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Problem with screen level temperatures above snow in ISBA scheme

In January 2017, there was a period of anticyclonic weather in Czech Republic. On the calm and clear nights, screen level temperature T_{2m} was falling below -15°C, especially on places with snow cover. However, operational ALARO-1 at CHMI was not able to predict such low minimum temperature, even if starting from realistically analyzed temperature and having reasonable amount of snow.

ALARO-1 at CHMI still uses ISBA land surface scheme of Noilhan and Mahfouf (1996), with two soil layers only – thin surface layer with temperature T_{surf} and thick deep layer with temperature T_{deep}. Snow parameterization is quite simple, characterized by setting `LSNV=.F.` and `LVGSN=.T.`. Snow cover is a part of the surface layer, and it is described by three prognostic variables – snow reservoir W_{snow} [$\mathrm{kg\,m^{-2}}$], snow albedo α_{snow} [1] and snow density ρ_{snow} [$\mathrm{kg\,m^{-3}}$]. Fraction of bare ground covered by snow is diagnosed as the function of snow reservoir

$$f^{\mathrm{bg}}_{\mathrm{snow}} = \frac{W_{\mathrm{snow}}}{W_{\mathrm{snow}} + W^{\mathrm{crit}}_{\mathrm{snow}}}, \tag{1}$$

where $W^{\mathrm{crit}}_{\mathrm{snow}}$ alias namelist variable `WCRIN` is a tuning parameter with default value $10\,\mathrm{kg\,m^{-2}}$. When the snow reservoir equals to this value, snow fraction over bare ground is $\frac{1}{2}$. Snow fraction over vegetation can be different from that of bare ground. Combined effect of snow and vegetation affects final gridbox albedo and emissivity. However, thermic coefficient C_{T} [$\mathrm{K\,m^2\,J^{-1}}$] of the surface layer is not affected by the presence of snow.

Remark: Setting `LSNV=.T.` and `LVGSN=.F.` would activate snow scheme of Douville et al. (1995). Use of this scheme is restricted to the climate configuration, since the past tests in the NWP environment were not successful.

Soil temperatures in ISBA are assimilated by CANARI optimal interpolation, following Giard and Bazile (2000). Analysis increment ΔT_{2m} of screen level temperature is applied directly to T_{surf} and its scaled value also to T_{deep}:

$$\Delta T_{\mathrm{surf}} = \Delta T_{\mathrm{2m}} \qquad \Delta T_{\mathrm{deep}} = \frac{\Delta T_{\mathrm{2m}}}{2\pi} \tag{2}$$

Evolution of soil temperatures in ISBA is driven by so called force restore method, used by Noilhan and Planton (1989). In the absence of freezing/melting of soil moisture it reads

$$\frac{\partial T_{\mathrm{surf}}}{\partial t} = C_{\mathrm{T}}(R + H_{\mathrm{sens}} + H_{\mathrm{lat}}) - \frac{2\pi}{\tau}(T_{\mathrm{surf}} - T_{\mathrm{deep}}) \tag{3}$$

$$\frac{\partial T_{\mathrm{deep}}}{\partial t} = \frac{1}{\tau}(T_{\mathrm{surf}} - T_{\mathrm{deep}}), \tag{4}$$

where R is net radiative flux including both shortwave and longwave contributions, H_{sens} is sensible heat flux, and H_{lat} is latent heat flux. All fluxes are evaluated at the surface, and their positive values correspond to downward net energy transfer. Finally, t is time and $\tau = 86\,400\,\mathrm{s}$ is the length of the day.

There are two basic problems with snow in ISBA scheme. In situations with few cm of snow covering all ground (e.g. fresh snow fallen at calm conditions), equation (1) with default tuning gives the snow fraction much less than one. As a consequence, surface albedo is strongly underestimated, leading to excessive solar heating during the day even if snow reservoir has realistic values. Second problem is related to the assumption that surface ISBA layer including snow cover is at single temperature T_{surf}. This is unrealistic with thicker snow cover, since the snow is a good thermal insulator, cutting off the heat exchange between atmosphere and soil. During calm and clear night, high temperature gradient across the snow layer develops, since the temperature of skin layer is significantly decreased by radiative cooling. Weak turbulent transfer then cools also thin adjacent layer of air, significantly affecting the screen level temperature.

Way out from the first problem might be retuned snow fraction, preferably combined with snow analysis. Second problem, however, cannot be solved within simple two layer ISBA framework. This is because the same temperature T_{surf} controls both the radiative cooling of the snow skin layer, and the heat exchange between surface and deep soil layers. One could reduce soil heat flux in the presence of snow, even if this goes against the spirit of the force restore method, where the relaxation coefficients in equations (3) and (4) are firmly given. By doing so, temperature T_{surf} represents the skin layer of snow and possible vegetation above, rather than the surface soil layer. Such approach is not fully consistent from energetics point of view (temperature T_{surf} is the measure of internal energy, so it should represent whole surface ISBA layer, not only its upper part). It was implemented in the past by Eric Bazile, but it was never used in operational model ARPEGE. It is still present in the code and can be activated by setting namelist variable `NCHSP` alias exponent n to some positive integer. Equations 3 and 4 are then modified to

$$\frac{\partial T_{\mathrm{surf}}}{\partial t} = C_{\mathrm{T}}(R + H_{\mathrm{sens}} + H_{\mathrm{lat}}) - \frac{2\pi}{\tau}\left[1 - (f^{\mathrm{bg}}_{\mathrm{snow}})^n\right](T_{\mathrm{surf}} - T_{\mathrm{deep}}) \tag{5}$$

$$\frac{\partial T_{\mathrm{deep}}}{\partial t} = \frac{1}{\tau}\left[1 - (f^{\mathrm{bg}}_{\mathrm{snow}})^n\right](T_{\mathrm{surf}} - T_{\mathrm{deep}}), \tag{6}$$

while default setting `NCHSP=0` preserves original solution corresponding to the limit $n \to +\infty$. The strongest damping of the soil heat flux is obtained for $n = 1$. Influence of the screen level temperature increment on the deep soil should be damped correspondingly in CANARI, replacing equation (2) by:

$$\Delta T_{\mathrm{surf}} = \Delta T_{\mathrm{2m}} \qquad \Delta T_{\mathrm{deep}} = \left[1 - (f^{\mathrm{bg}}_{\mathrm{snow}})^n\right]\frac{\Delta T_{\mathrm{2m}}}{2\pi} \tag{7}$$

However, modification (7) is missing in current CANARI code.

Parameters $W^{\mathrm{crit}}_{\mathrm{snow}}$ and n provide some space for tuning. Their impact was evaluated in 48 hour ALARO-1 integrations starting on 10-Jan-2017 at 00 UTC. Figure 1 shows evolution of T_{2m}, T_{surf} and T_{deep} for two stations with snow cover both in reality and in the model. Snow reservoir during model integration was around $9\,\mathrm{kg\,m^{-2}}$ for Praha-Libuš and around $11\,\mathrm{kg\,m^{-2}}$ for Košetice, only during last 6 hours it was increased by snowfall and eventually decreased due to warm advection. Top panels illustrate that in the morning 11-Jan-2017, operational run (red) overestimated observed 2m temperature (black dots) by ~5°C. At the same time, surface temperature was only by ~0.5°C colder (middle panels), while deep temperature was around -4°C (bottom panels), causing significant heat flux from warmer deep to colder surface ISBA layer, preventing the latter to cool more.

Experiment with snow fraction increased by setting $W_{\mathrm{snow}}^{\mathrm{crit}} = 1\,\mathrm{kg\,m^{-2}}$ (yellow) causes drop of surface temperature during the first day due to albedo feedback. During following night, 2m temperature remains ~0.5°C below operational run. Limitation of the heat exchange with deep soil by setting $n = 2$ (light green) prevents albedo feedback during the day, but its impact on night 2m temperature is very comparable to that of increased snow fraction. Using harder setting $n = 1$ (dark green) decreases 2m temperature by additional ~1°C, leaving it still too warm with respect to observations. Finally, combining harder setting $n = 1$ with increased snow fraction (cyan) decreases 2m temperature significantly, making it too low for Praha-Libuš and just right for Košetice. This indicates that model snow reservoir and related snow fraction can have very different quality in different gridpoints, so that tuning optimal for one place can be poor for the other. Also, one must keep in mind that screen level temperature is determined by simultaneous action of several processes, where the snow cover is only one contributing factor.

In order to have more robust evaluation of the above tunings, VERAL scores of 2m temperature calculated over Central Europe for the same run are shown on figure 2. Operational tuning (red) has a positive bias up to $0.5\,\mathrm{K}$. Increased snow fraction (yellow) reduces bias during the night, but albedo feedback spoils 2m temperature during the day, peaking at $-1\,\mathrm{K}$. Smallest bias is obtained for heat exchange with deep soil limited by setting $n = 2$ (light green), harder setting $n = 1$ becomes already too cold. Combining $n = 1$ with increased snow fraction (cyan) is an extreme, leading to cold bias peaking at $-3\,\mathrm{K}$.

Vertical span of all panels on figure 2 is the same, so it is clear that apart from cyan curve, RMSE error is dominated by its SDEV component alias random error, which is very comparable for remaining curves. Selection criterion is thus bias, and for examined case it clearly favours tuning $n = 2$ with default value $W_{\mathrm{snow}}^{\mathrm{crit}} = 10\,\mathrm{kg\,m^{-2}}$. It surely cannot cure the problem with screen level temperatures above snow in ISBA completely, but after more extensive testing in assimilation cycle including modification (7) it could bring a partial improvement. Still, the main conclusion is that with two layer ISBA scheme the problem of minimum temperatures above snow cannot be properly addressed. At least one extra layer representing snow cover is needed. An interesting possibility is to test multi-layer snow schemes available via SURFEX. For NWP purpose, snow scheme of intermediate complexity is preferable.

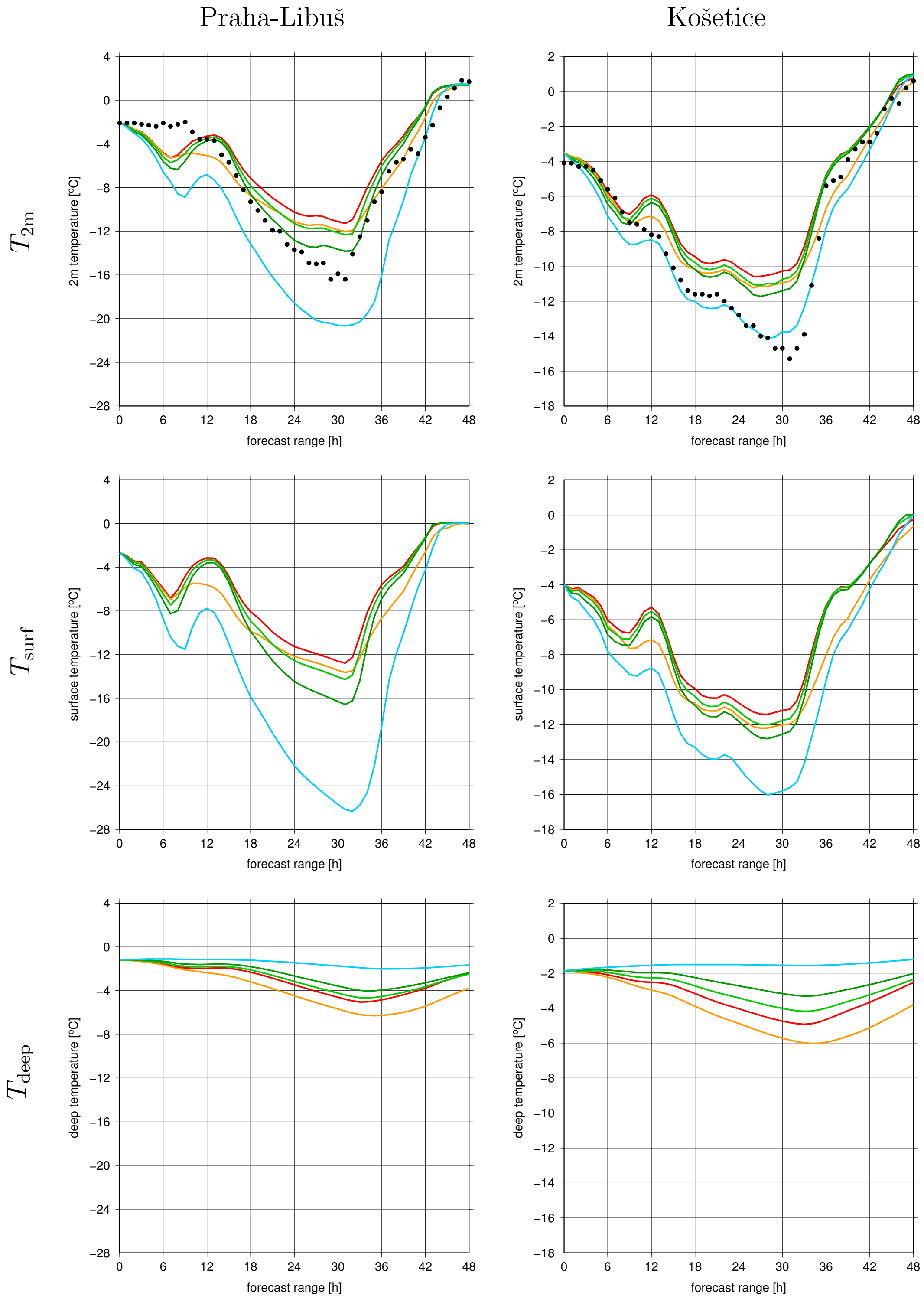

Figure 1: 48 hour ALARO-1 forecast for stations Praha-Libuš (left column) and Košetice (right column), starting on 10-Jan-2017 at 00 UTC: red – operational run; yellow – $W_{\mathrm{snow}}^{\mathrm{crit}} = 1\,\mathrm{kg\,m^{-2}}$; light green – $n = 2$; dark green – $n = 1$; cyan – $W_{\mathrm{snow}}^{\mathrm{crit}} = 1\,\mathrm{kg\,m^{-2}}$ and $n = 1$. Dots on upper panels denote SYNOP observations.

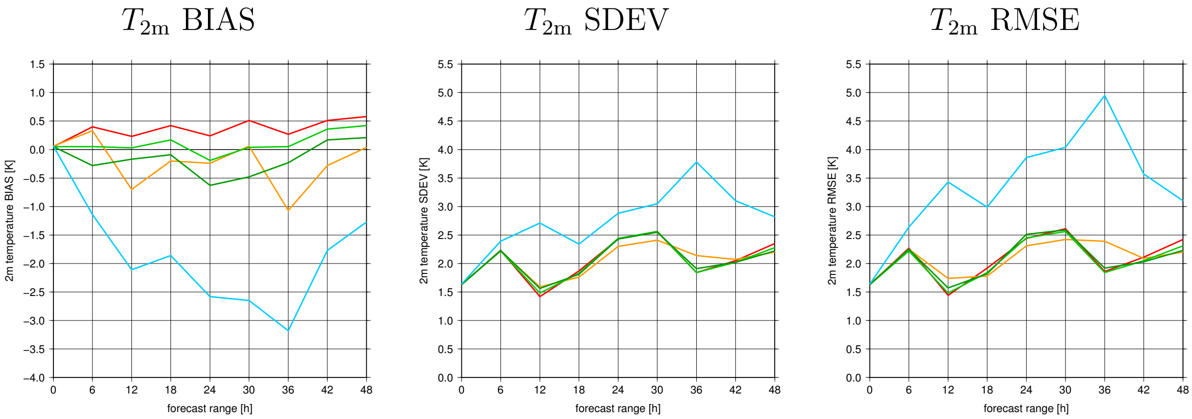

Figure 2: VERAL scores of 48 hour ALARO-1 forecast starting on 10-Jan-2017 at 00 UTC, calculated over Central Europe. Colors are the same as on figure 1: red – operational run; yellow – $W_{\mathrm{snow}}^{\mathrm{crit}} = 1\,\mathrm{kg\,m^{-2}}$; light green – $n = 2$; dark green – $n = 1$; cyan – $W_{\mathrm{snow}}^{\mathrm{crit}} = 1\,\mathrm{kg\,m^{-2}}$ and $n = 1$.

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