The Nordic temperature problem in winter.

The Hirlam models always have had problems representing the very cold conditions that can develop in winter over land over the Northern part of the model domains. Usually, these conditions develop under calm and clear conditions and over a thick snow deck. So far, researcher and model developers have thought that the problem of Hirlam representing these conditions has something to do with the evaporation in Winter being too large, leading to fog and low-cloud formation that diminish the radiative cooling.

In this note I will look at the processes taking place in the model under these conditions in 1D experiments. They may shed some new light on the problems.

1D experiment.

The 1D model that is used in this study is based on the Hirlam physics of version 6.3.5, the reference beta Hirlam version until January 31. As it is a 1D model, the impact of advection cannot be studied with this model. We will therefore limit ourselves to the study of processes that take place in a single column of air under (initially) clear and calm conditions. The reference 40-level Hirlam definition is used in these experiments, but they can be easily changed to any number of levels to study the impact of the vertical resolution.

To represent the wintry conditions the experiment starts with an isothermal temperature profile of -10°C. The relative humidity is 75% close to the surface and decreases with increasing height. The geostrophic wind is very weak with 1 m/s and a subsidence of 0.02 Pa/s is used to compensate for the radiative cooling of the atmosphere above the boundary layer. The integration time is 48 hours, starting at 00 UTC on January 1, and the latitude and longitude are 75°N and 0°W, so the short wave radiation is zero through the entire experiment.

The surface and deep surface temperature are equal to the temperature of the atmosphere initially, the soil moisture content is 0.1 and the run is started with a snow pack of 50 cm. The experiment is performed over ISBA tile 3, which represents bare soil, but as we are running with a snow deck of 50 cm, the impact of the soil itself should be relatively small.

Model results.

The first figure (left) shows the temperature of the air and the surface and the lowest part of the model as a function of time. The temperature at the surface (and with it the two metre temperature) drops very quickly, with about 10 degrees, in the first 12 hours of the experiment. The temperature at the lowest model level and deep in the soil are following more slowly and drop only 3 degrees in these 12 hours. Both surface heat fluxes (figure 1, right) are very small in this period and directed towards the surface. After 12 hours the drop of the surface temperature suddenly stops while the temperature at the lowest model level starts to decrease more quickly that before. After about 4 hours, the temperature at the lowest model level becomes lower than the temperature of the surface and the surface fluxes suddenly reverse sign and the soil starts heating and moistening the lowest model level.

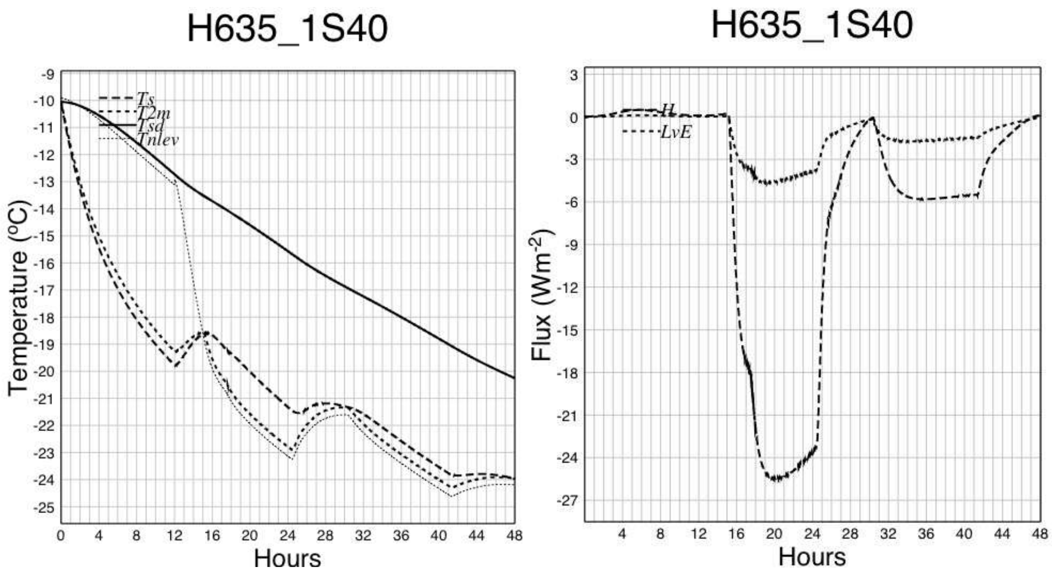

Figure 1: The temperature of the surface and close to the surface (left) and the surface heat fluxes (right) as a function of time in the reference 1D experiment.

Similar jumps and changes in the temperature and heat fluxes can be found later in the model run. At this point it is important to point out that the direction of the surface fluxes is according to theory for the first 12 to 16 hours of the model run, so we do not have evaporation from the model surface. Many explanations of the Nordic temperature problem point to the evaporation as the source of the problem.

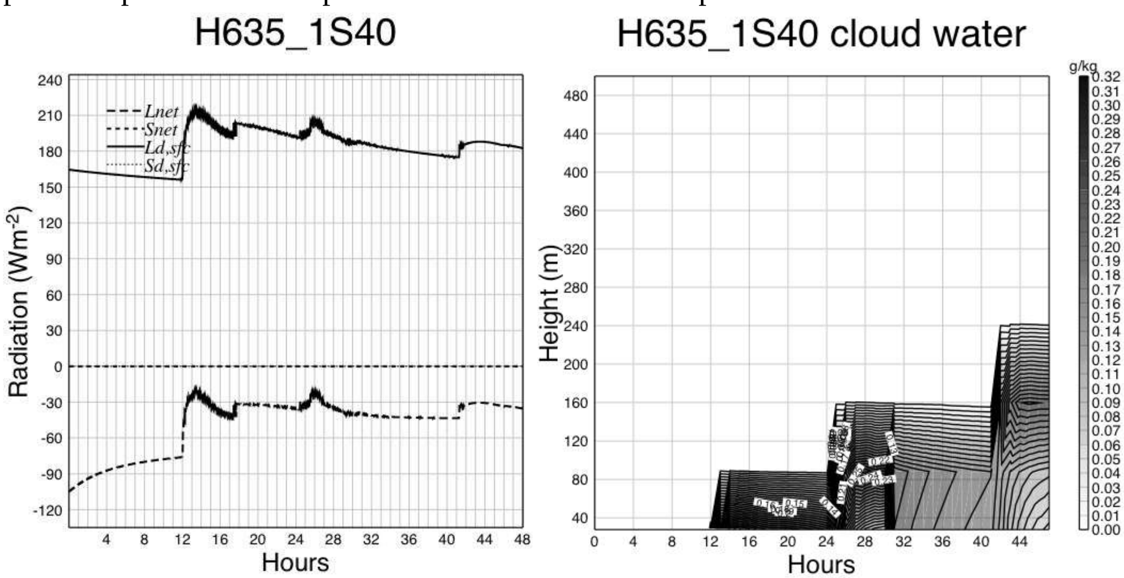

Figure 2: The net and downwards radiation at the surface as a function of time (left) and the cloud water as a function of time and height (right)

Figure 2 shows the reason for the increase of the surface temperature and the strong decrease of the temperature at the lowest model level. Around 12 hours into the integration, cloud water (fog) starts to develop at the lowest model level and this strongly impacts on the radiation balance at the surface. The cloud water is a much stronger emitter of long wave radiation than the cloud free atmosphere, so the surface suddenly gets more long wave radiation than before the formation of the fog. The increase of the surface temperature, and the T2m with it, is not caused by the long wave radiation, because the net long wave radiation still is negative. It therefore must be caused by a heat flux from the lower surface layers.

After about 16 hours, the lowest model level has been cooled so much due to the negative long wave radiation budget at the top of the fog layer, that the model level temperature is lower than the surface temperature, causing the surface heat fluxes to become directed towards the atmosphere. It is therefore not the evaporation that causes the fog and cloud formation in the model, but the formation of clouds that causes the evaporation and sensible heating of the atmosphere.

Another interesting phenomenon in the model is the growth of the fog layer into low clouds. For this case with very weak winds fog should not develop and grow into a layer of low clouds. According to rules of thumb of the meteorologists, fog only develops when the geostrophic wind speed is between 6 and 15 knots. Also, experience of the Nordic meteorologists tells that the conditions usually are clear under these very cold conditions and fog is almost never observed.

The fog problem may be caused by two processes that are not be represented well enough in the Hirlam model. The first one is the formation of rime, due to the moisture flux towards the surface that is colder than the air. A too high temperature of the surface may be responsible for a too low latent heat flux towards the surface so not enough moisture is removed. Another effect that may increase the latent heat flux towards the surface is the formation of ice crystals at the surface. The pointy tips of these crystals are more effective at collecting moisture from the air, and this effect is not taken into account at all. The second process is the formation of ice needles under the very cold conditions. These are observed quite regularly and probably are also not represented well enough in the model. Maybe too much cloud water is formed having a too strong impact on the radiation.

Using Kain Fritsch, Rasch Kristjansson

Sweden already is using the Kain Fritsch, Rasch Kristjansson scheme as there operational scheme. It is therefore interesting to see if this scheme gives the same problems as the current reference Hirlam physics does.

Figure 4 shows the same figures for the KF-RK scheme as for the reference Hirlam in figures 1 and 2. It shows remarkable differences when compared to the reference experiment. First, the surface temperature remains much colder than temperature at the lowest model level. The temperature at the lowest model level is some 3 degrees warmer higher in the KF-RK run than in the reference run. The radiative cooling is spread over a much thicker layer in the reference run.

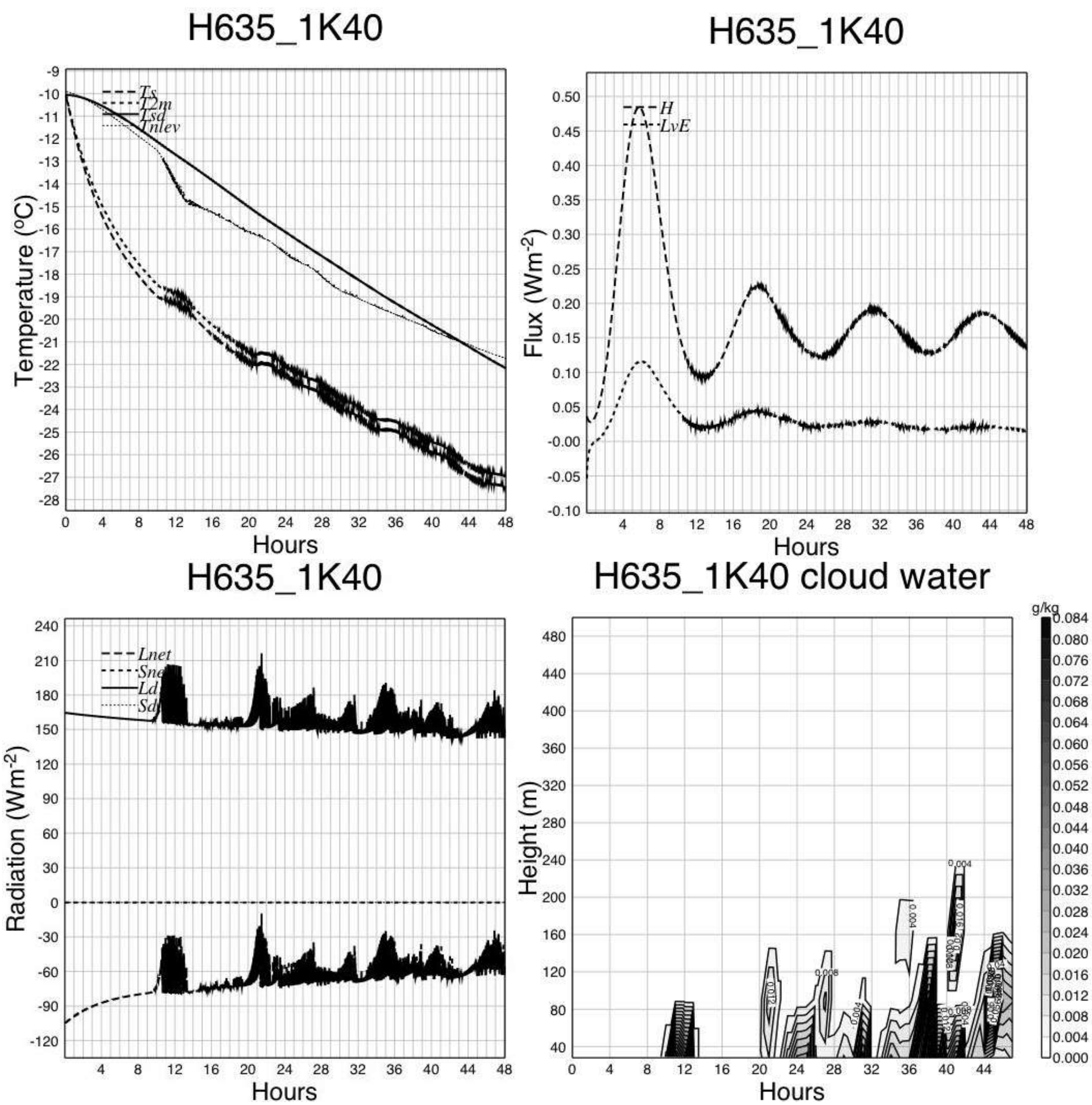

Figure 4: Same as 1 and 2 but for experiment with the Kain Fritsch Rasch Kristjansson convection/condensation scheme.

Another big difference is the behaviour of the surface fluxes. Due to the colder surface, the fluxes remain directed towards the surface and no heating or moistening of the atmosphere takes place. In the radiation we can also find a big difference. The baseline long wave net radiation remains at a much lower level than with the reference Hirlam. The reason for this can be seen in the cloud water plot. The KF-RK scheme produces much less cloud water than the reference STRACO, with a much smaller impact on the long wave radiation.

Note however, that the long wave radiation (and to a lesser extent the temperature and fluxes) show a very erratic behaviour. This is caused by the on and off nature of the KF_RK scheme. This is a behaviour that is not expected for stable situations almost without any flow and may be a serious drawback of the KF-RK scheme. Also, the levels of cloud water may be too low in other circumstances. When there are stratiform clouds at higher levels (e.g. stratocumulus) the impact on the radiation may be too small, causing the model to cool even with clouds overhead. Something like this happened in the forecasts of 27 and 28 January 2005, with the temperatures becoming 6-8 degrees too cold in the operational SMHI Hirlam forecasts.

Is Hirlam capable of producing low temperatures?

So far the problems of the too high winter temperatures seem to be caused by the condensation (main reason) and maybe the surface temperature remaining too high for a stronger moisture deposition on the surface. To see if the Hirlam surface scheme is capable of producing low temperatures when there are no clouds at the surface, an experiment without moisture in the atmosphere is performed.

Figure 3 shows the same parameters as figure 1 (left) for this experiment. The temperature drops much faster in this experiment in the first 12 hours than in the reference experiment. This is caused by the absence of moisture in the atmosphere which reduces the downward long wave radiation considerably. The 2-m temperature is -27°C after 12 hours into this experiment whereas it is only -19°C in the reference experiment. After about 8 hours the rate at which the temperature falls reduces considerably, but it still reaches -41°C after 48 hours. From this experiment we can conclude that Hirlam is capable of producing very low temperatures and that the surface scheme is not the primary reason for the temperature problems.

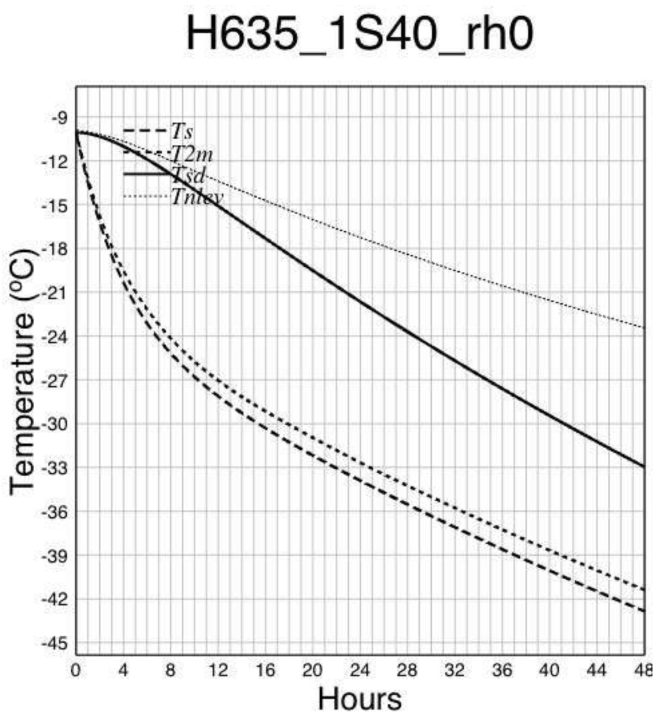

Figure 4: The temperatures in the soil and close to the surface as a function of time in the experiment with 0% relative humidity.

Conclusions

The sequence of events leading to a large positive temperature bias in Hirlam during very cold weather may not be a too large evaporation causing low clouds and a too weak radiative cooling (or a cooling over a too thick layer), but rather a formation of too much cloud water that strongly impacts the long wave radiation, making the temperature at the lowest model level(s) lower than the surface temperature which in turn will cause the heat fluxes to become directed towards the atmosphere. This situation is probably what is seen in the 3-D evaluations of the problem, evaporation from the surface and clouds at the lowest levels.

The impact of the cloud water is much less with KF-RK due to the much lower cloud water levels combined with the short times that cloud water is around (on/off behaviour). In this case this gives better results, but for other cases the impact on the radiation may be too small leading to erroneous cooling of the model (e.g. around 27 January in the SMHI operational model).

So the main problem we need to solve probably is the formation of fog under conditions that it should not form (low wind speed and very low temperatures). A part of the problem probably comes from cloud water (or cloud ice) forming too quickly under these cold conditions, with the second part being the too small moisture flux towards the surface so the atmospheric moisture is not removed quick enough. This may be caused by the understimation of the effect that ice crystals are much more efficient in taking moisture from the air than flat surfaces due to the pointy shape of the crystals. For more temperate conditions (temperatures between 0°C and +10°C) the latent heat flux is in good agreement with observations of dew formation from literature, so the formation of dew is taken care of by the model in the correct way.