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

Trang Van Pham1,2,3*, Jennifer Brauch2, Barbara Früh2 and Bodo Ahrens1,3

1 Senckenberg Biodiversity and Climate Research Centre, Frankfurt, Germany
2 Deutscher Wetterdienst, Offenbach, Germany
3 Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Frankfurt, Germany

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 strong convection, and heavy snow fall occurs. 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 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.

Keywords: convective snowbands, lake effect, Baltic Sea, coupled model, COSMO-CLM, NEMO, OASIS3

1 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 long-standing 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 ModelHIRLAM 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 COSMOCLM 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 1. To avoid the spin up problem in a 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. Section 3 discusses the experiment design and the data we used, which is followed by the results of the simulations and discussion in Section 4. We close the paper with conclusion in Section 5.

2 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).

2.1 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., 2006). 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. (2005) (http://www.cosmo-model.org/content/model/documentation/core/default.htm).

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).

2.2 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 (Figure 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).

2.3 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 (Figure 1), in this region COSMO-CLM gets the SST and the fraction of 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 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”.

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, Figure 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
Table 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 | VIIMA 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                           |

The COSMO-CLM model, on the other hand, receiving 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 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 under-catch 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 et al., 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.

4 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).

When looking at the mean sea level pressures, the pressure systems simulated in all three experiments look very similar to each other for the time period of the snowband occurrence. A high pressure system located north of the Baltic Sea and a low pressure system located to the south of the sea, this allows cold easterlies or north-easterlies from the continent flowing over the warm water surface. These similar pressure systems in all experiments are due to the fact that three experiments are forced by the same ERA-Interim data at the lateral boundaries. Therefore, they are all influenced by the large scale circulation from the global data, resulting in expected pressure similarities. There are only small shifts in locations of the high or low pressure which do not change the main wind direction. Small deviation of pressure values in CCLM-NEMO and CCLM-MOD compared to CCLM (not shown here) occurs around the North and Baltic Seas, where there are changes in the forcing from the ocean.

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 Figure 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
Figure 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.
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 Figure 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/m² 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 Figure 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. That can be seen in Figure 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/m². 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 Figure 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 Figure 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)
Figure 3: Same as Figure 2 but for daily sensible heat flux (W/m²).
Figure 4: Same as Figure 2 but for daily latent heat flux (W/m²).
Figure 5: Same as Figure 2 but for daily precipitation (mm).
Figure 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.

while an image from MODIS (Moderate Resolution Imaging Spectrometer) was used for the event in 2010.

Comparing the precipitation pattern in Figure 5 with satellite images of the cloud coverage in Figure 6, the only event the coupled run CCLM-NEMO missed the snowband is on January 3, 1985. Both CCLM-NEMO and CCLM-MOD simulate snowbands that are too far to the north of the Gulf of Finland. CCLM simulates this event well: the snowbands stayed at exactly the right location within the narrow Gulf of Finland, which is also observable from the satellite image.

The satellite image (Figure 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 (Figure 6c). These were properly simulated by CCLM and CCLM-NEMO. In Figure 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 (Figure 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 (Figure 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 (Figure 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, Figure 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 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 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.

5 Conclusion

Snowbands over the Baltic Sea often deposit huge amount of snow within a short period of time in the surrounding coastal cities and therefore setups and 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 models 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 models 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 the coupled models 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 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.
Acknowledgments

The authors thank the Centre for Scientific Computing (CSC) of the Goethe University Frankfurt and the German High Performance Computing Centre for Climate and Earth System Research (DKRZ) for supporting parts of the calculations.

We acknowledge support from the German Federal Ministry of Education and Research (BMBF) under grant MiKliP: LACEPS/01LP1154A for providing the reference COSMO-CLM simulation data within the MiKliP project.

Special thanks to Dr. Christian Dieterich and other colleagues from SMHI for providing the NEMO-NORDIC model.

The MODIS L0 data were obtained through the NASA Ocean Color Data Distribution Site and processed with the MODIS Level-1 Direct Broadcast software package. The MODIS true color images were generated with a software package written by Liam Gumbley, Jacques Descloières, and Jeffrey Schmaltz.

References

Akhbar, N., J. Brauch, A. Dobler, K. Béranger, B. Ahrens, 2014: Medicanes in an ocean-atmosphere coupled regional climate model. – Nat. Hazards Earth Syst. Sci. 14, 2189–2201, DOI:10.5194/nhess-14-2189-2014.

Andersson, T., N. Gustafsson, 1994: Coast of Departure and Coast of Arrival: Two Important Concepts for the Formation and Structure of Convective Snowbands over Seas and Lakes. – Mon. Wea. Rev. 122, 6, 1036–1049.

Andersson, T., S. Nilsson, 1990: Topographically induced convection snowbands over the Baltic Sea and their precipitation distribution. – Wea. Forecast. 5, 299–312.

Bartold, F.E., D.A.R. Kristovich, 2011: Observations of the Cross-Lake Cloud and Snow Evolution in a Lake-Effect Snow Event. – Mon. Wea. Rev. 139, 2386–2398, DOI:10.1175/MWR-D-10-05001.1.

Böhmer, U., M. Küchler, W. Ahrens, A. Block, D. Hauffe, K. Keuler, B. Rockel, A. Will, 2006: CLM - the climate version of LM: Brief description and long-term applications. – COSMO Newsletter 6.

Carpenter, D.M., 1993: The Lake Effect of the Great Salt Lake: Overview and Forecast Problems. – Wea. Forecast. 8, 181–193, DOI:10.1175/1520-0434(1993)008<0181:TLEOTG>2.0.CO;2.

Dee, D., S. Uppala, A. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. Beljaars, L. Van de Berg, J. Bidlot, N. Bormann, C. Delso, R. Dragani, M. Fuentes, A. Gerber, L. Haimberger, S. Healy, H. Hersbach, E. Holm, I. Isaksen, P. Kallberg, M. Kohler, M. Matricardi, A. McNally, B. Monge-Sanz, J. Morcrette, B. Park, C. Peubey, P. De Rosnay, C. Tavolato, J. Thepaut, F. Vitart, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. – Quart. Roy. Meteor. Soc. 137, 553–597.

Doms, G., J. Förster, E. Heise, H.J. Herzog, M. Raschendorfer, T. Reinhardt, G. Vogel, 2005: A Description of the Nonhydrostatic Regional Model LM. Part II: Physical Parameterizations. – Deutscher Wetterdienst (DWD), Offenbach.

Fennig, K., A. Andersson, S. Bakan, C.P. Klepp, M. Schröder, 2012: Hamburg Ocean Atmosphere Parameters and Flows from Satellite Data – HOAPS 3.2 – Monthly Means 6-Hourly Composites. – Satell. Application Facil. Climate Monitoring, DOI:10.5676/FUM_SAF_CM/HOAPS/3.2.

Giorgi, F., C. Jones, G.R. Asrar, 2006: Addressing climate information needs at the regional level: the CORDEX framework. – WMO Bull. 58, 175–183.

Gustafsson, N., L. Nyberg, A. Omstedt, 1998: Coupling of a High-Resolution Atmospheric Model and an Ocean Model for the Baltic Sea. – Mon. Wea. Rev. 126, 2822–2846.

Heidinger, A.K., W.C. Straka, C.C. Molling, J.T. Sullivan, W. Xiangqian, 2010: Deriving an inter-sensor consistent calibration for the AVHRR solar reflectance data record. – Int. J. Remote Sens. 31, 6493–6517, DOI: 10.1080/01431160.2010.496472.

Hordoir, R., B.W. An, J. Haapala, C. Dieterich, S. Schimanke, A. Höglund, H.E.M. Meier, 2013: A 3D Ocean Modelling Configuration for Baltic & North Sea Exchange Analysis. – Rep. Oceanogr. 48, ISSN: 0283–1112, SMHI.

Janssen, F., C. Schrum, J.O. Backhaus, 1999: A climatological data set of temperature and salinity for the Baltic Sea and the North Sea. – Dtsch. Hydrogr. Z. 51, DOI:10.1007/BF02933676.

Linndström, G., P. Pers, L. Rosberg, J. Strömqvist, B. Arheimer, 2010: Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. – Hydrol. Res. 41, 295–319.

Madec, G., 2008: NEMO ocean engine. – Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, 27, ISSN: 1288–1619.

Michelson, D., T. Andersson, J. Kostinen, C. Collier, J. Riedel, J. Szurcz, U. Giertsen, A. Nielsen, S. Overgaard, 2000: Baltic rex radar data centre products and their methodologies. – Technical Report RMK 90, SMHI, SE-60176 Norrköping, Sweden.

Reynolds, R.W., T.M. Smith, C. Liu, D.B. Chelton, K.S. Casey, M.G. Schlax, 2007: Daily High-Resolution-Blended Analyses for Sea Surface Temperature. – J. Climate 20, 5473–5496, DOI:10.1175/2007JCLI11824.1.

Rockel, B., A. Will, A. Hense, 2008: Regional climate modeling with COSMO-CLM (CCLM). – Meteor. Z. 17, 347–348.

Samuelsson, P., C.G. Jones, U. Willen, A. Ullerstig, S. Golliwik, U. Hansson, C. Janssen, E. Kjellström, G. Nikulin, K. Wyser, 2011: The Rossby Centre Regional Climate model RCA3: model description and performance, – Tellus A 63, 4–23.

Savić-Điřić, H.I., 2012: Cold air outbreaks over high-latitude sea gulfs, – Tellus A 64, 12244, DOI:10.3402/tellusa.v64i0.12244.

Pham, T.V., J. Brauch, C. Dieterich, B. Früh, B. Ahrens, 2014: New coupled atmosphere-ocean-ice system COSMO-CLM/NEMO: assessing air temperature sensitivity over the North and Baltic Seas, – Oceanologia 56, 167–189, DOI:10.5697/oce.56-2.167.

Vihma, T., B. Brügger, 2002: Observations and Modelling of the on-ice and off-ice air flow over the Northern Baltic Sea, – Bound. Layer Meteor. 103, 1–27.

Valcke, S., 2013: The OASIS3 coupler: a European climate modelling community software, – Geosci. Model Dev. 6, 373–388, DOI:10.5194/gmd-6-373-2013.

Vancoppenolle, M., S. Bouillon, T. Fichefet, H. Goose, O. Lecomte, M.A. Morales Maqueda, G. Madeuc, 2012: LIM The Louvain-la-Neuve sea Ice Model, Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No. 31, ISSN: 1288–1619.