Introducing a sea ice scheme in the COSMO model

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1 Introduction

The presence of sea ice on the ocean's surface has a significant impact on the air-sea interactions. Compared to an open water surface the sea ice completely changes the surface characteristics in terms of albedo and roughness, and therefore substantially changes the surface radiative balance and the turbulent exchange of momentum, heat and moisture between air and sea.

In order to deal with these processes the operational global model GME at the German Weather Service (DWD) includes a sea ice scheme (Mironov and Ritter 2004). In contrast, there was no such scheme in DWD's limited area model COSMO-EU (Doms and Schättler 2002, Schulz 2006) up to now. This model covers almost all Europe using a mesh size of 7 km, its lateral boundary conditions are provided by GME. Instead, the GME sea ice surface temperature is used to "emulate" the existence of sea ice in COSMO-EU by providing a realistic temperature at water points which are regarded as being ice covered. Using the threshold temperature value $T_{\mathrm{melt}} = -1.7°\mathrm{C}$ the COSMO-EU water points are distinguished between open water or ice covered. The albedo and the roughness length are set accordingly.

This procedure has the disadvantage that the GME sea ice surface temperature is transferred to COSMO-EU only once per day at 00 UTC, as part of the sea surface temperature (SST) analysis, and is then kept constant at this night time value during the data assimilation cycle and also during the forecasts. This means that there is no diurnal cycle of sea ice surface temperature possible in COSMO-EU. Furthermore, the ice temperature of GME may not fit well to the COSMO-EU surface conditions, depending on the weather situation, and may therefore introduce imbalances and noise.

For these reasons it was decided to implement a sea ice scheme in the COSMO model, the GME scheme has been selected for this. In the following sections a short description of the scheme is given and results of numerical experiments comparing COSMO-EU with and without the sea ice scheme are presented.

2 The sea ice scheme

The sea ice scheme by Mironov and Ritter (2004) accounts for thermodynamic processes, while no rheology is considered. It basically computes the energy balance at the ice's surface, using one layer of sea ice. From this the evolution of the ice surface temperature T_{ice} and the ice thickness H_{ice} are deduced. These two new prognostic variables allow for a better thermodynamically coupled treatment of sea ice in the COSMO model as lower boundary condition for the atmosphere. In particular, the scheme allows for very low surface temperatures which can be significantly lower than the water temperature below the ice.

The sea ice surface temperature T_{ice} is computed by the surface energy balance equation:

$$\frac{\Delta T_{\mathrm{ice}}}{\Delta t} = \frac{1}{c\,H_{\mathrm{ice}}} \left[\frac{Q_{\mathrm{A}} + Q_{\mathrm{I}}}{\rho_{\mathrm{ice}}\,C_{\mathrm{ice}}} \right] \tag{1}$$

where Q_A is the sum of all atmospheric energy fluxes at the ice's surface (solar and thermal radiation plus sensible and latent heat flux), Q_I is the vertical conductive heat flux through the ice layer of thickness H_ice, $\rho_\mathrm{ice} = 910$ kg m^{-3} is the ice density, $C_\mathrm{ice} = 2100$ J kg^{-1} K^{-1} the ice heat capacity, $c = 0.5$ a shape factor and t the time.

The internal heat flux Q_I through the ice layer is computed by

$$Q_\mathrm{I} = -\lambda_\mathrm{ice} \frac{T_\mathrm{ice} - T_\mathrm{bot}}{H_\mathrm{ice}} \tag{2}$$

where $\lambda_\mathrm{ice} = 2.3$ W m^{-1} K^{-1} is the ice heat conductivity and T_bot the temperature at the bottom of the ice layer. It is set constant to $T_\mathrm{bot} = -1.7°\mathrm{C}$ which is assumed to be the freezing temperature of salty sea water.

In the case of $T_\mathrm{ice} = 0°\mathrm{C}$ and $Q_\mathrm{A} \geq 0$ W m^{-2} all available energy at the ice's surface is used for melting, leading to a reduction of the sea ice thickness H_ice according to

$$\frac{\Delta H_\mathrm{ice}}{\Delta t} = -\frac{Q_\mathrm{A}}{\rho_\mathrm{ice}\, L_\mathrm{f}} \tag{3}$$

where $L_\mathrm{f} = 0.334 \cdot 10^6$ J kg^{-1} is the latent heat of freezing. In this case the heat flux Q_I is neglected.

In all other cases the evolution of H_ice is governed by the following equation:

$$\frac{\Delta H_\mathrm{ice}}{\Delta t} = \frac{Q_\mathrm{I}}{\rho_\mathrm{ice}\, L_\mathrm{f}} \tag{4}$$

This means that the internal ice heat flux Q_I is balanced by the amount of energy involved in the phase transitions between liquid and frozen water at the bottom of the sea ice layer, i. e. the interface between ice and water. If for instance $T_\mathrm{ice} < -1.7°\mathrm{C}$, this will lead to an ice heat flux Q_I which is directed upward from the water into the ice layer. The source of this heat flux is assumed to be the latent heat of freezing of an equivalent amount of water, which while freezing will lead to a growing sea ice thickness H_ice.

3 The sea ice distribution

The horizontal distribution of the sea ice cover in the model domain is governed by the data assimilation scheme. This is the same with or without the sea ice scheme. It means that the sea ice scheme in COSMO-EU changes the way the sea ice is represented, but it can not create new sea ice points, it can not start freezing the water by itself.

In the model chain at DWD first the remote sensing based sea ice mask from NCEP (National Centers for Environmental Prediction, USA) is provided by the SST analysis to the global model GME. This GME sea ice mask is then again interpolated by the SST analysis to the COSMO-EU grid. During this last interpolation an additional high-resolution sea ice mask is used to improve the ice distribution on the COSMO grid in particular in the Baltic Sea. This high-resolution sea ice mask is issued by BSH (Bundesamt für Seeschifffahrt und Hydrographie, Germany) and is updated every few days.

4 Cold start from GME using the SST analysis

In order to test the sea ice scheme in COSMO-EU two continuous numerical parallel experiments, running in the same way as the operational analyses and forecasts, were carried out:

A reference experiment of COSMO-EU without sea ice scheme (called REF), and an experiment of COSMO-EU with sea ice scheme (called ICE). The period was 03 Feb. – 31 May 2010. This period was selected because most of the sea ice season in the model domain in early 2010 was covered. Only the first few weeks of freezing were skipped, this allowed to test a cold start of the sea ice scheme from the fields of the driving model, i. e. here the GME.

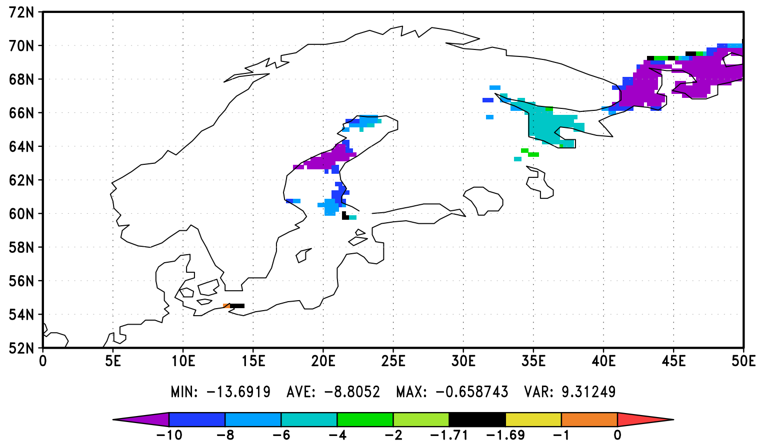

Figure 1: GME analysis of sea ice temperature (°C), 03 Feb. 2010, 00 UTC. Some parts of mainly the Gulf of Bothnia, the White Sea and the Barents Sea are already ice covered.

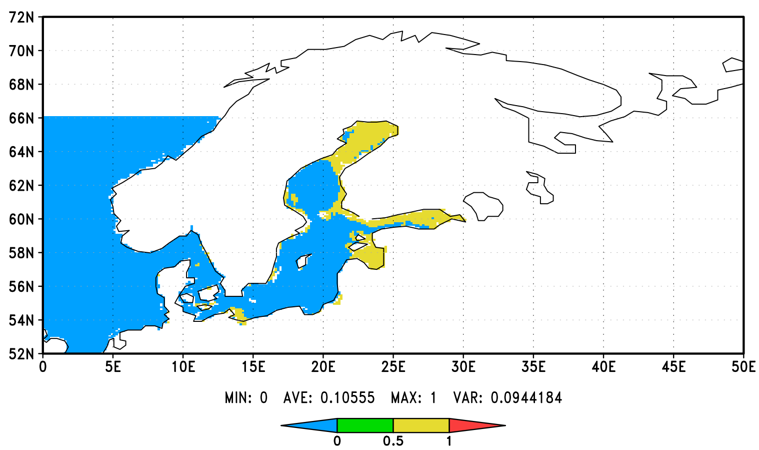

Figure 2: BSH observational sea ice mask used in the SST analysis for COSMO-EU, 03 Feb. 2010, 00 UTC. The mask covers the entire Baltic Sea and parts of the North Sea. A comparison with the GME sea ice distribution (Fig. 1) shows that BSH has more sea ice in the Gulf of Finland and the Gulf of Riga but less in parts of the Bothnian Sea.

Figure 1 shows the sea ice temperature as provided by the SST analysis to the global model GME on 03 Feb. 2010, 00 UTC. Some parts of mainly the Gulf of Bothnia, the White Sea and the Barents Sea are already ice covered. The temperatures in the Bothnian Sea and the Barents Sea have reached values below $-10°$C, temperatures in the White Sea range around $-5°$C. Figure 2 depicts the BSH observational sea ice mask on 03 Feb. 2010, 00 UTC. It is used in the SST analysis for COSMO-EU as a refinement for the NCEP ice mask. A comparison of the two sea ice distributions (Figs. 1 and 2) shows that BSH has more ice in the Gulf of Finland and the Gulf of Riga but less in parts of the Bothnian Sea.

Figure 3 shows the analysis of the surface temperature of water points which are regarded as being ice covered by the SST analysis for COSMO-EU running without sea ice scheme (REF), again on 03 Feb. 2010, 00 UTC. In the domain of the BSH mask (basically in the

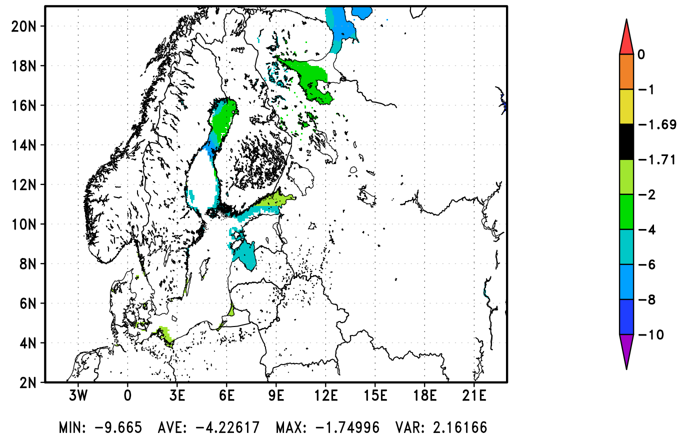

Figure 3: Analysis of surface temperature (°C) of water points which are regarded as being ice covered by the SST analysis for COSMO-EU without sea ice scheme (REF), 03 Feb. 2010, 00 UTC.

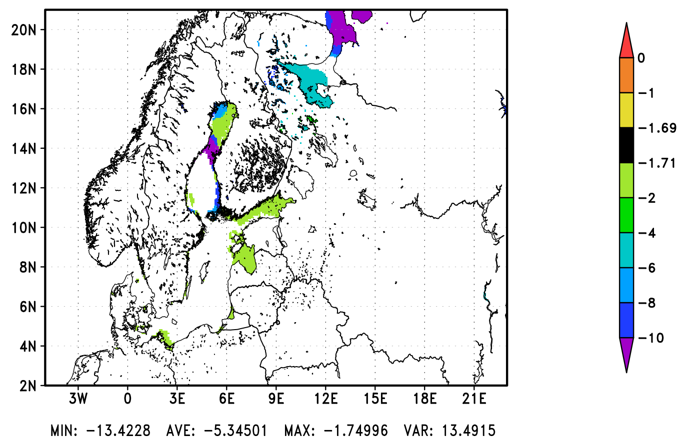

Figure 4: Analysis of sea ice temperature (°C) provided by the SST analysis for COSMO-EU with sea ice scheme (ICE), 03 Feb. 2010, 00 UTC.

Baltic Sea) the BSH ice distribution is used, outside of it (White Sea, Barents Sea) it is determined by GME, and therefore NCEP. Comparing the ice temperatures of GME and REF in the White Sea and Barents Sea it is noticed that REF is less cold than GME. The reason is that the SST analysis computes the sea ice temperature for REF in the following

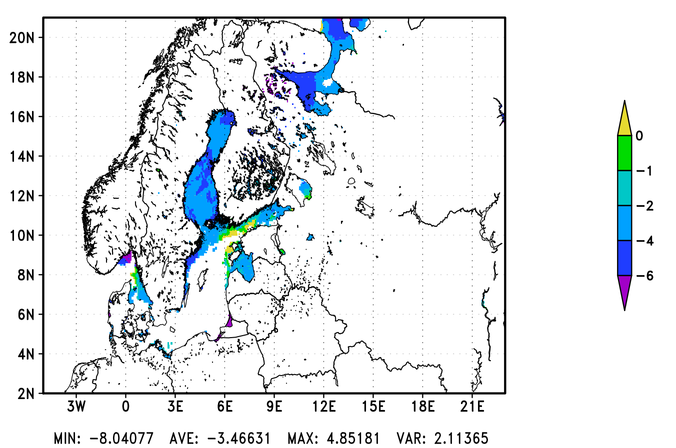

Figure 5: Difference of analysed surface temperature (°C) at sea ice points between COSMO-EU with and without sea ice scheme (ICE - REF), 07 Mar. 2010, 00 UTC.

way:

$$T_{\text{ice}}^{\text{REF}} = 0.5(T_{\text{ice}}^{\text{GME}} + T_{\text{melt}}) \tag{5}$$

with $T_{\text{melt}} = -1.7°\text{C}$. The idea behind this is that the atmospheric conditions may be very different between GME and COSMO-EU at certain regions, one may have clear sky and the other one cloudy conditions. Introducing the very cold GME temperatures in this example directly into COSMO-EU may have more negative than positive effects (M. Buchhold, pers. comm., 2009).

Within the domain of the BSH ice mask three cases need to be distinguished:

- GME = ice and BSH = ice, e. g. northern Bothnian Sea: Use same formula as outside BSH mask.
- GME = no ice and BSH = ice, e. g. Bothnian Bay: Create new ice point.
  Initialise: $T_{\text{ice}}^{\text{REF}} = T_{\text{melt}} - \epsilon, \epsilon = 0.05°\text{C}$.
  Then: Search in the neighbourhood for the warmest ice point which originates from GME. Use this temperature for $T_{\text{ice}}^{\text{REF}}$.
- GME = ice and BSH = no ice, e. g. central Bothnian Sea: Remove ice point, create water.
  Initialise: $T_{\text{ice}}^{\text{REF}} = T_{\text{melt}} + \epsilon$

Figure 4 shows the analysis of sea ice temperature provided by the SST analysis for COSMO-EU running with sea ice scheme (ICE), again for 03 Feb. 2010, 00 UTC. This is used as the actual cold start for ICE. Now, in the areas outside of the BSH ice mask and in the first case from before the GME sea ice temperatures are directly interpolated to the COSMO-EU grid:

$$T_{\text{ice}}^{\text{ICE}} = T_{\text{ice}}^{\text{GME}} \tag{6}$$

Consequently, here the cold start values in ICE are lower than the ones in REF (compare Figs. 3 and 4).

And in the second case from before, GME = no ice and BSH = ice, the newly created ice points are initialised as before, but the search in the neighbourhood for the warmest ice point which originates from GME is skipped. Therefore, several regions in the Bothnian Bay and the Gulf of Riga are warmer now (again compare Figs. 3 and 4).

In the third case from before there is no change.

The initialisation of the sea ice thickness works in a similar way. It is either directly interpolated from GME, or in case new ice points need to be created they are initialised with a thickness of 0.2 m.

A main difference between REF and ICE is actually the initialisation of $T_{\text{ice}}^{\text{REF}}$ according to (5). It leads to systematically higher ice temperatures in REF which is e. g. shown in Fig. 5 and which turns out to cause a warm bias of the surface temperature even on surrounding land areas (see Fig. 7).

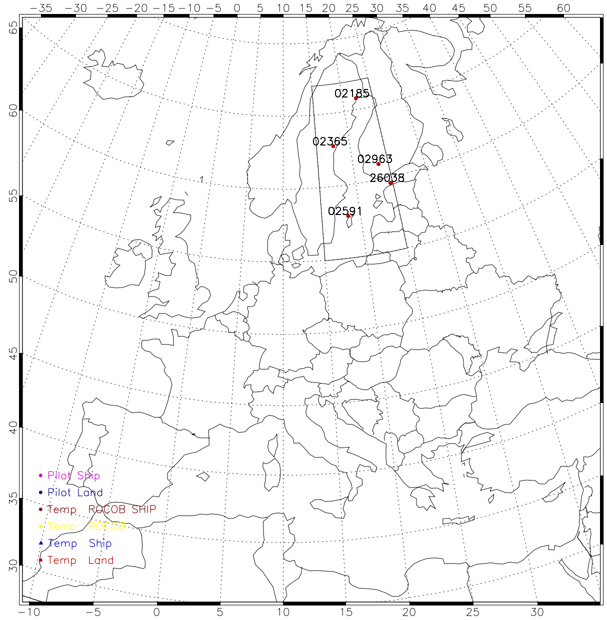

Figure 6: Verification domain for the 2-m temperature verifications shown in Figs. 7, 8 and 11. Additionally the locations of some radio sondes are indicated, two of them are used in Figs. 9 and 10.

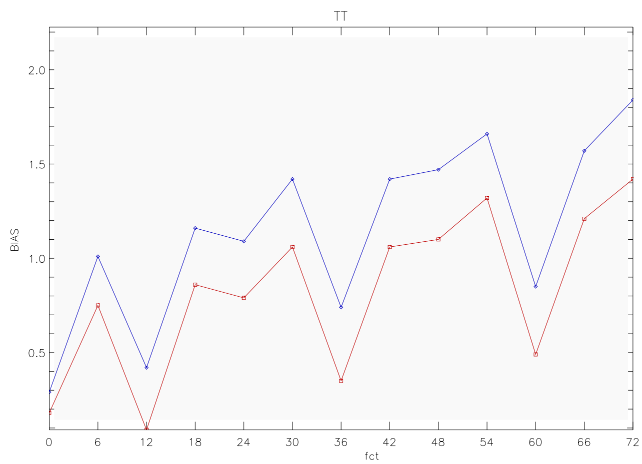

Figure 7: Bias of 2-m temperature (°C) versus forecast time (h) for the period 03 – 28 Feb. 2010, 00 UTC runs. Blue: Reference COSMO-EU without sea ice scheme (REF), red: COSMO-EU with sea ice scheme (ICE). All stations in the verification domain were used (see Fig. 6).

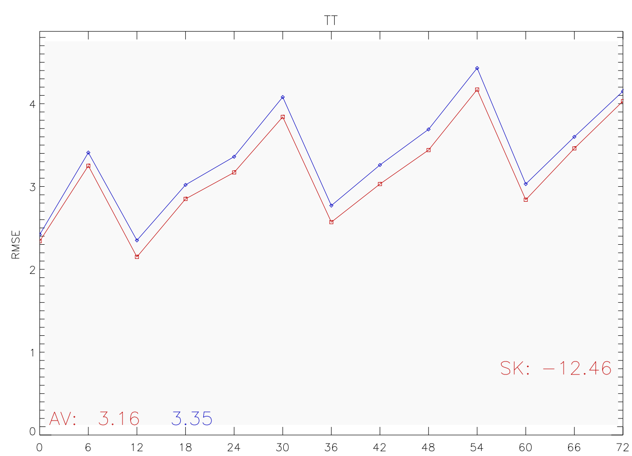

Figure 8: Same as Fig. 7, but for root mean square error of 2-m temperature (°C). Blue: REF, red: ICE. The reduction of its error variance in ICE amounts to about 12%.

5 Numerical parallel experiments

In this section an objective verification of the REF and ICE experiment is presented. The verification domain is shown in Fig. 6. Figure 7 compares the biases of the 2-m temperature versus the forecast time during the freezing period in February 2010. The REF experiment

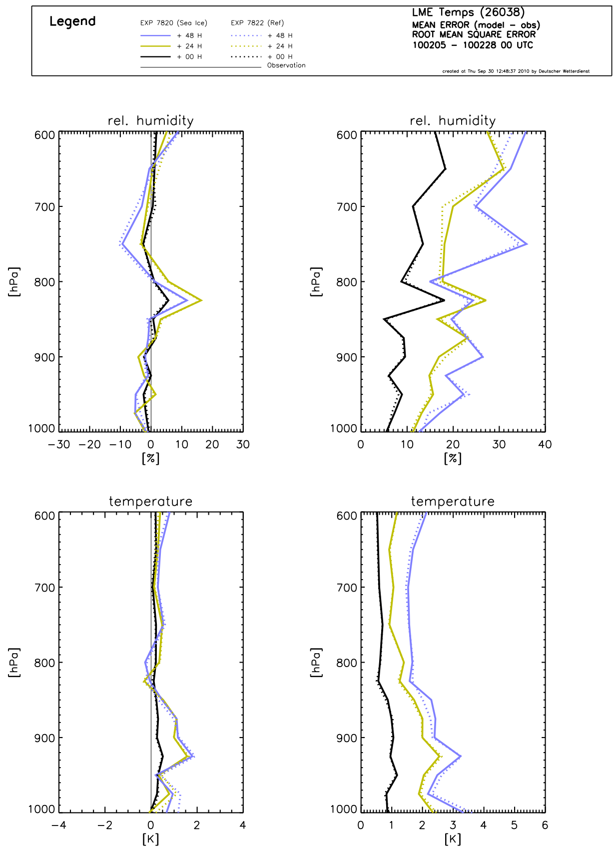

Figure 9: Upper air verification for Tallin, Estonia (Temp 26038) for relative humidity (top) and temperature (bottom) for the period 05 – 28 Feb. 2010, 00 UTC runs. Dotted lines: Reference COSMO-EU without sea ice scheme (REF), solid lines: COSMO-EU with sea ice scheme (ICE). Left column: Bias, right column: Root mean square error. Black lines: + 00h, yellow lines: + 24h, blue lines: + 48h.

shows a positive bias of up to 1.8°C, while in the ICE experiment the bias is reduced by up to 0.5°C. The root mean square error of the 2-m temperature is significantly reduced, namely, the reduction of its error variance amounts to 12% (see Fig. 8). This means that the surface temperature distribution even on surrounding land areas is much better captured by COSMO-EU with the sea ice scheme.

Figures 9 and 10 present upper air verifications of the two experiments with respect to relative humidity and temperature. They show a similar and consistent improvement of the model performance by the sea ice scheme as well. COSMO-EU without the sea ice scheme tends to develop a positive bias in the near-surface temperature. This is reduced by the sea ice scheme. The root mean square error of the near-surface temperature is slightly reduced as well. Figure 10 shows that bias and root mean square error of the relative humidity may benefit as well.

Figure 11 shows that during the melting period in April 2010 the REF experiment develops a negative bias of the 2-m temperature during day time. This is explained by the fact that the sea ice temperature is initialised by the SST analysis with night time values at 00 UTC which are kept constant during the entire forecast. A warming of the sea ice surface is not

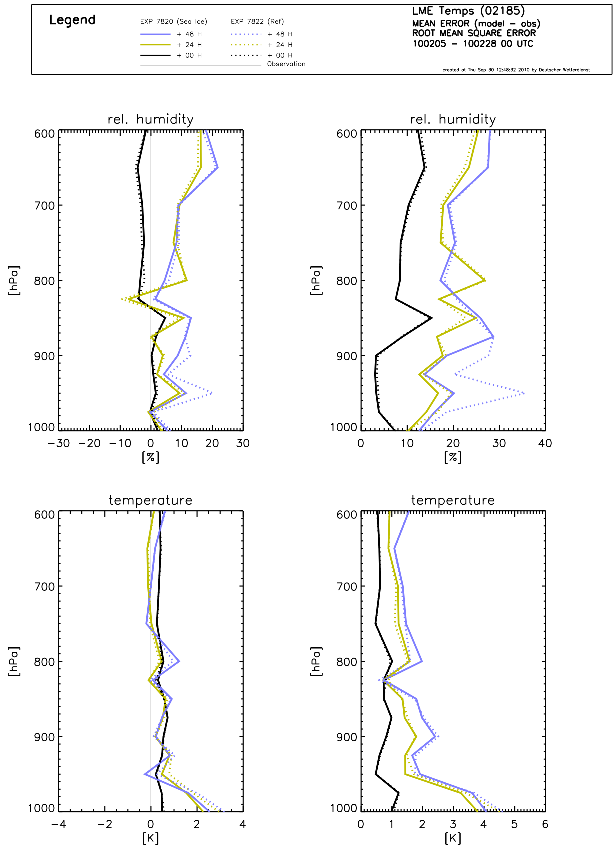

Figure 10: Same as Fig. 9, but for Lulea, Sweden (Temp 02185).

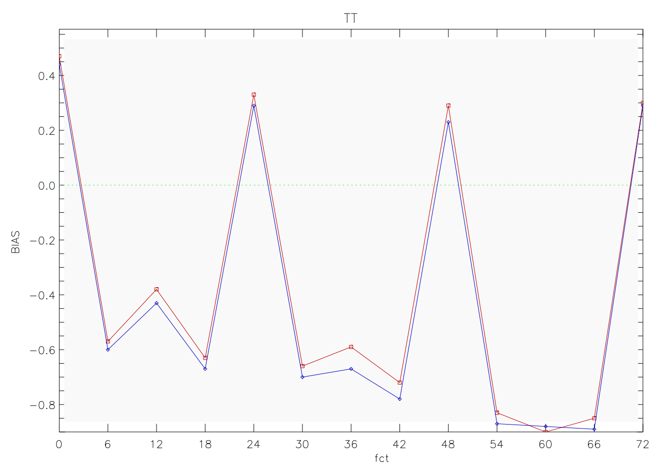

Figure 11: Bias of 2-m temperature (°C) versus forecast time (h) for the period 01 – 30 Apr. 2010, 00 UTC runs. Blue: Reference COSMO-EU without sea ice scheme (REF), red: COSMO-EU with sea ice scheme (ICE). All stations in the verification domain were used (see Fig. 6).

possible. On the other hand the ICE experiment allows for a diurnal cycle of the sea ice surface temperature, this slightly reduces the negative bias.

6 Conclusions

The sea ice scheme by Mironov and Ritter (2004) was implemented in the COSMO model. The scheme accounts for thermodynamic processes, it basically computes the energy balance at the ice's surface, using one layer of sea ice. From this the evolution of the ice surface temperature and the ice thickness are deduced. This allows for a better thermodynamically coupled treatment of sea ice in the COSMO model as lower boundary condition for the atmosphere. This means, the scheme allows for a diurnal cycle of sea ice surface temperature which was not present in the COSMO model before. Instead, the sea ice temperature was initialised by the SST analysis at 00 UTC and then kept constant at this night time value during the data assimilation cycle and also during the forecasts.

This behaviour of the sea ice scheme was successfully tested in COSMO-EU. The objective verification of a continuous numerical experiment for the period 03 Feb. – 31 May 2010 shows good improvements. In particular, the positive bias of the 2-m temperature during the freezing period in February is considerably reduced. Its root mean square error is even significantly reduced, namely, the reduction of its error variance amounts to 12%. This means that the surface temperature distribution even on surrounding land areas is much better captured by the model. In addition to the surface weather elements the upper air verification shows a similar and consistent improvement as well. In addition to this, here also the bias and the root mean square error of the relative humidity benefit. Furthermore, a negative bias of the 2-m temperature during day time, developed during the melting period in April, is reduced as well.

Acknowledgement

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