

Ideas about the water vapour saturation pressure

Carl Fortelius, Finnish Meteorological Institute

1 Introduction

Excessive cloudiness in the winter-time boundary layer at high latitudes is a common problem in the Hirlam system. The problem was very severe in the previous operational configuration of FMI, based on Hirlam 4.6.2 and running the simple surface scheme, but is still present in the current implementation running ISBA under Hirlam 5.1.4. (See the article by Eerola in the present volume for a description of the operational configurations).

It is not clear what causes these decks of low cloud to form and to remain, but surely some combination of insufficient ventilation of the boundary layer and excessive input of moisture from the surface seems to be involved. It has been noted repeatedly that the surface latent heat flux from high latitudes tends to be overestimated in winter. For instance, Navascués et al. (2003) suggest a reduction of the surface roughness for moisture as a corrective measure.

It is suggested in the present report, that the cloud problem is made worse by the somewhat unrealistic treatment of saturation water vapour pressure in the Hirlam system. In stead of the three familiar phases of water: gaseous, liquid and solid, Hirlam effectively recognizes only two: vapour and 'condensate'. On the code level, this is reflected in the use of one single function for the temperature-dependence of the saturation vapour pressure, instead of separate functions for saturation with respect to water and to ice. This single function follows the equilibrium curve between liquid water and vapour at warm temperatures, and the equilibrium between ice and vapour at cold temperatures, with a smooth transition taking place in between. Because liquid water is often present in the atmosphere at temperatures well below the freezing point, a fairly wide transition zone is used. In the current system, the transition takes place between 0°C and -15°C , although liquid cloud droplets may be present at much colder temperatures. Indeed, based on experiments with the Hirlam system, Ivarsson (2000) recommends the use of a much wider zone.

Given that the Hirlam system does not support separate prognostic variables for solid and liquid cloud condensate, it may be hard to find an alternative to using a 'mixed' saturation function in the case of clouds. However, as already pointed out by Ivarsson, the same function is used in all physics parameterizations, including the surface module, although supercooled water hardly occurs at the surface. In the surface module the flux of latent heat is driven by the moisture gradient, calculated as the difference between the specific humidity in the air and the saturation specific humidity at the temperature of the surface. Below the freezing point, relative humidity is always higher with respect to ice than with respect to liquid water at the same temperature. Therefore the mixed saturation function will tend to overestimate the moisture gradient for temperatures within the transition zone, thereby favouring excessive net evaporation from snow covered ground.

However, there is yet another, more interesting and possibly more serious drawback associated with the mixed saturation function. In nature, a water cloud can exist in equilibrium with a frozen surface only at the freezing point (the triple point, more accurately). A cloud finding itself in contact with a dry snow cover will thus

generally disintegrate (forming rime), unless water saturation can be maintained by some external agent like moist advection. Correspondingly, the air can never be moistened enough for clouds to form through surface sublimation alone, simply because ice saturation will be reached, and sublimation will stop, before cloud droplets can start to form. The situation is completely different in Hirlam, where there is only one common saturation curve for the cloud droplets and the surface. In those circumstances there is nothing to prevent surface evaporation to continue until a cloud is formed. Once formed, clouds may remain in equilibrium with the surface indefinitely, or until disintegrated through the action of some external agent. Physically the situation resembles somewhat a clear summer night with radiation fog in equilibrium with the wet surface. To summarize: In nature it takes an external agent to maintain a water cloud in contact with a frozen surface, in Hirlam it takes an external agent to keep the surface layer free from clouds.

This newsletter attempts to explore the potential impact of introducing separate saturation functions for water and ice into the ISBA surface scheme, while keeping the original mixed saturation function in the upper air calculations. The work relies on code written by Karl-Ivar Ivarsson. Section 2 contains a purely diagnostic study on wintertime high-latitude evaporation. Section 3 reports on a case study. Conclusions are presented in section 4.

2 Evaporation in early 2003

Fig. 1a shows an example of unrealistically large evaporation, found in pre-operational runs of the FMI ATX-suite. Over most parts of the region shown evaporation exceeds 0.4 mm/day on the average, and over southern Sweden and the Baltic states the values exceed 0.8 mm/day. According to hydrological expertise (Markus Huttenen, pers. comm.), evaporation from the Finnish winter landscape does not exceed 0.1 mm/day on average.

While it is clear that the evaporation is too large, the reasons for this cannot be easily seen. One should not, for instance, blame the saturation function without evidence from extensive experimentation to prove the case. Nevertheless, one may explore the potential importance of the saturation function in a simple way. Other things being equal, the evaporation is proportional to the moisture gradient. It is possible to recompute this gradient using the correct saturation function and define a correction factor $r = \frac{\Delta q}{\Delta q^*}$, where Δq is the original moisture gradient and Δq^* is the corresponding gradient computed using the appropriate saturation function.

Applying this correction factor to the instantaneous latent heat fluxes yields the modified evaporation map shown in Fig. 1b. As expected, the correction acts to reduce evaporation, and the reduction is actually quite substantial. This is even better seen in the cumulative area mean values shown in Fig. 1c. However, two things must be noted here: Firstly, even the reduced evaporation is very large, amounting to some 17 mm in two months over the area, corresponding to a daily average of almost 0.3 mm/day. Secondly, the magnitude of the correction factor defined here does not indicate what would actually happen if the corresponding change was allowed to interact dynamically with the model state. In all likelihood, the response of the dynamical system would be more modest on the average. Even so, there will probably be plenty of situations where the moisture gradient is mainly controlled by advection, vertical diffusion or radiation rather than by local latent heat flux alone. At least in these cases it would seem quite important to choose the right saturation function.

3 A case study

The impact of introducing separate saturation functions for ice and water in the surface scheme under Hirlam version 6.0.0 was examined in the frame of a case study on February 19-21, 2003. During this period a nearly stationary high pressure dominated the synoptic situation in Scandinavia and Finland. Weather in Finland was mostly clear, with light winds from the west and north, strengthening during the 21st. Snow still covered the whole country, and temperatures in southwestern Finland ranged between -10 to -15° C in the night time and 0 to 5° C in the day time. The operational forecast of 00UTC on the 20th gave completely different weather. Clouds started to form in the surface layer over the ice-covered Bothnian Bay in the early hours of the forecasts, and quickly spread over most of Finland, reaching Helsinki on the south coast in the early afternoon. Temperatures under the cloud deck stayed a few degrees below the freezing point.

The case study was carried out as a parallel experiment on the operational Finnish domain and grid (Suite ATX, described by Eerola in the present volume). One single pair of forecasts were run. These will be referred to below as REF for the control run and MOD for the modified run. Identical sets of operational analyses were used for initial states and boundary fields in both runs. The forecasts were initiated at 12UTC on the 19th of February.

It must be mentioned immediately that the modification did not improve the forecast dramatically. Both model configurations developed low clouds much as described above, even if the cloud deck was slightly smaller in extent and contained less condensate in the modified run.

Even in this single case, changing the saturation curve has a marked effect on the evaporation, as can be seen in Fig. 2. In this case, the difference arises mainly during the night between the 20th and 21st of February. During day time evaporation appears to proceed at a very similar pace in both experiments.

The difference between day and night is further highlighted in Fig. 3, showing the surface heat balance for the land and ice fraction of the box in Fig. 2b. As expected, the changes are not restricted to the latent heat flux, but are seen in all components of the budget. Most affected is the net long wave radiation, which becomes more negative at both day and night. During the day this is nearly compensated for by increased net short wave radiation. Overall, the changes in the radiative fluxes are consistent with a reduced cloud deck in the modified system.

It was argued in the introduction, that introducing different saturation curves for liquid water and ice should tend to reduce the amount of clouds and the relative humidity (relative to the mixed saturation curve) in the surface layer. Fig. 4 shows histograms of the relative humidity in the lowest model layer after 42 hours, at 06 UTC of the 21st of February 2003. Data are shown for for all grid points within the domain with a surface temperature between -15 and 0° C, i.e. inside the transition zone of the mixed saturation function. A time before sunrise over most of the domain was chosen so as to minimize the complicating influence of insolation, and also in order to have as many grid points as possible satisfying the selection criteria. At this particular time such grid points cover most of Europe and Quebec.

In the control run the most populated class is the one in or very near equilibrium with the mixed saturation curve. In the modified run, by contrast, there is a marked drop in frequency when going from the next highest humidity class to the highest. This is completely consistent with the arguments presented in the introduction.

4 Conclusions

The current use of a 'mixed' saturation vapour pressure function for defining the moisture gradient driving the surface latent heat flux may be more harmful than has been generally recognized. It has been shown in the present report, that using the mixed function may potentially lead to a quite serious distortion of the surface heat balance. Even more seriously, using the mixed function introduces a spurious state of equilibrium, permitting a cloud to exist indefinitely in contact with a frozen surface. It is suggested, that this is one factor contributing to the frustrating tendency of Hirlam to generate excessive clouds in the lowest layers at high latitudes in winter.

5 References:

Ivarsson, Karl-Ivar, 2000: Tests with separated tables for water vapor saturation pressure over ice and water. Hirlam Tech. Rep., 45, 20 pp.

Navascués, Beatriz, Ernesto Rodríguez, Juan José Ayuso and Simo Järvenoja, 2003: Analysis of surface variables and parameterization of surface processes in HIRLAM. Part II: Seasonal assimilation experiment. Hirlam Tech. Rep. 59, 38 pp.

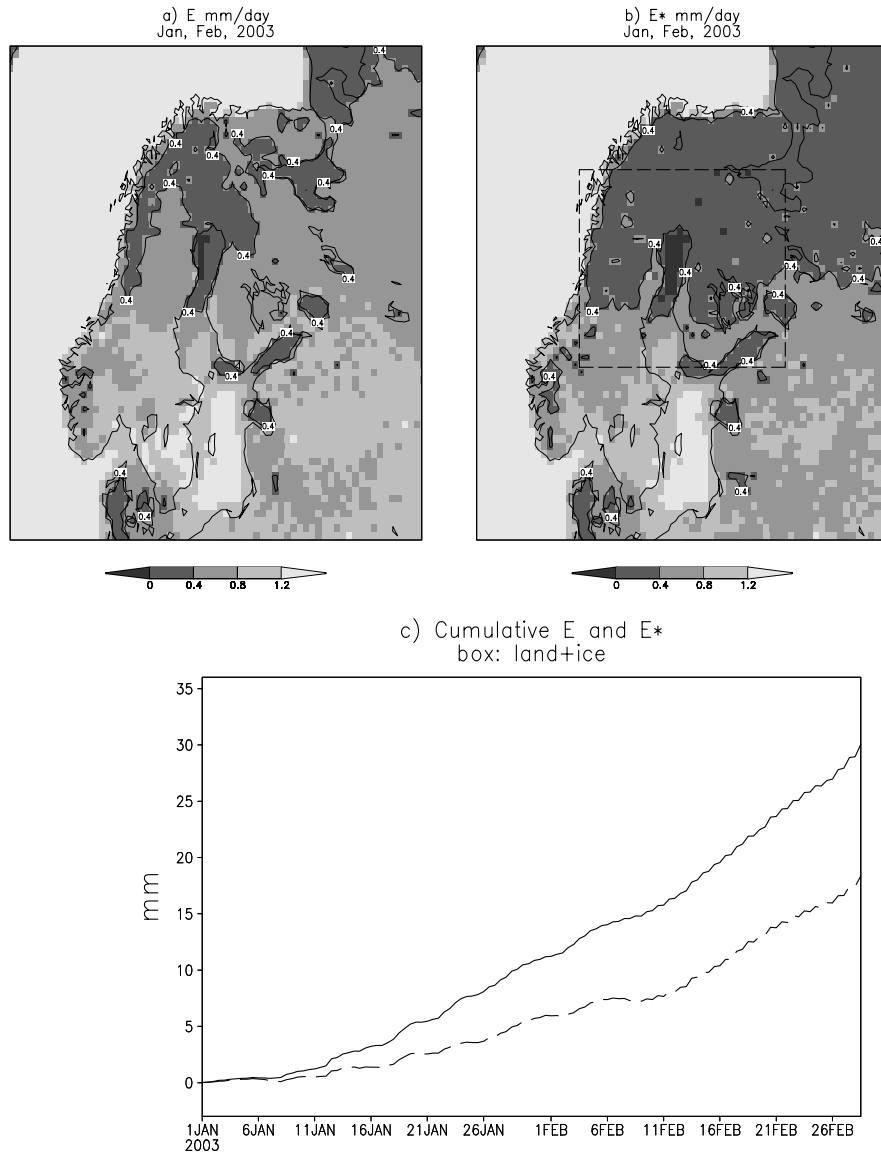


Figure 1: **a**: Average evaporation in January and February 2003 in the Finnish ATX suite, as estimated from instantaneous values corresponding to 24 hour forecasts, sampled twice a day. The shading interval is 0.4 mm/day, and a line showing the 0.4-contour is drawn for clarity. **b**: Same, after application of the ad hoc modification described in the text. **c**: Cumulative original (solid line) and modified (dashed line) mean evaporation from the land and ice fraction of the box shown in panel b.

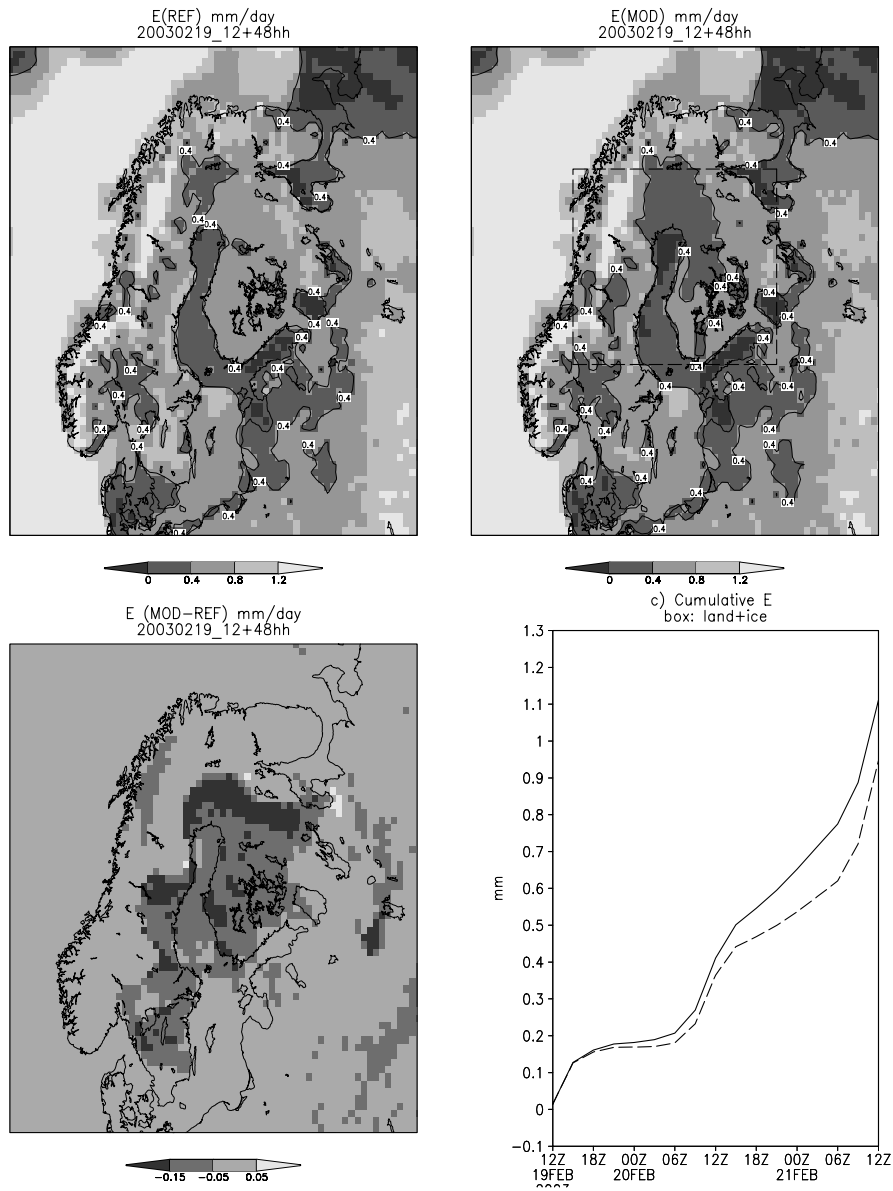


Figure 2: **a:** Average 48 hour evaporation in the control experiment (REF). The shading interval is 0.4 mm/day, and a line showing the 0.4-contour is drawn for clarity. **b:** Same as **a**, but from the experiment MOD. **c:** The difference between panels b and a. **d:** Cumulative mean evaporation from the land and ice fraction of the box shown in panel b from the two experiments REF (solid line) and MOD (dashed line).

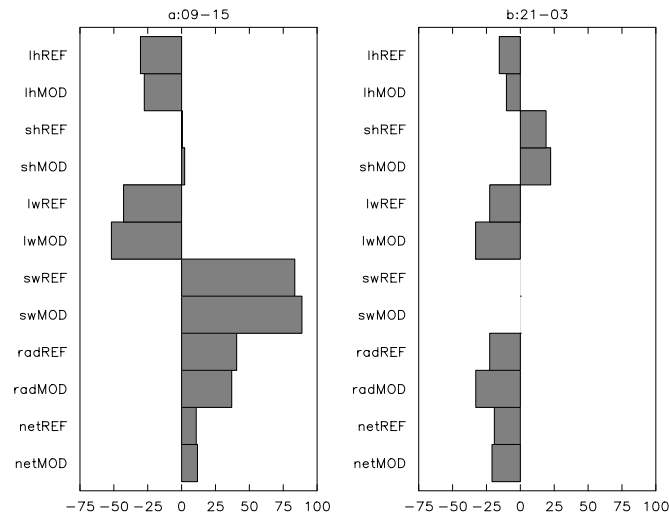


Figure 3: Components of the mean surface energy budget within the land and ice fraction of the box shown in fig. 2b during day time (09-15 UTC on the 20th of February, panel a) and night time (21-03 UTC on the the night between the 20th and 21st of February, panel b). From top to bottom the bars show, respectively for experiments REF and MOD, the latent heat flux, sensible heat flux, net long wave radiation, net short wave radiation, net radiation, and net surface heat flux in units of Wm^{-2} . Positive fluxes are directed towards the surface.

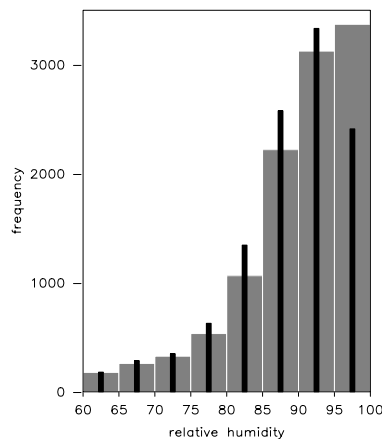


Figure 4: Histograms of relative humidity in the lowest model layer at 06 UTC of the 21st of February 2003 as given by the experiments REF (grey columns) and MOD (black columns). The figure shows data from grid points with a surface temperature in the range between -15 and $0^{\circ} C$.