Baltic Seas and MPI-ESM-LR elsewhere. The aim is to improve decadal forecasts for the surrounding area of the marginal seas by coupling an RCM to a high-resolution ocean model. The idea of using the coupled model for long-term forecasts emerged from the fact that regional climate forecasts strongly depend on the boundary conditions. These boundary data, if coming from GCMs, can not resolve the near coastal features well enough due to GCM coarse resolutions (approximately 200 km). In each set of experiments, five independent 10-year hindcasts from the 1961 to 2010 were done. The 25-km resolution and COSMO-EU domain were chosen for COSMO-CLM. Each decadal run was initialized on January 1st of the first year and ended on December 31st of the last year. The results from the coupled model were compared with the hindcasts from the forcing global model MPI-ESM-LR and COSMO-CLM stand-alone. The Mean Square Error Skill Score (MSESS) was calculated as a measure for the forecast quality; focus of evaluation was on 2-m air temperature. Because of a strong dependence of the weather situation in Europe on the phases of the NAO, model data were separated into positive and negative NAO periods. The monthly NAO index was calculated from sea level pressure (SLP) data from MPI-ESM-LR. These NAO index values were then compared with the data from the National Oceanic and Atmospheric Administration (NOAA). Only when calculated NAO index is in phase with NOAA data, the model data stratification was performed. Results showed that the coupling with an active ocean for the North and Baltic Seas led to better predictive skills (compared with global model and regional uncoupled model) for 2-m air temperature, especially at the southern coast of the North and Baltic Seas. As expected, the MSESS decreased with lead year as the effect of initialization faded and due to the limited predictability of the forcing model MPI-ESM. COSMO-CLM/NEMO had better skills up to about lead year 7. During the weak phase of the NAO, the coupling effect was more pronounced; therefore, the added predictive skill from the coupled model was seen more clearly. During winter when the impact of NAO is knowingly strong over Europe, the coupling effect was hindered, hence, COSMO-CLM/NEMO showed only added skill in limited areas and not as obvious as in spring or summer. The reduced skills with lead years implied that one of the potential sources of better forecasts is initialization. This result agrees with other studies on the climate forecast subject. Another source of skills is the better SST from the ocean model. The results of this chapter suggested a use of a coupled atmosphere-ocean-ice model system in order to perform better long-term climate forecast, especially when it comes to marginal seas with small-scaled topography details like the North and Baltic Seas.

Chapter 2

New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas [1]

2.1 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]Published as: Trang Van Pham, Jennifer Brauch, Christian Dieterich, Barbara Früh, and Bodo Ahrens. New coupled atmosphere-ocean-ice system COSMOCLM/ NEMO: assessing air temperature sensitivity over the North and Baltic Seas. Oceanologia, 56(2):167–189, 2014

2.2 Introduction

According to the description in Houghton et al. (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 and 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 et al. (2009). 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).

Kjellström 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, Döscher 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). 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 2.3 along with the modifications necessary to adapt them to the coupled system. Section 2.4 introduces the experiment set-ups. In section 2.5, 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 2.6, 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 2.7, 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 2.8.

2.3 Model description

A regional atmosphere-ocean-ice coupled system was established based on the regional atmospheric model COSMO-CLM version cosmo4.8_clm17 (Böhm 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 (2008). 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, 2013). 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.

2.3.1 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., 2009). The domain covers the whole of Europe, North Africa, the Atlantic Ocean and the Mediterranean Sea (see Fig. 2.1). 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 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.

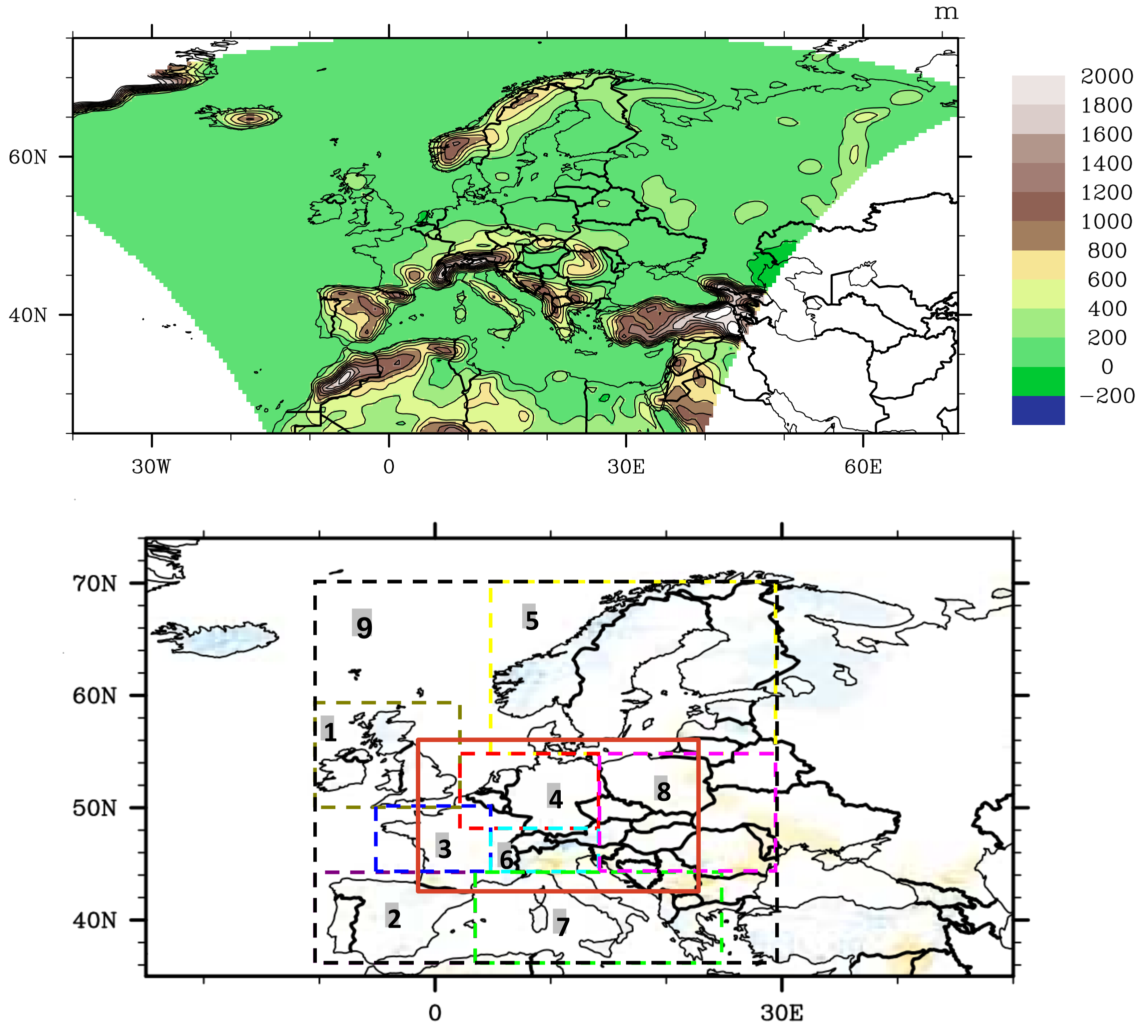

FIGURE 2.1: COSMO-CLM model domain (topography with contours every 200 metres from ERA-Interim re-analysis data) (left) and nine PRUDENCE evaluation areas within the COSMO-CLM domain (right); the solid orange box is the weather classification area)

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.

2.3.2 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 Fig. 2.6.

For the Baltic Sea, the fresh water inflow from the river basins plays a crucial role in the salinity budget. Meier and 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).

2.3.3 The coupled system COSMO-CLM/NEMO

The atmospheric and ocean models are coupled by the coupler OASIS3. The results from Meier and 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.

2.4 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 and 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.

2.5 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 and Christensen (2007)). Region 9 encompasses all eight sub-regions as shown in Fig. 2.1.

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 and Dittmann (2001).

Bissolli and Dittmann (2001) presented an objective weather type classification for the German Meteorological Service. Their study area was an extended central European area (Fig. 1 in Bissolli and 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 and Dittmann (2001) (Fig. 1b).

Bissolli and 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.

2.6 Results

2.6.1 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. Fig. 2.2 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 Fig. 2.2), that the coupled run has improvements compared to the uncoupled run.

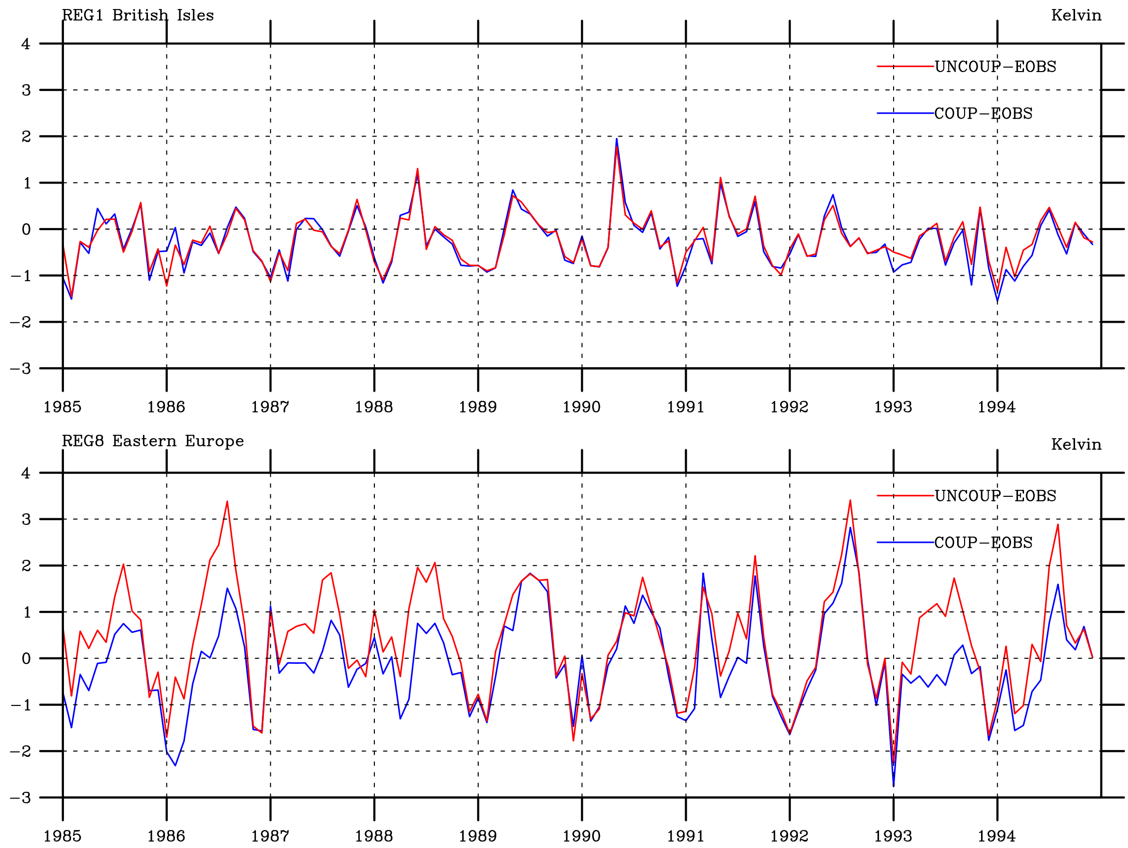

Figure 2.2: Monthly means of the difference in 2-m temperature between the coupled, uncoupled runs and E-OBS data over land in the period 1985–1994. Temperature is averaged for: sub-region 1, the British Isles (top); and sub-region 8, eastern Europe (bottom)

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. Fig. 2.3 shows the yearly and four seasonal means of temperature biases over the whole of Europe (region 9 on Fig. 2.1). 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 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.

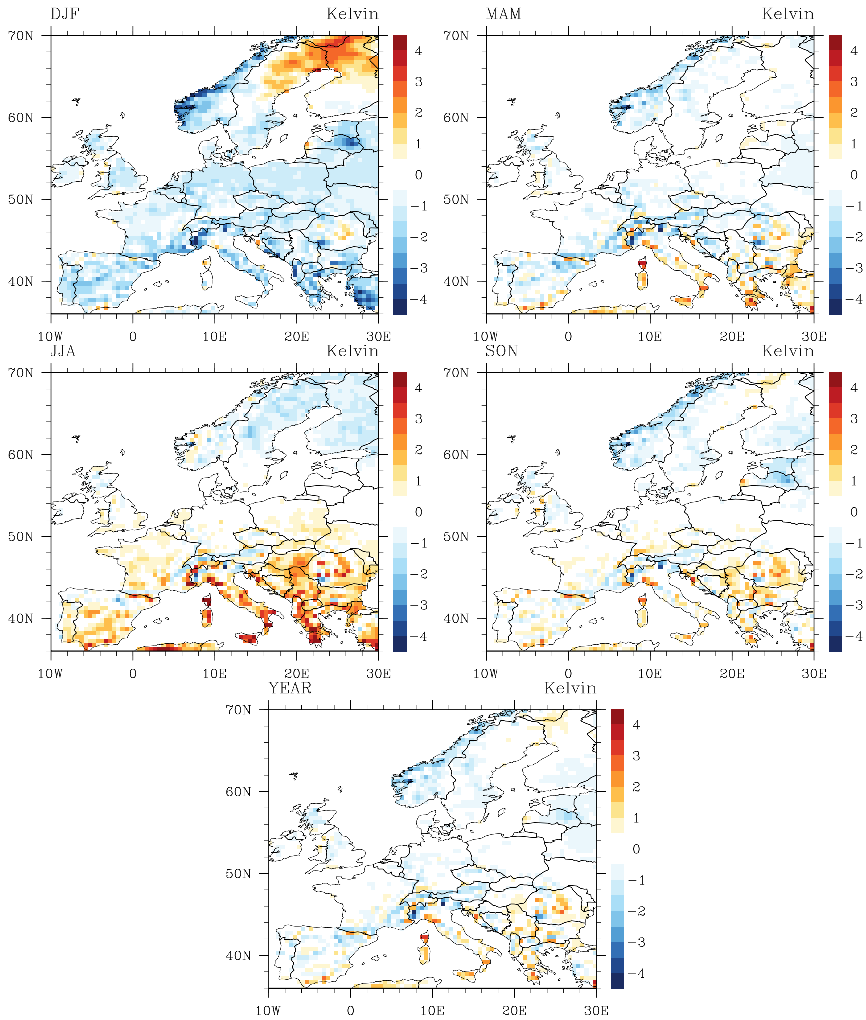

FIGURE 2.3: Yearly and seasonal means of the differences in 2-m temperature over land between the coupled run and E-OBS data, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{E-OBS}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

Fig. 2.4 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.

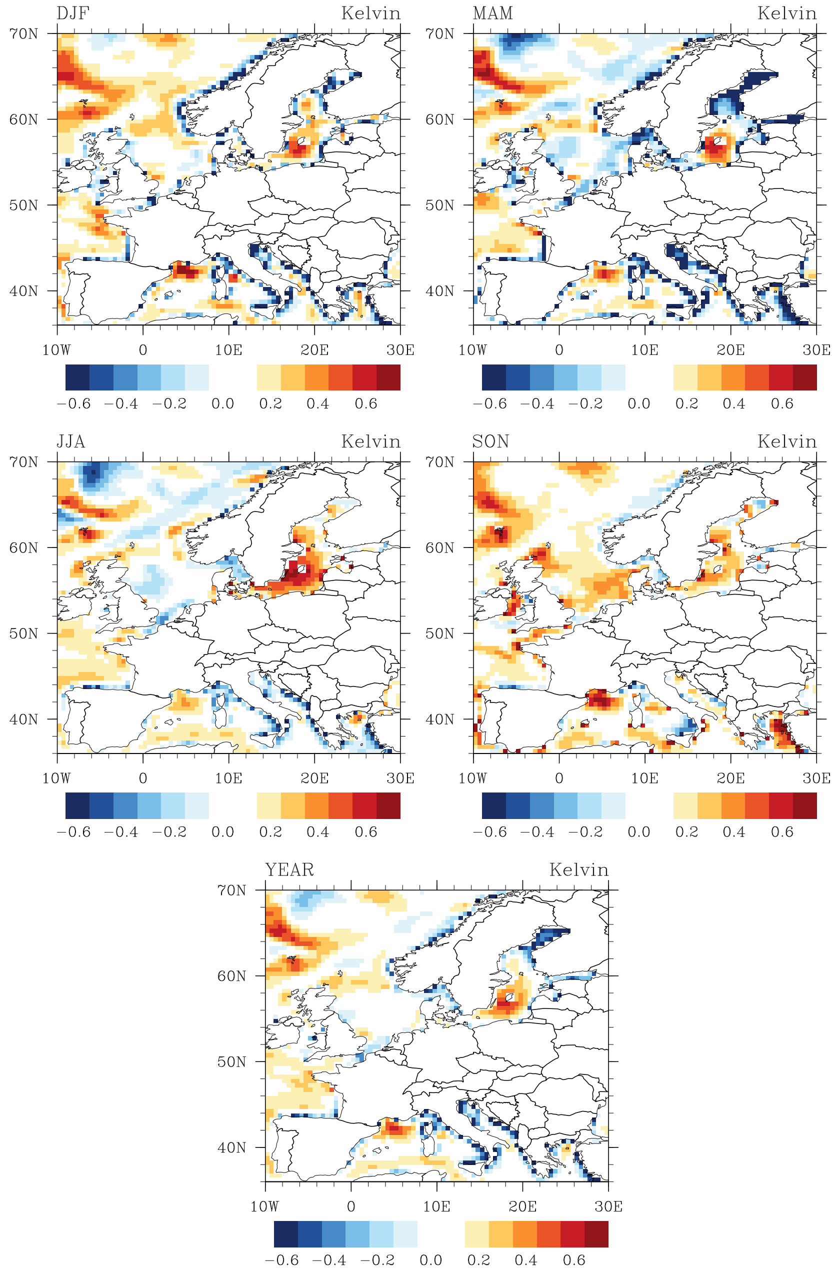

FIGURE 2.4: Yearly and seasonal means of the differences in SST between the coupled run and AVHRR data, averaged over the period 1985–1994 (SST_{COUP}–SST_{AVHRR}). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

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 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.

2.6.2 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 and multi-year seasonal mean of the difference between the two runs are calculated for all sub-regions. Fig. 2.5 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 Fig. 2.5.

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

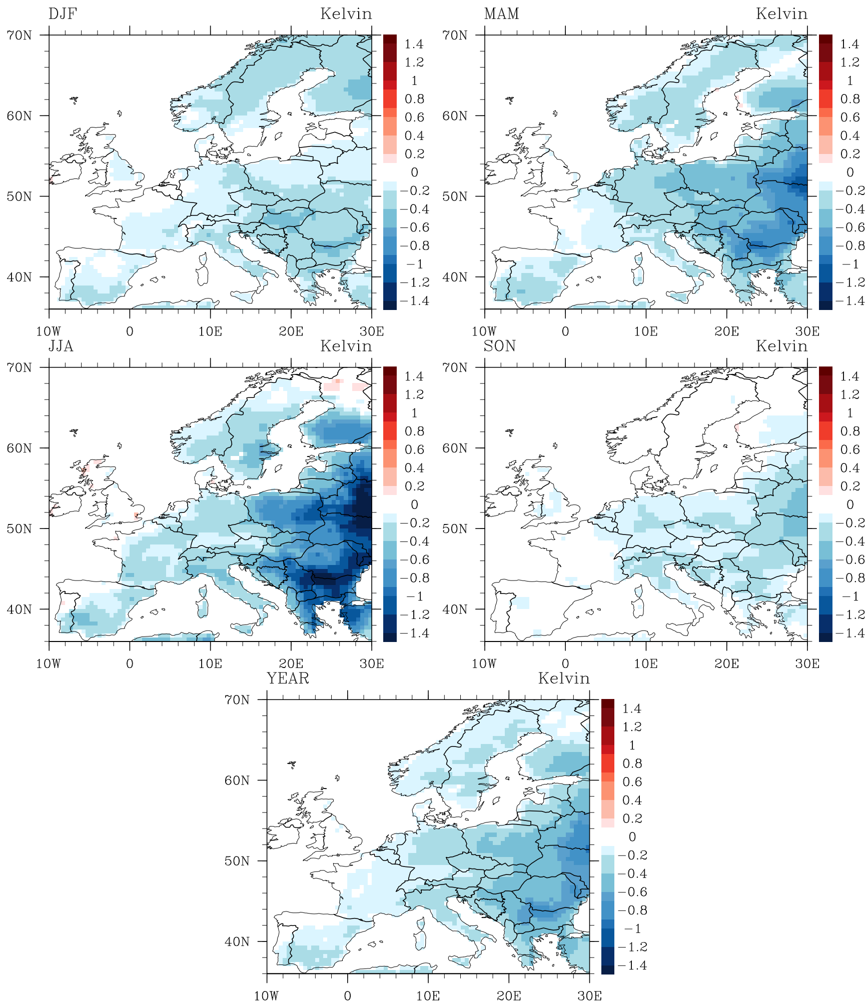

FIGURE 2.5: Yearly and seasonal means of the differences in 2-m temperature over land between the coupled and uncoupled runs, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{UNCOUP}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

much larger. Fig. 2.2 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.

2.7 Discussion

The COSMO-CLM model was evaluated for the European domain in many earlier studies. For example, Böhm 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 Böhm 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 Fig. 2.3; 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 Fig. 2.3. 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 Fig. 2.3, the biases are within those reported for the stand-alone COSMO-CLM model.

As can be seen in Fig. 2.5, 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 re-analysis 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). Fig. 2.6 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 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 model with a satellite-derived record (Loewe (1996), Høyer and She (2004)). They also found that the SSTs from their coupled model were low compared with observations, especially in summer.

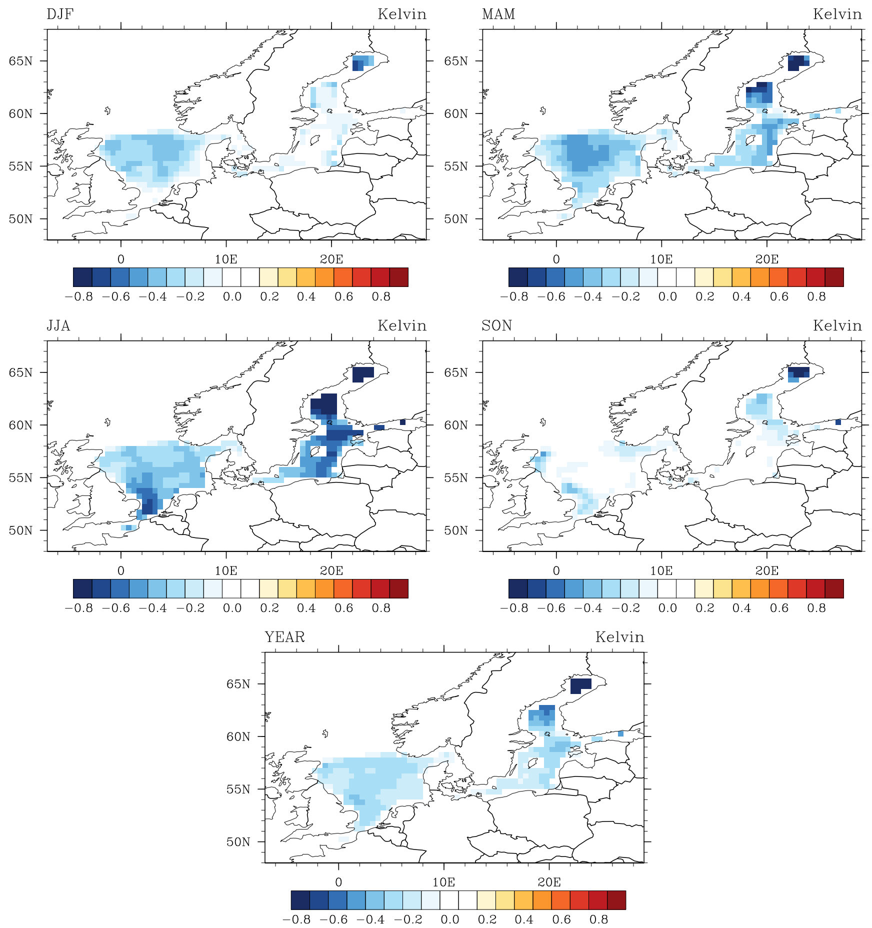

FIGURE 2.6: Yearly and seasonal means of the differences in sea surface temperature between the coupled run and the ERA-Interim re-analysis data, averaged over the period 1985–1994 for the North and Baltic Seas ($\mathrm{SST_{COUP}}$–$\mathrm{SST_{ERA-Interim}}$). YEAR: yearly mean; DJF: winter mean; MAM: spring mean; JJA: summer mean; SON: autumn mean

Looking at Fig. 2.5 and Fig. 2.6, 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 Fig. 2.7, 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. To separate the impact of the North and Baltic Seas from other factors,

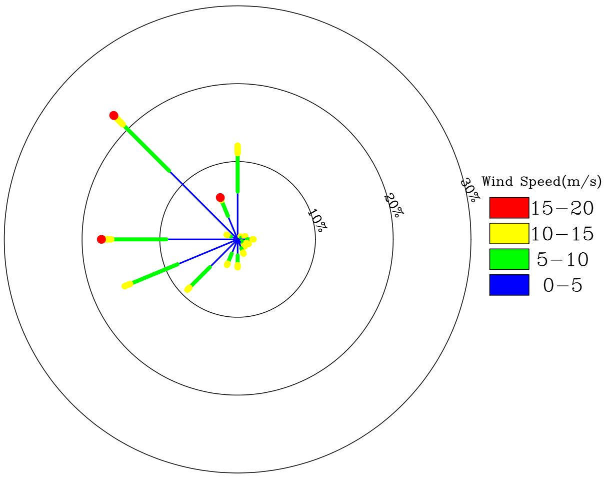

FIGURE 2.7: Wind directions from the coupled run over the period 1985–1994 in the weather classification area. The colours show the areal average wind speed at 950 hPa. The percentages show the frequency of wind direction occurrence

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. Fig. 2.8 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,

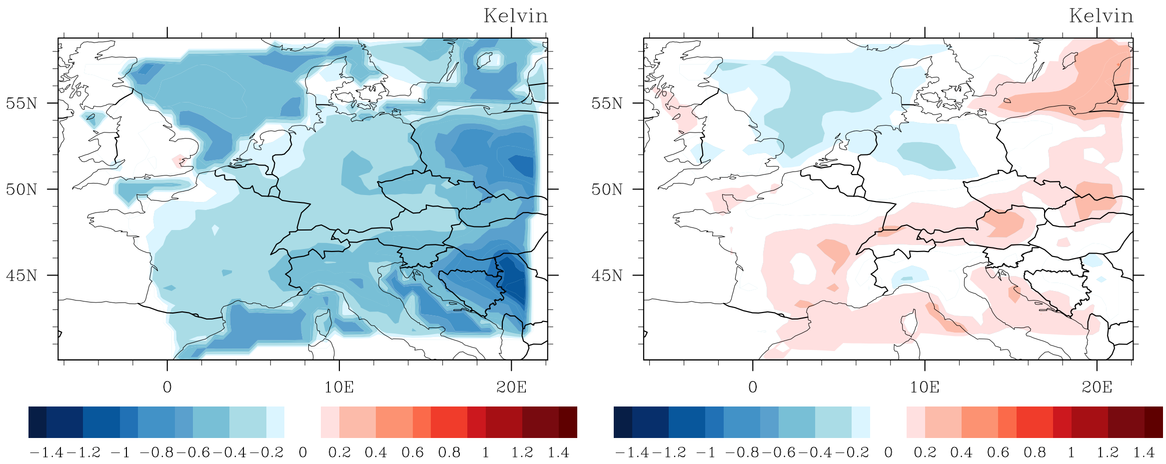

FIGURE 2.8: Mean 2-m temperature differences between the coupled and uncoupled runs, averaged over the period 1985–1994 ($T2M_{COUP}$–$T2M_{UNCOUP}$) for the weather classification area, for the dominant wind directions: North-West (left), or South-West (right)

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.

2.8 Conclusion

In this work, we have presented COSMO-CLM/NEMO an atmosphere-ocean-ice model system 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.

Chapter 3

Simulation of snowbands in the Baltic Sea area with the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO [1]

3.1 Abstract

Wind-parallel bands of snowfall over the Baltic Sea area are common during late autumn and early winter. This phenomenon occurs when cold air flows over the warm water surface, enhancing convection and leading to heavy snow fall. Six snowband events from 1985 to 2010 are simulated by using the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO. The model resolution is reasonably high to capture the snowbands; the atmospheric model COSMO-CLM has a horizontal grid-spacing of approximately 25 km and the ocean sea-ice model NEMO has a horizontal grid-spacing of approximately 3 km. The model results show that the coupled system COSMO-CLM/NEMO successfully reproduced the snowband events with a high contrast of temperatures between the surface and the atmosphere, sharp bands of precipitation over the sea, as well as the enormous heat fluxes released by the ocean to the atmosphere during the days when snowbands occurred. In the two cases when radar data are available, the model precipitation is shown to be in satisfactory agreement. The precipitation patterns closely follow the cloud shapes on satellite images. When not coupled with the ocean model, the atmospheric stand-alone model provided acceptable results if forced by high-quality sea surface temperatures (SSTs) from reanalysis data. However, COSMO-CLM forced with lower quality SSTs could not recreate the snowbands. The results indicate the need of

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an atmospheric model with high SST skill or a coupled ocean model when extreme event climatology is the primary aim in the Baltic Sea area.

3.2 Introduction

Snowbands often occur on the Baltic Sea in late autumn or early winter when the sea surface is still warm and maintains heat from the previous summer. When a cold air mass flows over a warm water surface, the air layer near the sea surface heats up, the large difference in temperature between the lower and upper air layers triggers strong convection. Enormous sensible and latent heat exchange between the sea surface and the air mass above enhances vertical turbulent mixing. Clouds are formed during convection, and heavy snow fall occurs. If the wind flows relatively strongly over the Baltic Sea surface, snowfall can be formed in wind-parallel snowbands (Andersson and Gustafsson, 1994). The impact of snowbands can be dramatic: when a large amount of snow is deposited in coastal areas, it can lead to severe traffic and communication disruptions or paralyze and isolate cities to an extreme extent.

Due to the extremity and rareness of events like snowbands, it is hard to get reliable observations for evaluation. Andersson and Nilsson (1990) demonstrated that it was impossible to use snowfall data from an established conventional precipitation gauge network over the sea for the detection of snowbands. There are two main reasons for this. First, drifting snow due to strong winds can result in a measurement of zero snow cover, even when there is significant snowfall. Second, snow cover is usually an accumulation of several snowfalls, and it can be difficult to attribute a specific amount of snow to an individual event. For these reasons, obtaining accurate snowband measurements has been a longstanding challenge in this area of research.

Because of the problem in determining the snowbands using measurements, researchers often focused on some connected meteorological elements of snowbands. This phenomenon has been studied in the Great Lakes of North America in a wide variety of literature. In this region, the snowband effect is often referred to as “lake effect”, but has basically the same features as snowbands. Carpenter (1993) proposed that the key criterion of the lake effect is the strong atmospheric instability, which is measured by the difference between the water surface temperature and the air temperature at 850 hPa. The temperature difference should exceed 13 K, enabling a typical lake effect. This criterion was also used in Barthold and Kristovich (2011) for a lake effect snow event study at Lake Michigan and in Andersson and Nilsson (1990) for their investigation of convective snowbands over the Baltic Sea.

Practice of short-term forecasting often does not need to consider an interactive ocean due to the fact that ocean often does not change much within a short time frame. However, when it comes to snowband simulations, it is important to realize that atmospheric model needs a realistic condition of the ocean to properly re-produce the bands of snow. Mesoscale ocean process plays a crucial role in interacting with the above atmosphere in order to enable the formation of snowbands. For the Baltic Sea, this issue is even more important because the sea is quite shallow and has complex topography; as a result, the SST and sea ice distribution tends to be very inhomogeneous and characterized by rapid change on small spatial and temporal scales. Therefore, an attempt to study the formation of snowbands on the Baltic Sea by Andersson and Gustafsson (1994) merely with the atmospheric model (High-Resolution Limited Area Model HIRLAM 25 km) is not adequate since at the lower boundary, the sea surface temperature (SST) over the Baltic Sea was kept constant during the model simulations. The fast changes in sea ice conditions and SSTs over the Baltic Sea and their impacts on weather developments were discussed by Gustafsson et al. (1998). Some events in this paper illustrated a dramatic change in the lower boundary due to rapid changes in sea surface conditions, which can occur within only 48 hours. As the results of testing one-way and two-way coupling, the paper noted the necessity of using a two-way coupled atmosphere ocean model for operational forecasts of snowbands.

Spin-up time is an issue in coupled atmosphere-ocean model simulation. In Gustafsson et al. (1998), the two-way atmosphere ocean coupling was implemented with a short spin-up of only 1.5 months. The results showed that in the case of a strong cold air outbreak, the coupled system failed to capture adequately the freezing of sea ice. A ten-day delay in freezing was found in the model results compared to the observations. Moreover, there was a cold bias of SST of approximately 1 K. These errors are due to the short spin-up period because in the Baltic Sea there is little vertical mixing in contrast to the North Sea which results in strong stratification. A longer spin-up time would give the ocean model more time to adapt to the current atmospheric conditions and to get a good initial condition; and consequently is required.

In this paper, we will simulate a number of snowband events over the Baltic Sea using the new generation coupled atmosphere-ocean-ice model COSMO-CLM and NEMO (Pham et al., 2014). The new improvement in our coupled system compared with the one from Gustafsson et al. (1998) is that the fluxes of sensible heat, latent heat and radiation are transferred directly from the atmospheric model to the ocean model. By that way, the fluxes are more consistent between the atmosphere and the ocean. The aim of our study is to investigate the necessity of using a coupled atmosphere-ocean-ice system for extreme events like snowbands in order to achieve an accurate forecast. The stand-alone atmospheric model driven by high resolution reanalysis data often performs sufficiently well. But when this source of data is not available, for example in case of climate projections, atmospheric models will have to rely on the lateral and lower boundary conditions from global climate models (GCMs). This second source of data is often coarse, and with a very coarse GCM, the Baltic Sea can be even unrepresented. For this reason, a high-resolution ocean model is supposed to become useful in providing more reliable ocean states for the atmosphere.

We will look at six snowband events over the Baltic Sea occurring in the period from 1985 to 2010. Among those, five were analyzed by separate studies, and a recent event of November 30, 2010 was reported by Deutscher Wetterdienst in Monthly Weather Report Express (Witterungsreport Express, November 2010). The dates and locations of where the snowbands occurred, along with the references, are listed in Table 3.1. To avoid the spin up problem in previous study, we tried to get a good initial condition for the ocean variables by running the stand-alone ocean model for a long period of time before spinning up together with the atmospheric model.

In the next section, a description of the atmospheric model, the ocean model, and the coupling is provided. Sec. 3.4 discusses the experiment design and the data we used, which is followed by the results of the simulations and discussion in sec. 3.5. We close the paper with conclusion in sec. 3.6.

3.3 Model description

We used the regional atmospheric model COSMO-CLM and the regional ocean and sea-ice model NEMO. The two models were coupled via the Ocean Atmosphere Sea Ice Soil Simulation Software (OASIS3) coupler (Valcke, 2013). OASIS3 acts as an interface model which interpolates and exchanges the data between COSMO-CLM and NEMO. The regional atmosphere-ocean-ice coupled system COSMO-CLM/NEMO was first introduced in Pham et al. (2014).

3.3.1 Atmospheric model COSMO-CLM

The atmospheric model COSMO-CLM (Böhm et al. (2006); Rockel et al. (2008), version cosmo4.8_clm17) is a non-hydrostatic regional climate model. COSMO-CLM is based on the thermo-hydrodynamical equations on rotated geographical coordinates. The model is written on Arakawa C-grid and the time integration scheme chosen for our case studies and experiments is a two time-level second order Runge-Kutta split-explicit scheme. The model is usually fed by global data at the lower and lateral boundaries. For convection, the Tiedtke mass-flux convection scheme with equilibrium closure based on moisture convergence is utilized in COSMO-CLM.

The model setup complies with CORDEX-EU in the CORDEX framework (Coordinated Regional climate Downscaling Experiment) (Giorgi et al., 2009). The horizontal resolution is 0.22° (approximately 25 km), and the time step is 120 seconds. It has 40 vertical levels. Details about the COSMO-CLM can be found in Doms et al. (2002) (`http://www.cosmo-model.org/content/model/documentation/core/default.htm`[2]).

We introduced the sub-grid scale ice into the surface roughness and albedo schemes of COSMO-CLM so that the atmospheric model can alter the surface roughness and the albedo based on the fraction of sea ice that it receives from NEMO. Instead of designating fixed values for surface albedo and roughness length for the whole grid cell, depending on a pre-defined freezing threshold of sea water (−1.7 K) like in the stand-alone COSMO-CLM, the model can calculate the grid's weighted average values depending on the sea ice fraction from NEMO's ice mask. More about the setup of COSMO-CLM can be found in Pham et al. (2014).

3.3.2 Ocean model NEMO

We used the NEMO ocean model version 3.3 (Nucleus for European Modelling of the Ocean) (Madec, 2008), including the sea-ice module named LIM3 (Louvain-la-Neuve Ice Model version 3) (Vancoppenolle et al., 2012). This model setup for the North and Baltic Seas called NEMO-NORDIC is described by Hordoir et al. (2013). The horizontal resolution is 2 minutes (approximately 3 km), there are 56 depth levels of the ocean. 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 (Fig. 3.1).

For fresh water inflow, we used 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 of a simulation with the atmospheric model RCA3 (Samuelsson et al., 2011) forced by ERA-Interim (Dee et al., 2011).

3.3.3 The coupled system COSMO-CLM/NEMO

The atmospheric and ocean models were coupled by the coupler OASIS3 with the coupling frequency of 3 hours. The coupled area is limited to the Baltic Sea and part of the North Sea (Fig. 3.1), in this region COSMO-CLM gets the SST and the fraction of

[2] Accessed August 22, 2016

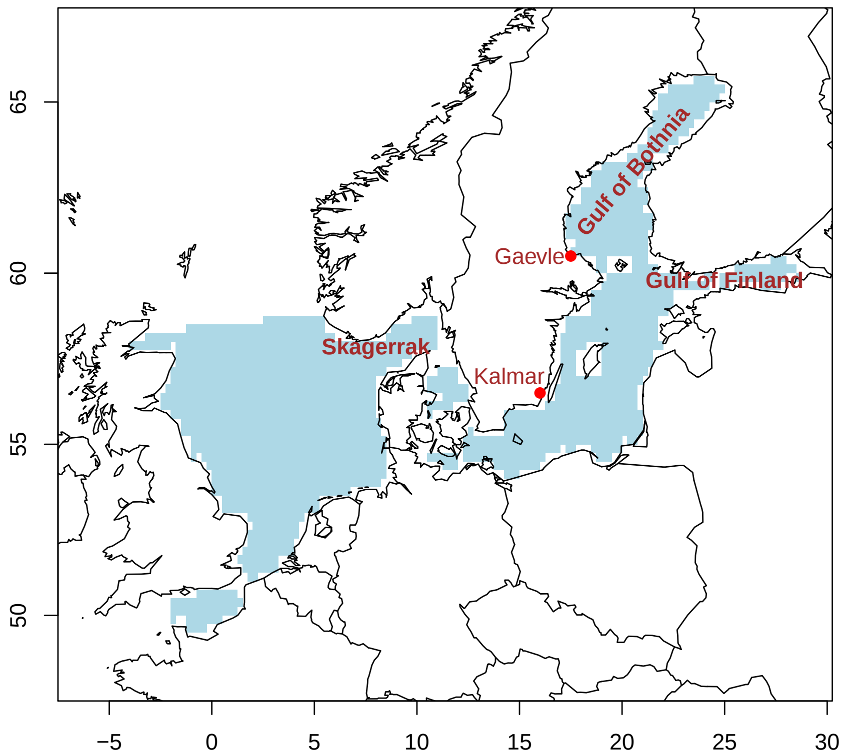

FIGURE 3.1: Geographical map. Blue area is the coupled North and Baltic Sea area.

sea ice from NEMO. Outside of the coupled ocean area, COSMO-CLM gets the lower boundary from the global forcing data for other sea surface areas as in the stand-alone mode. COSMO-CLM, in turn, feeds back the flux densities of water (precipitation - evaporation), momentum, solar radiation, non-solar energy and sea level pressure to the ocean. The fields are gathered by OASIS3 and then interpolated to the other model's grid.

3.4 Data and experiment set up

Six snowband events on the Baltic Sea were simulated by the coupled COSMO-CLM/NEMO model. In order to assess the ability of the coupled system to simulate the snowbands, we performed a COSMO-CLM stand-alone run forced by ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011) at the lower and lateral boundaries. This reanalysis data provide acceptable quality SSTs with approximately 80 km spatial and daily temporal resolution; therefore, this stand-alone experiment will act as a reference. The experiment is later referred to as "CCLM".

TABLE 3.1: Dates and locations of snowband events

Dates	Location	Reference	Start time for coupled model spin-up
03-07.01.1985	Gulf of Finland to Kalmar, Sweden	Andersson and Nilsson (1990)	01.01.1984
23.12.1986	Gulf of Finland	Andersson and Nilsson (1990)	01.01.1986
11.01.1987	Gulf of Finland	Andersson and Gustafsson (1994); Gustafsson et al. (1998)	01.01.1986
04-07.12.1998	Gulf of Bothnia to Gävle, Sweden	Vihma and Brümmer (2002); Savijärvi (2012)	01.01.1998
17-18.01.2006	Gulf of Finland	Savijärvi (2012)	01.01.2005
30.11.2010	Coast of Germany	Witterungsreport Express, Deutscher Wetterdienst (11.2010)	01.01.2010

A second experiment was carried out using COSMO-CLM stand-alone with a monthly averaged ERA-Interim SST over the North and Baltic Seas (the coupled area, Fig. 3.1) to test how well the snowbands could be simulated with poor resolution of SST. The rest of the domain was driven by ERA-Interim as in the reference run. This modified COSMO-CLM stand-alone experiment is called "CCLM-MOD". Note that we chose to test the temporal averaging here instead of coarser resolution because with coarse resolution as in GCMs, the Gulfs of Bothnia and Finland will hardly be resolved. Such case will apparently lead to the result that snowbands could not be reproduced.

The atmospheric and ocean models were run in the coupled mode. At the two open boundaries of NEMO, temperature and salinity were prescribed by the Janssen climatology (Janssen et al., 1999), which is a climatological monthly mean data set for temperature and salinity in the area of the North and Baltic Seas. At the upper boundary of the ocean model, the current atmospheric state was taken from COSMO-CLM. The COSMO-CLM model, on the other hand, received forcing from NEMO at its lower boundary over the coupled area, the North and Baltic Seas. Over the other sea areas COSMO-CLM was forced by ERA-Interim as in the stand-alone experiment. This experiment is later referred to as the "CCLM-NEMO".

The ocean and sea-ice model was spun up in stand-alone mode from January 1961 to the starting time when both atmospheric and ocean models were spun up in coupled mode. COSMO-CLM and NEMO were spun up together from January 1 of the previous year in the cases when snowbands occurred early in January. When the snowbands occurred late in November and December, the spin-up in coupled mode started from January 1 of the same year. The starting times for the coupled model spin-up in each case are presented in Table 3.1.

Model precipitation was not evaluated using station data because as discussed earlier winds are relatively strong during snowband events, which leads to a systematic undercatch in the gauge measurement due to snow drifting. Precipitation data from satellite products such as the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite

Data set (HOAPS) (Fennig et al., 2012) are provided on a regular latitude/longitude grid with a spatial resolution of 0.5°—0.5°. The grid is about four times larger than the COSMO-CLM output grid (0.22°—0.22°). In addition, the coverage of the HOAPS data over the Baltic Sea is very scarce; data are only available 50 km away from the coast and not all parts of the Baltic Sea are covered by the satellite. Consistent data availability is also a problem, as the events being studied in this paper range from 1985 to 2010, but the satellite products are often not available for all events. Therefore, cloud images taken by satellite were used in our study for qualitative comparison.

The radar products from Baltex Radar Data Center (Michelson, 2000) are available only as recently as 1999. Therefore, these radar data were used to evaluate only the two snow band events in 2006 and 2010.

3.5 Results and discussion

SSTs simulated by the coupled model were evaluated against SST data from Advanced Very High Resolution Radiometer (AVHRR) (Reynolds et al., 2007)). The gridded SST analysis is provided on a daily basis with a resolution of 0.25° using satellite data and in situ data from ships and buoys. The results (not shown here) exhibit acceptable agreement during the snowband periods. The differences range from -0.6 to 0.6 K, with large values limited to coastal areas. This might be caused by the difference in resolution between AVHRR data and NEMO output. NEMO has a grid size of 2 minutes while that of AVHRR is 0.25° (15 minutes). A more detailed evaluation of NEMO SSTs against AVHRR data can be found in Pham et al. (2014).

As mentioned above, according to Carpenter (1993), the contrast between the SST and air temperature at 850 hPa has to be at least 13 K to create an unstable atmospheric condition that enables strong convection. The vertical temperature gradient (SST - air temperature at 850 hPa) over the Baltic Sea for all six snowband cases and all three experiments are shown in Fig. 3.2. In general, the CCLM results meet this criterion. The difference in temperature always exceeds 13 K either over the whole Baltic Sea or at the location where the snowbands occurred. In contrast, CCLM-MOD simulates very limited differences (except the case in 2006). Most obvious are those for the 1987 event: CCLM-MOD results in a lower vertical temperature difference of less than 10 K over the Gulf of Finland where the snowbands are supposed to present. For the event of 1998, in CCLM-MOD, no obvious band occurs along the Gulf of Bothnia towards Gävle, Sweden, as seen in the CCLM and CCLM-NEMO result. Another case is the January 3, 1985 event, in which CCLM-MOD simulated much lower temperature difference values extended along the Gulf of Finland compared to CCLM. Similar patterns can be observed in the event of 1986. Along the Gulf of Finland and Bothnia, CCLM-MOD gives lower temperature differences than CCLM and CCLM-NEMO. For the events in 2006, CCLM-MOD over-estimates the temperature contrast around the Gulf of Bothnia due to its underestimation of SSTs.

On the other hand, CCLM-NEMO produces quite reasonable temperature differences compared with Carpenter's criterion at the location of the snowbands. For the December 7, 1998 event, within the central Baltic Sea, the vertical temperature gradient of the coupled model is only approximately 10 to 16 K. However, along the Gulf of Bothnia to Gävle, Sweden, where the snowbands are observed on satellite images, there is a distinguishable long band where the gradient is up to 26 K. On January 3, 1985, the snowbands extended from the Gulf of Finland to Kalmar, Sweden, and CCLM-NEMO is able to simulate a high contrast in temperature (always larger than 22 K) along this route, though to a lesser degree than CCLM. Similar to the two events in 2006 and 2010, the temperature patterns simulated by CCLM-NEMO are closer to the reference CCLM.

The pattern of the sensible heat flux follows quite closely to that of the temperature gradient. This is because in COSMO-CLM the sensible heat flux is defined proportionally to the difference between the temperature at the lowest grid level and the temperature of the ground. The results of daily sensible heat flux over the Baltic Sea from three simulations are shown in Fig. 3.3. CCLM and CCLM-NEMO reveal strong negative sensible heat fluxes over the Baltic Sea. These negative values refer to an upward sensible heat flux transferring heat from the ocean to the atmosphere. This is a typical phenomenon when snowbands take place, when cold air masses gain heat from the warm sea surface as they travel over open water. The large negative values of up to more than 220 W/m^2 can be seen as an indicator at the location where the snowbands occurred in all cases.

In most of the cases, CCLM-MOD produces much lower sensible heat fluxes. For example, in the events of 1985 and 1998, there are no clear bands from the Gulf of Finland to Kalmar, Sweden, and from Gulf of Bothnia to Gävle, Sweden, respectively. For the two events in 2006 and 2010, CCLM-MOD gave larger values of sensible heat fluxes than the two other simulations, but those are very distinct from the reference run CCLM; CCLM-NEMO is still closer to the reference run CCLM.

The sensible heat flux simulated by CCLM-NEMO is in good agreement with CCLM in most of the cases. Especially in the event of December 1998, a very distinct band from the Gulf of Bothnia to Gävle, Sweden, is evident in Fig. 3.3.

Due to the temperature contrast and significant mixing during a snowband event, a large quantity of latent heat must be transferred from the sea water surface to the atmosphere.

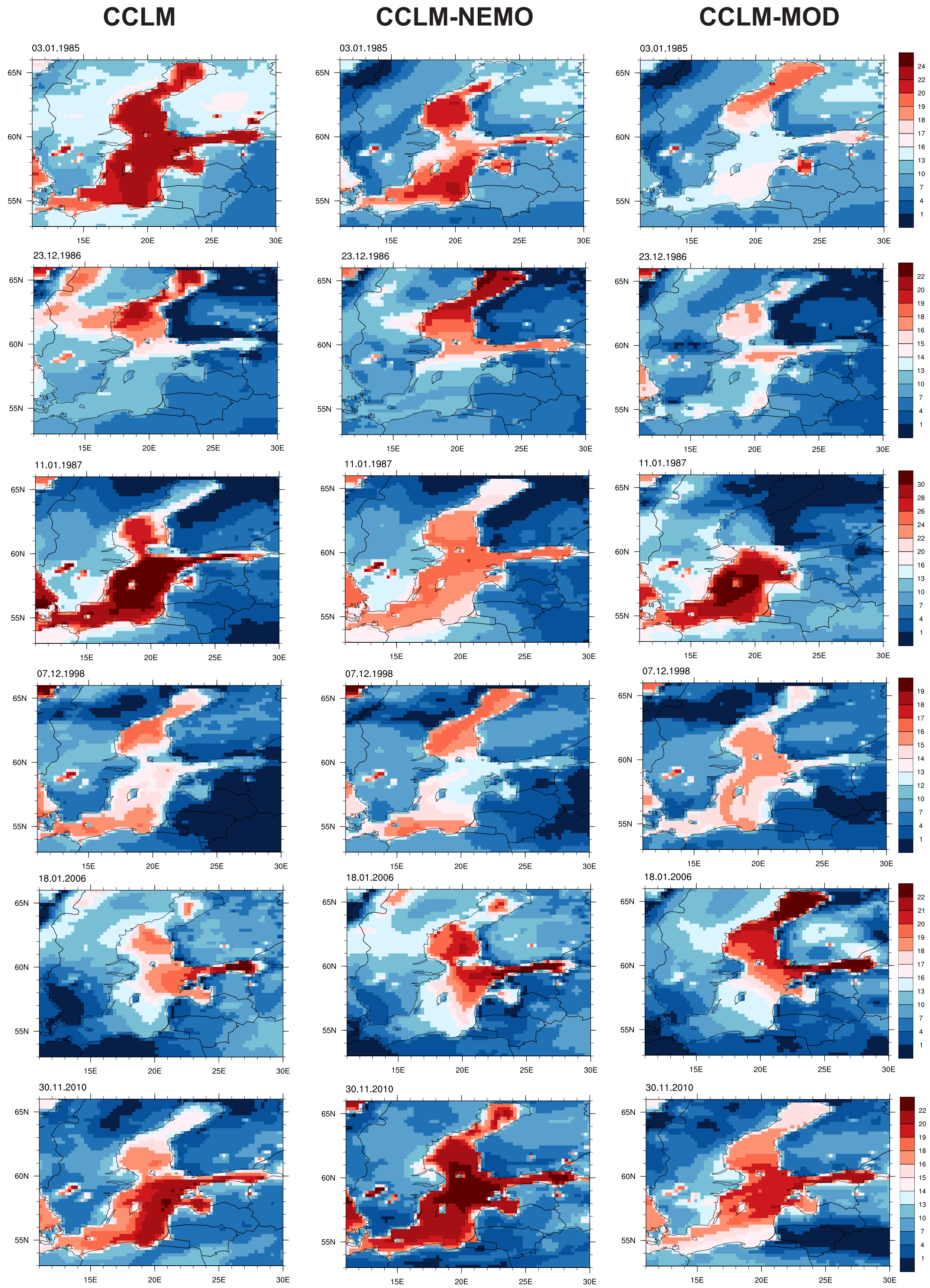

FIGURE 3.2: Results of daily average contrast between surface temperature and temperature at 850 hPa (Kelvin) over the Baltic Sea area as simulated with the experimental setups CCLM, CCLM-NEMO and CCLM-MOD for six snowband events.

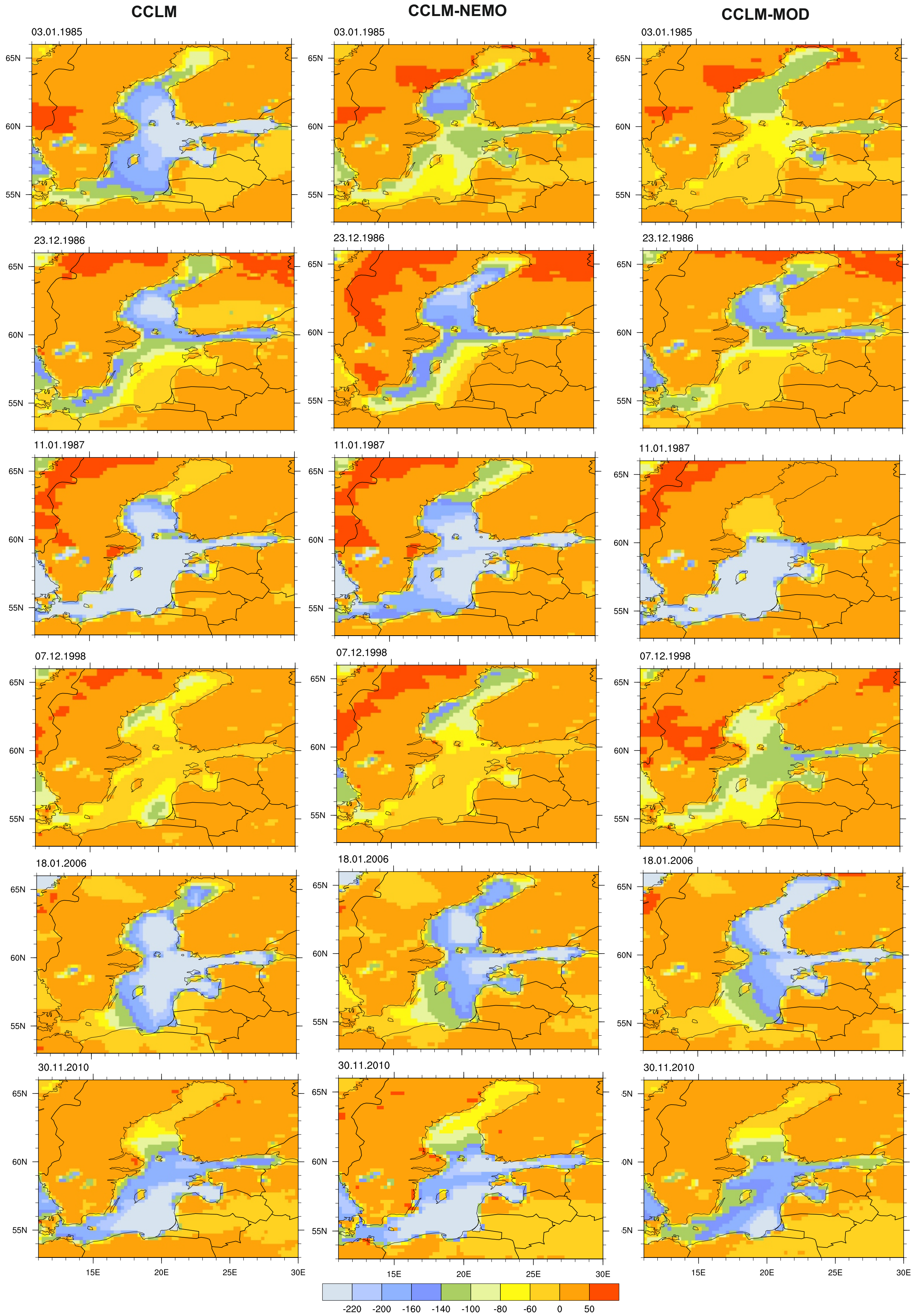

FIGURE 3.3: Same as Fig. 3.2 but for daily sensible heat flux (W/m^2).

That can be seen in Fig. 3.4, where the daily latent heat fluxes over the Baltic Sea from the three experiments are presented. The negative latent heat flux, which means an upward flux, has values of up to $-180\ W/m^2$. Overall, CCLM-NEMO simulates the six cases in closer agreement to the reference simulation CCLM than CCLM-MOD does. From the results of CCLM-MOD, hardly any bands of noticeably large negative latent heat flux can be seen in the events of 1985, 1986 and 1998. Most of the time, the latent heat flux simulated by CCLM-MOD has lower values than those in the CCLM and CCLM-NEMO simulations.

The simulated precipitation on the day the snowbands occurred is illustrated in Fig. 3.5 for CCLM, CCLM-NEMO and CCLM-MOD. All of the cases show the precipitation maxima at the west coast of Sweden, becoming weaker towards the east coast. Distinct bands of precipitation can be seen in the cases of 1987 and 1998 along the route of the snowbands (Gulf of Finland and Gulf of Bothnia to Gävle, Sweden). One can observe that on January 11, 1987, there is a clear band of large precipitation starting from the Gulf of Finland and extending to Kalmar, Sweden, in both CCLM and CCLM-NEMO. The precipitation distribution from the coupled model's output is very close to that of the reference run CCLM in this case. CCLM-MOD, on the other hand, failed to simulate this band. Similarly, in the event of December 1998, CCLM and CCLM-NEMO produce a band from the Gulf of Bothnia to Gävle, Sweden, which cannot be seen in the CCLM-MOD result. The Baltic Sea was completely ice free during the event in 1998 (Savijärvi, 2012) while in other cases, it was partly ice covered. The coupled model performs well in both situations, either when the surface roughness and albedo in the atmospheric model are altered according to the ice cover from the ocean or when those two parameters are the same as in the stand-alone experiment. For the event in 2010, CCLM and CCLM-NEMO simulate precipitation patterns which are quite close to each other with large precipitation of up to 10 mm around the German and Polish coasts on November 30, 2010. CCLM-MOD, however, results in lower precipitation values over the same area. In this case, CCLM and CCLM-NEMO show consistent bands from the Gulf of Finland to Kalmar, Sweden; however, the band simulated by CCLM-MOD is interrupted. For the 1985 event, CCLM-NEMO and CCLM-MOD do not follow the expected track. While CCLM appropriately simulates the snowbands in the Gulf of Finland, no bands were found in this gulf with CCLM-NEMO and CCLM-MOD.

To define the location of the snowbands, we looked at the satellite images shown in Fig. 3.6. Six images capturing the cloud cover for all six snowband events studied are shown. From 1985 to 2006, the infrared satellite images from NOAA (National Oceanic Atmospheric Administration) were utilized (Heidinger et al., 2010) while an image from MODIS (Moderate Resolution Imaging Spectrometer) was used for the event in 2010.

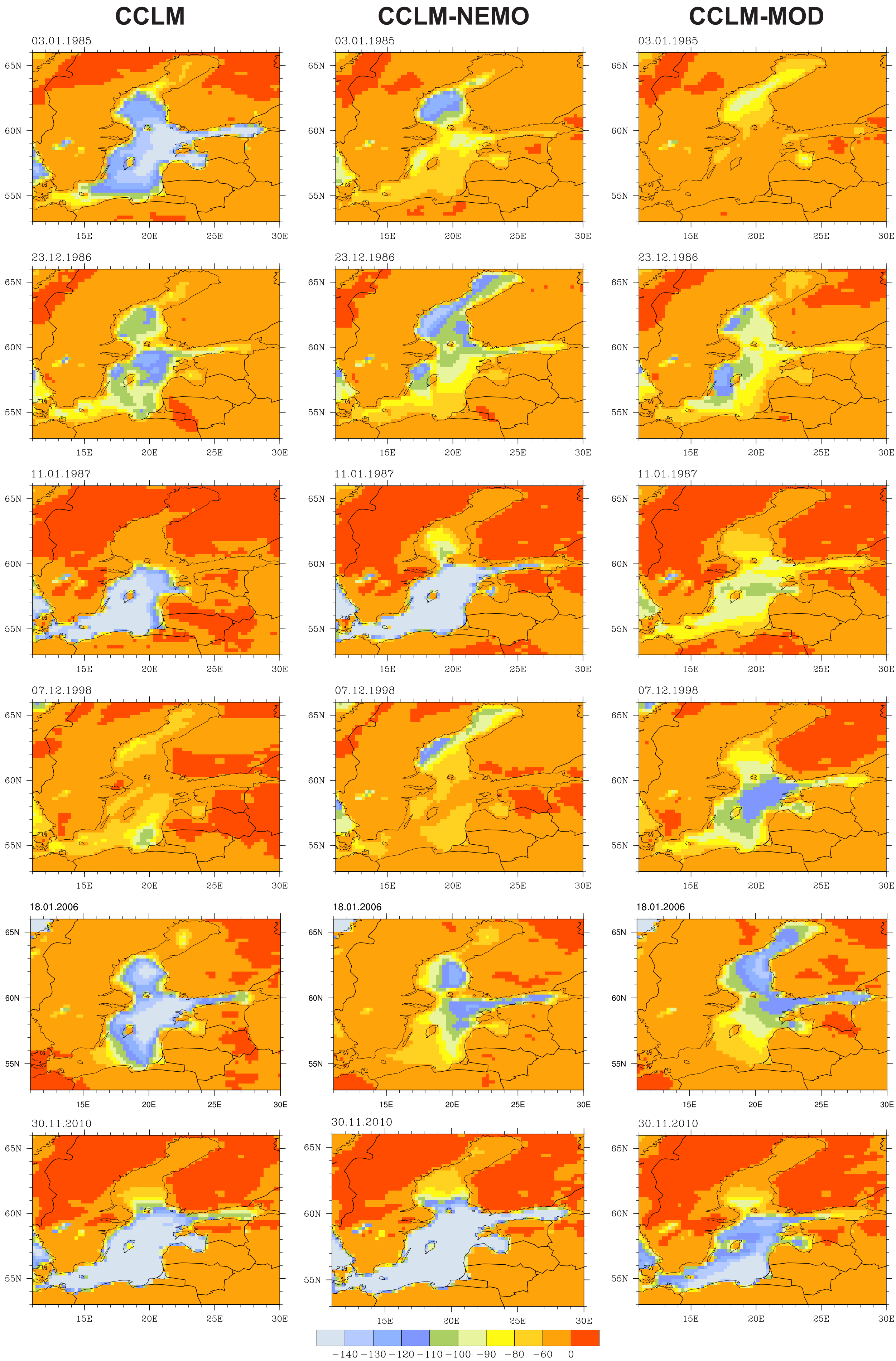

FIGURE 3.4: Same as Fig. 3.2 but for daily latent heat flux (W/m^2).

The satellite image (Fig. 3.6b) taken on December 23, 1986 does not show a very pronounced snowband, but the band is still observed as starting from the Gulf of Finland and extending westward. This occurred likely because of the poor timing when the satellite captured the image, so that the snowbands are not as obvious. Nevertheless, one can still see that CCLM and CCLM-NEMO are in agreement with the satellite image, especially CCLM-NEMO. CCLM-NEMO reproduced well the large precipitation located slightly to the southern coast of the Gulf; however, this feature cannot be seen in CCLM-MOD. The precipitation pattern from CCLM-MOD is different from that of CCLM and CCLM-NEMO, especially the parts along the east coast of Sweden and Latvia.

On January 11, 1987, there were distinct snowbands over the Gulf of Finland (Fig. 3.6c). These were properly simulated by CCLM and CCLM-NEMO. In Fig. 3.5 one can see the sharp, long snowbands starting from the Gulf of Finland and arriving at the coast of Sweden. This feature is completely missing in the CCLM-MOD precipitation map where in the Gulf of Finland the precipitation is zero.

The event in 1998 was featured in the literature (Savijärvi, 2012; Vihma and Brümmer, 2002) with the snowbands from the Gulf of Bothnia to Gävle, Sweden. They can be observed within the satellite image as a very straight strip (Fig. 3.6d). This feature can be seen within the CCLM-NEMO result as well and to a lesser extent on CCLM. Meanwhile, CCLM-MOD simulated very little precipitation over the Gulf of Bothnia.

In 2006, a snowband event occurred on January 18. This created long, thin snowbands from the Gulf of Finland to the coast of Sweden. The snowbands were best simulated by CCLM-NEMO with high precipitation along the Gulf of Finland. In the simulation, the high precipitation stays closer to the northern coast of the Gulf, in the same way as can be observed within the satellite image (Fig. 3.6e). CCLM can also reproduce this feature but with lower precipitation values and shorter snowbands that do not start from the very beginning tip of the Gulf. CCLM-MOD simulated even shorter and less obvious bands of precipitation.

On December 30, 2010, Deutscher Wetterdienst recorded snowbands near the German coast. On the satellite image (Fig. 3.6f), one can also observe parallel snowbands from the Gulf of Finland to Sweden and from the coast of Latvia extending towards the coast of Germany. These two parallel bands can be seen in the precipitation of CCLM-NEMO. Indeed, Fig. 3.5 shows two long, distinguished bands, one from the Gulf of Finland to the coast of Sweden and one from the coast of Latvia to the coast of Germany. To a lesser extent, CCLM also simulated these two bands, but the second band is shorter than in CCLM-NEMO; the band did not start from the continent but rather somewhere near the Gotland Island of Sweden. In the CCLM-MOD simulation, the two bands are

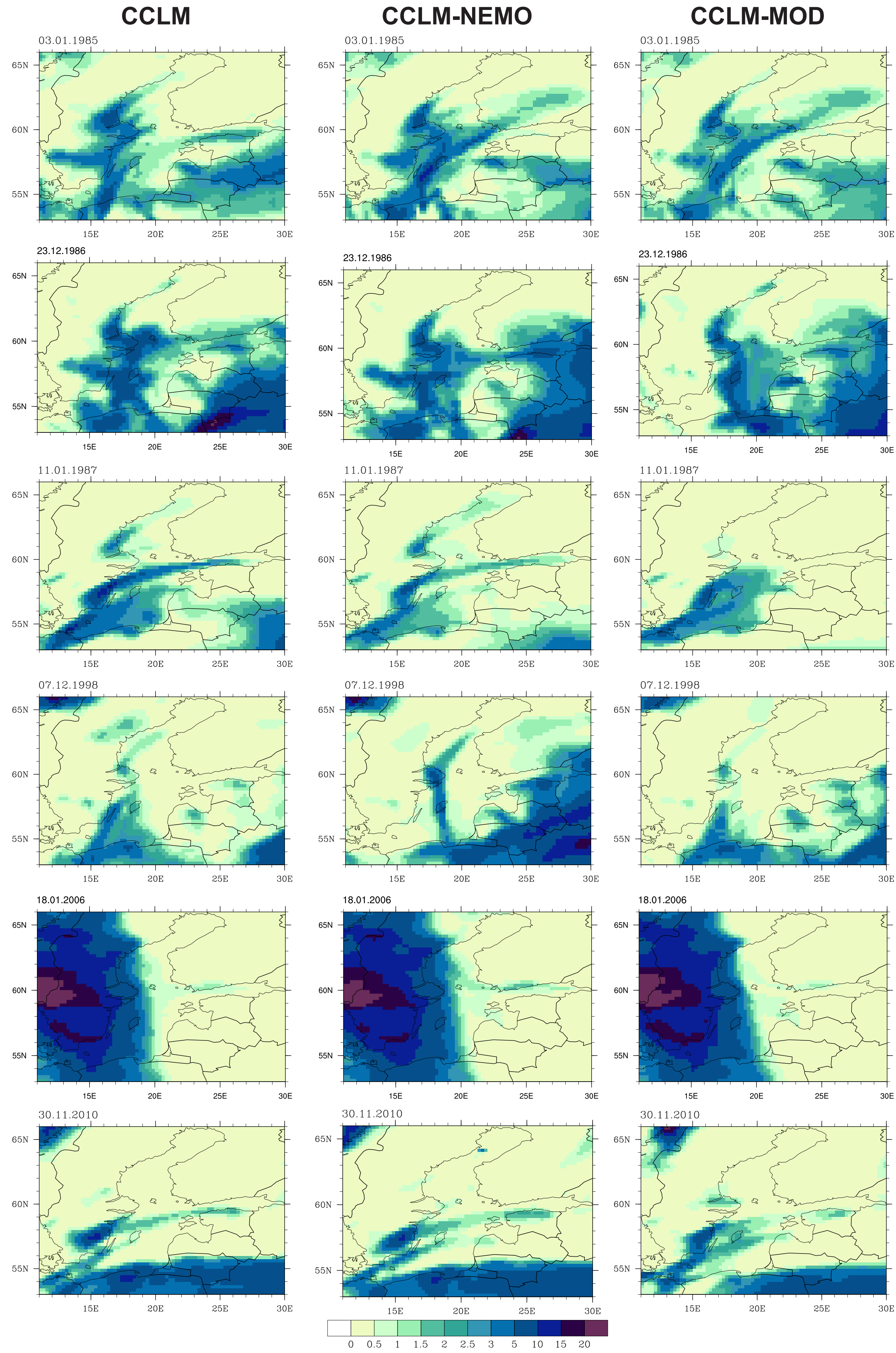

FIGURE 3.5: Same as Fig. 3.2 but for daily precipitation (mm).

not well separated, and the precipitation values are also lower in some parts of the bands compared with the two other experiments.

In comparison to the precipitation data from the radar products of Baltex Radar Data Centre, in both events 2006 and 2010, CCLM-NEMO gave smaller biases than CCLM-MOD. In Fig. 3.7, the differences between the precipitation from the three experiments and the precipitation from radar data are shown for the January 18, 2006 event. The experiment CCLM-MOD gives strongest biases, especially at the coast of Sweden where the snowbands deposit, the biases are larger than 12 mm. At the same time, CCLM and CCLM-NEMO show smaller biases over the Baltic Sea area as well as near the coastline. Root mean square errors (RMSE) from the experiment CCLM-MOD is also highest 5.7, compared with 4.9 from CCLM/NEMO.

3.6 Conlusion

Snowbands over the Baltic Sea often deposit huge amount of snow within a short period of time in the surrounding coastal cities and therefore locations and frequencies of such event should be well predicted to better prevent large damages. We have studied six snowband events over the Baltic Sea within a time period from 1985 to 2010. All of these snowbands occurred between November and January. This time is favorable for snowband formation due to the still relatively-warm SST where heat is stored from the last warm season, while snow already covers the continent. This condition leads to a large temperature contrast between the water surface and the air mass, triggering heavy snowfall over the sea. The parallel snowbands tend to expand as they approach the western coast of the Baltic Sea in Sweden or Germany, with heavy snow being deposited as the bands arrive at the coasts. In most of these cases, the northern Baltic Sea was partially covered by ice (in the Gulf of Finland and Gulf of Bothnia); however, one case in 1998 was studied when the Gulfs of Bothnia and Finland were completely ice-free.

The snowbands were investigated with the coupled atmospheric-ocean-ice model COSMO-CLM/NEMO. The stand-alone atmospheric model COSMO-CLM driven by reanalysis data ERA-Interim was used as a reference because of the assimilation of observed data into the reanalysis, the SST from ERA-Interim has a reasonably high quality. The results of the coupled model are quite close to those from the reference because the ocean sea-ice model NEMO is able to produce reliable SST values compared with ERA-Interim. Coupled model can be able to simulate typically large vertical temperature gradient between the sea surface and the air mass above. Observing the development of atmosphere instability as well as the heat fluxes, we saw that the coupled model captured well in time the snowbands for all events. The distribution of precipitation simulated by

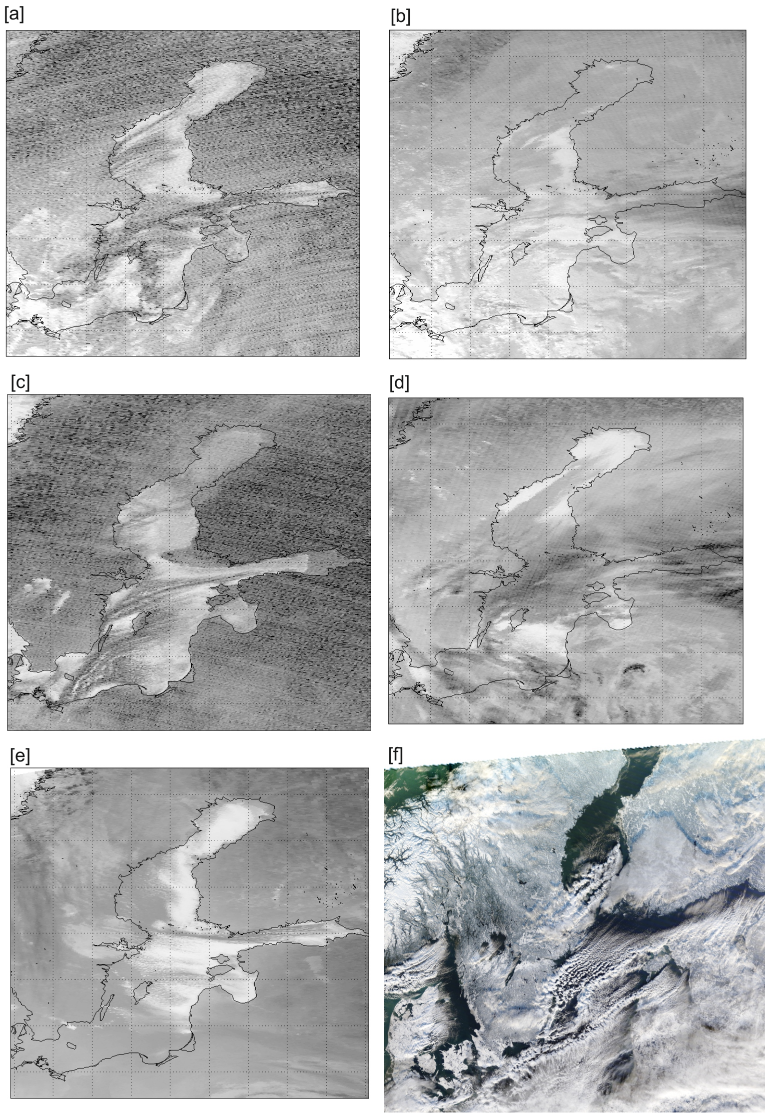

FIGURE 3.6: Satellite images for six snowband events over the Baltic Sea: a) NOAA-7 at 1156 UTC 03.01.1985; b) NOAA-9 at 1058 UTC 23.12.1986; c) NOAA-9 at 0210 UTC 11.01.1987; d) NOAA-12 at 0453 UTC 07.12.1998; e) NOAA-17 at 1903 UTC 18.01.2006; f) Terra MODIS at 1015 UTC 30.11.2010.

the coupled model agrees considerably with the cloud images. Additionally, a comparison of coupled model precipitation to radar data shows a similarity between the parallel bands in 2006 and 2010, although the analysis is limited by the lack of available radar data. Another example of coupled atmospheric-ocean model's capability to simulate extreme events is the work from Akhtar et al. (2014). The Mediterranean hurricanes were successfully recreated by the coupled COSMO-CLM and one-dimensional ocean model NEMO-MED12.

From this study, we concluded that the coupled atmospheric ocean model is indispensable for the climatology of extreme events like snowbands. The stand-alone atmospheric model forced by low-skill SSTs as in the GCMs resulted in lower temperature contrast

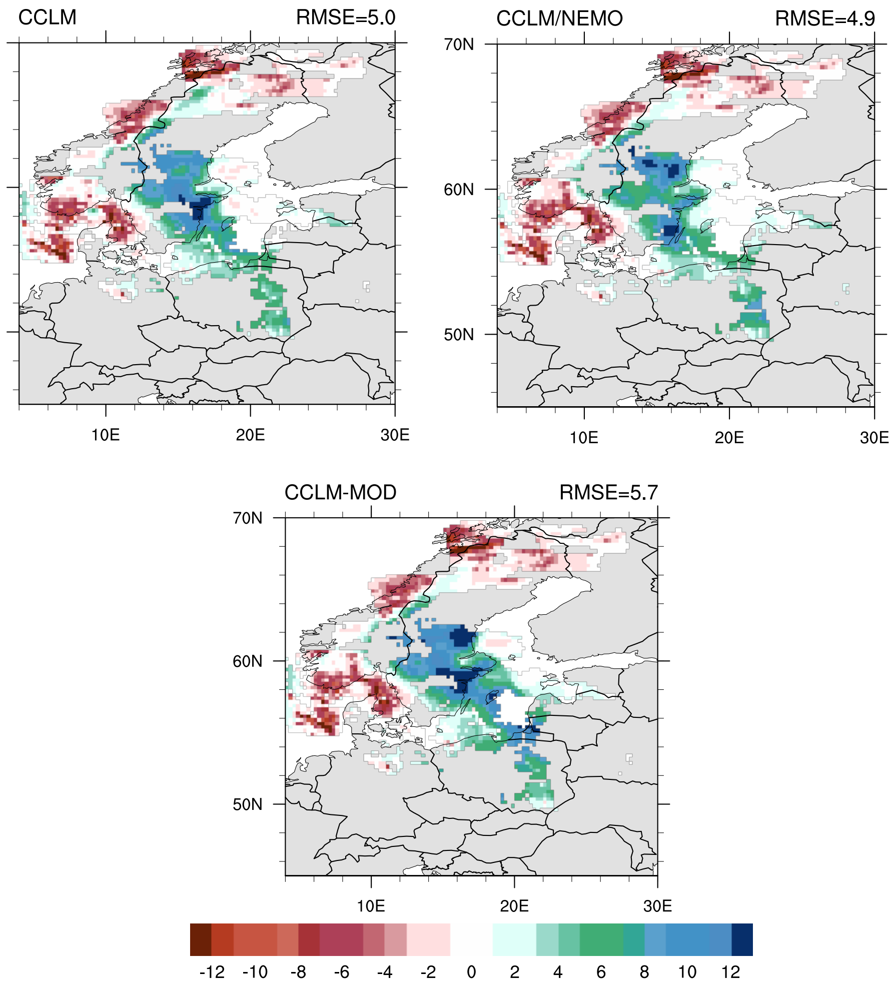

FIGURE 3.7: Differences in daily precipitation and RMSE (mm) between model outputs from experimental setups CCLM, CCLM-NEMO and CCLM-MOD and radar data. Figures are for the event 18.01.2006.

and sometimes a lower-than-required threshold. When there is no high resolution ocean states from an ocean model, the atmospheric model missed most of the parallel bands. Finally, snowbands are important extreme weather phenomenon as it affects strongly the Baltic region and its inhabitants, the regional climate model should be able to capture them. Because high resolution reanalysis data such as ERA-Interim are not available for climate projections, one must leverage SST values from GCM projection as forcing for COSMO-CLM. This will lead to results similar to the ones from our experiment, driven by low-skill SSTs or, in an even worse scenario, the Baltic Sea being unresolved in a very coarse GCM. In a climate simulation, such an experiment would underestimate the frequency of the snowband events. Furthermore, due to the exceptionally large surface heat fluxes that occur during snowband events, the simulation of such a unique and extreme event like snowbands is important not only for the event itself but also when studying monthly averages. The strong influence of the changes in sensible and latent heat fluxes from the ocean to the atmosphere proves that a relatively small body of water such as the Baltic Sea can have a pronounced impact on local weather, and it should be taken into account even in forecasting of extreme weather events or climate predictions.

Chapter 4

Added decadal prediction skill with the coupled regional climate model COSMO-CLM/NEMO [1]

4.1 Abstract

Regional climate models (RCMs) resolve regional climate features better than coarser-grid global climate prediction systems, which are often used to force the RCMs. This study attempted to enhance decadal climate predictions in a European modelling domain with the RCM COSMO-CLM by adding the interactive high-resolution ocean-ice component NEMO-NORDIC over the North and Baltic Seas. With this system, five decadal forecasts covering the period from 1960s to 2000s driven by global MPI-ESM predictions were prepared. The regional ocean was initialised with an ocean-alone assimilation run. The coupled RCM's results were compared with MPI-ESM and with atmosphere-only COSMO-CLM predictions. Coupling improved predictive skill for 2-m air temperature, especially near the southern coastlines of the North and Baltic Seas. However, forecast quality and the value added by coupling decreased with lead years (as expected). The skill gain was most evident during weak phases of the North Atlantic Oscillation, with relatively weak influence of westerlies and stronger impact of regional processes.

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4.2 Introduction

Atmosphere and ocean are two components of the climate system which interact at their common surface. The heat exchanged between ocean and atmosphere is a product of many processes, such as heating of the ocean water due to solar radiation, cooling of the ocean due to long wave radiation, sensible heat transfer by conduction and convection, and latent heat transfer by evaporation of sea surface water. Due to the capacity of the ocean to store a huge amount of energy, its adjustment to the incoming radiation and energy loss happens slowly compared to land surface and atmosphere adjustments. The ocean's memory can be up to decades or longer, making the ocean a very important component of the climate system when it comes to variability on long time scales.

In this paper, we looked at the impact of the North and Baltic Seas on the regional decadal climate. These seas feature complex coast topography with narrow straits and gulfs not represented in global climate predictions. The North Sea is characterised by a thermocline in summer, which allows the deeper layers to keep the temperature of the previous winter. In winter and autumn, this stratification breaks down and the North Sea is vertically well mixed. On the other hand, a permanent halocline exists in the Baltic Sea. This hinders water mixing between the near surface layer and deeper layers. Hence, only the upper part of the Baltic Sea is available to exchange heat with the air at short time scales. The heat stored in Baltic deeper layers can affect long-term climate of the region. Several studies have shown the important role of the Baltic Sea in defining the surrounding regional climate. For example, Jaagus et al. (2010) found that the Baltic Sea is the main factor deciding the precipitation pattern in some countries near its coast. In Feistel et al. (2008), the authors pointed out that the long water residence time in the Baltic Sea below the halocline influences the climate at time scales over 30 years. Therefore, proper consideration of the North and Baltic Seas must be taken in climate modelling.

To simulate the regional climate, dynamical downscaling techniques are often applied to the global climate data. Added values by RCMs to global climate models (GCMs) cover a broad spectrum, in which the RCMs may or may not be compared better with observations than GCMs. Additional detail information on climate simulations can be provided by an RCM; and thus added values in regions with complex orography, land-sea contrasts, etc. can be seen in downscaling (Rummukainen, 2016). Regarding model development, added values could underlie in more physically based models compared to GCMs; or a more comprehensive representation of the climate system with regional coupled atmosphere-ocean models. The added values via adding more climate information at regional scale are well-known in RCM applications. However, the question whether RCMs add climate predictabilities to GCMs' forecasts is a different topic. Adding local climate details does not necessarily lead to better predictive skills. This paper focuses on the added predictability of regional climate simulations, meaning the ability of the RCMs to forecast climate states closer to the observations compared with GCMs.

In literature, there is a wide variety of recent studies which have focused on decadal climate predictions at different spatial scales. On global scale, for example, Pohlmann et al. (2013) used the global model MPI-ESM to assess the role of initialization and the impact of the higher vertical resolution in the atmosphere and higher horizontal resolution in the ocean. Two sets of experiments, MPI-ESM-LR (low resolution, atmosphere: T63L47, ocean: 1.5°L40) and MPI-ESM-MR (mixed resolution, atmosphere: T63L95, ocean: 0.4°L40), were analyzed. They concluded that higher atmospheric and oceanic resolutions could improve climate predictions. This indicates potential benefit of decadal prediction downscaling with an RCM.

In the project MiKlip (Mittelfristige Klimaprognose, i.e., mid-term climate forecasting), various decadal forecast downscaling experiments were done with the limited area COSMO-CLM forced by the global MPI-ESM model (overview by Marotzke et al. (2016)). This project revealed that the regionalisation with COSMO-CLM could only maintain the forecast skills for air temperature but did improve the global model's precipitation prediction patterns (Mieruch et al., 2014; Paxian et al., 2016). Moemken et al. (2016) demonstrated a potential for forecasting wind energy up to several years into the future by downscaling. The results were promising, as the regionalisation preserved and at times improved global forecast skills. The effect of regionalisation, however, varies with lead time. Moemken et al. (2016) concluded that added predictive value found in the first few forecasting years by regionalisation are mainly because of forecast initialization.

The GCMs, that are frequently used in climate prediction studies, often consist of an atmospheric component and an oceanic component. Although the COSMO-CLM/MPI-ESM forecasting system comprises a global ocean model, there is no two-way interactivity between the global ocean and the RCM. Thus, the fine-scale flux information from the regional atmosphere cannot reach the global ocean. To overcome this drawback, Paxian et al. (2016) used an RCM – global ocean model system fully coupled within the regional model domain to make decadal predictions for West African rainfall. Although their global ocean model's resolution is still coarse (varying from 7-25 km to 60-65 km, depending on latitude), they found that the better representation of air-sea interactions strongly improved the sea surface temperature (SST) bias, and led to an added value in rainfall simulation.

The GCMs generally have very coarse resolution. For example, MiKlip's MPI-ESM-LR (T63L47) has an atmospheric horizontal grid resolution of approximately 200 km.

The North and Baltic Seas are represented by 2-3 grid cells. The straits of Skagerrak and Kattegat, which connect the Baltic Sea to the North Sea, are not resolved; therefore interactions such as freshwater or salinity exchange between the two seas are not captured by global models. Furthermore, inhomogeneous distribution of salinity in the Baltic Sea or the highly varied sea surface heights in the North and Baltic Seas (Gustafsson, 1997) cannot be seen in global simulations. Previous studies, such as Kirtman et al. (2012) and Fanning and Weaver (1997), proved that the local air-sea interaction in climate modelling is strongly subjected to the ocean model resolution.

However, to date no work has been done that utilises a regional coupled atmospheric and ocean model to provide decadal predictions. Published works under the extensive project MiKlip, which focuses strongly on decadal climate prediction, were so far mainly done with stand-alone atmospheric model. Whether a coupled regional model could improve climate forecasts compared with the global model or with the uncoupled regional model is still an open question.

In this study, we discuss five decadal forecasts using the stand-alone COSMO-CLM with and without coupling to the ocean-ice model NEMO for the North and Baltic Seas. This coupled model system was first introduced in Pham et al. (2014); an evaluation showed biases generally less than 2 K of the coupled model's 2-m temperature compared with observations. COSMO-CLM/NEMO is also capable of simulating extreme events as illustrated in Pham et al. (2017). Several snowband events over the Baltic Sea were successfully reproduced by this coupled system.

The present paper aims to demonstrate that the regional coupled atmosphere-ocean-ice model adds values in terms of decadal predictive skill over the atmospheric-only model forced by a global coupled atmosphere-ocean model. Given the availability and importance, we focus on 2-m temperature in Europe. Other climate variables are more difficult to evaluate and have shown less prediction value in former decadal experiments. Aiming at regional effects of coupling, the forecasts were investigated separately for periods of positive and negative North Atlantic Oscillation (NAO) index values with strong and weak Atlantic influence, respectively, in the area of the Baltic Sea. During the weak influence phase, we expected less impact from the Atlantic on the climate in the Baltic and North Sea area, which would help a better identification of the added predictability of the coupled North and Baltic Seas.

In the next section, we describe the atmospheric model, the ocean model and their coupling. Section 4.4 addresses the experimental design along with the skill score used in evaluating our forecasts. The method utilised for data stratification by NAO index is also presented in this section. In Section 4.5, the results of the simulations and a discussion are presented. We close with conclusions in Section 4.6.

4.3 Model description

This study used the coupled model COSMO-CLM/NEMO (Pham et al., 2014) which consists of two components: the atmospheric model COSMO-CLM in version cosmo4.8_clm17 (Rockel et al., 2008) and the ocean model NEMO (Nucleus for European Modelling of the Ocean) in version 3.3 (Madec, 2008). A sea ice model called LIM3 (Louvain-la-Neuve Ice Model version 3) is included in the ocean model component which is described in detail in Vancoppenolle et al. (2012). The atmospheric model is used with a horizontal grid resolution of 0.22° (approximately 25 km), with 40 vertical layers, and a dynamical time step of 120 s. The ocean model set-up that was used for the North and Baltic Seas is called NEMO-NORDIC (Wang et al., 2015). This three-dimensional set-up has a horizontal grid resolution of 2 minutes (about 3 km), 56 vertical layers, and a dynamical time step of 300 s. A surface-following z-coordinate with partial steps is used to enhance resolution of the vertical levels near the sea surface. The model domain (Figure 4.1) covers the Baltic Sea and parts of the North Sea with two open boundaries. The western boundary lies in the English Channel and the northern boundary is along a line from Scotland to Norway.

The atmospheric model COSMO-CLM and the ocean-sea-ice model NEMO-LIM3 are coupled with the coupler OASIS3. The Ocean Atmosphere Sea Ice Soil Simulation Software (OASIS3) coupler (Valcke, 2013) works as an interface communicating between the component models at certain time intervals. This coupling frequency is user dependent and a three-hourly time step was chosen. The ocean model receives the fluxes of water (precipitation - evaporation), momentum, heat and sea level pressure from the atmosphere and in turn feeds SST and the fraction of sea ice back to COSMO-CLM.

COSMO-CLM, itself, includes a sea-ice parameterisation, which is switched off in the coupled mode. COSMO-CLM's sea-ice parameterisation assumes a completely frozen grid-cell with an ice albedo and ice surface roughness if the skin temperature is below the preset freezing point of -1.7°C. The freezing point is set globally and assumes a sea water salinity of 35 PSU (Practical Salinity Unit). The Baltic Sea, however, is a brackish sea with much lower regionally varying salinity (Gustafsson, 1997), which might lead to underestimation of sea ice cover (thus underestimation of sea surface albedo and overestimation of sea surface roughness) in the Baltic Sea. In coupled mode, COSMO-CLM calculates the weighted grid-cell averages of sea surface albedo and roughness depending on the water/ice fraction it receives on the NEMO grid from LIM3 (Pham et al., 2014).

4.4 Experiments and evaluation methods

Decadal forecast simulations were set up for five decades spanning from 1961–1970 to 2001–2010. For each decade, the 10-year simulations started on 1 January of the first year (e.g. 01.01.1961) and ended on 31 December of the last year (e.g. 31.12.1970). The simulation experiments were carried out with the stand-alone atmospheric model COSMO-CLM (hereinafter referred to as CCLM) and the coupled atmosphere-ocean-ice model (CCLM/NEMO). At the lateral and lower boundaries, CCLM was forced by global MPI-ESM (Max-Planck Institute for Meteorology Earth System Model) simulations. The global simulations were taken from the MiKlip experiments MPI-ESM-LR (T63L47/GR1.5L40) baseline 1 realization 1 (Pohlmann et al., 2013). These global decadal forecasts were started from a combined atmosphere-ocean initialization derived from an assimilation experiment. For this assimilation run, temperature and salinity anomalies from the ocean re-analysis data ORAS4 (Balmaseda et al., 2013) were added to the model climatology defined by a historical run for the period of 1958-2005.

In the coupled experiment CCLM/NEMO, the boundary conditions for NEMO were taken from seasonal cycle of Janssen's ocean climatology (Janssen et al., 1999). Fresh water inflow from the climatology of hydrological model E-HYPE output was used for the North and Baltic Seas (Lindström et al., 2010). The atmospheric input for the E-HYPE simulation was derived from a simulation with the atmospheric model RCA3 (Samuelsson et al., 2011) forced by ERA-Interim re-analysis data (Dee et al., 2011). NEMO was initialized each decade using data from a NEMO-NORDIC stand-alone historical run (started in 1961) driven by ERA40 (Uppala et al., 2005) and ERA-Interim data. Note that in coupled mode, COSMO-CLM got the lower boundary condition over the coupled sea area (blue area on Figure 4.1) from NEMO-NORDIC otherwise from MPI-ESM-LR forcing predictions.

This work aimed at quantification of the added predictive skill of coupling an ocean model to an RCM compared to the stand-alone RCM or the forcing global model. Therefore, we used the Mean Square Error Skill Score (MSESS) which was recommended by Goddard et al. (2013) as the primary metric to measure the improvement of a model forecast over a reference forecast.

The skill score was first introduced by Murphy (1988) with

$$MSESS = 1 - \frac{MSE_I}{MSE_R} \tag{4.1}$$

The MSE_I and MSE_R are the mean square errors of the forecasts of interest and reference, respectively, against an observation. Positive skill score values indicate added

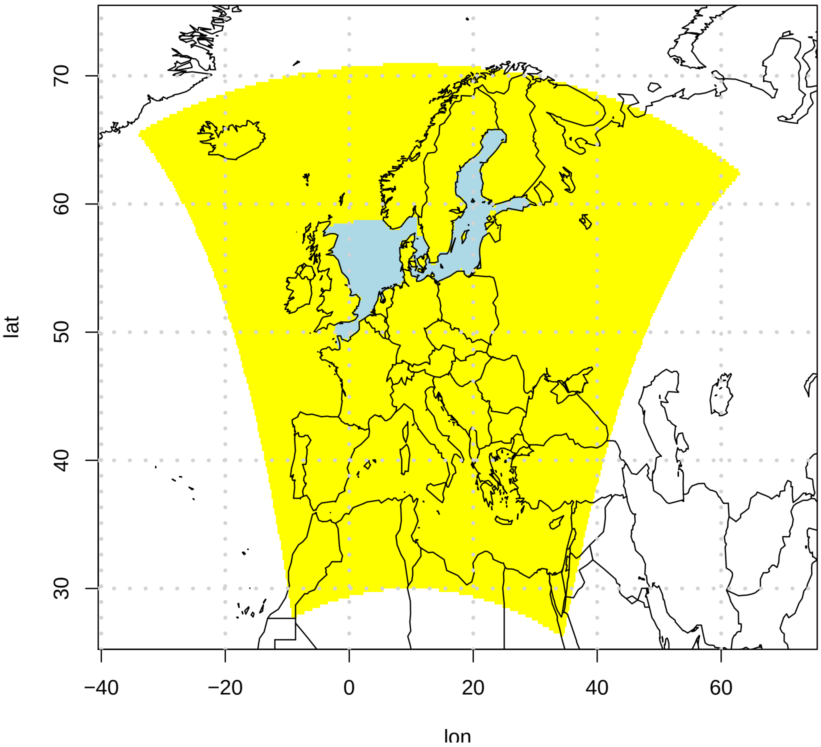

FIGURE 4.1: NEMO-NORDIC model domain (blue area) inside the COSMO-EU domain (yellow).

predictive skill by the interest model forecasts; zero or negative skill score values imply no gain or loss in forecast performance of the interest model.

Single forecasts for five decades only limit the sample size usable in forecast evaluation. However, data pooling of monthly average quantities from multiple decades improved the robustness of our results (more details on pooling and data stratification below).

As 2-m temperature observations, we applied E-OBS (version 10.0) data (Haylock et al., 2008). E-OBS is a 0.25° gridded daily dataset covering all of Europe, with data retrievable from quite recent back to 1950. In order to compare 2-m temperature data from different datasets, a height correction was performed. The model temperature values at E-OBS 2-m height were calculated based on the differences between model and E-OBS surface elevation and the moist adiabatic lapse rate (0.0065K/m).

The model performance in simulating SST was assessed using the Optimum Interpolation Sea Surface Temperature (OISST) data (Reynolds et al., 2007; Reynolds, 2009) from the National Oceanic and Atmospheric Administration (NOAA). This is a daily dataset constructed by combining observations from different platforms (satellites, ships, buoys) on a regular global 0.25° grid. Since this data set only covers the period from late 1981 to the present, part of our SST simulations could not be evaluated.

In evaluation, we stratified the data with respect to seasonality, lead years, and NAO regime. The NAO is widely recognized as one of the most prominent teleconnection patterns in all seasons (Barnston and Livezey, 1987) over the North Atlantic Ocean and Europe. The strength and direction of the westerly winds over Europe are governed by the permanent low pressure system, the Icelandic Low, and the permanent high pressure system, the Azores High. The relative strength of these two pressure systems are represented by the NAO index. While positive NAO index values (NAO+) are associated with strong activity of westerlies which leads to a relatively strong large-scale circulation impact on the northern Europe regional climate, negative NAO index values (NAO–) imply weaker influence of the large-scale weather system, and therefore a more pronounced local impact of the marginal North and Baltic Seas is expected.

For that reason, we analysed our coupled and uncoupled model's forecast skills during positive and negative NAO phases separately. Since our interpretation relied on the phases of NAO, and the model forecasts are compared with observations in different NAO situations, it is important to make sure that model data taken for analysis only if the NAO index values forecasted by MPI-ESM-LR are in phase with observation's index values. Monthly averaged NAO index values as predicted by the MPI-ESM-LR global simulations (derived from sea level pressure fields following Hurrell (1995)) were compared with NAO observations (taken from NOAA's reference monthly NAO index data (Chen and Van den Dool, 2003), `http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml`[2]). MPI-ESM-LR's NAO phases agreed slightly more than half of the time with observed NAO phases. Figure 4.2 shows the differences between the forecasted monthly NAO index and the NOAA reference index for the decade 2001-2010. MPI-ESM's low predictability of the NAO index reduced sample size substantially (in total, there are 306 data points spanning over 600 months), but this was accepted because it allows zooming into combined NAO– phases with potentially pronounced regional coupling impact.

The forecasts were pooled and the skill scores were calculated for different lead periods: lead year 1, lead years 2-4, 5-7 and 8-10. That left us with about 14-51 data points for each lead time period (Table 4.1). We also analysed forecast skills for different seasons. Stratifying the data with respect to NAO phases and seasons left us with about 23-62 data points for each seasonal analysis (Table 4.1).

The significance of prediction differences was estimated with one sample t-tests, with the sample consisting of the MSESS grid point values. The MSESS values sample approximately a normal distribution, and thus meets the assumption of the t-test. In

[2]Accessed July 18, 2018

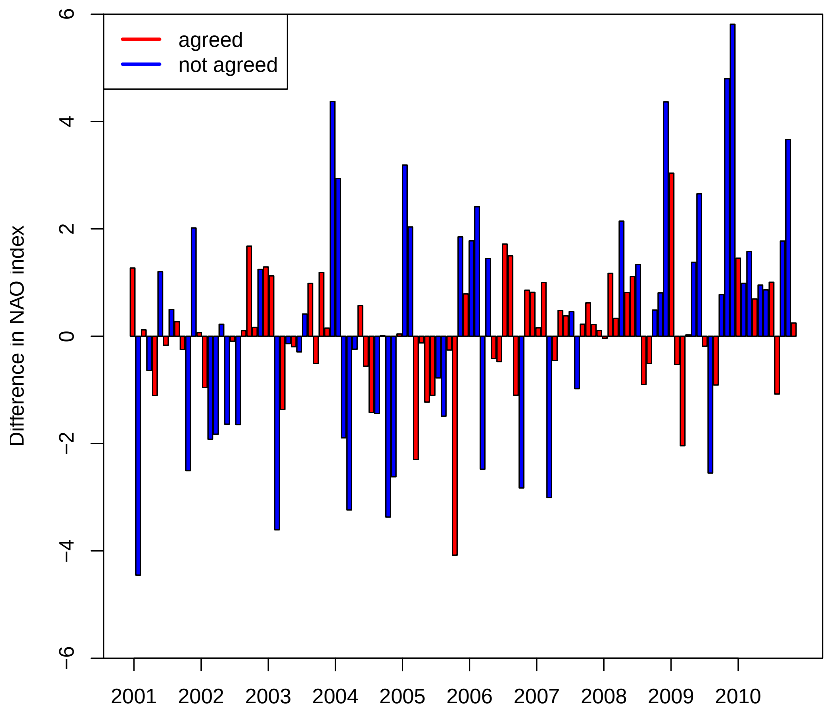

FIGURE 4.2: Differences in monthly NAO index between MPI-ESM and NOAA for the decade 2001-2010. Red color shows the months when the two datasets agree in phase. Number of agreement: 67/120 monthly indices.

TABLE 4.1: Sample sizes (monthly mean values) available after data stratification by NAO phases.

Lead years	1	2-4	5-7	8-10
NAO+	15	51	41	46
NAO–	14	42	50	47

Seasons	Winter	Spring	Summer	Autumn
NAO+	62	33	30	28
NAO–	23	47	39	44

our results below, we highlighted areas with skill score values significantly different from zero at 95% confidence level.

4.5 Results and discussion

Figure 4.3 shows the averaged biases of the five decadal 2-m temperature predictions with the coupled CCLM/NEMO. The biases generally stay within +/-1.5 K over Europe with larger biases found over mountainous area (the Alps and the mountain range in Norway). The 2-m temperature biases of the coupled model are in the order of magnitude or slightly larger than reported for RCMs including COSMO-CLM (Kotlarski et al., 2014). However, it should be emphasized that the experiments evaluated by Kotlarski et al. (2014) were driven by ERA-Interim re-analysis data (which is assumed to be better forcing data than MPI-ESM predictions). The uncoupled CCLM prediction had similar bias pattern and magnitudes as CCLM/NEMO (not shown).

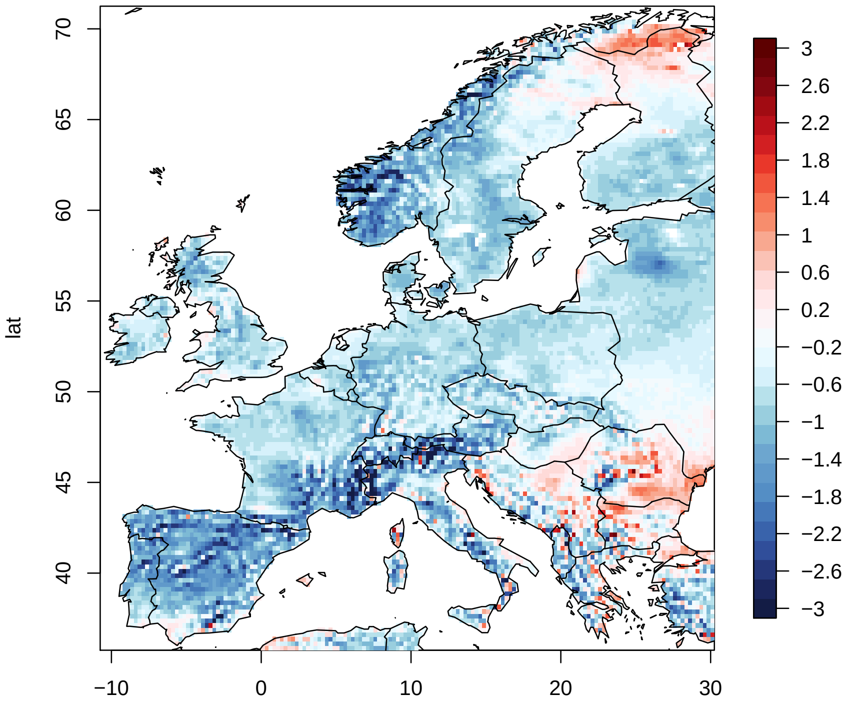

FIGURE 4.3: Biases of monthly 2-m temperature [K] from experiment CCLM/NEMO compared with E-OBS data for the period 1961-2010.

Comparing the two regional experiments CCLM/NEMO and CCLM with the global experiment MPI-ESM-LR, we found that regionalisation adds forecast skill over almost the entire European area. Figure 4.4 shows the MSESS of the uncoupled and coupled forecasts with reference to MPI-ESM-LR forecasts in the first lead year. The skill score was calculated on the coarser model grid of MPI-ESM-LR. The predictability added was more pronounced in the coupled experiments, especially in south eastern Europe. The MSESS was as good as 0.8, but also negative in some areas. The skill score values decreased with lead time (not shown) which indicates that regionalisation was less able to add prediction value for longer lead times.

As discussed above, we discriminated the Atlantic Ocean impact by stratifying the prediction data by positive and negative NAO phases. Skill scores were only computed for the months in which MPI-ESM-LR predictions of NAO index are in phase with observations. Figure 4.5 shows the MSESS calculated with MSE from interest forecasts (CCLM/NEMO) and MSE from reference forecasts (CCLM) for different lead periods.

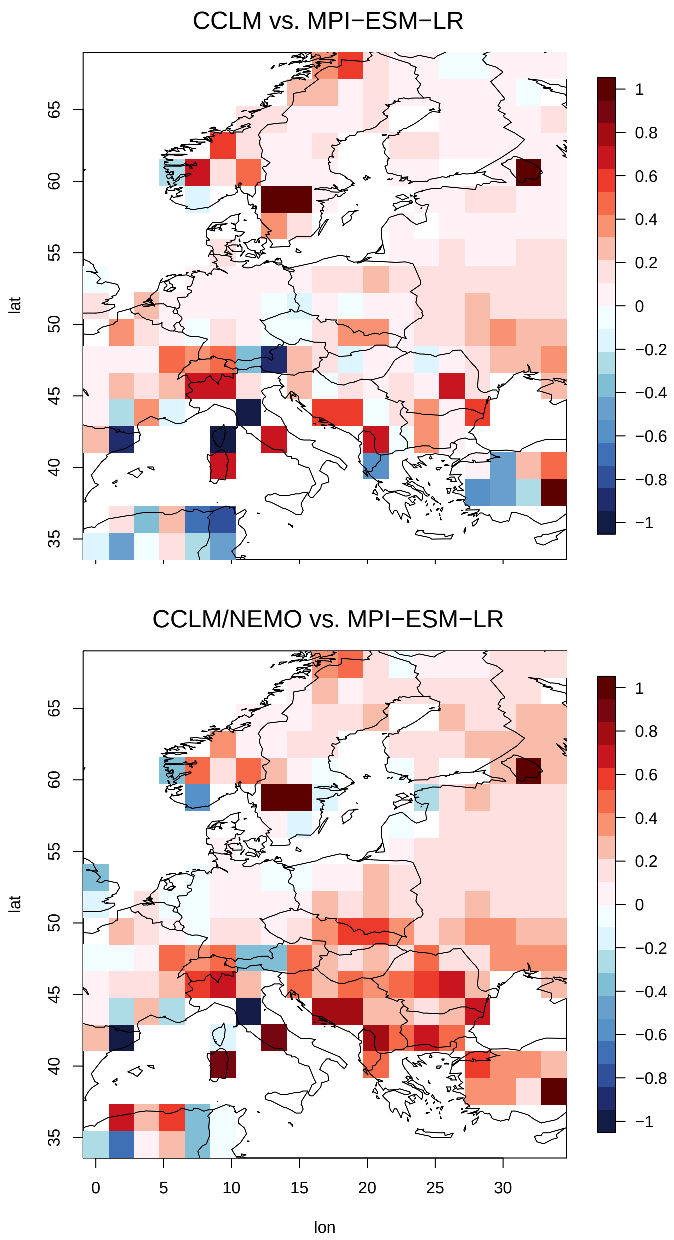

FIGURE 4.4: MSESS of CCLM (above) and CCLM/NEMO forecasts (below) for monthly 2-m temperature. Skill scores are calculated with respect to observational data E-OBS and reference forecasts from MPI-ESM-LR in the first lead year.

In general, the coupled model provided better forecasts around the coupled seas, except in the most northern Baltic Sea. The forecast skills added by the coupled model dropped with lead years, i.e. with distance from MPI-ESM and CCLM/NEMO forecast initialisation. This finding agrees with the results from Müller et al. (2012) who showed that initialised MPI-ESM-LR forecasts perform better than non-initialised MPI-ESM-LR climate simulations. CCLM/NEMO adds more value to predictions than CCLM in NAO– years implying a relatively larger positive impact of the coupled marginal seas.

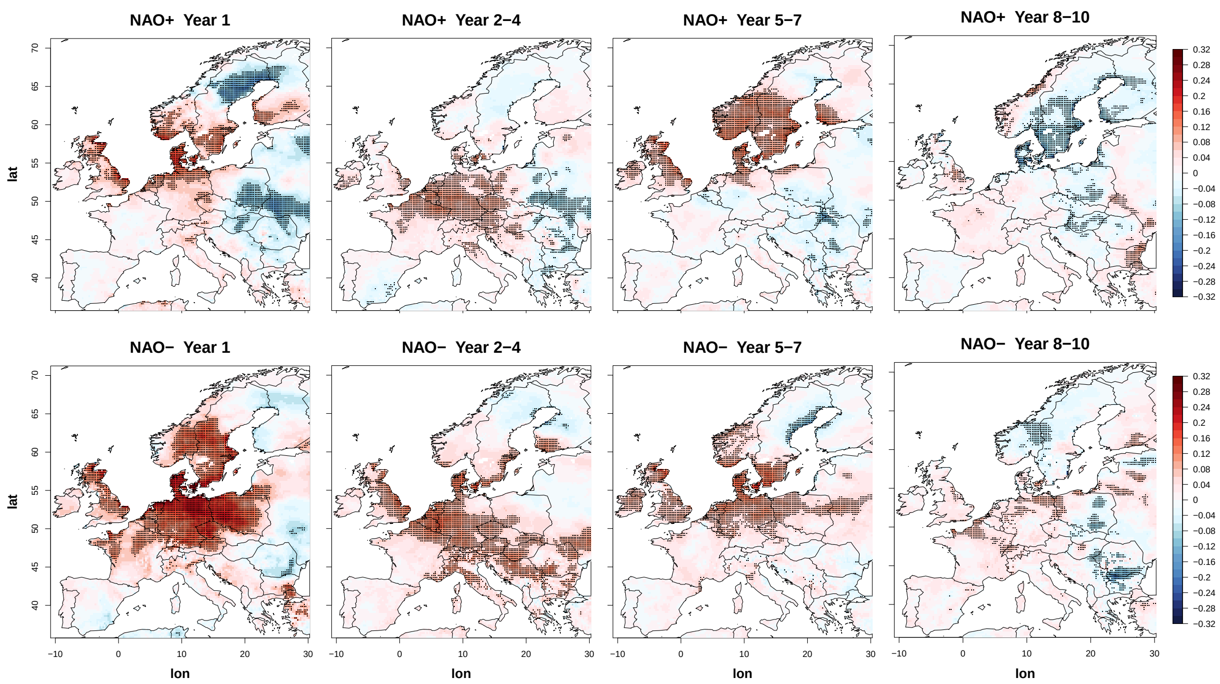

FIGURE 4.5: MSESS of monthly 2-m temperature forecasts stratified by positive (upper panel) and negative (lower panel) NAO phases. Comparison between forecasts from CCLM/NEMO and reference forecasts CCLM with respect to observational data E-OBS for period 1961-2010. Shown for lead years 1, 2-4, 5-7, 8-10. Dotted area shows significant values at a 95% confidence level.

Or, in other words, strong westerlies during positive NAO phase dominate the local sea effect and inhibit the coupled model's added contribution. But independent of NAO phases, the added predictive skill of coupling is minor in the last lead period (year 8-10). Since neither CCLM nor CCLM/NEMO adds predictability to MPI-ESM-LR in this last period, this indicates that the regional forecasts are deteriorated by the skill–poor global forecasts for long lead times.

The models' performance season by season is shown on Figure 4.6. MSESS for a season was calculated with MSE from interest forecasts (CCLM/NEMO) and MSE from reference forecasts (CCLM) with respect to E-OBS data. All months in that season in the five decades were taken for calculation, but only if the model's monthly NAO phases is align with the observed phases. The first impression once again is that the MSESS is higher with negative NAO index. Generally, NAO index values are more extreme in winter than in the other seasons (not shown here). Hurrell (1995) discussed the remarkable strongly positive winter NAO phase occurred since 1980, with some winters having the highest positive values of NAO index recorded since 1864. This implies an intensive large scale dynamics during that season, which suppresses the positive coupling effect (Figure 4.6, upper left panel). Spring showed most added value of CCLM/NEMO with

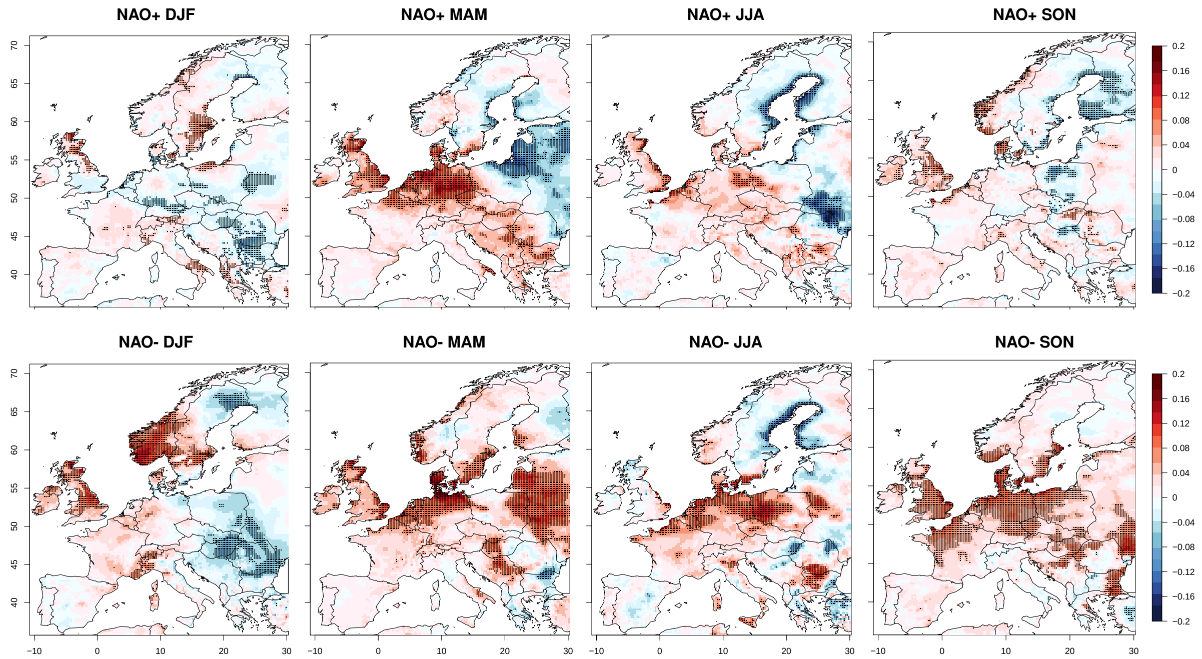

FIGURE 4.6: MSESS of monthly 2-m temperature forecasts stratified by NAO positive (upper panel) and negative (lower panel) phases for four seasons: winter (DJF), spring (MAM), summer (JJA), autumn (SON). Comparison between coupled model forecasts CCLM/NEMO and reference forecasts CCLM with respect to observational data E-OBS for the period 1961-2010 (no separation by lead year). Dotted area shows significant values at a 95% confidence level.

an approximately 30% increase in forecast performance in some areas (especially south of the North Sea and south-west of the Baltic Sea during NAO–).

The added skill of coupling faded with lead time (Figure 4.5). This indicates that regional ocean initialisation is an important source of skill gain. But it is not just the initialisation that contributes to higher predictability of the coupled model. As explained in Section 4.4, in the uncoupled experiment, the forcing SSTs from MPI-ESM was also initialised by an assimilation run. So in both experiments, the ocean was initialised. The fact that CCLM/NEMO results are better might be an indication that another potential source of skill gain is in better simulation of SSTs with the high-resolution NEMO-NORDIC than represented in the lower-resolution MPI-ESM-LR.

When comparing SST forecast skill of the CCLM/NEMO and CCLM experiments with respect to OISST data, we found most added skill in winter (Figure 4.7). Winter is the season with SST most sensitive to vertical mixing and lateral water and salinity transport, which is better represented in NEMO-NORDIC than in MPI-ESM-LR. The OISST dataset is available only from 1981, therefore the SST forecast skill score cannot be calculated for separated lead year groups due to the limited data. However,

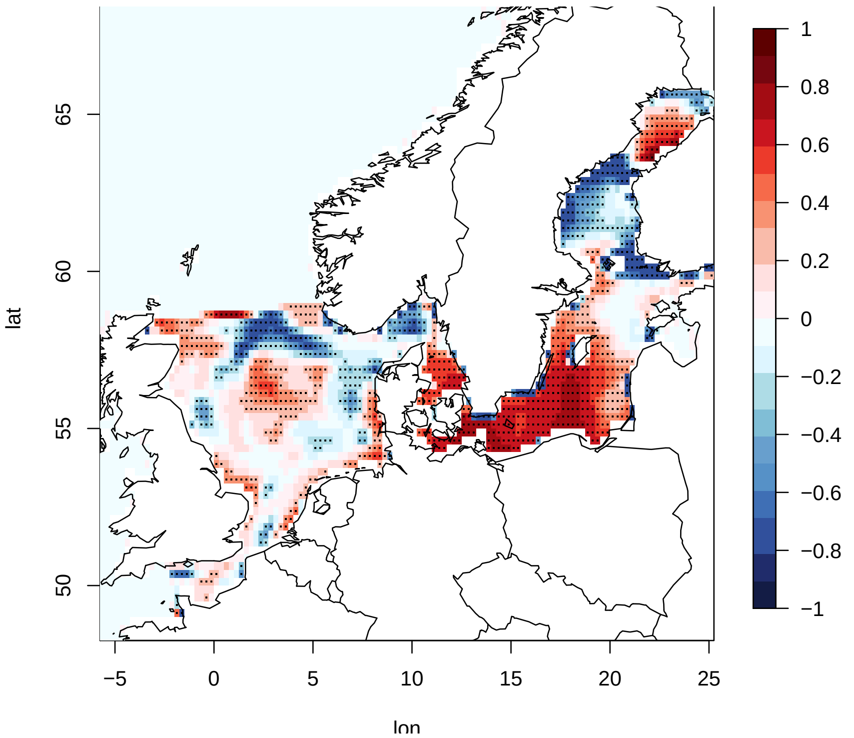

FIGURE 4.7: MSESS of SST for winter months. Comparison between coupled model forecasts CCLM/NEMO and reference forecasts CCLM with respect to OISST data for the period 1981-2010.

CCLM/NEMO predictability of SSTs is expected to drop by time, since the 2-m temperature skill score drops. Additionally, NEMO's sea ice representation is more detailed than COSMO-CLM's parameterisation. Still added predictability in 2-m temperature is largest in spring (Figure 4.6). The positive local effect is suppressed in winter through relatively strong Atlantic influence, but the sea's memory is able to transfer gain into spring (especially near the winterly vertically mixed North Sea). We further looked at the relation between the spatial averages of the SST over the North and Baltic Seas and the 2-m temperature over Germany during the entire forecast period from 1961 to 2010. Correlation coefficients were calculated for the 30 day moving averages of these quantities in different seasons. Winter SST correlated with averaged 2-m temperature in all seasons, but was largest in spring (with values larger than 60%). This indicates that part of the forecast skill gain of the coupled model derives from the improved SSTs because of a better ocean model.

4.6 Conclusions

This study compared the decadal forecast performance in 2-m temperature of two regional model systems: the stand-alone atmospheric model COSMO-CLM and the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO. COSMO-CLM/NEMO added skill over COSMO-CLM up to few lead years and especially during NAO– phases, i.e. with relatively weak Atlantic disturbances. Additionally, both regional systems added value to the forcing global predictions by MPI-ESM-LR (MSESS values up to 0.8) in most parts of continental Europe.

The discussion indicated that both regional ocean initialisation and better regional ocean modelling, especially in winter, added value to the predictions. But, the added predictability was not always positive and strongly controlled by the forcing's model performance. Müller et al. (2012) and Pohlmann et al. (2009) suggested that MPI-ESM-LR losses predictability for air temperature fast after the first 5 years. No-skill forcing does not allow the regional forecasting systems to show predictability. Additionally, it should be mentioned that the uncoupled COSMO-CLM was implicitly tuned by former applications and therefore had an advantage over the new coupled set-up. Simply coupling a regional ocean model does not necessarily lead to better predictions everywhere in the domain. However, it is expected that further experience with the coupled model could improve its performance. A future study also should increase the sample size of predictions and additionally use predictions from other GCMs as forcing aiming for more robust results.

We should also emphasise that the boundary conditions of the ocean model NEMO were from climatological data which probably have less predictability than the global MPI-ESM-LR forecasts. This and the application of more sophisticated regional ocean initialisation have the potential to further add value to regional coupled forecasts. And, of course, regional ensemble forecasting would add value to both predictions with uncoupled and with coupled simulations.

Chapter 5

Conclusion

5.1 Summary

In this thesis, an important subject for the European climate modelling, the added values of coupling an ocean model for the North and Baltic Seas to a regional atmospheric model, was studied. The motivation is to learn how the fine-scale air-sea coupling over these two seas affects the local climate to decide whether we need an ocean model to represent them in regional climate simulations or a use of a stand-alone atmospheric model as often done suffices. Within the technical part of this work, a new regional coupled atmosphere-ocean-ice model COSMO-CLM/NEMO/OASIS3 with the two-way active coupling over the North and Baltic Seas was developed. This model system was already installed and ran on different computer systems; it can perform climate simulations on different time scales with stability. Our coupled model has been used by other authors in scientific publications. Will et al. (2017), for example, used a model set-up based on our coupled model with another version of the coupler OASIS3. Other authors (Akhtar et al., 2018) have applied our coupling system NEMO-NORDIC to COSMO-CLM in parallel with NEMO-MED for the Mediterranean Sea, so that both sea areas are coupled to COSMO-CLM. Our coupled model serves as a helpful tool for scientists in climate or oceanography studies.

The scientific part of this research focused on three major aspects of the climate studies in the European region. Results of these aspects are summarized below:

1. The long-term climatology of air temperature over Europe and SST over the North and Baltic Seas was studied by two experiments with the coupled COSMO-CLM/NEMO model and with the stand-alone atmospheric model COSMO-CLM forced by ERA-Interim re-analysis data. Key findings from these experiments were as follows:

- The high-resolution SST data simulated by the regional ocean model NEMO were comparable to the ERA-Interim re-analysis data.
- SST data from NEMO have an advantage over ERA-Interim, especially over the North and Baltic Seas, since they are at much finer spatial resolution (about 3 km compared with 80 km).
- There is a close link between air temperature over Europe and the interaction between the atmosphere and the marginal seas. Fine-scale air-sea representation in the climate simulation produced realistic air temperature values.
- In situation when the winds from north-west are dominant over the European continent, the air-sea coupling effect could be seen more clearly. Larger differences between the two experiments were found in this case.

The added values of coupling the North and Baltic Seas to an RCM were evident in term of air temperature and SST simulation. The two seas show stronger influence on the local climate when there is north-west wind passing the seas flowing over Europe. The high-resolution re-analysis data are not always and for every region available. Therefore, coupled models will be good substitutes. The results show a great potential of using fine-scale SSTs from an active ocean model to replace coarse SSTs from GCMs in climate predictions.

2. The Baltic Sea showed an important role in the regional climate system not only on long-term climate but also during rapid weather phenomena. The climate of extreme parallel snowband events over the Baltic Sea was studied in this work. Six snowband events in the past were recreated in three sets of simulation: two sets with the coupled and uncoupled models forced by re-analysis data; and one set with the uncoupled model driven by the monthly averaged re-analysis data over the coupled area. Several important characteristics of the convective parallel bands were examined in these experiments. From the results of this study, the following points are the most prominent:

- The coupled model produced equally good simulations of the snowbands in comparison with the uncoupled model forced by high-resolution SST and sea ice from the re-analysis data.
- Fine-scale active air-sea interaction led to high contrasts of vertical air temperature and increased the intensity of latent and sensible heat fluxes, which are both strongly triggered by the sea during the snowband events. The results thus indicate that the strength of a snowband event is closely linked with the air-sea exchange.
- The fine-scale air-sea interaction contributed to the well-simulated precipitation values, patterns as well as the precipitated locations by the coupled

model. In addition, the timing of the snowband occurrences was correctly simulated by the coupled model.

- The coupled model strongly improved the simulation of snowbands compared to the stand-alone atmospheric model without high-resolution fluxes from the ocean.

These results demonstrate the necessity of using a coupled atmosphere-ocean-ice model to properly predict the climate of extreme events which involve the fast changes of the sea surface.

3. The main purpose of coupling an ocean model to an atmospheric model is to seek for better climate predictions as the result of more realistic air-sea feedback. Two sets of experiments with the coupled and uncoupled models, each has five decadal hindcasts, were carried out in the third part of the thesis. These simulations were driven by global forecasts from MPI-ESM-LR. In addition, the relation between the influence of NAO and the local seas' impact on the regional climate was studied in this part. For this purpose, data stratification was done to separate the model data into positive and negative NAO phases. The major findings of this part are:

   - The coupled model simulated monthly averaged 2-m temperature with biases comparable to other COSMO-CLM studies.
   - COSMO-CLM/NEMO enhanced the global model's forecast skills in general, the effect was better seen over the high mountain areas as the topography is better resolved in the regional model.
   - The ocean initialization contributed to improve decadal forecasts in the first few lead years. The coupled model barely added forecast skills in the later lead years due to the limited predictability of the forcing GCM and the weakening impact of the ocean initialization.
   - During strong phases of NAO, the impact of local seas was not clearly seen. The large scale circulation, in that case, plays a decisive role in determining the climate in the European region. When NAO is in weak phase, the North and Baltic Seas, on the other hand, have strong impact on the climate. Forecast skills were highly improved by the coupled model in the latter case.
   - The added prediction skill of the coupled model potentially came from the ocean initialization and the better simulated SSTs and the more realistic presentation of the sea-ice over the Baltic Sea by the high-resolution ocean model NEMO.
   - There was still some unexplained low performance of the coupled model in some areas of the domain. This might be the result of the limited model

simulations as only one set of five decadal experiments could be done for each model system. Another possible explanation is that COSMO-CLM might be well-tuned to the stand-alone mode by previous applications. It should be re-tuned in the coupled mode to achieve good skills over the overall domain.

- It is shown that using the coupled model in decadal forecasting brings benefits. A regional forecast system with an active high-resolution ocean model is recommended to achieve better climate predictions.

Throughout this study, it is evident that coupling a regional ocean model to a regional atmospheric model is required for the North and Baltic Seas in order to pursue better climate predictions. Although only the North and Baltic Seas were investigated in the scope of this research, the results show a potential for better performance from coupled models for marginal seas in general.

5.2 Outlook

The present research contributes a new tool to simulate a more comprehensive climate system in the North and Baltic Sea region and to investigate the interaction between the atmosphere and the marginal seas. This is a very useful tool to perform climate predictions and projections for the future. In the main parts of this study, the impact of fine-scale air-sea feedback on the climate was assessed. Some remaining concerns and key recommendations that arose from the present work are:

- The added values of the coupled atmosphere-ocean-ice model for the North and Baltic Sea region was proven. However, the sources for those added values were not fully understood. Whether they come from the ocean model's SST, or sea-ice, or both; and how important each of these variables is for the air-sea interaction? One possible direction to find the answers to these questions could be coupling only the SST or the sea-ice separately to get a better insight into their influences on the atmosphere.

- There are still uncertainties remaining due to the limited number of model experiments. The high cost of running the coupled system during this study made it difficult to carry out a large number of experiments. To reduce the uncertainties, an ensemble of experiments should be done to cover the range of uncertainties. In order to do that, effort should be taken to lower the computing cost.

- Another way to limit the uncertainties possibly produced by the coupled model is inter-comparing the model's outcome with other coupled models' results. This work can give more quantitative understanding of the air-sea coupling process in the North and Baltic Sea region. However, the multi-model comparison could also be misleading due to the differences in model setups which are unavoidable. Therefore, one should take this into account when interpreting the results from various coupled model systems.

- An important component of the climate system is the river runoff, which was prescribed as boundary condition for the ocean model in the scope of this thesis. The ocean model NEMO was fed with river discharge data from the boundaries. The Baltic Sea is characterized with large fresh water inflow through hundreds of river mouths (Gustafsson, 1997; Dieterich et al., 2013). Therefore, fresh water is very crucial for the closure of water cycle in the Baltic Sea basin. To complete a realistic climate system, the ocean model needs the river runoff calculation from a river routing model at the boundaries, not as externally prescribed parameter. Future studies should go towards the direction of including a hydrological model to the coupled atmosphere-ocean-ice system.

- The results of the coupled model can be improved by using re-analysis or global model data instead of climatological data to prescribe the lateral sea boundary conditions.

- With ever increasing resolutions of global model systems, the coupled regional systems can still be of use. Because of their limited areas, they are technically less expensive and therefore can be useful to perform long simulations.

Chapter 6

Supplement: Zusammenfassung

Dieser Abschnitt enthält eine deutschsprachige Zusammenfassung der vorliegenden Arbeit. Hierzu werden die Motivation und Ziele der Doktorarbeit, die wesentlichen Ergebnisse und Aussagen der Kapitel 2 bis 4, und das Fazit wiedergegeben.

6.1 Motivation

Die Nord- und Ostsee sind die größten Randmeere der mittleren Breiten (Backhaus, 1996). Diese beiden Meere können daher umliegende Gebiete wesentlich beeinflussen. Die Ostsee ist mit der Nordsee über den engen Skagerrak und Kattegat Meerengen verbunden. Dies limitiert nicht nur den Wärmeaustausch zwischen den beiden Meeren sondern auch deren Wasseraustausch. Auf Grund des halb geschlossenen Meeres und das durch darin mündende Flüsse reichlich zugeführte Frischwasser besteht ein erheblicher Teil der Ostsee aus Brackwasser, mit einem deutlichen Salzgradienten von Nordost nach Südwest. Im Kattegat und Skagerrak (Fig. 6.1) weist der Salzgehalt ungefähr 20 PSU auf. In der zentralen Ostsee (Baltic Proper) beträgt der Salzgehalt noch 7-8 PSU, Richtung Bottnischem und Rigaischem Meerbusen ist er sogar noch geringer Gustafsson (1997). Der Salzgehalt dieses bekannten Brackwasserbeckens ist somit deutlich geringeren auf als jener der großen Ozeane (durchschnittlich 35 PSU). Wird nun die Ostsee in regionalen Klimamodellen wie ein normaler Ozean behandelt, kann dies zu erheblichen Fehlern in der Meereis-Simulation führen. Zusätzlich wird die komplexe Topographie der Nord- und Ostsee, mit ihren kleinen Meerengen und langen schmalen Meerbusen, von den Antriebsmodellen nur unzureichend aufgelöst. Allerdings ist das Meereis ein wichtiger Faktor für das Klima im Ostseeraum, da es sowohl den Strahlungsfluss als auch die Turbulenz wesentlich beeinflusst. So weist Meereis eine deutlich höhere Albedo auf als Meerwasser (0.7 verglichen mit 0.07). Die Meereisverteilung kann die Strahlungsbilanz daher dramatisch verändern. Zudem wird die Meeresoberfläche deutlich glatter wenn

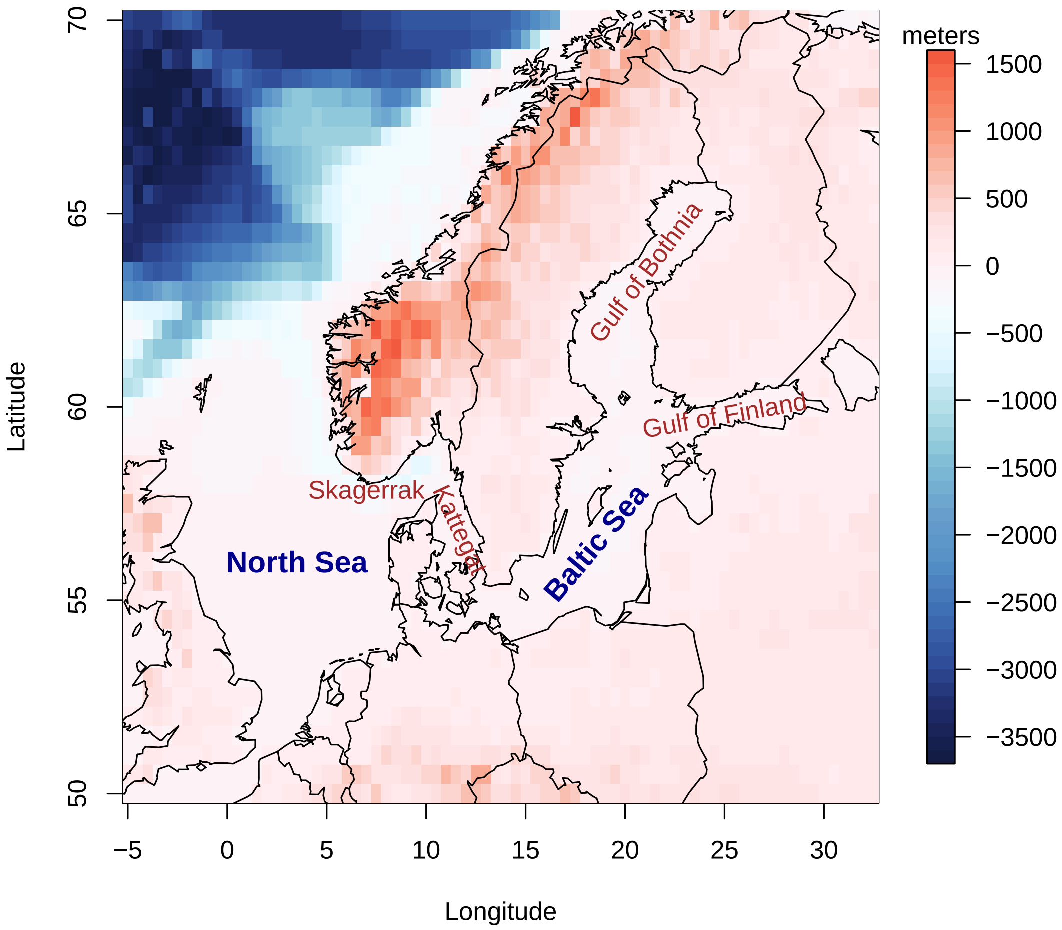

Figure 6.1: Die Topographie der Nord- und Ostsee.

sich darauf Meereis bildet. So ist die Oberflächenrauigkeit über dem offenem Meer typischerweise rund zehn Mal höher als über Meereis. Ein kleiner Fehler in der Simulation der Meerwasser/Meereisverteilung kann somit zu markanten Fehlern im Impulsstrom (momentum flux) führen. Auf Grund des deutlichen Einflusses der Eis-Wasser-Verteilung auf die atmosphärischen Flüsse können klimatische Prozesse über der Ostsee und in angrenzenden Gebieten mittels grob aufgelöster Globalmodelle nur unzureichend wiedergegeben werden. Sämtliche oben aufgeführte Bedenken legen die Verwendung eines gekoppelten Atmosphäre-Ozean Modells nahe. Denn nur so kann das regionale Klima über der Binnenmeerregion Ostsee hinreichend untersucht werden. Daneben ist auch die Implementierung eines Eis-Modells notwendig, um die Eisbedeckung über der Ostsee korrekt wiederzugeben. Durch die Kopplung mittels eines feinauflösenden Modells soll die Modell-Performance verglichen mit nicht gekoppelten Modellen verbessert werden.

6.2 Ziele

Das Hauptziel dieser Doktorarbeit ist die Entwicklung eines gekoppelten Atmosphäre-Ozean-Eis-Modells für die Nord- und Ostsee und die Anwendung dieses Modells, um langfristiges Klima und extreme Wetterereignisse zu studieren.

6.3 Hauptergebnisse

In dieser Arbeit wurde das gekoppelte Atmosphäre-Ozean-Eis-System COSMO-CLM/NEMO für die Nord- und Ostsee entwickelt, um die Rolle dieser Randmeere in der Klimamodellierung besser zu studieren. Es ist wichtig den Einfluss dieser zwei Meere zu verstehen, so dass man entscheiden kann, ob man diese in Klimasimulationen beachten muss und unter welchen Umständen die Berücksichtigung dieser Meere entscheidend ist. In Rahmen der Arbeit sind drei Veroeffenlichungen geschrieben: Pham et al. (2014), Pham et al. (2017), Pham et al. (2018). Der Inhalt konzentrierte sich auf drei Aspekte des Kernthemas Luft-See-Kopplung:

1. Der erste Teil stellt das neu entwickelte regionale Atmosphäre-Ozean-Eis-Modell COSMO-CLM/NEMO mit Rückkopplungen für die Nord- und Ostsee vor. Zwei Experimente mit gekoppeltem Modell und eigenständigem Atmosphärenmodell COSMO-CLM wurden durchgeführt. Diese fünfzehnjährigen Simulationen wurden durch Reanalysedaten angetrieben. Die Ergebnisse des gekoppelten Modells wurden mit Ergebnissen des ungekoppelten Modells und Beobachtungsdaten verglichen. Die wichtigsten Erkenntnisse dieser Experimente waren wie folgt:

   - Die 2-m-Temperaturwerte des gekoppelten Modells hatten Abweichungen bis 2.5 K verglichen mit Beobachtungsdaten. Mit besserer Repräsentanz der Nord- und Ostsee im Ozeanmodell NEMO waren die Abweichungen vor allem über den Gebieten nahe der Randmeere kleiner. Das ist eine klare Verbesserung verglichen mit Vorgängerstudien, die das eigenständige COSMO-CLM angewendet haben.
   - Die Abweichungen des gekoppelten Experimentes waren im Bereich derer des ungekoppelten Experimentes, und manchmal auch leichte besser. Da bereits das eigenständige Experiment, angetrieben durch hoch aufgelöste Reanalysedaten, sehr gute Ergebnisse zeigte, ist das gekoppelte Experiment folglich sogar besser. Das gekoppelte Modell verspricht damit auch bessere Klimaprojektionen mit Antrieb durch Globalmodelle.

- Die Oberflächenwassertemperaturen des gekoppelten Modells zeigen Abweichungen in Höhe von -0.6 K bis 0.6 K verglichen mit Advanced Very High Resolution Radiometer AVHRR-Daten. Diese Abweichungen und die der antreibenden Reanalysedaten sind ungefähr gleich groß.
- Eine kältere Meersoberfläche über der Nord- und Ostsee des gekoppelten Experimentes führt zu entsprechend niedriger Lufttemperatur. Die saisonalen Unterschiede der 2-m-Temperatur und der Oberflächenwassertemperatur zwischen gekoppeltem und ungekoppeltem Experiment sind ähnlich. Das ist ein Hinweis, dass eine Verbindung zwischen den änderungen der Oberflächenwassertemperatur und der 2-m-Temperatur aufgrund der Luft-See-Kopplung existiert.
- Wenn über Europa eine nordwestliche Windrichtung dominiert, ist der Luft-See-Kopplungseffekt klarer zu sehen, da in diesem Fall größe Unterschiede zwischen den zwei Experimenten auftreten. Die Nord- und Ostsee spielt also eine wichtige Rolle für das zentraleuropäische Klima, wenn die Hauptwindrichtung Nord-West ist.

2. Die Rolle des Meeres im Klimasystem wird meist berücksichtigt, wenn der Simulationszeitraum hinreichend lang ist. Der Grund dafür ist, dass das Meer oft langsam auf die Entwicklung des Wetters reagiert, und die Rückkopplung des Meeres deshalb häufig zeitlich verschoben erfolgt. Allerdings gibt es lokale Wetterphänomene, die den Oberflächenzustand schnell ändern können. Veränderungen der Seeoberfläche können wiederum die Atmosphäre schnell beeinflussen und dadurch die Wettersituation rapid ändern. Ein Beispiel für extreme Wetterlagen sind die Schneebänder, die oft im Spätherbst oder Frühwinter über der Ostsee auftreten. Diese Wetterlage kann sich relativ schnell entwickeln; innerhalb von 48 Stunden kann eine riesige Schneemasse dann über der Ostsee und Küstengebieten niedergehen. Auf Grund ihres schädlichen Potentials müssen die Lagen und Häufigkeiten der Schneebänder gut vorhergesagt werden. Deshald wurden im zweiten Teil der Dissertation sechs Schneebänder in der Vergangenheit in drei Experimentgruppen nachgebildet: zwei Gruppen mit gekoppeltem und ungekoppeltem Modell angetrieben durch Reanlysedaten; eine Gruppe mit ungekoppeltem Modell angetrieben durch Monatsmittel der Reanalysedaten. Einige wichtige Merkmale der konvektiven Schneebänder wurden durch diese drei Experimentgruppen getestet. Von den Ergebnissen dieser Studie sind die folgenden Punkte die wichtigsten:

   - Verglichen mit ungekoppeltem Modell angetrieben durch hoch aufgelöste Oberflächenwassertemperatur der Reanalysedaten kann das gekoppelte Modell vergleichbar gute Simulationen der Schneebänder liefern. Schneebänder waren geprägt in gekoppeltem Experiment durch den hohen Temperaturkontrast zwischen dem Boden und der 850 hPa-Atmosphärenschicht sowie erheblich hohen Wärmemengen (Latentwärme und fühlbare Wärme) ausgeübt von der See.

- Die Zeiten, an denen die Schneebänder aufgetreten sind, wurden von dem gekoppeltem Modell korrekt simuliert. An Tagen, an denen Schneebaänder beobachtet wurden, wurden im gekoppelten Experiment scharfe Bänder der Niederschlag simuliert. Die simulierten Muster und Lagen des Niederschlags sind den Formen und Lagen der Schneebänder in der Satellitenbilder sehr ähnlich.
- Die Analyse war aufgrund des Datenmangel in diesem Gebiet limitiert. Niederschlagsdaten sind nur für zwei Schneebändereignisse verfügbar. Die Ergebnisse zeigten ähnlichkeiten zwischen simuliertem und beobachtetem Niederschlag.
- Das eigenständige Atmosphärenmodell, angetrieben durch niederig aufgelöste Oberflächenwassertemperatur, konnte die meisten der Schneebänder nicht wiedergegeben. Es simulierte einen zu niedrigeren Kontrast der Temperatur zwischen der Seeoberfläche und der Atmosphäre, der entscheidend für die Auslösung der starken Konvektion ist. Mit geringe aufgelöster Oberflächenwassertemperatur berechnete das ungekoppelte Modell auch zu niedrige Wärmeflüsse von der See.

Diese Ergebnisse belegten die Notwendigkeit der Anwendung eines gekoppelten Atmosphäre-Ozean-Eis-Modells, wenn man richtige Vorhersagen der extremen Wetterereignisse machen will.

3. Der Hauptzweck der Kopplung zwischen dem Atmosphärenmodell und dem Ozeanmodell sind bessere Klimavorhersagen als Ergebnis einer realistischen Luft-See-Rückkopplung. Fünf dekadische retrospektive Experimente wurden mit dem gekoppelten und ungekoppelten Modell in dem dritten Teil dieser Dissertation durchgeführt. Diese Simulationen wurden durch die Globalvorhersagen des MPI-ESM-LR-Modells angetrieben. NAO-Stratifizierung (NAO: nordatlantische Oszillation) wurde gemacht, um die positiven und negativen Phasen des NAO-Indexes voneinander zu trennen. Die wesentlichen Erkenntnisse dieses Teiles sind folgende:

   - Im Vergleich mit den Beobachtungsdaten sind die 2-m-Temperatur-Abweichungen des gekoppelten Modells in den meisten Teilen Europas kleiner als 3 K. Allegemein erhöhte COSMO-CLM/NEMO die Globalevorhersagegüte; aufgrund der höheren Auflösung des regionalen Modells sind die Effekte über den Gebirgsregionen besonder klar zu sehen.

- Das gekoppelte Modell zeigte signifikante Verbesserungen verglichen mit ungekoppeltem Modell in den ersten Jahren nach der Initialisierung. Vorhersagegüte war höher in gekoppeltem Experiment bis Lead-Jahr 7.
- Die Rückmeldung des Ozeans auf die Atmosphäre hat eine zeitliche Verschiebung; die Veränderungen der See im Winter beeinflussten die Atmosphäre in den nachfolgenden Frühling. Die größtene Erhöhung der Vohersagegüte des gekoppelten Modells war im Frühling, obwohl das gekoppelte Modell mehr änderungen der Seeoberfläche im Winter produzierte.
- Während der starken Phase der NAO, waren die Auswirkungen der lokalen Seen nicht so klar zu erkennen. Die grossräumige Zirkulation spielte eine entscheidende Rolle zur Bestimmung der Wetterbedingungen in europäischem Gebiet. Wenn die NAO Aktivität schwach war, hatten die Nord- und Ostsee starkeren Einfluss auf das regionale Klima. Vorhersagegüten wurden in diesem Fall deutlich verbessert.
- Die Mehrwerte des gekoppelten Modells kommen warscheinlich aus der Initialization des Ozeanmodells da die Vorhersagegüte sich mit der Zeit verringerte. Eine andere Quelle der verbesserten Ergebnisse des COSMO-CLM/NEMOs ist die besseren simulierten Oberflächenwassertemperaturen des Ozeanmodells NEMO und die realistischere Repräsentation des Meereises über der Ostsee.
- In einiger Bereichen der Domäne gab es noch ungeklärte niedrige schlectere Ergebnisse des gekoppelten Modells. Ein Grund könnte die beschränkten Modellexperimente sein denn nur ein Mitglied der fünf dekadischen Vorhersagen wurde produziert. Außerdem ist das COSMO-CLM für den eigenständigen Modus konfiguriert werden. Es soll im Kopplungsmodus neu konfiguriert werden, um höhe Vorhersagegüte in der ganzen Domäne zu erreichen.

6.4 Schlussfolgerung und Ausblick

Die vorliegende Studie befasst sich mit einem neuen Tool, um das Zusammenspiel zwischen der Atmosphäre und den Randmeeren zu untersuchen. Klimavorhersagen und Klimaprojektionen können mit diesem Tool durchgeführt werden. Im Rahmen dieser Dissertation wurde der Einfluss der lokalen Meere auf das Klima beurteilt. Zusammenfassend lässt sich sagen, dass das gekoppelte Atmosphäre-Ozean-Eis-Modell COSMO-CLM/NEMO in verschiedener Fällen zufriedenstellend funktionierte, als da sind: Langzeitsimulationen angetrieb von der Reanalysedaten oder globaler Vorhersagen. Die extremen Schneebänder wurden auch von diesem Modell gut wiedergegeben.

COSMO-CLM/NEMO zeigte Verbesserungen verglichen mit eigenständigem COSMO-CLM wenn dieses Atmosphärenmodell nicht von der Reanalysedaten angetrieb wurde.

Die wichtigsten Weiterempfehlungen, die in dieser Studie entstanden, lauten wie folgt:

- Für die Evaluierung extremer Wetterereignisse, wie zu Beispiel Schneebänder, gibt es nur eine unzureichende Menge an Daten. Schneebänder treten meist in Verbindung mit relativ starkem Wind auf. Aufgrund der so entstehenden Schneeverwehungen können die Daten von Niederschlagsmessern nicht genutzt werden. Die gemessene Schneemenge an diesen Stationen kann durch den wind aus der Umgebung zusammen getragen worden sein. Außerdem könnte es akkumulierter Schnee von mehreren Schneefallereignissen sein. Deshalb ist es schwierig die Schneemenge einem einzigen Schneebandereignis zuzuordnen. Andere Wege der Niederschlagsmessung sollten benutzt werden und für die wissenschaftliche Arbeit zu Verfügung stehen.

- Die Mehrwerte des gekoppelten Atmosphäre-Ozean-Eis-Modells für die Nord- und Ostsee wurden überprüft. Allerdings konnte der Ursprung dieser Werte nicht vollständig nachvollzogen werden. Das Ozeanmodell bekommt diese Werte entweder von der Oberflächentemperatur über Wasser, Eis oder von Beiden zusammen. Auch die Wichtigkeit jede dieser Variable für die Luft-Wasser Interaktion ist noch fraglich. Eine Möglichkeit diese Frage zu beantworten ist nur eine Bodenvariable einzukoppeln, Wasser oder Eis. Auf die Art bekommt man ein besseres Verständnis für Einflüsse dieser Variablen auf die Atmosphäre.

- Weitere Unsicherheiten bestehen aufgrund der geringen Anzahl an Modellexperimenten. Die hohen Rechenkosten, während der Studie, haben es schwierig gemacht eine große Anzahl an Experimente durchzuführen. Für robuste Ergebnisse und geringere Unsicherheiten sollte ein ganzes Ensemble an Experimente gerechnet werden.

- Eine andere Methode, die Unsicherheiten der Modellergebnisse zu reduzieren, ist der Vergleich mit den Ergebnissen anderer gekoppelten Modelle. Diese Arbeit könnte ein mehr quantitatives Verständnis der Luft-See Kopplungsprozesse in der Nord- und Ostsee geben. Allerdings sollte man bei der Durchführung eines Multi-Modell Vergleiches beachten, dass die unterschiedlichen Modellsetups auch weitere Unsicherheiten beinhalten.

- Eine wichtige Komponente des Klimasystems ist der Abfluss, der im Rahmen dieser Studie als Randbedingungen des Ozeanmodells vorgegeben wurde. Das Ozeanmodell wurde mit Abflussdaten von der Ränder gefüttert. Die Ostsee is geprägt durch großen frischen Wasserzufluss der hunderten Flussmündungen (Gustafsson, 1997; Dieterich et al., 2013). Deshalb ist das Frischwasser wesentlich für die Schließung des Wasserkreislaufs im Ostseebecken. Der Abfluss sollte nicht als Randbedingung vorgegeben werden, statt dessen sollte er durch ein Flussmodell berechnet werden. Es wird empfohlen, dass weitere Arbeiten ein Flussmodell in dem Atmosphäre-Ozean-Eis-Kopplungssystem einbinden.

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Resumé

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2002–2007 **Bachelor of Water Engineering and Environment**.
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Master thesis

title *Tracking the uncertainty from precipitation to streamflow prediction in hydrology forecasting*

supervisors Dr. Martin Krol, Dr. Martijn Booij (University of Twente, Enschede, Netherlands)
Dr. Maria Helena Ramos (National research Institute of Science and Technology for Environment and Agriculture, Antony, France)

description Quantifying and propagating the different kinds of uncertainty sources which play roles in flood forecasting; and investigating methods to assess the quantified uncertainties and proper measures to evaluate the uncertainty quantification

PhD thesis

title *The consideration of North and Baltic Seas in regional climate modelling with the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO*

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description Assessing the impact of modelling the marginal seas, North and Baltic Seas, on climate with the newly developed regional atmospheric-ocean-ice model COSMO-CLM/NEMO

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2012–2016 **Research Assistant**, *Senckenberg Biodiversity and Climate Research Center*, Frankfurt am Main, Germany.

- Developing the coupled atmospheric-ocean-ice system COSMO/CLM-NEMO.
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Publications

Trang Van Pham, Jennifer Brauch, Christian Dieterich, Barbara Früh, and Bodo Ahrens. New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas. *Oceanologia*, 56(2):167–189, 2014.

Trang Van Pham, Jennifer Brauch, Barbara Früh, and Bodo Ahrens. Simulation of snowbands in the Baltic Sea area with the coupled atmosphere-ocean-ice model COSMO-CLM/NEMO. *Meteorol. Z.*, 26(1):71–82, 2017.

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