The Nordic temperature problems

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1: 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, researchers 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 article 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.

1.1: 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.

1.2: 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 atmospheric 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 than 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.

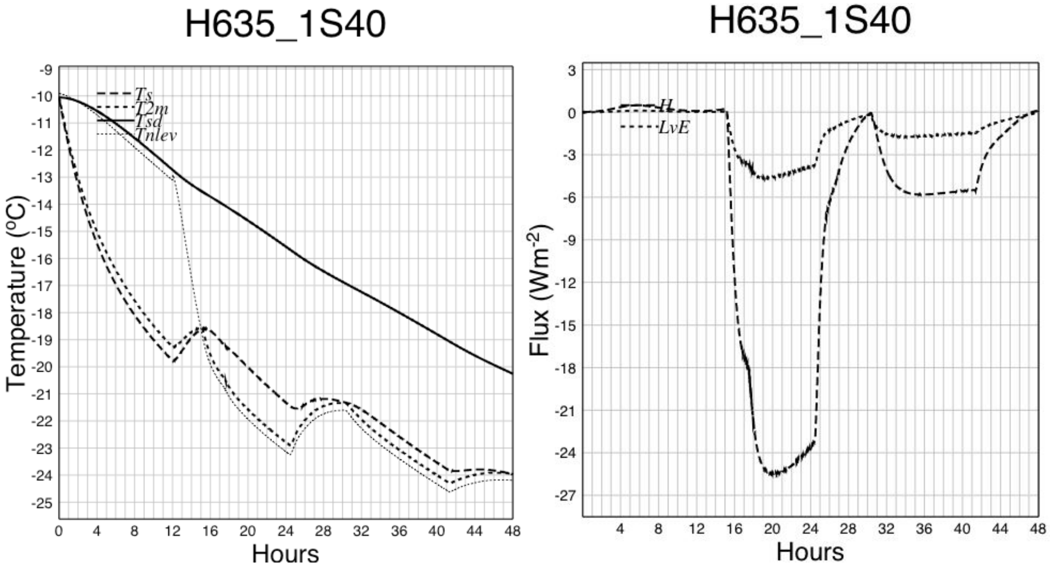

Figure 1: The temperature of the surface and close to the surface (left) and the surface heat fluxes (right) as a function of time in the reference 1D experiment.

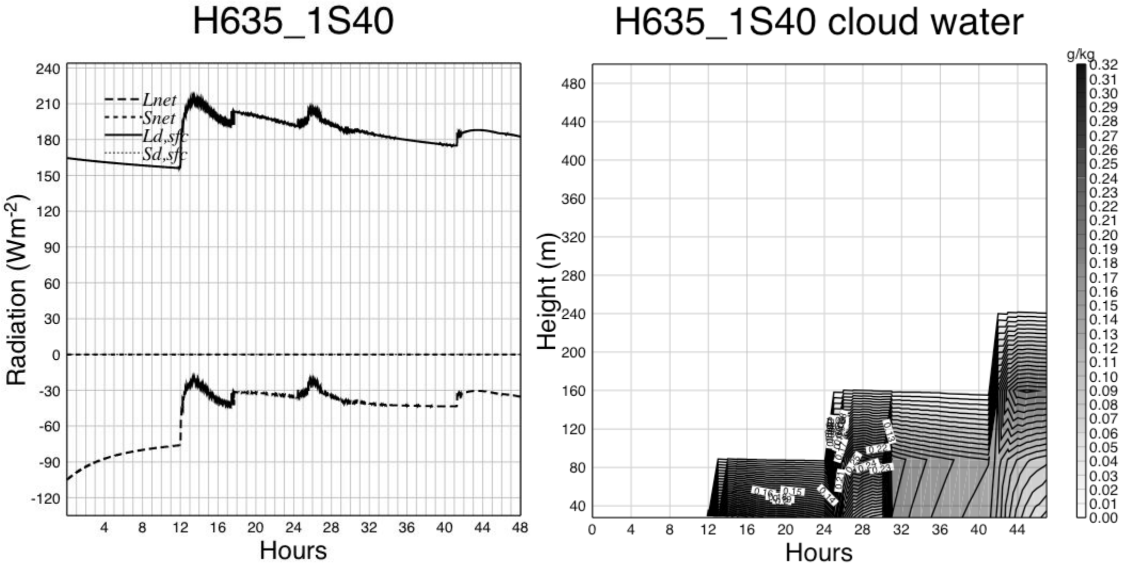

Figure 2: The net and downwards radiation at the surface as a function of time (left) and the cloud water as a function of time and height (right)

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 expectations 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 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/ice (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 skies 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.

The surface scheme may have something to do with the problems too, because the snow pack of 50 cm should isolate the soil quite effectively. However, figure 2 shows that the deep soil temperature drops quite fast in this experiment, providing the energy for the heating of the top soil layer after the fog has formed. The absence of the isolation between the soil and atmosphere by the snow causes the surface temperature to become higher than the temperature of the atmosphere and the fluxes to become directed towards the atmosphere. The new surface scheme, which includes the isolating effects of the snow, may therefore give much better results than the current surface scheme.

1.3: Using Kain Fritsch, Rasch Kristjansson

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

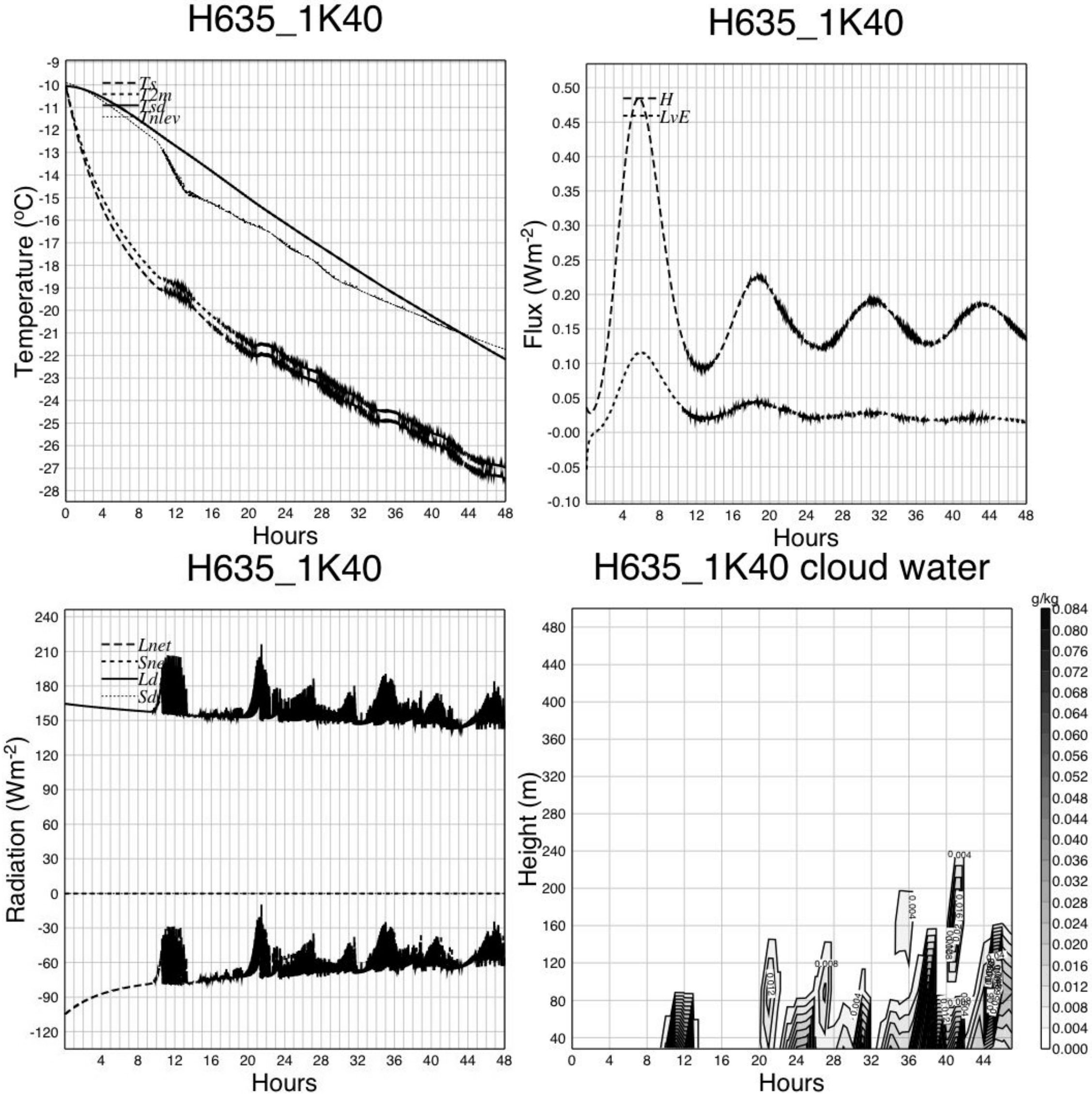

Figure 4: Same as 1 and 2 but for the experiment with the Kain Fritsch Rasch Kristjansson convection/condensation scheme.

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 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.

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 average 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, or any situation where we have a scheme representing grid box average parameters, 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 may have 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. Very recently, however, Karl-Ivar Ivarsson seems to have reduced the on/off behaviour of KF-RK quite effectively.

1.4: Is Hirlam capable of producing low temperatures?

So far the problems of the too high winter temperatures seem to be caused by the condensation and maybe the surface temperature remaining too high for a stronger moisture deposition on the surface, combined with a too high surface temperature when a thick snow pack should effectively isolate the surface and diminish the heat loss by 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 4 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, but the characteristics of the surface scheme (no isolation from the snow) combined with the formation of fog cause the model to stay too warm under conditions that are clear in reality.

1.5: Conclusions Winter case

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.

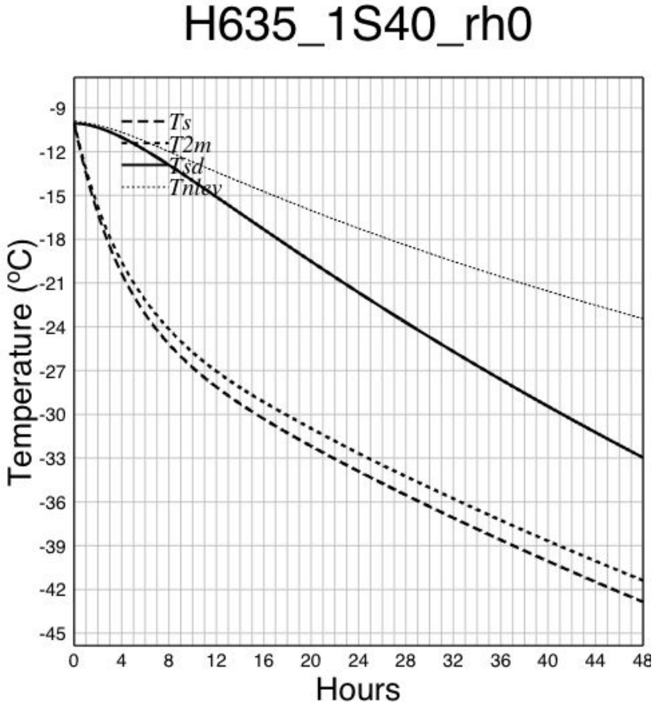

Figure 4: The temperatures in the soil and close to the surface as a function of time in the experiment with 0% relative humidity.

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 the cloud water exists (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 or becoming too dense, with the second part being the too small moisture flux towards the surface so the atmospheric moisture is not removed quick enough because of a too high surface temperature. 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 when the temperature is larger than 0ºC.

2: Spring

One typical example of Nordic spring temperature problem was presented at the meeting on January 31 in Helsinki, the too low T2m day time temperature in Sodankyla on 13 April 2004 in the RCR run (see figure 5 top). The too low temperature was caused by a wrong distribution of the available energy over the sensible and latent heating of the model atmosphere (see figure 5). A maximum sensible heat flux of around 220 W/m^2 was observed while the model produced a sensible heat flux of only 50 W/m^2. The opposite is true for the latent heat flux. The observed latent heat flux was only about 50 W/m^2 while it was about 220 W/m^2 in Hirlam.

These different fluxes have a major impact on the temperature (too small daily cycle) and the relative humidity, that is almost constant at a value of around 90% while in the observations the relative humidity reaches a minimum of 40%.

2.1: 1D results from Hirlam version 6.2.1

First we try to reproduce the results from the 3D run with the 1D model. To enable this reproduction of the problem, a column from the 3D RCR Hirlam was extracted as start condition for the 1D experiments. The settings in the 1D model also were chosen as to mimick the 3D Hirlam near Sodankyla as closely as possible. The results from the 1D model version 6.2.1 will be shown first.

Figure 6 clearly shows that the 1D model reproduces the problems that were encountered in Sodankyla. A quick rise in the temperature is suddenly stopped when the temperature reaches about 1°C. This is also the time that the sensible heat flux stops increasing, while the available energy should still be increasing. The latent heat flux, however, keeps increasing and remains at a relatively high level until 12 UTC. After 8 UTC clouds start developing in the 1D model, a feature that was also observed in the 3D model while the sky was clear in the observations. The amount of energy available in the 1D model for heating and evaporation is much smaller than in the observations because of the clouds that develop in the 1D model.

Somehow, Hirlam evaporates too much compared to the observations. As the temperature is too low for the vegetation to be actively evaporating. the moisture has to come from the surface (bare soil. snow or canopy water). To see if the snow or the canopy water are the source of the evaporation, the initial values are decreased to a small fraction of the original values.

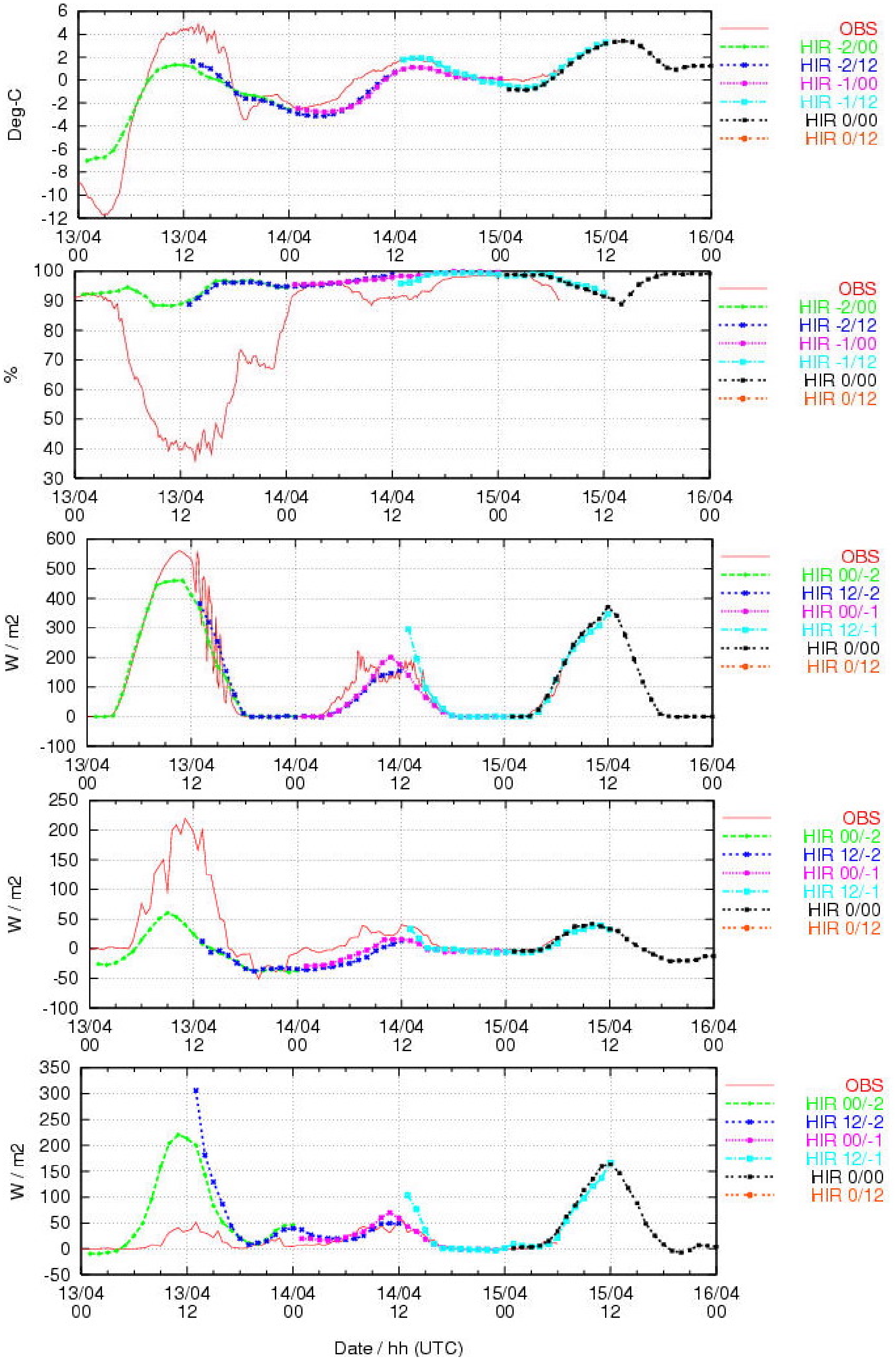

Figure 5: Observed and forecasted T2m (top), relative humidity (second), global radiation (third), sensible (fourth) and latent heat flux (bottom) at Sodankyla from 13-16 April 2004 (from Fortelius, 2004).

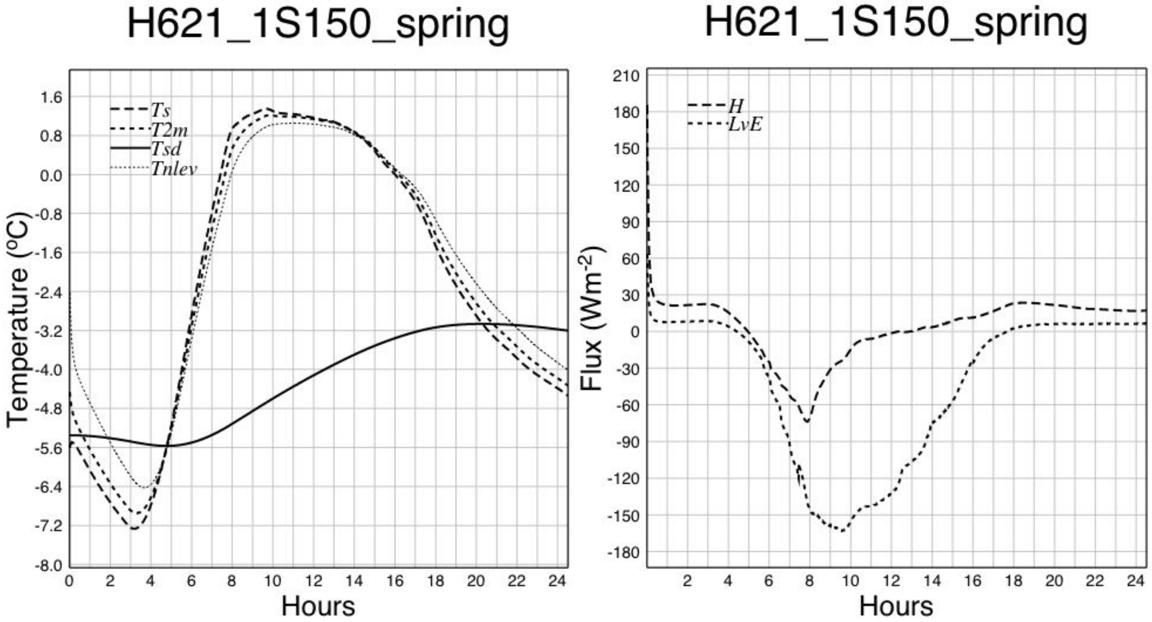

Figure 6: Temperatures (left) and heat fluxes (right) as a function of time in the 1D model in Sodankyla for 13 April 2004.

Figure 7 shows the impact of the reduction of the canopy water (left) from 0.877 kg/m^2 to 0.05 kg/m^2 or snow depth (right) from 0.15 m water equivalent to 0.01 mwe. The impact of the reduction in the canopy water is very limited. The fluxes are very similar to the experiment with all canopy water still present (compare with figure 6 right). The impact of the reduction in snow depth is much larger. Initially, the heat fluxes are quite similar to the first two experiments. After 8 UTC, however, the latent heat flux decreases compared to the first two experiments and the sensible heat flux increases. At 14 UTC the situation is almost the reverse of the first experiment with a sensible heat flux that is more than twice as large as the latent heat flux. The impact of the snow on the evaporation therefore is most significant and at the end of the afternoon the fluxes are almost as they were in the observations.

An interesting feature of the experiment with reduced snow depth is the increase of the sensible heat flux at the expense of the latent heat flux between 8 and 14 UTC. This behaviour is caused by the evaporation of the canopy water which is almost vanished at 13 UTC. The last experiment performed with the 6.2.1 version of the 1D model is a run with reduced canopy water and snow depth. Figure 8 shows the temperatures and the surface fluxes of this experiment. The fluxes of this experiment now compare quite favourably with the observed fluxes. The maximum latent heat flux is not much larger than 60 W/m^2 while the sensible heat flux (260 W/m^2) reaches levels that are also relatively close to the observed maximum flux of 220 W/m^2. The temperature also improves considerably. The maximum temperature increases from around 1°C in the reference experiment to around 5°C.

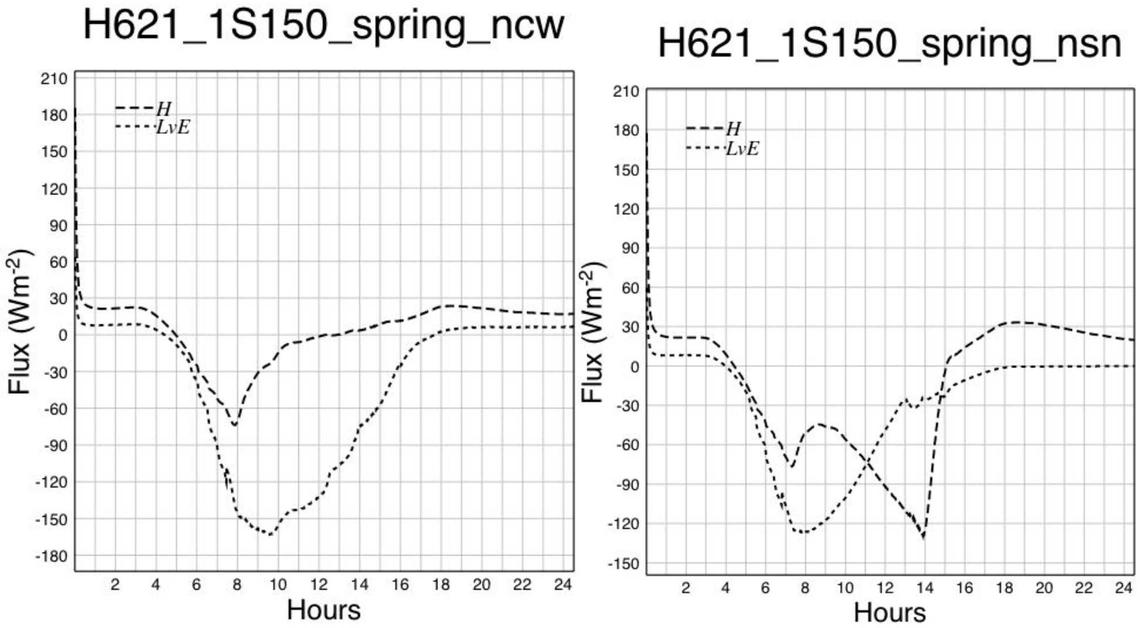

Figure 7: Sensible and latent heat fluxes in the experiments with reduced canopy water (left) and snow (right).

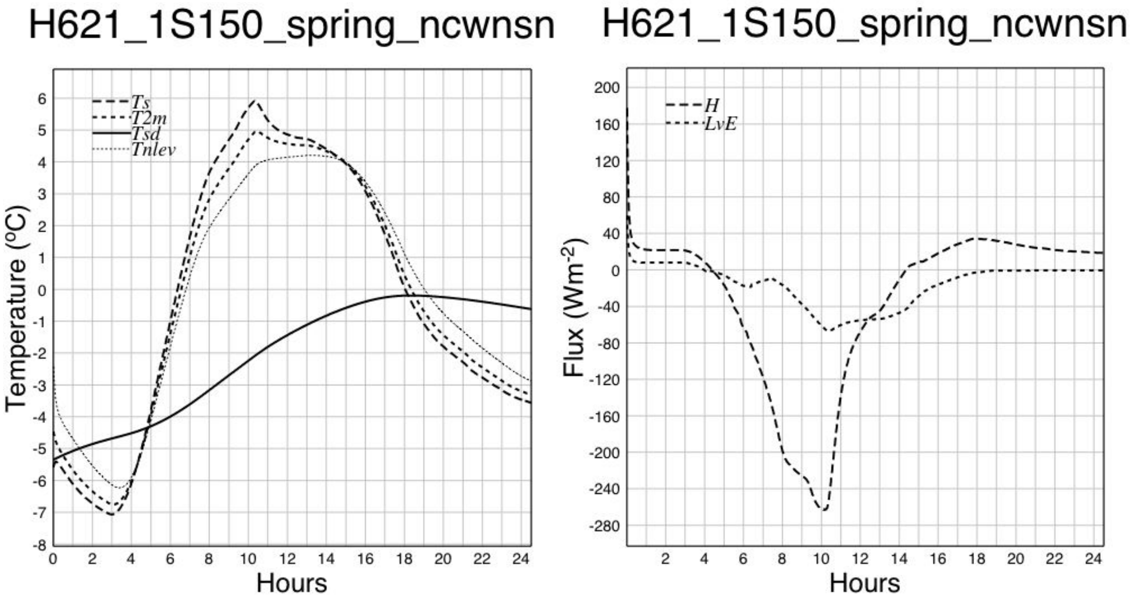

Figure 8: Temperatures (left) and sensible and latent heat fluxes (right) in the experiment with strongly reduced snow depth and canopy water.

Fortelius (2004) wrote snow depth and snow cover were correct in Hirlam RCR. So the results from this last experiment only show that the evaporation from the snow is causing the large latent heat flux, but a removal of the snow from the model off course is not a reasonable option.

2.2: Results from the 1D model with the new surface scheme

An improved surface scheme with a better representation of the impact of snow and forest on the fluxes has been developed recently and a few test with the 3D Hirlam have been carried out. Together with Stefan Gollvik, I have included this new surface scheme (Gollvik and Samuelsson, 2004) in the 1D Hirlam, version 6.3.4. The reference Hirlam 6.3.4 produces results that are similar to the ones presented above. Here the results with the new version of the surface scheme will be shown.

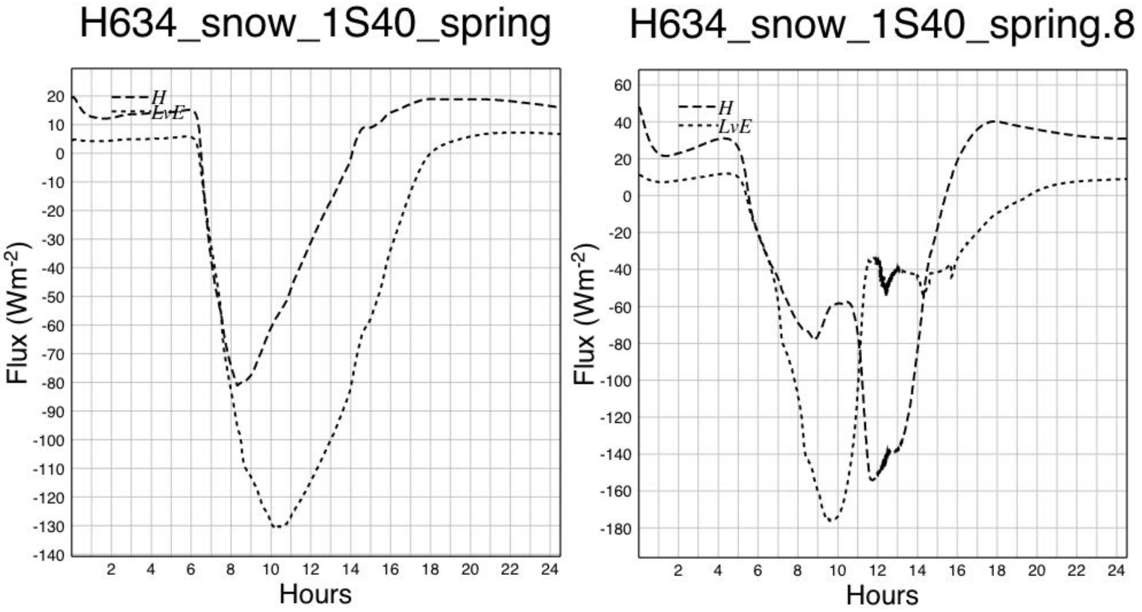
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Figure 9: Sensible and latent heat fluxes in Hirlam 6.3.4 with the new surface scheme with the normal formulation of the snow fraction (left) and with the snow fraction limited to a maximum of 80% of the tile (right).

Figure 9 left shows the surface heat fluxes of the same experiment as shown in figure 3, but now with the new surface scheme. In this experiment the sensible heat flux already is a little larger than in the 6.2.1 version and the evaporation is almost halved. The magnitude of the sensible heat flux compared to the latent heat flux still is not in accordance with the observations, however. The sensible heat flux should be about four times the latent heat flux so the bowen ratio is still completely wrong, even with the new snow scheme.

The way of determining the snow cover fraction strongly influences the behaviour of the scheme. In the original version of the new surface scheme the snow cover fraction for the forest tile is determined by dividing the snow depth with a critical snow depth (15 cm). If the snow depth is larger than this critical value, the snow fraction is set to 100%. In the first experiment the snow fraction is 100%, so the snow has a relatively large impact on the surface fluxes.

In the second experiment the snow fraction was limited to a value of 80%. Initially, the impact of this change is relatively small. The fluxes during the night increase a little while only the latent heat flux increases during the day time. After 10 UTC, however, the differences between the two experiments become larger. Suddenly the sensible heat flux increases strongly while the latent heat flux reduces to only 40 W/m^2. This change in distribution of the heat fluxes over the sensible and latent heat flux is caused by the evaporation of the water on the canopy. After 10 UTC the canopy water has almost completely evaporated, leaving more energy available for the sensible heating of the atmosphere. Initially, almost 0.9 kg/m^2 water lies on the canopy and the latent heat necessary for the evaporation of this water is around 100 W/m^2 over a period of 6 hours.

If this canopy water has such a large impact on the distribution of the available energy over the different surface fluxes, it is off course also interesting to see how the fluxes would look if almost no canopy water is present at the start of the model run.

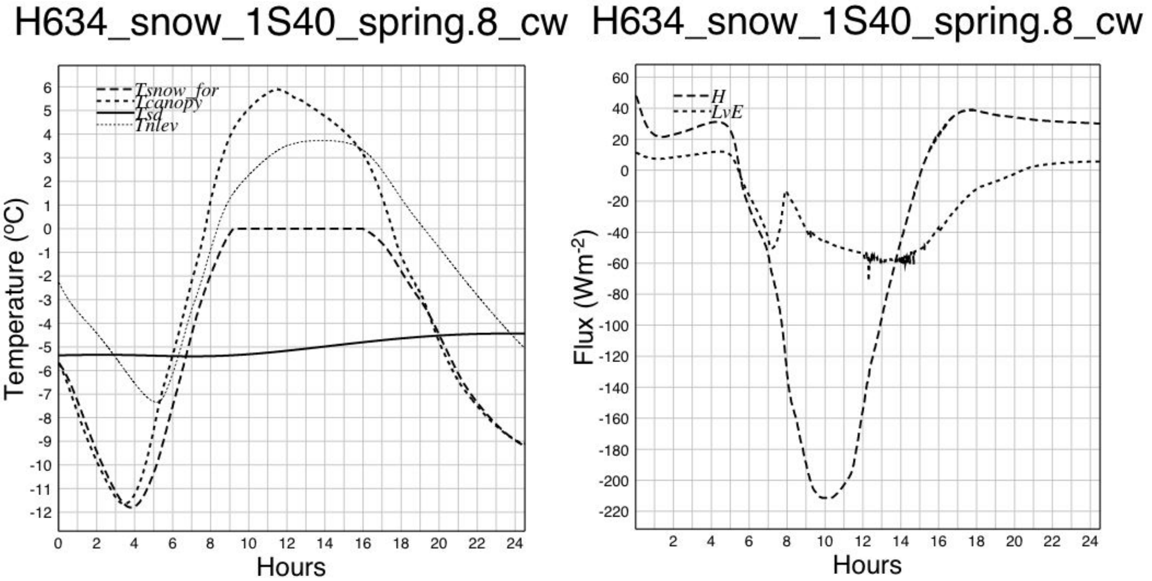

Figure 10: Temperatures (left) and sensible and latent heat fluxes (right) in the experiment with strongly canopy water and the snow fraction limited to a maximum of 80%.

Figure 10 shows the temperatures (left) from the experiment with a reduction of the canopy water by 95%. The canopy air temperature now closely resembles the observed T2m, while the initial experiment with the snow scheme produced a maximum canopy air temperature of only 2ºC. The differences in the fluxes and the similarity with the observed fluxes are even more striking. The sensible heat flux now is much larger than the latent heat flux and has almost exactly the same maximum value as the observed flux. The latent heat flux is very strongly limited to a maximum value of around 60 W/m^2, also almost exactly what is found in the observations.

2.3: Conclusions

The experiments with the 1D model show that the Nordic spring problem, as seen in the comparison between Hirlam and the observations of Sodankyla on 13 April 2004, cannot be solved by the ISBA surface scheme as currently is used in the reference Hirlam. As with the Nordic winter temperature problem, the new snow/forest scheme can improve the model considerably. When the influence of the canopy water is reduced in the 1D experiment, the temperatures and the heat fluxes can be reproduced almost exactly when the snow fraction is limited to 98% or less. The large impact of the limitation of the snow cover from 100% to 98% on the average fluxes is a little suspicious, because two percent of the surface should not account for the largest part of the surface sensible heat flux when it is around 200 W/m^2. There may still be an error in the averaging over the extra tiles.

An introduction of this scheme into the Hirlam reference system will probably reduce the bias in the T2m considerably, but it may not lead to a better standard deviation because the surface temperature of the new scheme reacts to changes in the long wave radiation much more quickly than the current reference scheme. The correct prediction of cloud cover will become even more important. The larger variance, although wanted, may cause the standard deviation to stay the same.

General conclusions

The new surface scheme provides a much better behaviour of the near surface temperatures and surface fluxes than the current reference Hirlam. There are a few problems, however, that remain. Under calm conditions, the surface (snow) temperature will become much lower than the temperature of the lowest model level and the T2m. In the Hirlam model flux profile relations and the constant flux assumption are used to translate the temperature at the lowest model level and the surface temperature to the T2m. However, under these conditions the boundary layer may be shallower than the height of the lowest model level, while the assumptions that are used in the translation are valid only in the lowest 10% of the boundary layer. Therefore a new translation will have to be developed for these conditions.

The results of the experiments in this article show that the solution to the Nordic temperature problem is available in the new surface scheme. We now need to implement it as quickly as possible and test it to be ready for implementation before the next winter.

Reference

Fortelius, 2004

Gollvik and Samuelson, 2004