Comparison of two algorithms to simulate the effect of soil moisture freezing and thawing on the energy balance

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1 Introduction

The existence of a solid phase of soil water involves several modifications affecting the energy and water transfer in the soil. The most relevant effects are the following ones: 1) effect of the latent heat of fusion/freezing in the energy balance; 2) suppression of plants transpiration when the root is embedded in frozen soil; 3) the soil thermal properties (conductivity, heat capacity) change due to the presence of ice (*e.g.*, thermal conductivity of ice is about 4 times that of water); 4) reduction of hydraulic conductivity leading to either more run-off due to the decreased infiltration or higher soil moisture due to restricted drainage. From the point of view of NWP, the first effect is the important one, as the amount of energy involved during the change of phase process is considerable and may affect greatly to soil temperatures. The impact can be visible both at seasonal and daily scales. The soil cooling, either in the beginning of the cold season or during night-time, is delayed or damped by soil water freezing. The same effect appears in spring and at daytime: the soil heating is also damped by soil water thawing. The final effect in both cases is that soil temperature is less responsive to the atmospheric forcing and consequently the amplitude of the temperature cycle is damped (Slater *et al.*, 1998; Viterbo *et al.*, 1999).

The representation of the process of soil water freezing and thawing in NWP models can be grouped into two rather broad categories (Boone *et al.*, 2000), so-called explicit and implicit schemes. The explicit schemes keep track of the actual quantity of soil ice. They use a freeze/thaw, drying/wetting analogy to model the evolution of soil ice. This group of schemes are more physically based and sound than the implicit schemes, as they model the evolution of the relevant physical magnitude. The usage of a new predicted variable for soil ice involves more complexity and in turn introduces the additional problem of its initialization. Examples of explicit schemes are described by Slater *et al.* (1998), Giard and Bazile (2000), Boone *et al.* (2000) and Cox *et al.* (1999). The implicit soil ice schemes model the effect of freezing and thawing on heat and water transfers within the soil and at the surface in a relatively simple way without adding extra variables. Some schemes stress the effect of the latent heat released/consumed during the freezing/thawing process damping the amplitude of the soil temperature cycle caused by the atmospheric forcing around the melting point temperature (*e.g.*, Viterbo *et al.*, 1999). Other schemes limit vertical soil water fluxes (including infiltration and drainage) as the soil temperature depression (below freezing) increases (Sellers *et al.*, 1996), or these fluxes are completely shut off when soil temperature falls below freezing (Koster and Suarez, 1996). This class of implicit schemes circumvects the problem associated to the initialization of extra variables.

Two schemes will be compared in this work: i) one explicit scheme which adds one extra variable for soil ice and uses simple expressions to parameterize the partition of the available energy into sensible heating and latent heating originally described by Giard and Bazile (2000) and further developed by Boone *et al.* (2000); and ii) one implicit scheme which puts emphasis on the reduced responsiveness of soil temperature to the atmospheric forcing around the soil freezing temperature described by Viterbo *et al.* (1999). This work has been mainly focused on the heat transfer aspects and the impact on 2m-temperature and relative humidity which are specially relevant for NWP modelling. Section 2 provides a brief description of the compared explicit and implicit schemes. Section 3 describes 1D experiments with prescribed atmospheric forcing, whereas results of the parallel runs in full 3D assimilation mode are discussed in Section 4. Finally, Section 5 gives some general conclusions and proposal of algorithm for the HIRLAM reference system.

2 Brief description of the schemes

2.1 Explicit scheme

The explicit scheme tested here was originally described Giard and Bazile (2000) in a preliminary version introducing only one additional prognostic variable for the total frozen soil water content. Some deficiencies were soon detected in connexion with the insuficient increase of surface temperature in the daytime as long as frozen water was present. This problem was solved by adding another prognostic variable for the superficial reservoir of frozen soil water content (Bazile and Giard, 1999; Bazile, 1999). Some slighly different version was also presented by Boone *et al.* (2000). The two additional equations for surface and total liquid water equivalent ice content (both expressed in mm), W_{si} and W_{pi}, are:

$$\frac{\partial W_{si}}{\partial t} = {F^s}_f - {F^s}_m \tag{1}$$

$$\frac{\partial W_{pi}}{\partial t} = +({F^s}_f - {F^s}_m) + ({F^p}_f - {F^p}_m) \tag{2}$$

The phase change flux terms ($F_{f/m}$) from either soil ice production (f) or melt (m) also appear in the corresponding equations for the liquid water soil content but with opposite sign, as ice soil content production/reduction must be exactly compensated by the corresponding change in liquid water content.

The release/comsumption of latent heat due to the phase change of soil water has impact on both surface and mean (or restore) soil temperatures. To take into account such effects the following terms are added to the surface and mean temperature equations:

$$\left(\frac{\partial T_s}{\partial t}\right)_{f/m} = C_t L_f({F^s}_f - {F^s}_m) \tag{3}$$

$$\left(\frac{\partial T_p}{\partial t}\right)_{f/m} = C_t L_f({F^p}_f - {F^p}_m) \tag{4}$$

The amount of ice in the soil is determined on a supply and demand basis: ice production from soil water freezing and reduction from melting are modelled to occur if, at the end of the time step, there is available energy and sufficient mass. The phase change flux terms for the surface and deep layers are parameterized as:

$$F^p{}_f = \frac{K_p}{\tau_p} \cdot (\frac{W_{pl}}{W_{sat}}) \cdot \frac{max(0, T_t - T^+{}_p)}{C_i L_f} \quad (5)$$

$$F^s{}_f = \frac{K_s}{\tau_s} \cdot (\frac{W_{sl}}{W_{sat}}) \cdot \frac{max(0, T_t - T^+{}_s)}{C_i L_f} \quad (6)$$

$$F^p{}_m = \frac{K_p}{\tau_p} \cdot (\frac{W_{pi}}{W_{sat}}) \cdot \frac{max(0, T^+{}_p - T_t)}{C_i L_f} \quad (7)$$

$$F^s{}_m = \frac{K_s}{\tau_s} \cdot (\frac{W_{si}}{W_{sat}}) \cdot \frac{max(0, T^+{}_s - T_t)}{C_i L_f} \quad (8)$$

(9)

It should be noticed that a dependency on the water/ice mass has been introduced for the freezing/melting process. The result of this dependence on soil water/ice content is that the cooling/warming of a soil layer with large soil water/ice content is more effectively damped than the cooling/warming of a soil layer with small soil water/ice content. Nevertheless, the soil water content when the freezing processes takes place is for most of the cases close to the saturation point.

The insulating effect of the canopy is modelled through a dependency of the $K_{p/s}$ parameter on vegetation cover (veg) and leaf area index (LAI):

$$K_{p/s} = (1 - \frac{veg}{K_1}) \cdot (1 - \frac{LAI}{K_2}) \quad (10)$$

where K_1 and K_2 are adjustable constants, which have been tuned to the values $K_1 = 5.0$ and $K_2 = 30.0$. The characteristic timescales for the phase changes, which are related to the rate of freezing/melting of the soil are $1/\tau_s = 5 \cdot 10^{-5} s^{-1}$ and $1/\tau_p = 3 \cdot 10^{-5} s^{-1}$ for the surface and deep layers, respectively. The ice thermal inertia coefficient, C_i, is set to $5.6 \cdot 10^{-6} K m^{-2} J^{-1}$. L_f is the fusion latent heat. The most direct effect of the vegetation is to slow the freezing/thawing rate of soil water/ice as the vegetation canopy is augmented. The insulating effect of the snow (see Bazile (1999)) has not been included here, as separate computations are conducted for the snow covered fraction within the same tile in the HIRLAM surface routine. The freezing/thawing process is only active over snow free land.

The computation of the evaporation over ice (sublimation) should go accompanied by the usage of water vapour saturation pressure tables over ice. K. Fortelius (see this issue) has demonstrated the positive impact of using the saturation tables over ice for the case of evaporation over snow covered surfaces. The modification of the tables for both cases (evaporation over snow and over frozen soil) should be implemented at the same time. The experimentation shown here has not included the use of saturation tables over ice.

2.2 Implicit scheme

The implicit scheme applied here was developed by Viterbo *et al.* (1999). The scheme is based on the fact that freezing and thawing of soil water manifest as a "thermal barrier" at about 0^oC, damping the effect on soil temperature of the atmospheric forcing. Therefore, the main impact will be both to delay the soil cooling when dropping temperatures and to delay the soil warming when the solar forcing starts to melt frozen surfaces.

The flux due to the soil water change of phase (F_i) can be expressed by:

$$F_i = L_i \rho_w (1 - veg) d_2 \partial w_i / \partial t \tag{11}$$

where L_i is the latent heat of fusion and $\partial w_i/\partial t$ is the variation of the total ice water. The total ice water content can be assumed to be $w_i = f(T_s)w_2$, where $f(T_s)$ is a function taking the value 1 for temperatures well below 0^oC (all soil water content is in solid phase), 0 for temperatures well above 0^oC (all soil water content is in liquid phase) and with some smooth transition around 0^oC. To avoid undesirable coupling between the temperature and water equations w_2 is additionally assumed to be equal to the field capacity value, w_{fc}, in the expression for F_i. The final expression for the flux due to the soil water change of phase is:

$$F_i = [L \rho_w (1 - veg) d_2 w_{fc} df(T_s)/dT_s] \partial T_s / \partial t \tag{12}$$

This term has been included in the left-hand side term of the surface temperature equation and incorporates the barrier effect through the pulse-like function of surface temperature, $df(T_s)/dT_s$, to simulate the soil water content freezing/thawing around 0^oC.

2.3 Analysis of soil temperature

The current analysis of surface, T_s, and mean, T_2 soil temperatures consist of correcting soil temperatures proportionally to the analysed increments of 2-metre temperature at every assimilation step (see Rodriguez *et al.* (2003)):

$$\Delta T_d = \Delta T_{2m}/(2\pi) \tag{13}$$

$$\Delta T_s = \Delta T_{2m} \tag{14}$$

In the reference HIRLAM code (version 5.1.3), the soil temperature correction is always applied, disregarding any consideration to the degree of coupling between soil temperature and near-surface temperature. Of course, this rather crude approach to the soil temperature analysis is only a first practical approximation to the analysis of soil temperatures which will need further revision in the short term. The effect of the phase change of soil water is mainly manifested as a damping of oscillation of surface soil temperature when temperature crosses the melting/freezing point. This feature, however, might be suppressed by the soil temperature correction which could cause a jump over the freezing point. The assimilation step could, therefore, eliminate the characteristic retardation of soil temperature when the freezing point is traversed. To prevent such unrealistic behaviour, the soil temperature correction can be switched-off always that the surface soil temperature falls in the $+/-2K$ window around the melting point for the case of the implicit treatment. The soil temperature correction is not so critical in the explicit treatment, as soil ice keeps memory of the melting/freezing process and is the ultimate responsible of the lack of responsiveness of soil temperature around the melting point. The role of soil temperature correction around the melting point has been additionally explored by running also experiments without switching-off soil temperature corrections during the freezing/melting process.

3 1D simulations forced by observations

The following set of experiments were carried out to explore the behaviour of the described algorithms for soil moisture freezing/thawing using 1D simulations forced by observations:

- Experiment OLD: The soil moisture freezing/thawing process is treated implicitely following Section 2.2, as in HIRLAM reference version 5.1.3.
- Experiment EXP: The explicit scheme for the freezing/thawing process follows the description in Section 2.1.
- Experiment IMP: The implicit scheme is essentially the same as experiment OLD (see Section 2.2), but reducing the barrier height. Similarly to the treatment by the explicit scheme, a factor K is introduced to tune the barrier height and to force a more extrict dependency on vegetation properties: $K = K_1 \cdot (1 - veg) \cdot (1 - \frac{LAI}{K_3})$, where K_1 and K_3 have been tuned to the values $K_1 = 0.2$ and $K_3 = 30.0$.
- Experiment NOB: It has no treatment (neither implicit nor explicit) of the freezing/thawing soil moisture process.

Two different sites, Illinois and Col de Porte, have been used to compare and validate the above described algorithms for soil freezing and thawing processes. For both sites the same atmospheric forcing variables were supplied (atmospheric temperature, humidity, pressure and wind components, liquid precipitation, and downwelling longwave and shortwave radiation).

3.1 Illinois dataset

It was originally described by Meyers and Hollinger (1998). It corresponds to a continental-climate experimental site very adequate for validation of SVAT schemes. Besides the atmospheric forcing variables, surface atmospheric (R_n, H, and LE) and ground heat (G) fluxes are available at 30-min intervals. Infrared soil temperature and temperature observations at soil depths of 0.02, 0.04, 0.08, 0.16, 0.32, and 0.64 m, and volumetric water content at depths of 0.05, 0.20, and 0.60 m are available at a time increment of 30 min. The site is located in Illinois (USA) at $40^0 00.366' N$, $88^0 17.512' W$, which is within the Global Energy and Water Cycle Experiment Continental- Scale International Project Large-Scale Area North Central, and on the northeastern edge of the Large-Scale Area Souteast region. The same dataset was already used by Boone *et al.* (2000) to validate a refined version of the explicit scheme (Bazile and Giard, 1999) both in the force-restore ISBA scheme and in a multilayer explicit diffusion soil heat and mass transfer scheme.

3.2 Col de Porte dataset

The Col de Porte site is described by Etchevers and Martin (1997). The site is located at $45^0 N$, $6^0 E$ in the Alps near Grenoble (France). It has an altitude of 1320 m above mean sea level. As snow usually covers the surface between November and the beginning of May, data from this site have been used to evaluate snow schemes. Besides the atmospheric forcing variables, infrared soil temperature and temperature observations at soil depths of 0.10, 0.20 and 0.50 m are available. This dataset was already used by Bazile and Giard (1999) to validate the explicit scheme.

3.3 Results of the 1D simulations

All 1D simulations shown here include only the effect of the evolution of soil variables (temperature, soil water content and ice water content (for the explicit experiment)) when the observed atmospheric forcing is applied. Contrary to the 3D simulations, no assimilation of the soil variables is conducted. The three periods here shown (two corresponding to the Illinois site and one to the Col de Porte site) have in common the absence of snow over ground which could mask the soil freezing and melting processes.

The observed and simulated surface temperatures for the two selected periods of the Illinois site are shown in Fig.1. The first period (DoY 355-360, 1998) is characterized by a prolonged cold outbreak with temperatures below the freezing point almost continuously during 5 days (Fig.1 (upper graph)). The second period (DoY 40-54, 1999) shows a typical evolution of temperatures above and below the freezing point for day and night time, respectively (Fig. 1 (lower graph)).

The OLD experiment shows a very unrealistic behaviour in both periods. The crossing through the freezing temperature for the first period is too damped during the first night (day 356), whereas the oscillation around $0^0 C$ is almost suppresed from day 44 onwards for the second period. Both periods suggest that the "thermal barrier" is excessively high.

The NOB experiment, without any simulation of the freezing and thawing processes, shows too much cooling for both periods.

The IMP experiment behaves closely to the NOB experiment during the first period as temperatures oscillate during most of the period well below the $0^0 C$ border, and consequently the "thermal barrier" has no impact on the temperature evolution. The slight damping effect is clearly seen at the first period when the $0^0 C$ line is traversed (day 356, 1998). For the second period, there is still an excessive tendency to damp the daily temperature oscillation, being this effect not so exagerated as with experiment OLD.

The explicit EXP experiment follows closely the observations for both periods. It performs particularly well in the first period, reducing the excessive cooling by freezing the soil water in the total layer after the complete freezing of the surface layer. On the other hand, the experiments based on the "thermal barrier" approach (OLD and IMP) have no mechanism to damp the cooling once the $0^0 C$ border is well surpassed.

Figure 2 shows the evolution of observed and simulated surface temperatures for one period

(DoY 90-106, 1995) at the Col de Porte site. The behaviour of different experiments follows closely the Illinois second period. NOB experiment cools excessively at night time. OLD experiment almost supresses oscillation around the 0^0C line. IMP experiment gives a realistic oscillation for most of the days except for a few days (DoY 99-102) with excessively damped oscillation. EXP experiment tends to oscillate too much compared with observations. The EXP experiment, however, seems to evolve more closely to the observed temperatures.

4 Parallel runs: impact on 2m-temperatures

Parallel tests with the HIRLAM reference system (version 5.1.3) and the above described experiments have been carried out. The common features for all experiments are:

- Domain: Area corresponding to the HIRLAM Delayed Mode Run (DMR) domain covering most of Europe. with a 0.5° horizontal resolution
- 166 * 130 grid points; 31 levels in the vertical
- Semi-Lagrangian advection, dt = 10 min
- Each suite with its own data assimilation (OI, 6 h cycling)
- Lateral boundary conditions: ECMWF analyses
- 48 h forecasts from 00 UTC analyses only
- Period: 20 March-5 April 2002.

The parallel tests are now run in assimilation mode and therefore surface variable corrections are also applied at the surface analysis step. Additionally to the features described in Section 3 for the different 1D experiments, the following corrections to the surface variables are conducted: i) surface and mean soil temperature corrections were always applied for experiments OLD, EXP and NOB at the surface analysis step following Section 2.3.; ii) soil water assimilation is switched-off whenever soil ice is present for experiment EXP; iii) soil ice is always passed without modification from first guess to analysis for experiment EXP; and iv) temperature correction is switched-off in the window $(+2^oC, -^oC)$ around the melting point for experiment IMP. The idea behind of the last point is to prevent "jumps" over the "thermal barrier" during the assimilation step.

Two additional experiments were also carried out to explore the impact of the soil temperature correction on 2-metre temperature scores:

- Experiment IM2: The same as experiment IMP, but with surface and mean soil temperature correction always applied.
- Experiment EX2: The same as experiment EXP, but with surface and mean soil temperature correction only applied when soil ice is not present.

Figure 3 shows the simulated H+6 forecasted surface temperatures corresponding to the experiments OLD, NOB, IMP and EXP for the period 20-30 March 2002 for two selected grid points with temperatures below freezing and without presence of snow on the soil. The soil temperature correction at the assimilation step is also plotted as a vertical line. The frozen surface soil water corresponding to the explicit EXP experiment is also plotted. The experiments manifest the same features already seen in the 1D simulations. The grid point with temperatures oscillating around the melting point (Fig.3, upper graph) shows an excessive damping of surface temperature for the OLD experiment, partially compensated by the big temperature corrections. More attenuated diurnal cycle for IMP than for EXP as response to the atmospheric forcing. Both experiments, IMP and EXP, show a realistic evolution. The excessive cooling shown by the NOB experiment in 1D experiments is clearly compensated here by the temperature correction at the assimilation step. At night time (00 UTC) a high positive temperature correction is frequently applied reducing the excessive cooling produced by the physics. The grid point with temperatures well below the freezing point (Fig.3, lower graph) does not show so much dispersion among different experiments. It is noticeable that all surface soil water gets frozen after 1 day of simulation, remaining totally frozen for the rest of the period. Only the slow freezing of soil water in the total reservoir attenuates the cooling, as it is observed in the EXP experiment.

Figures 4 and 5 show the impact on 2-metre temperature of the soil moisture freezing and thawing processes. As it has already been commented before, the greatest impact takes place around the freezing temperature and for snow free areas. Therefore only limited periods and reduced geographical zones result to be affected. If 2-metre temperature bias and rms error scores are averaged for a two weeks periods over a big domain almost no effect can be appreciated. Therefore we limit ourselves to the daily H+6 forecasts averaged for all stations in the integration area (Fig.4, upper graph), and to certain areas where the effect was proven to be relevant: Scandinavia (Fig.4, lower graph), France (Fig.5, upper graph) and Ireland and Great Britain (Fig.5, lower graph). Again for all Figs. 4 and 5 the most unrealistic and degraded forecasts correspond to the OLD experiment showing too cold 2-metre temperatures at midday. The other three experiments (EXP, IMP and NOB) do not show big differences among them mainly due to the positive impact of the temperature correction at the surface analysis step (for EXP and NOB in the whole soil temperature range and for IMP in the range outside of $(+2^oC, -^oC)$ window).

Figure 6 additionally illustrates the effect of the temperature correction. The upper graph corresponds to the 2-metre temperature bias and rms error of H+06 forecasts over the France for the EXP and EX2 explicit experiments. The surface and mean temperature corrections are applied always in EXP and only when no ice soil is present in EX2. The slight difference in favour of the EXP experiment shows the positive effect of temperature correction in connexion with the freezing and thawing process. The lower graph shows the 2-metre temperature bias and rms error of H+06 forecasts also over France for the IMP and IM2 implicit experiments. The surface and mean temperature corrections are always applied in the IM2 experiment, whereas they are only applied when soil temperatures fall out of the range $(+2^oC, -^oC)$ in the IMP experiment, preventing jumps over the “thermal barrier” during the assimilation step. During a few days (26-29), the positive error of 2-metre temperature at 06 UTC produces a negative correction during the assimilation step for the IM2 experiment accompanied by a jump over the barrier which makes more difficult the warming at midday with the consequent degradation of scores at that time.

5 Conclusions

From the experiments carried out both in 1D setting with prescribed observed atmospheric forcing and in 3D parallel runs with quasi- operational conditions, the following conclusions can be drawn:

- The explicit treatment is preferable due to its more physical approach and to the more realistic simulation of the freezing and thawing processes under a variety of environmental conditions, including prolonged cold situations and oscillating daily process of freezing/thawing corresponding to night and day time. The explicit treatment seems to be further improved by the soil temperature correction at the analysis step. Although this correction is rather crude and it will need of future improvements it has a beneficial impact with the current formulation. The only drawback of this explicit treatment is the codification effort and the increase of memory requirements. Two additional variables need to be introduced for each land tile, with the corresponding modifications "upwards" in the routines for physics and dynamics.

- The ice in the total layer is a slow evolving variable (as water content) which is only produced/eliminated by freezing/thawing of the water/ice content in the total layer. As the soil ice is not modified by the assimilation step, its amount could easily show some drifting in monthly or seasonal time scales. This drifting could be caused either by soil temperature bias or by an inaccurate tuning of the parameters introduced to model the freezing and thawing fluxes. Nevertheless, the assimilation of soil temperature is expected to alleviate this possible drifting. The behaviour of the evolution of ice in the total layer for seasonal scales will need of additional evaluation.

- The implicit treatment gives also reasonable results after a careful tuning of the "barrier height" and of its dependency on the vegetation parameters. The main advantage of this approach is that it does not require any additional variables, with the consequent burden of modifications in the code and of additional memory. The careful tuning of the "barrier height" in the implicit treatment and of the parameters weighting the freezing and melting fluxes in the explicit treatment are very critical to the performance of both methods. The dependency on vegetation parameters is a direct consequence of the existance of only one surface layer including the soil first *cm* and the vegetation.

- The correction of soil temperature in the assimilation step also has a positive impact in the 2-metre temperature scores. One exception seems to be soil temperature corrections jumping across the "thermal barrier" in case of the implicit approach.

- The original formulation of the soil moisture freezing/thawing process (OLD experiment) showed an excessive damping of the soil temperature diurnal cycle around the melting point (HIRLAM version 5.1.3). This effect was later somehow reduced by switching-off the freezing/thawing process for the forest fraction (HIRLAM version 5.1.4). Experiments here have shown the unrealistic behavoir of this formulation, unless some additional tuning is conducted (experiment IMP).

- The absence of any soil moisture freezing/thawing algorithm in the code usually gives excessive cooling at night time, which is partially palliated by the soil temperature correction during the assimilation step.

- The impact of the selected approach for the freezing/ thawing process on 2-metre temperature is relatively small for big areas and averaging over many integrations. Both the explicit (EXP) and the well tuned implicit approach (IMP) tend to give reasonable results for short range integrations. Of course, for longer integrations involving monthly or seasonal time scales the explicit scheme will be preferred.

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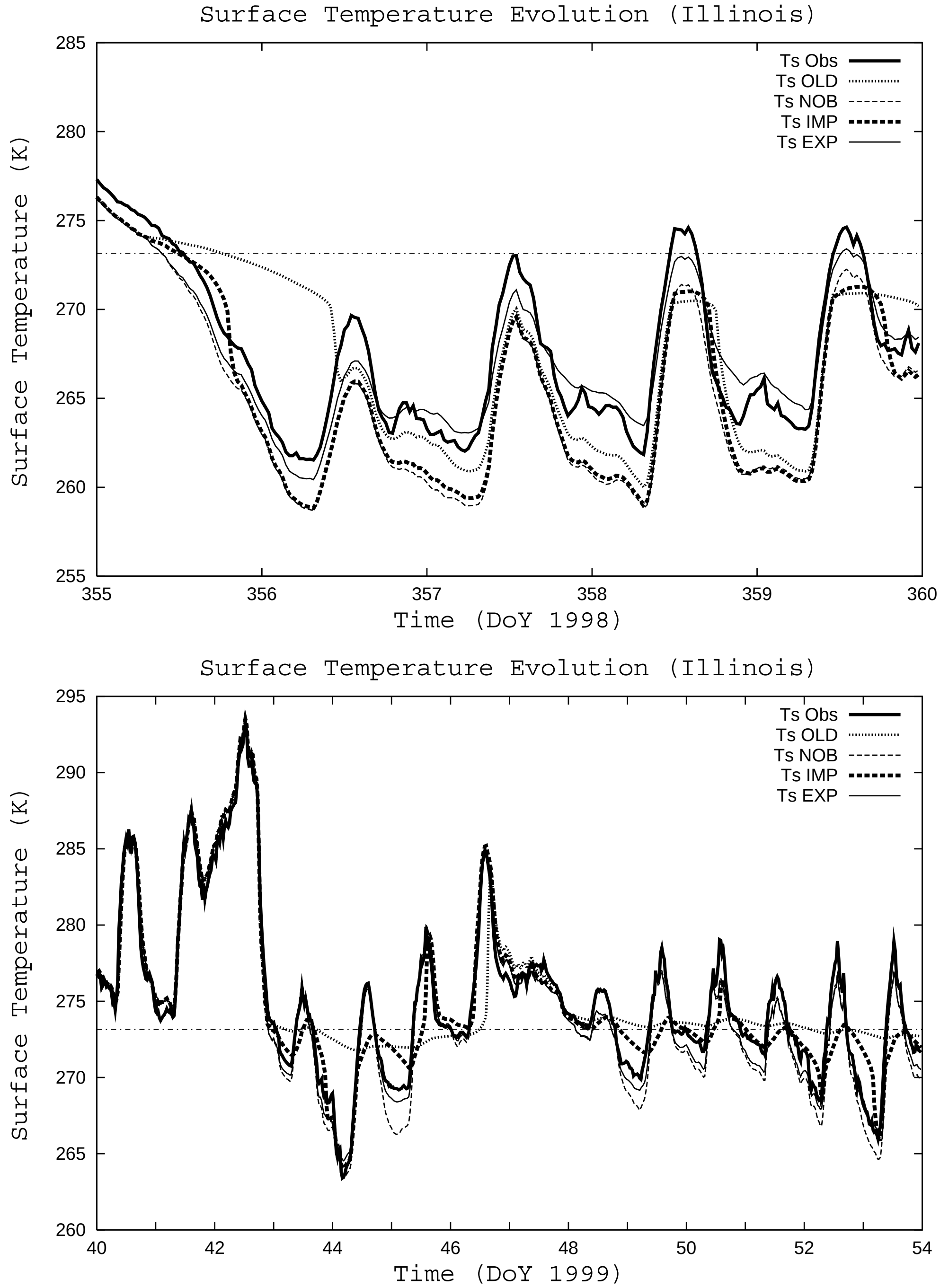


Figure 1: Observed surface temperature (thick solid line) and simulated surface temperatures with the experiments OLD, NOB, IMP and EXP (see text for their description) for the periods from day of the year (DoY) 355-360, 1998 (upper graph), and DoY 40-54, 1999 (lower graph) at the Illinois site. The horizontal dashed line represents the freezing point temperature of water.

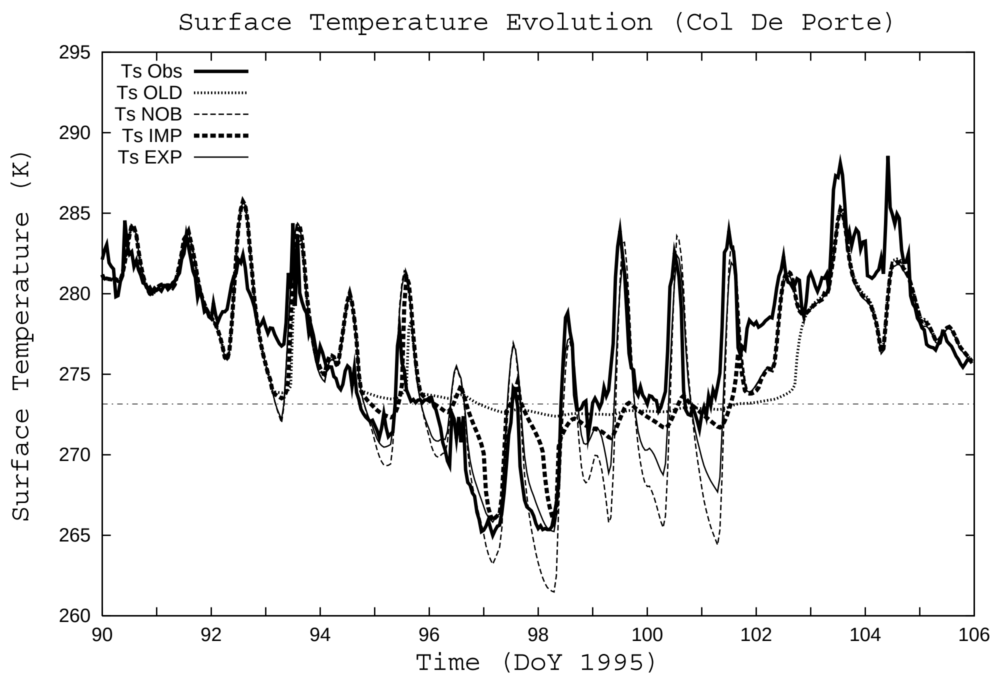
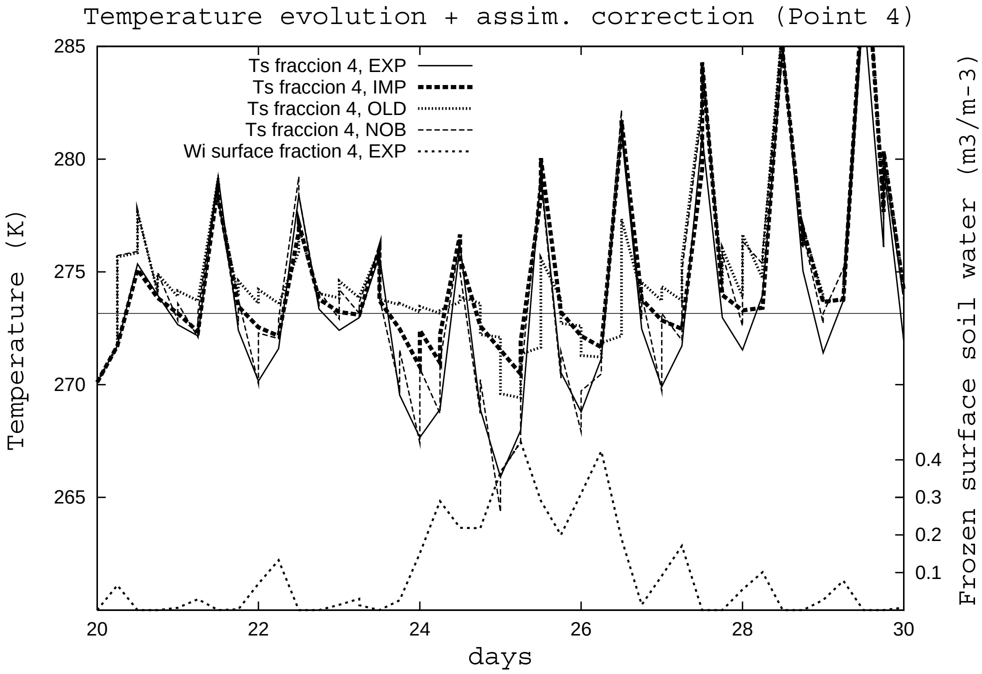


Figure 2: As in Fig.1, but for the period from the day of the year (DoY) 90-106, 1995 at the Col de Porte site.



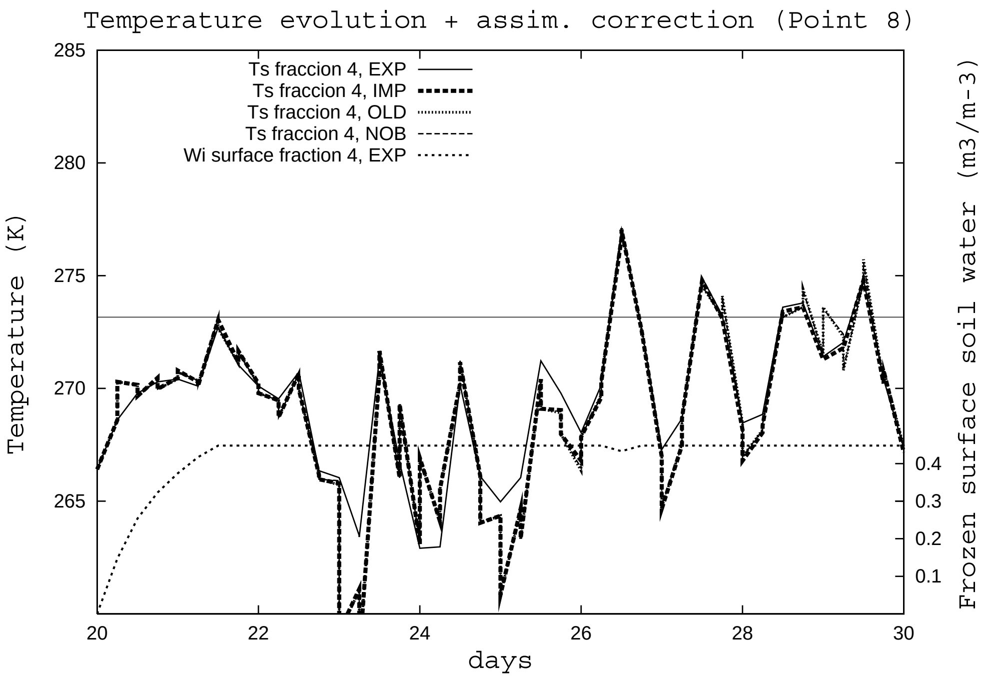
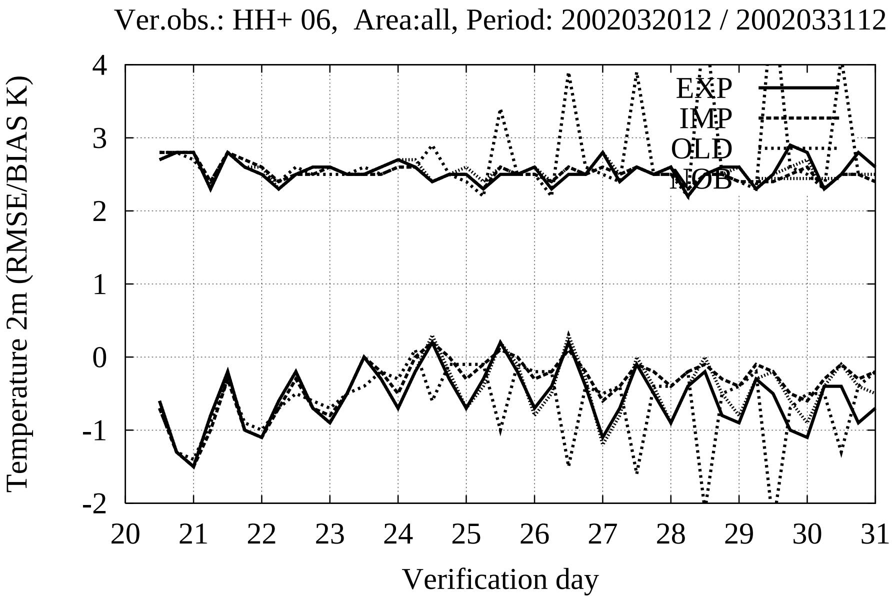


Figure 3: Simulated surface temperatures with the experiments OLD, NOB, IMP and EXP (see text for their description) for the period 20-30 March 2002 corresponding to two grid points with coordinates $(59.^oN, -25.^oE)$ (upper graph) and $(67.37^oN, -26.63^oE)$ (lower graph), respectively. Both the H+6 forecasted temperature and the soil temperature correction at the assimilation step are plotted. The corrections at the assimilation step are represented by vertical lines (see text for further explanations). The corresponding frozen surface soil water is also plotted. All values are referred to the fraction 4 (low vegetation).



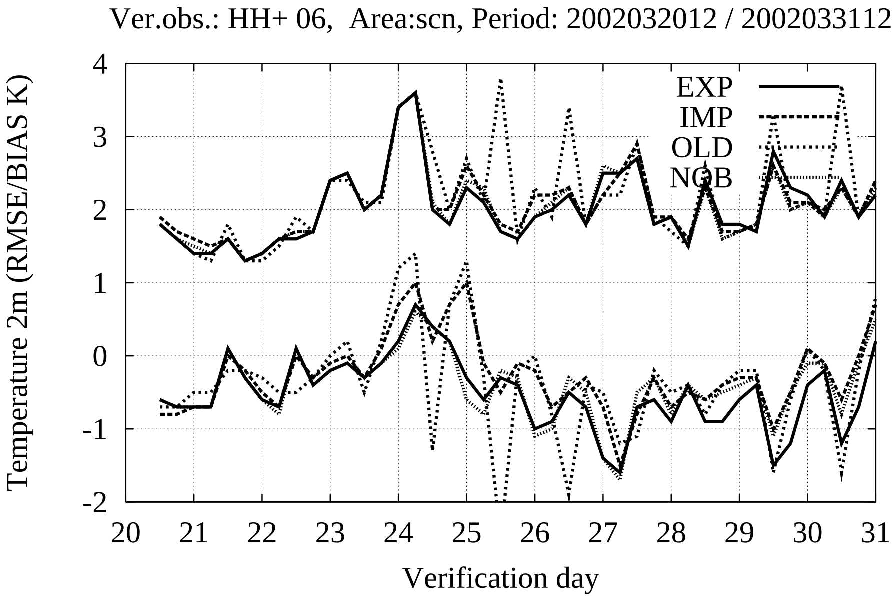


Figure 4: 2-metre temperature bias/rms error of H+06 forecastings with the experiments EXP, IMP, OLD and NOB (see text for their description) for the period 20-30 March 2002. The upper and lower graphs corresponds to verification against all stations in the integration domain and Scandinavian (55.N, 70.N, 32.E, 8.E) stations, respectively

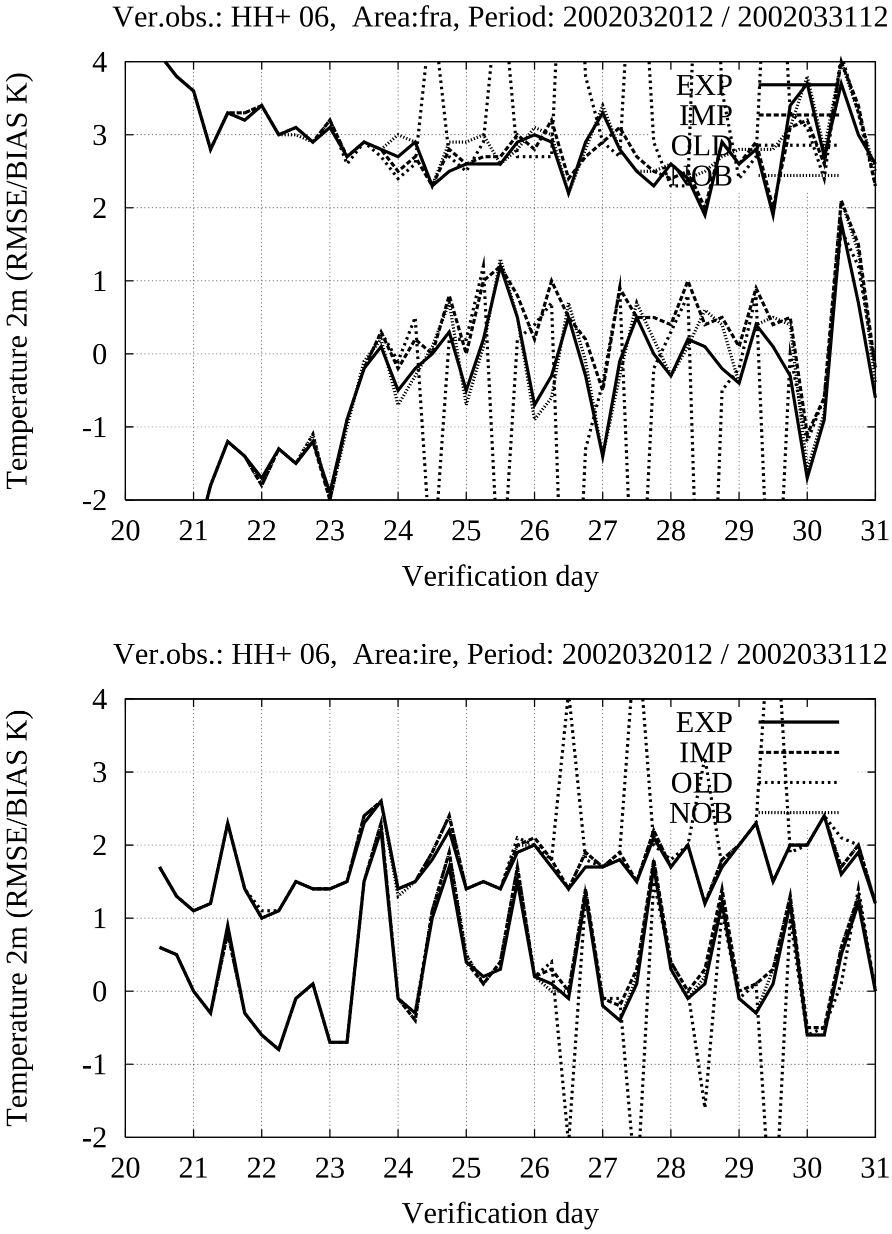
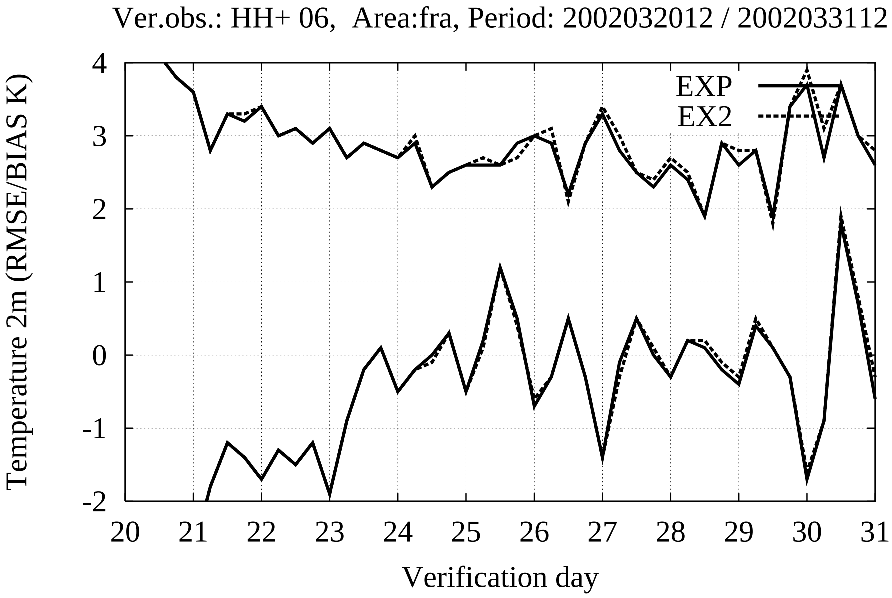


Figure 5: As in Fig. 4, but for France (44.N, 50.N, 8.E, -2.E) (upper graph) and Ireland/Great Britain (55.5N, 50.N, 2.E, -11.E) (lower graph).



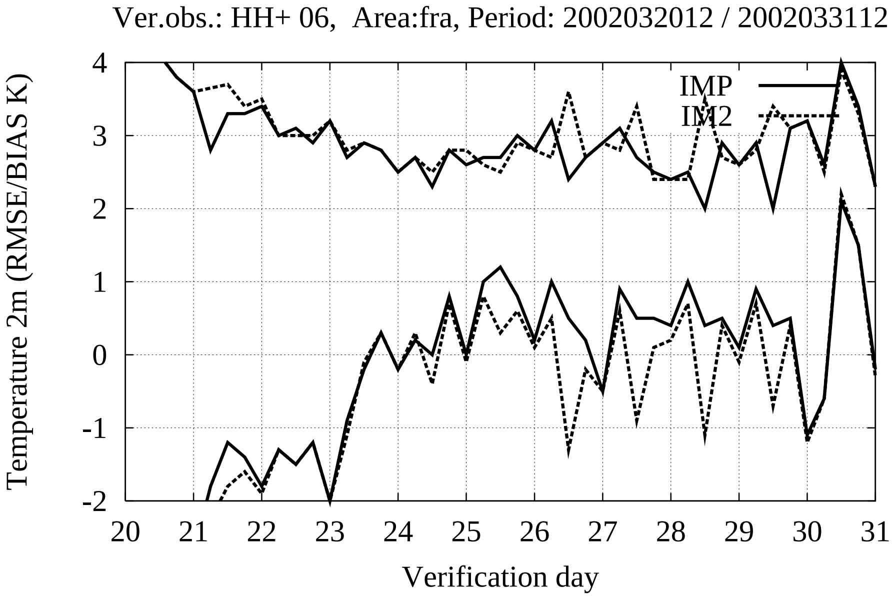


Figure 6: 2-metre temperature bias/rms error of H+06 forecastings with the experiments EXP and EX2 (upper graph) and IMP and IM2 (lower graph). The verification area is France (44.N, 50.N, 8.E, -2.E), for both graphs. The period is also 20-30 March 2002.