Numerical Modelling of Convective Snow Bands in the Baltic Sea Area

Numerisk modellering av konvektiva snöband över Östersjön

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Abstract

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Convective snow bands develop commonly over the open water surface of lakes or seas when cold air gets advected from a continent. Enhanced heat and moisture fluxes from the comparatively warm water body trigger shallow convection and an unstable boundary layer builds up. Relatively strong wind can organize this convection into wind-parallel quasi-stationary cloud bands with moving individual cells. Depending on various factors like the horizontal wind, the vertical shear or the shape of the coast, those cloud bands can form of different strength and structure. When the air mass meets the coast orographic forcing causes horizontal convergence and vertical lifting intensifies the precipitation at the coast. If the wind direction stays constant for several days a single snow band would accumulate its precipitation in a very restricted region and cause locally a significant increase in snow depth. This process leads in the cold season repeatedly to severe precipitation events at the Swedish east coast. Large amounts of snow along with strong wind speeds can cause serious problems for traffic and infrastructure.

Two different cases of convective snow bands in the Baltic Sea area were selected to simulate the associated atmospheric conditions with a total of five different model systems. The atmosphere climate model RCA has been used independently at default settings as well as with increased resolution on a vertical and a horizontal scale and furthermore coupled either to the ice-ocean model NEMO or the wave model component WAM.

Comparing all models the crucial parameters like wind, temperature, heat fluxes, and precipitation vary generally in a reasonable range. However, the model systems show systematical differences among themselves. The strongest 10 meter wind speeds can be observed for both RCA models with increased resolution. The RCA-WAM simulation shows its wind enhancement during the snow band event with a time shift to the other models by several hours. The mean directional wind shear above the Gulf of Bothnia, the snow band’s region of origin, is for all models small. The warmest sea surface temperatures are reached by the RCA-NEMO simulation, which as a result also stands out for its most intense heat fluxes in both sensible and latent heat. Both high resolution RCA models as well as RCA-NEMO give the most remarkable local precipitation rates. The original RCA and RCA-WAM simulate significantly less snowfall. Local comparison with SMHI station measurements show that the models represent the trend of wind, temperature and precipitation evolution well. However, all models decelerate the air mass too rapidly when meeting the coast. Moreover, it remains a challenge to simulate the exact time and location of the extreme precipitation.

The coupling of the atmosphere model with the ice-ocean model as well as the increased resolution of the atmospheric component have been observed to show great improvements in the model performance and are suggested for future research work to be used in combination with each other for the regional modelling of convective snow bands in the Baltic Sea area.

Keywords: Shallow convection, extreme precipitation, Baltic Sea, SST, regional climate system modelling

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Populärvetenskaplig sammanfattning

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Julia Jeworrek


Två olika fall av konvektiva snöband i Östersjöområdet valdes för att simulera de associerade atmosfäriska förhållanden med totalt fem olika modellsystem. Den atmosfäriska modellen RCA har använts oberoende, samt med ökad upplösning på en vertikal och en horisontell skala och dessutom kopplad antingen till en is/hav-modell NEMO eller en vågmodell-komponent WAM.


Kopplingen av atmosfärmodellen med is/hav-modell samt ökad upplösning av den atmosfäriska komponenten visar stora förbättringar i modellens prestanda och rekommenderas att i framtida forskning användas i kombination för den regionala modelleringen av konvektiva snöband i Östersjöområdet.

Nyckelord: Grund konvektion, extrem nederbörd, Östersjön, ytvattentemperatur, regional klimatsystem-modellering

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1 Introduction to the theory

The following sections are providing the elementary background and the motivation for an investigation of convective cloud bands that entitle the focus and objective of this thesis. For this purpose it is necessary to summarize the previous research conducted on these weather phenomenon.

1.1 Convective Snowbands in the Baltic Sea Area

Water bodies often generate subclimates due to their roughness and temperature difference with the land environment. Depending on the seasonal climate, stable and unstable periods tend to occur (Niziol, Snyder & Waldstreicher 1994). In spring and summer, when the water surface temperature is still colder than the average air temperature, stable stratification is encouraged in low levels. During autumn and winter the opposing phenomenon, a rather unstable environment develops when the ice-free water surface appears as a source of moisture and heat to the overlying air mass. As a result mesoscale convective precipitation events like convective snow bands may develop.

Convective snow bands are also known and studied as snow canon (‘snökanon’ in Swedish), lake effect snow (popular for the Great Lakes) or cloud streets, horizontal convective rolls or vortices with solid precipitation. They commonly develop over the open water surface of lakes or seas when cold air gets advected from the continent triggering shallow convection due to enhanced heat and moisture fluxes in an unstable boundary layer. Depending on various factors like the horizontal wind, the vertical shear or the shape of the coast, different snow band structures can form, which will be explained in subsection 1.2.2. When the prevailing atmospheric conditions stimulate a strong development of convective snow bands extreme precipitation events occur locally where the snow bands hit the coast.

Convective snow bands act like conveyor belts for snow precipitation. The cold air mass takes on moisture and heat from the warm water surface when traveling across the sea, supporting the formation of shallow convective clouds. Strong winds transport the changing air mass towards the Swedish east coast from the northeast Baltic Sea. Once the hydrometeors within the clouds grow large enough for precipitation, snow flakes begin to fall out. The topographic changes from sea to coast result in additional convergence and orographic lifting, enhancing once more the precipitation intensity. This process leads in the cold season repeatedly to severe precipitation events at the Swedish east coast. Large amounts of snow along with strong wind speeds can cause serious problems for traffic, infrastructure and other important establishments of society.

One famous case of an intense convective snow band with extreme precipitation occurred in early December 1998. Most affected was the small Swedish town Gävle which experienced such heavy snowfall that the snow depth increased by 130 centimeters within just three days (SMHI 2015). As a result of the heavy snow storm, the entire town was paralyzed, trains and busses had to close down their daily service, cars were unable to move, schools had to be closed, roofs collapsed under the weight of the snow and some houses even suffered power failure (Norinder 2013). The Gefle Dagblad (Norinder 2013) reported furthermore about many people that were unable to get home and were forced to stay overnight at their working place or book a room in a hotel nearby.

Intense convective snow bands affect usually only a limited area. The location of the extreme precipitation depends strongly on the wind direction. Only small inaccuracies in the wind field can result
in large uncertainties for the prediction of the hazard area. The exact forecast of convective snow bands is challenging, but nowadays numerical high resolution models perform well in predicting such extreme mesoscale weather events (NOAA 2012). Due to global warming it is expected that larger areas of the Baltic Sea will stay longer ice-free. As a result the occurrence of those convective snow band events may become more frequent as well as more intense.

1.2 Formation of Convective Cloud Bands

1.2.1 Characteristics and Criteria for the Formation

Convective snow bands form in response to cold air outbreaks over a relatively warm water surface. As cold and relatively dry air travels across a much warmer sea surface, the difference in temperature and moisture causes enhanced heat and moisture fluxes and convection develops. The resulting unstable boundary layer favours vertical movement. When the rising air parcel cools down and reaches the saturation vapour pressure, condensation takes place, clouds form and latent heat will be released. Is the temperature cold enough, ice crystals will form and fall as snow precipitation when they grow large enough. Relatively strong wind can organise this convection into wind-parallel quasi-stationary cloud bands with moving individual cells.

When the air mass meets the coast, the surface roughness and topography change forces the air to slow down and slide on the land mass. This orographic forcing can further intensify the precipitation at the coast. However, when the air mass leaves the warm ocean and reaches land, the atmospheric conditions change to rather stable stratification at the ground due to the colder land surface. The reduced heat and moisture fluxes from the ground will cause the convective snow bands eventually to dissolve and the heavy snowfall will not extent far inland. If the wind direction stays constant for several days like in Gävle 1998 (see section 1.1), a single snowband would accumulate its precipitation in a very restricted region and cause locally a significant increase in snow depth.

![Conceptual Model of Convective Snowbands](Figure 1.1 Conceptual Model of Convective Snowbands. Modified from Theeuwes et al. (2010).)
Recent studies by Evans & Wagenmaker (2000), Niziol, Snyder & Waldstreicher (1994), Andersson & Gustafsson (1993) and Niziol (1987) investigated that convective snow band events occur under typical conditions. The most important forcing for the development of snowbands is the thermal difference between the water surface and the overlaying air (Mazon et al. 2014). This difference determines the extent of the required heat and moisture fluxes.

A first necessary condition is therefore an open and ice-free water surface. An ice-covered sea implies a very cold water temperature below the salinity dependent freezing point. The rates of evaporation as well as sensible heat release would be significantly decreased.

Holroyd (1971) observed for the Great Lakes that the minimum temperature difference between water surface and 850 hPa level must be 13 °C to initiate convective snow bands without additional synoptic scale forcing. As 850 hPa correspond to about 1500 meters altitude, this lapse rate matches approximately the dry adiabatic lapse rate. A temperature gradient similar or bigger than the dry lapse rate implies the presence of an absolute unstable layer within the lowest 850 hPa. Hence, convection occurs and an unstable boundary develops. A big thermal difference enhances furthermore the evaporation rate and thus the moisture flux towards the air mass, supporting the formation of clouds and precipitation. The larger the temperature difference, the better the conditions for an intense development of convective snow bands.

The convective cloud growth is restricted in its vertical extent by a very stable layer. A capping subsidence inversion determines the height of the unstable boundary layer. The stronger the subsidence, the shallower the convection. However, the inversion layer may not be lower than 1 kilometer above the surface in order to allow sufficient convective cloud growth. Nevertheless, Niziol, Snyder & Waldstreicher (1995) point out that very large heat and moisture fluxes from the water surface can significantly lift and even erode the inversion layer. Common boundary layer heights for convective snow band events are 1.5 or 2 kilometers, in strong cases up to 2.5 kilometers instability.

Another crucial parameter for the evolution of convective snow bands is the wind throughout the mixed layer. The cloud bands are usually nearly parallel orientated to the prevailing wind. Only at light background winds (less than 5 m/s), the thermally driven circulation like the land breeze dominates the cloud band alignment (see Type IV snowbands in section 1.2.2). However, the convective snow bands in the Baltic Sea that were investigated for this thesis are associated with relatively strong wind speeds of more than 10 m/s (Andersson & Nilsson 1990). In connection with snow bands it is observed that the directional wind shear within the convective boundary layer is very small. The development of increasing directional wind shear usually entails the decline of the snow bands. Niziol (1987) established the criteria that convective snow bands are likely to occur when the wind shear between boundary level and 700 hPa is smaller than 30°. At a directional wind shear between 30° and 60° convective snow bands are possible to develop, but beyond 60° wind shear the band structure will break down.

The distance and path that the air mass travels over the sea determines together with the wind speed how much time the air has to take up heat and moisture from the sea. The wind field decides the path and fetch. The longer the distance, the stronger a convective snow band is possible to develop. Laird, Kristovich & Walsh (2003) found with idealised cases that cloud bands form when the ratio between the wind speed and the fetch distance over the open water is between 0.02 and 0.09 m/s·km. Accordingly, for 10 m/s wind speed cloud bands could develop for fetch distances between 110 and 500 kilometers. Stronger winds require larger fetch distances.
Finally the shape and topography of the coast is influencing the snow band evolution considerably. The large differences between land and water surface in temperature and evaporation are the decisive factors. Andersson & Gustafsson (1993) found that bays at the coast of departure act as genesis areas for convective cloud bands. A convergence zone develops as the two land breezes from both coasts meet in the center of the sea. The secondary circulation system forces convection, that may continue downwind as cloud band. The convection can intensify by another land breeze when reaching the coast of arrival, raising the capping inversion. Snow bands tend to align parallel to the coast when the shore has a concave shape. In addition, orographic lifting at the coast enhances vertical motion and thus convection. Moreover, islands that are located along the fetch disturb the heat and moisture flux from the sea to the air mass and can cause multiple bands to merge or split up.

1.2.2 Types of Convective Snow Bands

Niziol, Snyder & Waldstreicher (1994) found five different snow band types to develop over the Great Lakes. 50 to 200 kilometer long wind-parallel bands that form parallel to the longest axis of a lake belong to Type I. A strong convergence zone develops at the center of the water leading to a narrow single-band structure. Cloud bands that form parallel to a wind that is directed perpendicular to the long axis of the lake are called Type II bands. The shorter fetch does not allow such a strong development as a Type I snow band. Instead multiple less intense 20 to 50 kilometer long and 5 to 20 kilometer wide cloud bands form, which distribute the snow precipitation over a larger area along the shore. Niziol, Snyder & Waldstreicher (1994) define Type III bands as a hybrid of Type I and II bands. Type IV snow bands develop due to a land breeze parallel to the shoreline at light gradient winds. They are often associated with an arctic high pressure. The strong subsidence inversion limits the convective cloud growth with height and the precipitation is usually not as intense as that from Type I bands. However, Type IV bands remain stationary along a coastline and can therefore result in large snow accumulation. Finally there are mesoscale vortices that represent the last type. Type V bands develop similar to Type IV as shallow clouds in very stable conditions. They cause moderate snowfall and the shoreline is usually bowl-shaped.

Hence, Type I includes the snow band with the strongest development resulting in the most intense snowfall. Their scientific understanding and predictability is of great importance. This thesis deals mainly with convective snow bands of Type I, II or III, as they are most common for the Baltic Sea area.

![Figure 1.2](image)

(a) Single snowband due to land breeze such as Type IV  
(b) Multiple snowbands such as Type II

Figure 1.2 Difference between single and multiple Lake Effect snowbands. Robbins & Moran (2014).
2 Numerical Model Systems

In connection with the analysis of the mesoscale processes determining convective snow band events, the evaluation of the use of different regional climate model systems has been the objective. In order to give a good representation of the Baltic Sea and North Sea, regional models with high resolution are essential to reproduce topographical features and substantial processes. The next chapter will describe the used model systems, summarize their properties and explain the elaborated working method for the analysis of the subject.

2.1 RCA4

The Rossby Center of the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping is developing and applying climate models since 1997 (Jones, Samuelsson & Kjellstrom 2011). RCA4 is the forth and latest version of their regional atmospheric climate model and is running over many different CORDEX domains (Nikulin 2013). The domain used for this thesis (illustrated in red in figure 2.1) covers generously Europe. RCA is based on the operational numerical weather prediction model HIRLAM, although, RCA is developed to simulate on climatological time scales. RCA4 is a hydrostatic model based on primitive equations using terrain-following hybrid vertical coordinates and a rotated longitude-latitude-grid. The original model set-up uses time steps of 15 minutes, 40 model layers as vertical coordinates and a spherical resolution of 0.22°, which is corresponding to about 25 kilometer horizontal grid spacing (Dieterich et al. 2013). Initial and lateral conditions for parameters like ice cover, sea surface temperature or wind speed are provided to the model every six hours by the interpolated ECMWF reanalysis data ERA-40 (Dieterich et al. 2013).

Figure 2.1 The domain of the NEMO model (in blue) embedded in the RCA European CORDEX domain (in red). Dieterich et al. (2013).
2.2 RCA4-NEMO

The atmosphere-ocean interaction is of great importance of the atmosphere’s properties and dynamics as well as the entire earth’s climate system. The Nucleus for European Modelling of the Ocean NEMO (Madec 2012) is a regional ice-ocean model based on primitive equations that can be coupled to the RCA4 model in order to exchange information at the interfaces between air and sea or ice. In comparison with the RCA model, NEMO has a very high resolution with a horizontal grid spacing of two nautical miles, corresponding to circa 3.7 kilometers, and 56 geopotential levels at the vertical scale (Dieterich et al. 2013). NEMO provides parameters like ice fraction and albedo as well as sea surface temperature to the atmospheric model. In turn RCA4 communicates heat, freshwater and momentum fluxes to the ice-ocean model (Dieterich et al. 2013). The used NEMO domain can be seen in blue in figure 2.1 and covers the North Sea and the Baltic Sea. The boundaries at the northern North Sea and the English Channel are kept open and consider thus information of the Atlantic Ocean outside the NEMO domain (Dieterich et al. 2013).

The coupling of two independently developed model components such as RCA4 and NEMO can be realized by OASIS3 - the Ocean Atmosphere Sea Ice Soil Simulation Software. This coupler is developed by PRISM, the Project for Integrated Earth System Modeling and is commonly used in the climate modelling community (Valcke 2013).

2.3 RCA4-WAM

The W Ave Model (WAM) is a third generation full-spectrum prognostic wave model using the basic transport equation (WAMDI Group 1988), that can be used for a atmosphere-wave coupled system. The WAM model solves explicitly the energy balance equation in order to gain the evolution of the wave spectrum (Janssen 2004). ECMWF is running a coupled system of WAM in communication with an atmospheric component since 1998 (ECMWF n.d.).

For the purpose of coupling, WAM and RCA4 have the same resolution and time step frequency (see section 2.1) in this study. Here the WAM model component is treated as a subroutine which is called by RCA with every time step communicating the essential information between the model components. The WAM model provides RCA4 with wave information in exchange for wind field data from the atmospheric model. The important wave data for the RCA model is obtained by a two-dimensional ocean wave spectrum and involves parameters like wave height and period as well as roughness length.

The roughness length in the WAM model is calculated by

\[ z_0 = \alpha \frac{\tau}{g \rho_{air} (1 - \frac{\tau_w}{\tau})^{1/2}} \]  

(2.1)

where \( \tau \) describes the total stress, \( \rho_{air} \) the density of the air and the Charnock coefficient \( \alpha \) is set to 0.01 (WAMDI Group 1988). The wave induced stress \( \tau_w \) is a function of the water density, the growth rate of the wave, the angular frequency, the wave spectrum density, the wave direction as well as the wind direction.
2.4 Model experiments

For this study five different numerical model systems and set-ups are used to investigate their specific behaviour in connection with convective snow band events in the Baltic Sea area. The regional atmospheric climate model RCA has been used by itself in the already mentioned resolution of 40 vertical model layers and 0.22° (about 25 kilometers) horizontal grid spacing. A spin-up time of approximately two month ahead of the snowband event was applied.

A coupled simulation of the RCA with the ocean model NEMO was carried out to investigate the impact of the sea surface temperature on such convective precipitation events. In order to provide enough time for adjustment between the models, a spin-up of almost two years was used.

The coupled system of RCA and WAM is operated equally to the separate RCA model, as the horizontal resolution and time step of the WAM is kept the same as for RCA. The WAM is providing the RCA model with a surface roughness of the ocean corresponding to the atmospheric wind field above. While WAM computes the roughness length from the 2D wave spectrum (see section 2.3), RCA calculates it based on Monin-Obukhov using a constant Charnock coefficient $\alpha$ of 0.0185 in this study and a wind speed function $f(U)$, by

$$z_0 = f(U) \times \frac{u^2}{\alpha g} + (1 - f(U)) \times 0.11 \frac{v}{u^*}$$

with $u_*$ representing the friction velocity and $v$ the air kinematic viscosity (Wu et al. 2015).

Finally two experiments were done increasing the resolution of the RCA model either in horizontal spacing or in vertical direction. The horizontal resolution was refined from 0.22° to 0.11° (about 12.5 kilometers). And the 40 model layers of the original RCA set-up were increased to 62 layers. The spin-up time was used similar to the RCA simulation. A higher resolution, however, requires a lower time step in order to keep the model numerically stable. The time step was therefore decreased from 15 minutes to only 5 minutes.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Abbreviation</th>
<th>Horizontal resolution</th>
<th>Vertical levels</th>
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<tbody>
<tr>
<td>RCA4-NEMO</td>
<td>RCA-NEMO</td>
<td>0.22° (~25 km)</td>
<td>40</td>
</tr>
<tr>
<td>RCA4</td>
<td>RCA</td>
<td>0.22° (~25 km)</td>
<td>40</td>
</tr>
<tr>
<td>RCA4-WAM</td>
<td>RCA-WAM</td>
<td>0.22° (~25 km)</td>
<td>40</td>
</tr>
<tr>
<td>RCA4 with increased horizontal resolution</td>
<td>RCA hires</td>
<td>0.11° (~12.5 km)</td>
<td>40</td>
</tr>
<tr>
<td>RCA4 with increased vertical resolution</td>
<td>RCA hivert</td>
<td>0.22° (~25 km)</td>
<td>62</td>
</tr>
</tbody>
</table>
3 Results

Five different model systems were used to investigate their performance for two cases of convective snow band events. Their impact on crucial parameters like wind, temperature, heat fluxes and of course precipitation will be compared with each other. It is studied how the time series of SMHI station measurements agree with the evolution of the respective grid point values. Finally a Lagrangian experiment presents how the atmospheric conditions change for an air mass traveling across the Baltic Sea.

3.1 Synoptic situation of the selected cases

3.1.1 1998, December 4th-7th

In early December 1998 a low pressure system developed from a trough between Scandinavia and middle Europe (see appendix figure 5.1). The low pressure system deepened while slowly moving eastwards. It caused strong pressure gradients and hence high wind speeds over the Baltic Sea. Due to the slow motion of the pressure system the wind direction remained consistent over several days, transporting continuously cold air from north Asia and Finland southwestwards over the still comparatively warm Baltic Sea surface. Strong convective snow bands caused extreme snowfall in Gävle and serious problems for the inhabitants (see subsection 1.1).

3.1.2 2001, February 1st-3rd

On the 1st of February 2001 an eastwards moving deep low pressure system was active over the north Atlantic south of Greenland (see appendix figure 5.2). Another well developed through located over middle Europe was reaching all the way down to Italy and the Mediterranean Sea. At the same time two strong surface high pressure systems over Russia’s Kara Sea and north Scandinavia were steering the dry and cold polar air mass southwestwards across the Baltic Sea. The resulting convective snow bands become visible at the TERRA satellite pictures in figure 3.1. On February 1st a strong single band (see subsection 1.2.2) forms along Sweden’s east coast at the long fetch of the Gulf of Bothnia. The cloud band is aligned with the wind direction. Since the north Scandinavian high pressure system is moving

![Figure 3.1 TERRA Modis Atmosphere images. MODIS (2016).](image-url)
northwards in the following days, the wind is turning and it is seen in figure 3.1(b) and 3.1(c) that the single band becomes shorter while more multiple cloud bands appear.

### 3.2 Model performance for essential parameters

#### 3.2.1 Wind field

The theory requires moderate to strong wind speeds for the formation of Type I, II and III cloud bands. It is the wind together with the shallow convection what organises the clouds into bands. The wind direction determines the fetch and hence, how intense the snow bands may develop as well as where the snow bands meet the coast and cause enhanced precipitation.

Horizontal and vertical wind field images across the Baltic Sea show that all five model simulations behave in a very similar way for the wind field evolution in both snow band cases. In the figures 5.3 and 5.4 in the appendix is an example seen for the 1st of February 2001. The vertical cross section images (figure 5.4) include a black line, which represents the mixed layer depth calculated by the models. The strongest winds occur over the Gulf of Bothnia, where the roughness length is small and the pressure gradient is large. The local maximum of the wind speed is therefore often closer to the Swedish east coast. The wind speeds increase rapidly right before the snow band event takes place and slowly decrease again in the following days. However, when taking a closer look minor differences between the model systems can be observed. At 12 UTC the RCA-NEMO model gives the weakest 10 meter wind speeds together with the high horizontal resolution RCA. The increased horizontal resolution model brings the high wind speeds also even closer to the coast. The RCA model of high vertical resolution agrees well for the 10 meter wind speeds in the Gulf of Bothnia, but in the surroundings of the Åland islands in the strait between Sweden and Southern Finland, the wind speeds become significantly lower than in the other models. The vertical profiles in the cross sections (figure 5.4) show also some differences. RCA-WAM and RCA indicate a larger area of high wind speeds in boundary layer height. The high resolution RCA models and RCA-NEMO show a rather limited area of the high wind speeds in the cross section. However, all models show the air mass to speed up over the Baltic Sea.

In order to compare all model systems and investigate their accordance on the wind field evolution a limited area in the Bothnian Gulf surroundings was chosen, which can be seen in subfigure 3.2(a). Setting an additional threshold to only consider grid cells with a 10 meter wind speed value of 10 m/s or larger results in an even smaller area. The remaining grid points of the RCA simulation on the 1st of February at 12 UTC can be seen in subfigure 3.2(b). For every hourly time step the value and the amount of the grid points change.

Figure 3.3 shows the evolution of the wind field with respect to the local maximum as well as the area of high horizontal wind speeds larger than 10 m/s. The subfigures 3.3(a) and 3.3(b) represent the highest 10 meter wind speed found in the selected area for each case. The subfigures 3.3(c) and 3.3(d), however, show the area of grid points covering the region in figure 3.2(a) that meet the criteria of a 10 meter wind speed larger than 10 m/s (as in subfigure 3.2(b)). The value of the area was calculated under the assumption that the original resolution grid box amounts to 25 × 25 kilometers and the increased horizontal resolution has a grid box size of 12.5 × 12.5 kilometers. In the case of 1998, the local wind speed increased in the night from the 4th to the 5th of December. While RCA, RCA-WAM and RCA-NEMO give maximum 10 meter wind speeds of about 15 m/s, both high resolution simulations of RCA
Figure 3.2 Grid point selection for model comparison in figure 3.3

(a) Maximum 10 meter wind speed, 1998
(b) Maximum 10 meter wind speed, 2001
(c) Area of wind speeds larger than 10 m/s, 1998
(d) Area of wind speeds larger than 10 m/s, 2001

Figure 3.3 Evolution of the wind field in the Gulf of Bothnia.
give 10 meter of up to 16.5 m/s. The maximum is furthermore reached several hours later, when RCA and RCA-NEMO wind speeds already decrease again. The trend of the maximum 10 meter wind seems to agree better between the models in the case in 2001 (subfigure 3.3(b)). Here only the high vertical resolution RCA stands out with a peak of 15.5 m/s. The high horizontal resolution gives a less extreme development for the 10 meter wind. The area of the wind speed greater than 10 m/s in 10 meters height (subfigure 3.3(c) and 3.3(d)) correspond well with the development of the local maximum. The high horizontal resolution RCA seems to give generally larger areas, however, this could be an effect of the assumptions made for the area calculation which is not entirely correct for a curved surface like the earth. With the applied assumption the entire area in figure 3.2(a) would cover then $2.575 \cdot 10^5$ km$^2$ for all models except the RCA with increased resolution, which takes up $2.61 \cdot 10^5$ km$^2$.

Moreover, all subfigures show a delay of the RCA-W AM compared with the other simulations. This delay is caused by the communication between the two models RCA and W AM. Both models need time to adjust one another. Increased wind close to the surface simulated by the atmospheric RCA will trigger larger waves at the sea surface, which causes the W AM model to respond in a greater surface roughness, which will in turn slow down the wind in the lowest air layers.

The divergence in the 10 meter wind field is similar between all models. As seen in the appendix figure 5.5 the 'coast of departure' (where the air mass leaves the land mass) generates divergence zones, while the 'coast of arrival' (where the air mass enters the land) creates additional convergence when meeting an obstacle with changed surface roughness like the coastal topography. The RCA model shows in comparison the most intense convergence and divergence values.

Based on the analysis of the two cases it has been observed that the increased resolution of the RCA model in either dimension results in higher maximum wind speeds as well as larger high wind speed areas in 10 meter height. Moreover, the RCA-W AM model shows a time shift in the maximum 10 meter wind speed evolution in comparison with the other models.

### 3.2.2 Sea surface temperature and ice cover

The sea surface temperature (hereafter called 'SST') is provided to the RCA model by the ECMWF reanalysis data ERA-40. The spectral resolution of the ERA-40 data is T159, which corresponds to 1.125 degrees or approximately 125 kilometers (‘Advancing Reanalysis’ 2016) and is thus coarser than the original RCA resolution itself. The NEMO model, however, simulates its own SST based on initial and lateral conditions as well as reanalysis data in a much higher resolution than RCA (see section 2). The daily SST output has been compared between RCA and RCA-NEMO. The high resolution RCA setups as well as the RCA-W AM use the same source for the SST as the RCA and show therefore no difference with the RCA SST that can be seen in the subfigures 3.4(a) and 3.4(d). Figure 3.4 shows for the two cases a map of the RCA and the NEMO SST in their original resolutions, as well as a difference map between these two. For the difference map an interpolation was carried out to average the high resolution NEMO SST towards the coarser RCA grid and subtract each RCA grid value from the respective NEMO grid point.

Figure 3.4 shows that NEMO can resolve locally extremer values than RCA. The seen differences are significant. The Gulf of Bothnia is in both cases much colder for the RCA than for the NEMO simulation. Also the SST of the southern Baltic Sea tends to give colder values in the RCA simulations. Only in the Baltic Sea straits where a bay (such as the Gulf of Bothnia or the Gulf of Riga) connects
to the sea and the Baltic Sea is shallow, the difference between RCA and NEMO SST is small. A few grid points even show warmer values for the RCA SST, but this may be a result of the interpolation over an area with islands. However, the region of interest in the two selected cases of this thesis is the Gulf of Bothnia, which shows remarkable differences. NEMO gives up to 5 °C warmer SST’s than RCA. The difference between the models is larger in the case of December 1998 than in February 2001. In the appendix (figure 5.8) a comparison of the respective model SST with Optimum Interpolation Sea Surface Temperature data (OISST) is shown for one day of the case in December 1998. The OISST dataset is the result of the combination of measurements from satellites, ships and buoys (NOAA n.d.). It is seen that the ERA-40 data is in some regions still up to 5 °C colder than the OISST data. NEMO on the other hand shows smaller differences, however, it tends to give slightly higher SST values with differences in the Gulf of Bothnia of up to 2 °C.

Furthermore, it is important to consider possible sea ice, since the presence of ice changes the shape of the coast and significantly affects the heat fluxes. In December 1998 the ERA-40 data indicates no ice cover for the entire Baltic Sea. The NEMO model, however, develops some ice cover on the most northern part of the Baltic Sea within the case period (see figure 5.9 in the appendix). On the 3rd of February 2001 both ERA-40 and NEMO give a considerable ice cover in the northern bay of the Gulf of Bothnia. However, ERA-40 has no ice cover the two days before and develops from one day to the other sea ice as in figure 3.5(a). NEMO on the other hand represents the slow freezing of the bay in a
high resolution over many days in advance (figure 3.5(b)). Also some ice cover close to the islands in the Baltic Sea has been simulated. Nevertheless, the corresponding satellite picture in figure 3.1(c) shows an ice cover, too, although the visible ice fractions appears to be much smaller than the one given by ERA-40 or NEMO in figure 3.1.

The SST computed by the ocean model component NEMO results in significantly higher values than the SST given by ERA-40. In order to give a good representation of the SST or the ice cover for a water body of the size of the Baltic Sea, the ERA-40 data is inferior to the NEMO output just due to the resolution differences.

### 3.2.3 Temperature trend

Apart from a few exceptions, the ground level temperatures show in horizontal maps an overall similar distribution (see appendix figure 5.6). The RCA simulation of increased vertical resolution gives slightly higher 2 meter temperatures in south Sweden as well as over the North Sea and the Atlantic Ocean. RCA-NEMO (figure 5.6(b)), however, shows higher temperatures over the Baltic Sea.

Comparing vertical cross sections as in appendix figure 5.7 even more differences become visible. The Baltic Sea appears clearly as a heat pool, especially for RCA-NEMO. Also the RCA-NEMO temperature gradient with height is larger than for the other models. Visibly colder temperatures are reached already at boundary layer height. The other models show additionally warmer temperatures over the Finish land. All uncoupled RCA simulations give furthermore a light inversion. RCA-WAM and the increased vertical resolution RCA allow the Baltic Sea to warm up the air above up to higher altitudes than the other models.

Figure 3.6 is the result of the same method as used for the above described figure 3.3. The grid point of the highest 2 meter temperature was selected within the same area as in figure 3.2(a) in order to compare the temperature evolution of the different models. Especially in the case of December 1998, the RCA-NEMO simulation stands out since it is generally warmer by about 1 °C throughout the whole time series. Only the extreme values of the high horizontal resolution RCA agrees eventually better.
with RCA-NEMO, when the temperatures of RCA, RCA-WAM and the high vertical resolution RCA decrease stronger. All models seem to match better in figure 3.6(b) for the case of February 2001. The reason is probably the temperature difference between the Baltic Sea and the air above. In December the Baltic Sea is still relatively warm from the summer months, but until February the water body had more time to cool down and the difference may not be as big any more.

The 2 meter temperature evolution above the Baltic Sea develops in direct response to the SST. It is therefore no surprise that the RCA-NEMO simulation is noticed to give rather warm temperatures in comparison with the other models. The difference between RCA-NEMO and the other models is larger in December 1998 in accordance with the larger SST difference. The coupling of the atmosphere RCA model to an ocean model has been observed to show a great impact on the local temperature extremes.

### 3.2.4 Sensible and latent heat fluxes

During a convective snow band event cold air travels across a comparatively warm water surface and causes enhanced sensible and latent heat fluxes. The time evolution of the heat fluxes in figure 3.7 indicate increasing values while the event already begun. The maximum heat flux is reached in a later period of the event just before the cloud bands dissolve. Both cases show the most intense heat fluxes for the RCA-NEMO model. It looks like RCA-NEMO goes along with the other models until the snow bands form. The difference between the models develops later. In 2001 it is the night between 31st of January and 1st of February when both heat fluxes of RCA-NEMO increase significantly and split up from the less intense increasing other models. The maximum heat fluxes are reached on the 2nd of February. The latent heat flux decreases again before the sensible heat flux. In the case of RCA-NEMO the sensible heat flux actually increases beyond the 2nd of February and reaches its maximum on the 3rd of February instead. In 1998 the difference arises on the 4th of December. However, the high horizontal resolution RCA gives locally even larger sensible heat fluxes on the 5th of December. RCA and RCA-WAM on the other hand seem to stay constantly in the lower part of the heat flux curve.

The horizontal distribution of the heat fluxes in the Gulf of Bothnia can be seen for the case of 2001 in the appendix figures 5.10 and 5.11. The figures represent a time step close to the maximum of the heat fluxes.
flux evolution in figure 3.7, at 12 UTC on the 2nd of February. The RCA-NEMO subfigures confirm the highest heat flux rates among the models. The sensible heat flux of the RCA model appears rather weak in comparison. In the northern part of the Gulf of Bothnia the weakest sensible heat flux is given by the RCA of increased vertical resolution. Except from the RCA-NEMO, which again is noticed to give larger values, also the latent heat flux is horizontally very similar distributed between the model setups.

The largest maximum heat fluxes have been seen clearly for the RCA-NEMO system in both cases. The high resolution RCA models however, give comparatively high heat fluxes too. Even though the SST difference between NEMO and RCA is smaller in February 2001, RCA-NEMO shows a larger difference to the other models in 2001 than in 1998. In February 2001 stronger heat fluxes were observed most likely as a result of the more rapid cold snap.

### 3.2.5 Mixed layer height

The planetary boundary layer describes the lowest layer of the troposphere under the direct influence of the earth’s surface. This layer is determined by turbulence and hence vertical mixing. The stronger the convective mixing, the deeper the boundary layer may develop.
Figure 3.8 shows the mean boundary layer height for the different models in both cases. The figure represents the same cross section as seen in subfigure 5.4(a). The respective boundary layer height is calculated for every coordinate by the mean value of two days. Since the RCA model of increased horizontal resolution is built on a different spatial grid than the other models, an interpolation had to be done towards the coarser grid first. Both subfigures show a similar picture: The RCA-NEMO and the RCA of high vertical resolution follow approximately the same trend and give at some point over the Baltic Sea the usually highest mixed layer depths. RCA and RCA-WAM stay also close together, although they give usually smaller values than the previous two. Finally the RCA simulation of increased horizontal resolution appears to give the smoothest as well as shallowest curve of boundary layer height across the Baltic Sea.

That the horizontal distribution of the boundary layer height still varies between the models can be seen in the appendix, figure 5.12. The Gulf of Bothnia shows increased boundary layer heights on its west side, as the convective mixing is here the strongest. However, the local maximum is differently located for the models. While most models have evenly high boundary layers along the Swedish coast, the deepest mixed layer height of the high vertical resolution RCA model for example is shifted northwards. Such a systematic shift can distort the impression in a cross section figure such as the figure 3.8 above. However, choosing different cross sections confirms the statement that RCA-NEMO tends to give the deepest boundary layers and the RCA of high horizontal resolution usually represents the smallest mixed layer depths. The RCA simulation of increased vertical resolution shows a rather unpredictable jumpy behaviour. When viewing the mixed layer heights for the single time steps instead of the mean, the rising of the boundary layer can be observed for the time of the snow band period.

Based on the two investigated cases it has been seen that RCA-NEMO represents comparatively high boundary layer heights, while the high horizontal resolution tends to give rather shallow boundary layers.

3.2.6 Precipitation rates

Depending on the strength of the convective snow band the precipitation can vary a lot. Just the two cases investigated in this thesis give very different amounts of snow. A slight turning of the wind can
distribute the snowfall along the coast instead of accumulating it at one restricted location.

In order to compare the precipitation of the different models a similar method was used as the one described in section 3.2.1. This time a slightly different area was chosen to cover the precipitation area along the Swedish east coast better. Figure 3.9(a) represents this area together with the 48 hours accumulated total precipitation of the RCA-NEMO model in 2001. It is seen that most of the lake effect snow falls within the selected area. Figure 3.9(b) shows the same area for the hourly precipitation of the RCA-NEMO at 12 UTC with the additional criteria to only consider precipitation rates larger than 0.5 mm/h. The precipitation scale refers to the volume the snow would have in liquid rather than solid form. As an approximate relationship it is reasonable to assume one milimeter of melted snow to correspond roughly to one centimeter of snow, although the density of the snow depends strongly on parameters like temperature or age (SMHI 2016).

Figure 3.10 shows the hourly values of the total snowfall with time. The upper subfigures represent the maximum precipitation simulated anywhere within the selected area. The subfigures beneath represent the approximate area of precipitation rates larger than 0.5 mm/h. The popular snow band case in 1998 gave significantly more snowfall than the case in 2001. Not only a larger area was affected by the lake effect snow, also the local precipitation rates were higher. Very remarkable is the RCA simulation of increased horizontal resolution. Especially in the case of 1998 the local maxima are significantly higher than any other model system. However, is does not cover the largest precipitation area. The other high resolution RCA and the RCA-NEMO model give high snowfall rates as well. The original RCA and RCA-WAM tend to model rather smaller precipitation rates in comparison. The horizontal distribution of the 48 hours accumulated snowfall can be compared between the models in the appendix figures 5.13 and 5.14. The area of the maximum precipitation agrees overall well between the models. However, the accumulated amount of the snow varies very much. Moreover, the high horizontal resolution RCA shows much more detail on the precipitation area and the location of the maximum. The figures show furthermore that the precipitation area in 1998 is aligned with the snow band itself giving precipitation already over the Baltic

Figure 3.9 Grid point selection for model comparison in figure 3.10
Sea, while the area of extreme snowfall in 2001 is rather following the shoreline. This gives reason to assume that in December 1998 an intense single band hit the Gävle region enhancing the already precipitating cloud band due to frictional convergence at the coast. In February 2001, however, little precipitation is seen over the Baltic Sea itself. The cloud band may have been triggered to precipitate only due to the orographic forcing at the coast. The precipitation area along the coast indicates the presence of multiple cloud bands or the turning of the wind. The original RCA, the RCA-NEMO and the RCA-WAM model seem to suggest even a second less intense precipitation area north of the Gävle region closer to Sundsvall.

The amount of the precipitation varies considerably between the model systems. RCA-NEMO and the two high resolution RCA models have shown significantly higher snowfall rates than RCA and RCA-WAM, which agrees with the observation of higher temperatures and heat fluxes for these models. The greatest difference for the local maximum shows the RCA model with increased horizontal resolution.

Figure 3.10 Evolution of the total precipitation along the Swedish east coast.
3.2.7 Cloud fraction

Since convective snow bands develop first of all from cloud bands, it can also be useful to investigate how the different models simulate the cloud fraction over the Baltic Sea. Figure 3.11 shows the model’s cloud fraction of one time step in the case of 1998 for one vertical model level. The appendix contains furthermore two figures (5.15 and 5.16) of the case in 2001 that represent the vertical cross section through the clouds as well as their horizontal distribution at one model level. Within the project work is was unfortunately not possible to exploit any cloud data from the RCA-NEMO system, which can therefore not be compared with the remaining models.

The figures show stratocumulus clouds as the result of shallow convection over the warm Baltic Sea. The exact location of the clouds varies between the models. Also the altitude and the extent of the cloud differ. In figure 3.11 the vertical model level of about 980 hPa is seen for most of the models. Only the RCA model of increased vertical resolution gives the cloud band no lower than at 955 hPa. However, all available models simulate the expected cloud band in 1998. Figure 5.16 of 2001 represents the cloud fraction of the models in approximately the same height of 930 hPa (corresponding to the 32nd out of

![Cloud Fraction Maps](image)

**Figure 3.11** Horizontal cloud fraction maps of all available models, 1998.
40 model levels). RCA-WAM represents the linear cloud cover better in a lower level of about 950 hPa (model level 33). And the RCA of the increased vertical resolution shows a bandlike cloud structure higher up at about 910 hPa (51 out of 62 vertical model levels). For comparison the SMHI radar image of the same time was added. Also here, most model subfigures seem to show some kind of linear cloud alignment in the region of the expected snow band, although they do not agree as clearly and at the same height as in 1998 (figure 3.11). In both cases an improvement for the representation of a cloud band is noticed for the RCA model of increased horizontal resolution.

3.3 Model vs. SMHI station observations

In order to determine how well the model results agree with observational data, measurements from SMHI stations at the Swedish east coast were analyzed in connection with the corresponding grid point model data. The data of three weather stations is available for the respective time periods within the precipitation area. Their location can be seen in the map, figure 3.13. Since in the case of December 1998 almost exclusively Gävle was affected, only the Gävle station (with the decimal degree coordinates 60.674722 latitude and 17.141667 longitude) was used. Figure 3.12 and 3.14 show the time series for the 10 meter wind speed, the two meter temperature as well as the 3 hour accumulated precipitation at the SMHI station. The SMHI observational data is plotted in black on top of the model results. For better comparison, the solid line of the respective model data represents the value of the grid box closest to the station coordinates, while the shaded area shows the variances with the neighboring grid points. For all models with the original RCA resolution of 0.22° only the four directly adjacent grid points where used. As the high horizontal resolution RCA would under this criteria cover a much smaller area, three grid points in each direction were used instead.

All stations experience an increase in wind speed with the beginning of a convective snow band event. When the wind strengthens the SMHI 10 meter wind speed gives higher values in comparison with the models. It has been noticed that the highest wind speeds of the model was always given by the closest gridpoint to the Baltic Sea, which usually agrees better with the SMHI observation. All models seem to decelerate the air mass too soon when meeting the land mass. Only the increasing 10 meter wind in 1998 in Kuggören was modelled well by the RCA with increased
Figure 3.13 Location of the SMHI stations.

Figure 3.14 Time series of the SMHI station data in comparison with the grid point model results, 2001.
horizontal resolution. The stations Kuggören and Brämön are located directly at the coast on a peninsula or even an island, while the Gävle station is built within the town. The influence of the distance to the open water is clearly seen in the figures. The Gävle station barely exceeds 10 m/s in both cases while the other stations easily reach 10 meter wind speeds of 15 m/s even though the horizontal maps show very similar wind speeds along the coast.

Both cases indicate the arrival of a colder air mass by decreasing temperatures. In December 1998 the SMHI station gives warmer 2 meter temperatures than any of the model grid points. Even the trend of the model temperature development differs from the almost linear decrease measured at the Gävle station. However, in February 2001 the model results match the SMHI station data. The models appear slightly colder than the station measurements in Gävle, at the Brämön station on the other hand they are slightly warmer. In agreement with the earlier investigation of the 2 meter temperature, here too, the RCA-NEMO model gives mostly higher results in comparison with the other models.

Finally the precipitation was accumulated every three hours to compare the model output with the station data. In Gävle precipitation rates of up to 5.5 mm/3h were observed in 1998. Most models simulate much smaller rates, only the RCA of increased horizontal resolution even exceeds this value on the 6th of December. In February 2001 the total precipitation was less and the difference between the models was also less extreme. However, both high resolution RCA models and RCA-NEMO tend to give the largest precipitation rates in comparison. The models show furthermore difficulties to simulated the exact time and location of the precipitation showers.

3.4 Model vs. radio sounding

Another way to verify the models with measurement data is using radio soundings. The University of Wyoming is providing radio sounding data every day at 00 UTC and 12 UTC for Sweden at the sites in Visby at the island Gotland as well as in Sundsvall at the east coast of middle Sweden (University of Wyoming 2016). In Finland radio soundings are only available inland for Jockis in the southwestern part of Finland.

For the closest model column to the horizontal coordinates of the starting point of the sounding, the vertical profiles can be compared between sounding measurements and model output. Figure 3.15 shows this comparison for the Jockis site at 12 UTC on the 31st of January 2001 as well as for the Sundsvall site at 12 UTC on the 1st of February 2001. Except for RCA-NEMO all models represent their vertical profile by model levels. Hence the high vertical resolution RCA shows the smoothest curve. For RCA-NEMO the vertical profile is represented by pressure levels and shows therefore a rather coarse resolution. The shaded area shows again the deviation with the neighboring grid boxes as described in the previous section.

The temperature profile of the sounding is in both sites colder than the models. The high horizontal RCA appears to be the closest to the sounding at least in low levels. The inversion in Sundsvall is not simulated by any of the models, but the overall temperature gradient agrees. Consequently, the stable stratification of the atmosphere is also represented by all models. The exact height and depth of the stable and neutral layers differ between all models and the sounding. The wind speed profile in Jockis is best represented by the original RCA model, although it always stays below the sounding measurements. In Sundsvall the high horizontal resolution RCA gives the closest profile to the sounding. The profile
Figure 3.15 Vertical profiles of the models in comparison with radio soundings in Jockis and Sundsvall.
of the specific humidity is also best represented by the RCA model of increased horizontal resolution. However, all models show higher specific humidity values than the sounding does.

All model profiles show a systematic shift from the sounding data. The models appear warmer, often less windy and moister than the sounding measurements. However, it should be noted, that the sounding measurements do not represent a vertical column like the models, but usually show a drift of the balloon that is carried with the wind direction when rising. Out of all model systems the RCA of increased horizontal resolution gives the closest profile to the sounding data.

3.5 Following an air parcel across the sea

A final experiment was carried out aiming the investigation of the changing air mass which is travelling from the Finish land across the Baltic Sea towards the Swedish coast where it finally causes extreme precipitation. For this purpose four grid points were chosen along the long fetch of the Gulf of Bothnia, that could represent the approximate trajectory of an air parcel arriving in Gävle. Figure 3.17 shows the location of these grid points as white dots on top of the respective horizontal RCA cloud fraction map. Since the synoptic situation of the two cases is relatively similar, the same grid point locations were used. The distance between the grid point at the Finish coast and the grid point in Gävle is approximately 625 kilometers. With an average wind speed of 15 to 20 m/s the air mass takes almost 9 to 12 hours to

Figure 3.16 Vertical profiles across the Baltic Sea, 1998.
Figure 3.17 Location of the selected grid points to follow an air parcel across the Baltic Sea in the cloud fraction maps.

Figure 3.18 Vertical profiles across the Baltic Sea, 2001.
travel this distance. With four grid points on the way, the air mass takes three to four hours from one grid point location to the other. The figures 3.16 and 3.18 show the atmospheric conditions in vertical profiles for the different grid points and time steps. The shaded areas represent again the variation of the neighboring grid boxes, depending on the resolution (as described in section 3.3). Since the six hour output frequency from RCA-NEMO could not be increased, a time difference of three hours was assumed between the grid points, so that the RCA-NEMO result could be included at least in two of the four time steps. The profiles were created with help of the hybrid model layers, which resolve the levels close to the ground well. However, for RCA-NEMO only pressure levels are available in a coarse vertical resolution.

Both figures (3.16 and 3.18) show an example for an air mass leaving Finland at 12 UTC and arriving at 21 UTC in Gävle within one day of the snow band event. The temperature profile includes the dewpoint temperature as a dotted line. The figures show that the air mass gets warmed in the lowest layers by the Baltic Sea. A clear inversion is not always available. In 1998 a low level inversion is seen at the Finish coast. In Gävle only the high horizontal resolution RCA gives an inversion. However, all models show the boundary layer clearly in the subfigures of the potential temperature profile. RCA-WAM tends to give more stability above the boundary layer for all grid points. In 2001 all models match much better. The profiles are so close that they can barely be distinguished. RCA and RCA-NEMO appear just slightly warmer over the Baltic Sea. As already seen in figure 3.8 the boundary layer is rising towards the Swedish coast and it is deeper in 2001 than in 1998. In figure 3.16 the air mass accelerates strongly between Finland and Sweden and the RCA of increased vertical resolution simulates the highest wind speeds in the profiles. In 2001 the differences of the wind speed between the models is again very small and an air parcel keeps approximately the same velocity along the whole way. Finally the profile of the specific humidity confirms that the air mass is taking up moisture from the Baltic Sea. While the humidity subfigures in 3.18 show again barely any differences between the models, figure 3.16 of 1998 gives the highest moisture values in all grid points for the RCA setup of increased horizontal resolution.
4 Discussion

The above analysed observations and results of the different model systems are in the following chapter discussed. It will be reviewed how the coupling with an ice/ocean model or a wave model or the increasing of the model resolution affects the simulation of such high impact events. Finally the criteria listed in the introduction chapter will be checked and verified for the two investigated cases.

4.1 Impact of the coupling of RCA with WAM on the model performance

The simulations of RCA and RCA-W AM gave the least conspicuous behaviour. Since the coupling of the atmospheric model with a wave model mainly has an influence on the surface roughness at the sea, the largest impact was expected on the wind field. Indeed the wind data shows some difference with the other models. The maximum wind speed appears in similar magnitude as the other models, but the time evolution shows some delay. When all models simulate a changing 10 meter wind speed, RCA-W AM remains unchanged for several hours before it follows the trend of the other models (compare figure 3.3). As discussed before this delay is a result of the communication between the model components that take time to adopt to each other. However, the vertical wind profiles seen in section 3.4 and 3.5 show slightly lower wind speeds in comparison with the other models. Furthermore the cross section profiles (figure 5.4) indicate in 1998 partially a larger area for high wind speeds in boundary layer height for RCA-W AM.

With regard to the temperature or heat flux development as well as the boundary layer height RCA-W AM does not show any systematic differences compared to RCA. Just the potential temperature profile of the RCA-W AM model indicates slightly more stability above the boundary layer. Furthermore, the two models give very similar results also for the precipitation rates. The RCA-W AM cloud cover in 2001 shows the organised cloud alignment slightly below the vertical level of RCA, but both models agree well on the horizontal distribution of the clouds.

The coupling of the atmospheric RCA model with the wave model component WAM uses a different roughness length computation by the 2D wave spectrum of the WAM. However, this coupling has a rather small impact on the atmospheric conditions describing convective snowband events.

4.2 Impact of the coupling of RCA with NEMO on the model performance

RCA-NEMO is a coupled atmosphere-ocean system that benefits clearly from the high resolution SST of the NEMO component. The ERA-40 data that otherwise provides the uncoupled RCA with the SST has an even coarser resolution than the RCA itself. For water bodies of the size of the Baltic Sea, this resolution is insufficient and the quality of the simulation is impaired as local extremes can not be represented. Comparing the SSTs used for RCA and RCA-NEMO it has been observed that NEMO provides the RCA model in both cases with warmer temperatures than the ERA-40 data does (see figure 3.4). Especially in the region of interest, the Gulf of Bothnia, the RCA SST is significantly colder than the NEMO SST. In December 1998 the difference amounts to up to 5 Kelvin. In February 2001 the difference was not as extreme, but still considerable. Also in the representation of the sea ice the RCA-
NEMO model has an advantage over the original RCA model. While the NEMO component shows the development and growth of ice shields at the coast in detail, the ERA-40 data gives no ice cover at all until it suddenly covers a considerable area (see figure 3.5).

The higher SST of the RCA-NEMO model are also reflected in higher 2 meter temperatures as well as higher heat fluxes. This might furthermore be the reason why the RCA-NEMO model results in larger local precipitation rates and areas than RCA or RCA-W AM. Although, the RCA-NEMO wind speeds appear rather neutral in comparison with the other models, the boundary layer height of the RCA-NEMO tends to give one of the highest altitudes the models.

### 4.3 Impact of an increased resolution of the RCA model

A high resolution is of great importance when it comes to the regional modelling of mesoscale high impact events. Increasing the resolution of the atmospheric RCA model results in great improvement for the model performance. It has been observed that both high resolution simulations show increased values for the local maxima of the 10 meter wind speed as well as the precipitation. The most remarkable differences with the other models for many of the considered parameters gives the RCA model of increased horizontal resolution. It surprises with a systematically shallower boundary layer and gives in 1998 significantly higher local precipitation rates. In the Lagrangian experiment of 1998 (figure 3.16) the air of the high horizontal resolution RCA seems to contain more moisture than the air masses in the other models. This observation, can not be confirmed with the same figure of 2001 (figure 3.18), but it explains the big difference of the precipitation rates between the models in 1998 (figure 3.10).

The horizontal maps show naturally more detail and resolve therefore slightly different images than the other models. The 10 meter wind speed for example reaches its highest values even closer to the Swedish coast than any other model (figure 5.3). Also the elevation of the mixed layer at the Swedish coast is locally more restricted (figure 5.12). Moreover, the precipitation area is much more precise than the other models. It gives a more specific representation of the precipitation hazard area as well as the location of its maximum. Also cloud bands are more clearly represented by the increased horizontal resolution model (figure 3.11 and 5.16). For the temperature or the heat flux evolution, on the other hand, there is no clear behaviour seen.

### 4.4 Verification of the snow band criteria

In the introduction of this thesis criteria were listed that describe the atmospheric conditions required for convective snow bands to develop. This section will verify whether these criteria are fulfilled for the two cases.

In both cases the Baltic Sea was mainly ice-free. In February 2001 a small area in the northeast part of the Gulf of Bothnia showed some ice over (figure 3.5). However, the shoreline and the shape of the sea was only slightly affected so that the fetch would barely be reduced.

In order to guarantee instability to trigger convection somewhere within the boundary layer, a temperature difference between the surface and the 850 hPa level should be not smaller than 13 °C. To verify this criteria, horizontal difference maps were generated like the ones in the appendix, figure 5.17. For an easier comparison and the representation of the time evolution, figure 4.1 was created in the same way
as described in section 3.2.1. All models show an increasing temperature difference with the beginning of the convective snowband event. Although the case in December 1998 gave a much more intense snow band precipitation, the temperature difference and hence the instability was larger in February 2001. The figure 4.1 indicates in agreement with the SST differences between the models that the RCA-NEMO model results locally also in the largest temperature differences between surface and 850 hPa. However, in 1998 the RCA model of high vertical resolution gives partially even larger temperature gradients. The smallest temperature difference is observed for the original RCA model. RCA covers on the 6th of December 1998 a very large area over the Baltic Sea fulfilling the criteria. Since the total area considered is only $2.61 \times 10^5$ km$^2$, the RCA model is getting in 1998 close to cover almost the entire area. In 2001 on the other hand, RCA-NEMO meets the criteria in comparison with the other models for a smaller area, even though it gives locally the largest differences. All models fulfill the criteria of a temperature gradient between the surface and 850 hPa to be not less than 13 Kelvin in both cases. However, the criteria does not seem suitable for the prediction of convective snow bands since the temperature gradient increases rather with the beginning than in advance of the snow band event.

The convective boundary layer is in both cases observed to be of approximately 1 to 1.5 kilometers
height (figure 3.8). This appears to be rather shallow considering the criteria formulated in section 1.2.1. As the boundary layer is restricted by a capping subsidence above, according to the theory, the inversion layer may not be lower than one kilometer. However, the stable layer above the boundary layer in these two cases is not always a real inversion. And it has been seen that the boundary layer height is rising for the convective snow band event, especially at the Swedish coast. It was furthermore shown in section 3.2.7 that the cloud bands are available in very low altitudes within one kilometer height. The case in December 1998 showed a more intense development of the snow band, even though the boundary layer height was shallower than in February 2001.

The next required criteria considers the directional wind shear. In order to maintain the band structure of the circulation the wind shear between boundary level and 700 hPa should be as small as possible, however, no larger than 60°. To investigate this parameter for the two selected cases, the wind direction between two levels was compared for each model and each time step. Figure 4.2 shows the directional wind shear between the levels of 975 hPa and 700 hPa. The choice of the lower level is well below the boundary layer height and rather represents the prevailing wind direction within the boundary layer. The upper two subfigures show the mean value of the wind shear between these two levels only considering

![Figure 4.2](image-url)
the grid points of a wind shear smaller than 60°. The subfigures below show the area that has wind shear values smaller than the threshold of 60°. It is seen that partially the entire area considered for the time series gives wind shear values small enough for convective snow bands to develop. In 2001 the area increases with the beginning of the snow band event on the 1st of February and decreased again at the 3rd of February when the snow bands start to dissolve. In 1998 the area shrinks when the snow bands were already generated before the area grows again to the maximum covering the entire Baltic Sea area on the 5th of December. On the 7th, when the precipitation in Gävle stopped already, the area is still on maximum for all models. However, the mean wind shear values of the grid points with wind shear below 60° stay somewhere close to 30°. In 1998 the mean wind shear shows no specific trend. Just on the 7th of December all models seem to even reduce their wind shear. In 2001 the mean wind shear indicates low values for the snow band period. A systematic difference between the single models can not be seen. However, both cases fulfill the criteria of small directional wind shear well. The mean values stay often even below the threshold of 30°, which indicates good conditions for the development of convective snow bands.

The Baltic Sea serves the formation of convergence zones well with its numerous bay-shaped coasts. The northern part of the Gulf of Bothnia acts as a good location for the generation of convergence. With the right synoptic conditions to result in a south-west-wards wind direction along the long fetch of the Gulf, convective snow bands can be favoured. Assuming the air mass takes the path suggested in section 3.5, the fetch distance would be 625 kilometers between the Finish coast and Gävle. According to the ratio between the wind speed and the fetch distance to be a number between 0.02 and 0.09 m/s/km (see section 1.2.1), the required wind speed must be larger than 12.5 m/s over the Baltic Sea. Also this condition can be confirmed for both cases.
5 Conclusions

The following chapter summarizes the most important results of this thesis. Furthermore some suggestions will be given for further research work on the subject of convective snow bands in the Baltic Sea area using the tested models.

5.1 Summary of the results

Two case studies of convective snow band events were carried out using regional climate modelling. The simulations were based on the atmospheric model RCA4, which had been used in the original setup, as well as with increased vertical or horizontal resolution and moreover coupled either to the ice/ocean model NEMO or the wave model WAM. Those five different model systems represent the atmospheric conditions for convective snow bands well. However, systematic differences were investigated between the models.

As case periods the famous snow band event in December 1998 was selected together with a less intense snow band event in February 2001. Both cases show similarities in their synoptic situation. Cold air from the Finish land was transported over the Gulf of Bothnia causing extreme snow precipitation at the Swedish coast close to Gävle. However, the seasons were different and accordingly also the sea surface and air temperatures. While in December 1998 the wind direction remained unchanged for several days, in February 2001 the wind changed slightly and distributed the precipitation better along the Swedish coast.

In the beginning of a snowband event, the wind speed increases over the Baltic Sea before the wind calms slowly down again. In 1998 the two high resolution models indicate that it was windier than in 2001. Comparing weather station data with the model results, the measurements give nearly always higher 10 meter wind speeds than the models. The temperatures close to the ground show a falling trend throughout both snow band periods. In 1998 the two meter temperatures were decreasing by approximately 4 Kelvin, while in 2001 the temperatures were falling by almost 10 Kelvin. A large difference has been observed for the SST of the atmosphere model provided with the coarse reanalysis data and the high resolution ocean model. The coupled atmosphere-ocean system gave results of significantly higher SSTs, which showed direct impact on the 2 meter temperatures and the heat fluxes. The sensible and latent heat in both cases were increasing during the snow band event. However, because of the more rapid cold snap in 2001 a much steeper development was seen from lower initial heat flux rates up to a significantly higher maximum, in which the coupled atmosphere-ocean model would always present the highest values. The boundary layer showed a rising development for the snow band period with the strongest elevation along the Swedish coast. The mixed layer reached overall higher in 2001 than in 1998. On a larger scale all models agree overall well on the precipitation area. However, the exact location on a smaller scale as well as the amount and the time of the snowfall remain a challenge. The models differ to a great extent in the amount of the two day accumulated precipitation. The largest precipitation rates are given by the two high resolution models as well as the atmosphere-ocean model. Even the band like structure of the clouds could be represented by most of the models.

All models simulate the atmospheric conditions for convective snow bands and fulfill the criteria established in previous research. However, the models show differences that must be considered when
using them for case studies of extreme impact events. Since the atmosphere ocean interaction is of great importance for the regional climate modelling of events like convective snow bands, the coupling with the high resolution ocean model NEMO is advantageous over the use of the coarse reanalysis data used in the original RCA model. Furthermore the increased resolution of the atmospheric model has a positive impact on the model results. Especially the high horizontal resolution showed great improvement on the representation of the cloud bands, the precipitation area as well as the wind speed.

Based on the investigation of the two cases and the just reviewed results found, the use of a coupled atmosphere-ocean system in connection with a high horizontal resolution of the atmospheric component is suggested for a more accurate representation of convective snow bands in regional climate models.

5.2 Suggestions for future research work

The here presented results require more quantity in order to make a statistical statement. The study would gain quality when selecting some more cases of similar synotical background and analysing the behavior of the single models for more events of different intensity.

In first continuation of this project a list of cases similar to the ones analysed here could be simulated in order to verify the results found. Then other synoptic situations could be explored developing convective snow bands in the Gulf of Finland and giving precipitation in different regions of the Swedish east coast, such as Stockholm or Norrköping. One model system could be set up combining the two model experiments that have shown the greatest improvements: the coupling of the atmosphere with the ocean model as well as the increased resolution of the atmospheric component. Once a reliable model system has been set up, the atmospheric properties and mesoscale processes could be investigated in more detail.

Sensibility studies could be made for different resolutions, to determine which horizontal and vertical resolution provides the best improvements of the results and are simultaneously reasonable on the computational resource. It would furthermore be interesting whether the models are able to simulate weak cloud band events and horizontal convective rolls without precipitation.
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References


Internet resources


Appendix

Figure 5.1 Synoptic situation on the 6th of December 1998 at 6 UTC. ‘wetter3.de’ (2016).

Figure 5.2 Synoptic situation on the 1st of February 2001 at 12 UTC. ‘wetter3.de’ (2016).
Figure 5.3 Horizontal 10 meter wind speed maps of all models, 2001.
Figure 5.4 Vertical wind speed cross section for all models, 2001.
Figure 5.5 Horizontal 10 meter divergence maps of all models, 2001.
Figure 5.6 Horizontal 2 meter temperature maps of all models, 2001.
Figure 5.7 Vertical temperature cross section for all models, 2001.
Figure 5.8 Difference between OISST satellite data and the model SST on the 5th of December 1998.

Figure 5.9 Ice cover on the 6th of December 1998.
Figure 5.10 Horizontal sensible heat flux maps of all models, 2001.
Figure 5.11 Horizontal latent heat flux maps of all models, 2001.
Figure 5.12 Horizontal mixed layer height maps of all models, 2001.
Figure 5.13 Horizontal total precipitation maps of all models, 1998.
Figure 5.14 Horizontal total precipitation maps of all models, 2001.
Figure 5.15 Vertical cloud fraction cross section of all available models, 2001.
Figure 5.16 Horizontal cloud fraction maps of all available models, 2001.
Figure 5.17 Horizontal temperature difference maps of all available models (surface level minus 850 hPa level larger than 13 Kelvin), 2001.