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IMPROVING THE COMPUTATION OF SCREEN LEVEL FIELDS (TEMPERATURE, MOISTURE)

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1. Introduction

For comparison of model with ground observations, it is necessary to diagnose model quantities like temperature and humidity in 2m measurement height. At current ALARO-1 vertical resolutions the lowest model level is typically about 10m above ground, so the forecast 2m values must be obtained by interpolation between lowest model level and surface. Interpolation must deal with sharp gradients often observed near the surface, it is therefore based on Monin-Obukhov similarity theory, supposing suitable shape of stability functions with a free parameter that can be determined from consistency of sub-grid reconstruction with model values at the surface and at the lowest full level, respecting prescribed turbulent flux (in the layer of constant flux). Use of stability functions not having analytic solution of Monin-Obukhov equations leads to cost expensive iterative numerical computations. In 1988 J.F. Geleyn [1] proposed simple Monin-Obukhov stability functions, from which it is easy to calculate dry static energy as a function of the height. However, Geleyn solution in strongly stable conditions suffers from a cold bias, that can be attributed to the oversimplified linear stability function. In order to remove it, L. Kullmann in 2009 [2] proposed more realistic stability function motivated by results of Arctic Ocean Experiment [3] and derived a new formula for vertical dependence of dry static energy. Unfortunately, Kullmann solution turned to be too warm in strongly stable conditions. At the end of 2014, provisional fix was implemented at CHMI based on mix of Geleyn and Kullmann solutions. Even if it helped to remove warm bias of pure Kullmann solution, it suffered from abrupt T_{2m} oscillations in strongly stable conditions, given by construction of mixing weight. Here we propose a revision of Kullmann solution that removes the problem cleanly, by consistent application of Geleyn procedure on suitably chosen stability function.

2. The interpolation technique

2.1 Monin-Obukhov theory

In this section we follow Geleyn paper[1]. Monin-Obukhov equations are:

$$\frac{\partial u}{\partial z} = \frac{u_*}{\kappa(z+z_{0D})}\varphi_D\Big(\frac{z+z_{0D}}{L}\Big), \tag{2.1}$$

$$\frac{\partial s}{\partial z} = \frac{s_*}{\kappa(z+z_{0H})}\varphi_H\Big(\frac{z+z_{0H}}{L}\Big), \tag{2.2}$$

$$L = \frac{\tilde{s}u_*^2}{g\kappa s_*}, \tag{2.3}$$

where u is wind, s is dry static energy $s = C_pT + gz$, C_p is specific heat of air at constant pressure, T is temperature and $g = 9.80665$ ms^{-2} is gravitational acceleration, z is height above surface, L is Monin-Obukhov length, u_* and s_* are friction values of velocity and dry static energy in the layer of constant flux, z_{0D} and z_{0H} are roughness lengths for momentum (drag) and heat respectively, $\tilde{s}$ is dry static energy at the surface, $\kappa = 0.4$ is Von Karman's constant and φ_D, φ_H are Monin-Obukhov stability functions for momentum and heat. There is no analytic solution of these three equations for arbitrary φ_D, φ_H. The following procedure needs two surface exchange coefficients and their values in neutrality (denotes by subscript N) relative to the lowest model level z_L:

$$C_D = \frac{u_*^2}{[u(z_L)]^2}, \qquad C_{DN} = \frac{\kappa^2}{\ln^2\left(\frac{z_L+z_{0D}}{z_{0D}}\right)},$$
$$C_H = \frac{u_* s_*}{u(z_L)[s(z_L)-\tilde{s}]}, \qquad C_{HN} = \frac{\kappa^2}{\ln\left(\frac{z_L+z_{0H}}{z_{0H}}\right)\ln\left(\frac{z_L+z_{0D}}{z_{0D}}\right)}, \tag{2.4}$$

where C_D is momentum surface exchange coefficient, C_H is heat surface exchange coefficient. For final formulation it is convenient to introduce:

$$b_D = \frac{\kappa}{\sqrt{C_D}} = \frac{\kappa}{u_*}u(z_L), \qquad b_{DN} = \frac{\kappa}{\sqrt{C_{DN}}} = \ln\Big(\frac{z_L+z_{0D}}{z_{0D}}\Big),$$
$$b_H = \frac{\kappa\sqrt{C_D}}{C_H} = \frac{\kappa}{s_*}[s(z_L)-\tilde{s}], \qquad b_{HN} = \frac{\kappa\sqrt{C_{DN}}}{C_{HN}} = \ln\Big(\frac{z_L+z_{0H}}{z_{0H}}\Big). \tag{2.5}$$

From now we restrict only to calculation of dry static energy (not momentum). Integrating eq. (2.2) from 0 to z gives:

$$s(z) - \tilde{s} = \frac{s_*}{\kappa}\Big[\ln\Big(\frac{z+z_{0H}}{z_{0H}}\Big) - \Psi_H\Big(\frac{z+z_{0H}}{L}\Big) + \Psi_H\Big(\frac{z_{0H}}{L}\Big)\Big], \tag{2.6}$$

where

$$\Psi_H(\xi) = \int_0^\xi \frac{1-\varphi_H(\zeta)}{\zeta}d\zeta \tag{2.7}$$

and for $z = 0$ it gives $s(0) - \tilde{s} = 0$, consistently with definition of $\tilde{s}$ as the surface value of s. Substituting (2.5) into (2.6) we get:

$$s(z)-\tilde{s} = \frac{s(z_L)-\tilde{s}}{b_H}\left[\ln\left(1+\frac{z}{z_L}(e^{b_{HN}}-1)\right)-\Psi_H\left(\frac{z}{L}+\frac{z_L}{L(e^{b_{HN}}-1)}\right)+\Psi_H\left(\frac{z_L}{L(e^{b_{HN}}-1)}\right)\right] \tag{2.8}$$

2.2 Interpolation formula for conservative variables

Geleyn solution (1988)

In paper [1] following stability function and its integral was used for stable case:[1]

$$\varphi_H(\xi) = 1 + \alpha_G\xi, \quad \Psi_H(\xi) = -\alpha_G\xi, \tag{2.9}$$

where α_G is a free parameter, to be determined from consistency requirements at lowest model level. Linear stability function (2.9) fits experimental data well in weakly stable conditions when $\xi < 1$. Such fitting delivers value $\alpha_G \sim 5$ [4], but below α_G will be determined from consistency requirements. Substituting (2.9) into (2.8) gives:

$$s(z) - \tilde{s} = \frac{s(z_L)-\tilde{s}}{b_H}\left[\ln\left(1+\frac{z}{z_L}(e^{b_{HN}}-1)\right)+\alpha_G\frac{z}{L}\right]. \tag{2.10}$$

Putting $z = z_L$ in (2.10) gives for α_G this condition:

$$\alpha_G = \frac{L}{z_L}(b_H - b_{HN}). \tag{2.11}$$

Finally, using α_G in (2.10) gives Geleyn formula for vertical dependence of dry static energy:

$$\boxed{s(z) - \tilde{s} = \frac{s(z_L)-\tilde{s}}{b_H}\left[\ln\left(1+\frac{z}{z_L}(e^{b_{HN}}-1)\right)-\frac{z}{z_L}(b_{HN}-b_H)\right].} \tag{2.12}$$

It should be noted that formula (2.12) doesn't contain Monin-Obukhov length L.

Kullmann solution (2009)

Interpolation (2.12) suffers from cold bias in strongly stable conditions observed in winter months. It can be attributed to the fact that for strong stability (small L), argument ξ becomes much larger than one and Geleyn formula is applied beyond its validity range. L. Kullmann attempted to remove this problem by using more realistic non-linear stability function for heat, fitting well experimental data [3] in strongly stable conditions:

$$\varphi_H(\xi) = 1 + a_K\frac{\alpha_K\xi}{1+\alpha_K\xi}, \quad \Psi_H(\xi) = -a_K\ln(1+\alpha_K\xi), \tag{2.13}$$

[1] Let us note that $\varphi_H(\xi) = 1$ implies $\Psi_H(\xi) = 0$ and $s(z) - \tilde{s} = \frac{s(z_L)-\tilde{s}}{b_{HN}}\left[\ln\left(1+\frac{z}{z_L}(e^{b_{HN}}-1)\right)\right]$. When consistency condition at the lowest model level $s(z_L)$ is required, then $b_H = b_{HN}$ which corresponds to neutral temperature profile.

where a_K is recommended to be ≈ 5 for consistency with experiments[3], but Kullmann set this as tuning parameter and introduced a new elimination parameter α_K as a factor multiplying argument ξ. Elimination parameter α_K is determined from condition at lowest model level z_L:

$$\alpha_K(a_K) = L \frac{\exp\left(\frac{b_H - b_{HN}}{a_K}\right) - 1}{z_L + z_{0H}\left(1 - \exp\left(\frac{b_H - b_{HN}}{a_K}\right)\right)}. \tag{2.14}$$

In this case, vertical depedence of dry static energy is:

$$s(z) - \tilde{s} = \frac{s(z_L) - \tilde{s}}{b_H}\Big[\ln\Big(1 + \frac{z}{z_L}(e^{b_{HN}} - 1)\Big) + a_K \ln\Big(1 + \frac{z}{z_L}\Big(e^{\frac{b_H - b_{HN}}{a_K}} - 1\Big)\Big)\Big], \tag{2.15}$$

where limit $a_K \to \infty$ gives back Geleyn formula (2.12).

Mix of Geleyn and Kullmann solutions

At the end of 2014, provisional fix was implemented at CHMI to remove warm bias of pure Kullmann solution. It combines Geleyn and Kullmann solutions, with mixing weight being based on stability parameter σ:

$$\sigma = \begin{cases} 0 & b_H - b_{HN} \leq 400, \\ \frac{b_H - b_{HN} - 400}{400} & 400 < b_H - b_{HN} \leq 800, \\ 1 & 800 < b_H - b_{HN} \;. \end{cases} \tag{2.16}$$

In order to be smooth, mixing weight is calculated as:

$$w = 3\sigma^2 - 2\sigma^3, \tag{2.17}$$

where in the limit of strong stability $w = 1$ and near neutrality $w = 0$. Both equations for dry static energy (2.12) and (2.15) can be written as:

$$s(z) - \tilde{s} = W(z)(s(z_L) - \tilde{s}), \tag{2.18}$$

where $W(z)$ is interpolation weight (the same weight is used also for interpolation of specific humidity q). Finally the interpolation weight of mixed solution $W_{GK}(z)$ is calculated:

$$W_{GK}(z) = w \cdot W_G(z) + (1 - w) \cdot W_K(z), \tag{2.19}$$

where $W_G(z)$ is interpolation weight for dry static energy of pure Geleyn solution (2.12), $W_K(z)$ is interpolation weight for dry static energy of pure Kullmann solution (2.15). In the limit of strong stability $W_{GK}(z) = W_G(z)$ which seems opposite as was intended. In any case, adding certain proportion of colder Geleyn solution reduces warm bias of Kullmann solution.

2.3 Obtaining temperature and relative humidity

Monin-Obukhov theory was applied for conservative variables: dry static energy and specific humidity. From their dependence on the height z we can calculate 2m temperature, where dependence of specific heat C_p on specific humidity q is taken into account. Temperature as a function of height is:

$$T(z) = \frac{\tilde{C}_p \tilde{T} + W(z)(C_{pL} T_L + z_L - \tilde{C}_p \tilde{T})}{C_p(z)}, \tag{2.20}$$

where $\tilde{C}_p$ is specific heat of air at the surface, $\tilde{T}$ is surface temperature, C_{pL} is the specific heat of air at the lowest model level and $C_p(z)$ is specific heat of air at height z:

$$C_p(z) = C_{pd} + (C_{pv} - C_{pd}) q(z), \tag{2.21}$$

where C_{pd} is specific heat of dry air, C_{pv} is specific heat of water vapor and $q(z)$ is specific humidity:

$$q(z) = \tilde{q} + W(z)(q_L - \tilde{q}), \tag{2.22}$$

where q_L is specific humidity at lowest model level and $\tilde{q}$ is specific humidity at the surface.

3. New interpolation formula

Due to large variability of difference $b_H - b_{HN}$ ($0 < b_H - b_{HN} \lesssim 1000$) at night, term $e^{\frac{b_H - b_{HN}}{a_h}}$ in (2.15) oscillates rapidly. In order to avoid the problem, we suggest modified stability function in a shape:

$$\varphi_H(\xi) = 1 + \alpha \frac{\xi}{1 + a\xi}, \quad \Psi_H(\xi) = -\frac{\alpha}{a} \ln(1 + a\xi), \tag{3.1}$$

where the main difference between Kullmann stability function (2.13) and modified stability function (3.1) is that the free parameter α is before fraction, so that it becomes simple multiplier in integral Ψ_H. Tuning parameter a is introduced in denominator of stability function φ_h. Using the same elimination procedure as in section 2.2 we get:

$$s(z) - \tilde{s} = \frac{s(z_L) - \tilde{s}}{b_H} \left[\ln\left(1 + \frac{z}{z_L}(e^{b_{HN}} - 1)\right) - \frac{\ln\left(1 + \frac{z}{\frac{L}{a} + \frac{z_L}{\exp(b_{HN}) - 1}}\right)}{\ln\left(1 + \frac{z_L}{\frac{L}{a} + \frac{z_L}{\exp(b_{HN}) - 1}}\right)} (b_{HN} - b_H) \right], \tag{3.2}$$

where L is expressed by (2.3) and (2.5):

$$L = \frac{b_H}{g{b_D}^2} \frac{\tilde{s}}{s(z_L) - \tilde{s}} u^2(z_L). \tag{3.3}$$

For $a \to 0$ (3.2) reduces to Geleyn formula (2.12).

4. Results

Mix of Geleyn and Kullmann solutions suffers from 2m temperature oscillations especially in the calm, clear sky conditions at night, where the strong surface inversion builds up. In order to investigate the problem, we chose several suitable cases. Results presented in this section are based on 36 hour run of ALADIN/CHMI, starting on 23th December 2015 at 00 UTC. We produced detailed point diagnostics for Prague, see fig. 4.1. One reason for this particular choice was the observed 2m temperature lying between values forecast at the surface and at the lowest model level, guaranteeing their small bias. Other studied cases had even smoother observed 2m temperature evolution, but they were contaminated by non-negligible model bias.

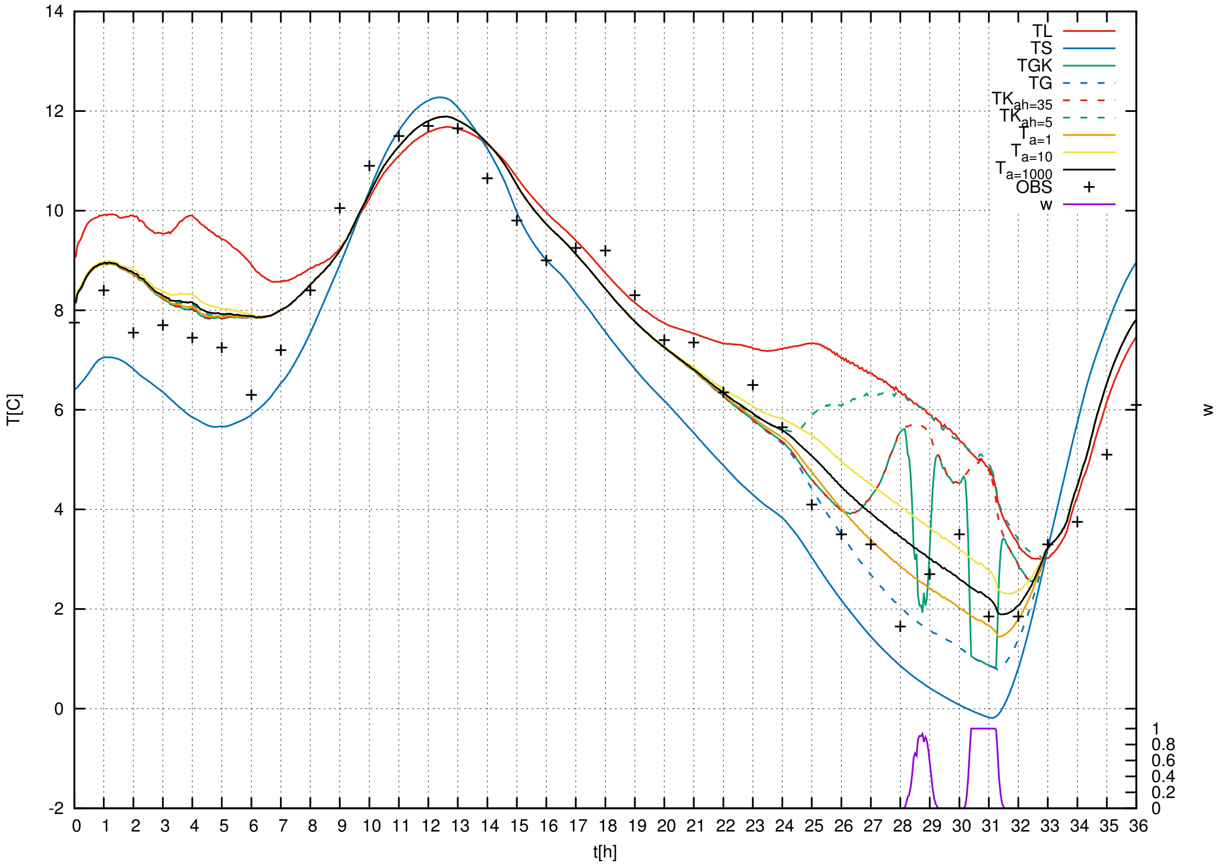

Fig. 4.1: Temperature forecast for Prague from 23th December 2015 00UTC to next 36hours. Blue solid line: Surface temperature. Red solid line: Lowest model level temperature. Green solid line: Reference T_{2m} (mixed Geleyn and Kullmann solution). Blue dashed line: T_{2m} pure Geleyn solution. Red dashed line: T_{2m} pure Kullmann solution for $a_K = 35$. Green dashed line: T_{2m} pure Kullmann solution for $a_K = 5$. Orange, yellow, black solid lines: T_{2m} the new interpolation formula with $a = 1$, $a = 10$ $a = 1000$ respectively. Black crosses: Observation data for Prague. Purple solid line: Weight w (2.17).

Most interesting period on fig. 4.1 is from +24 to +32 hour forecast, corresponding to window from 1:00 to 9:00 local time. Sunrise on this date and location is around 8:00 local time. Blue solid line corresponds to surface temperature $\tilde{T}$ and red solid line corresponds to the lowest model level temperature T_L. Black crosses denote 2m observations, one can see that majority of them indeed lies between T_L and $\tilde{T}$. Evolution of observed 2m temperature in examined window is smooth, with exception of two jumps visible at +28 and +30 hours. They might be related to changes in the local wind and will be ignored in further analysis. Early in the morning the difference $T_L - \tilde{T}$ reaches almost +6K, confirming very strong stability near the surface.

Dashed blue line corresponds to Geleyn solution (2.12). This solution is smooth, but in the morning it becomes slightly colder than observations. Dashed green line corresponds to Kullmann solution (2.15) with $a_K = 5$. It suffers from strong warm bias, closely following the temperature of the lowest model level in the morning. In order to mitigate the problem, value $a_K = 35$ was used operationally as indicated by the dashed red line. It is however still too warm, moreover it oscillates by 1–2K. Green solid line corresponds to reference 2m temperature obtained by mix of Geleyn and Kullmann solutions (the latter with $a_K = 35$). It reduces the warm bias of pure Kullmann solution, but in the morning it switches abruptly between the two limiting curves, with oscillations reaching 3–4K. The reason for this behaviour is the shape of mixing weight w (2.17), denoted by purple solid line (vertical scale on the right).

Finally, our new interpolation formula (3.2) for $a = 1$, 10 and 1000 is marked orange, yellow and black respectively. The solution is smooth and without any oscillations. Bias of diagnosed 2m temperature can be tuned by changing parameter a, but such tuning is meaningful only when T_L and $\tilde{T}$ are unbiased. Preliminary recommended setting is $a = 1$, using lower/higher value would give colder/warmer 2m temperature.

Figure 4.2 shows maps of 1 hour increment of forecast 2m temperature in the morning. Left column is the reference mix of Geleyn and Kullmann solutions, right column is the new formula. Problem with temporal oscillations can be clearly identified in spatial structure of the increment, visible as a short scale noise. While the new formula gives a noise free field, reference solution is heavily contaminated.

Figure 4.3 shows vertical temperature profiles between the surface and the lowest model level given by formulas (2.12), (2.15) and (3.2). When the difference $b_H - b_{HN}$ is small then Geleyn (2.12) and Kullmann (2.15) solutions are similar, see the left panel on fig. 4.3. On the contrary, when $b_H - b_{HN}$ is sufficiently big, Kullmann solution becomes different, with a very sharp gradient near the surface, see the right panel on fig. 4.3. In the limit of infinite stability, Kullmann solution becomes vertically constant with a discontinuity at the surface. Such behaviour is undesirable and it is avoided by our new formula (orange, yellow and black solid lines for $a = 1$, $a = 10$ and $a = 1000$ respectively). For $a > 0$, the new solution is warmer than Geleyn one. Black solid line with $a = 1000$ represents the limit $a \to \infty$, since the dependence saturates for large a.

More robust verification containing other stations is provided by VERAL scores, see fig. 4.4. They must however be interpreted with care, since the error of diagnosed 2m temperature does not depend only on interpolation formula, but also on temperature and humidity errors at the surface and at the lowest model level. Unfortunately, these are not known due to the lack of corresponding observations. Anyway, 2m temperature bias computed over whole model domain (left panel) confirms that Geleyn solution (green) is coldest, while reference mixed solution (black) is nearly unbiased in this case. New solution with $a = 1$(red) lies in between, and the new solution with $a = 10$ (blue) is warmest, having lowest overall bias. During the

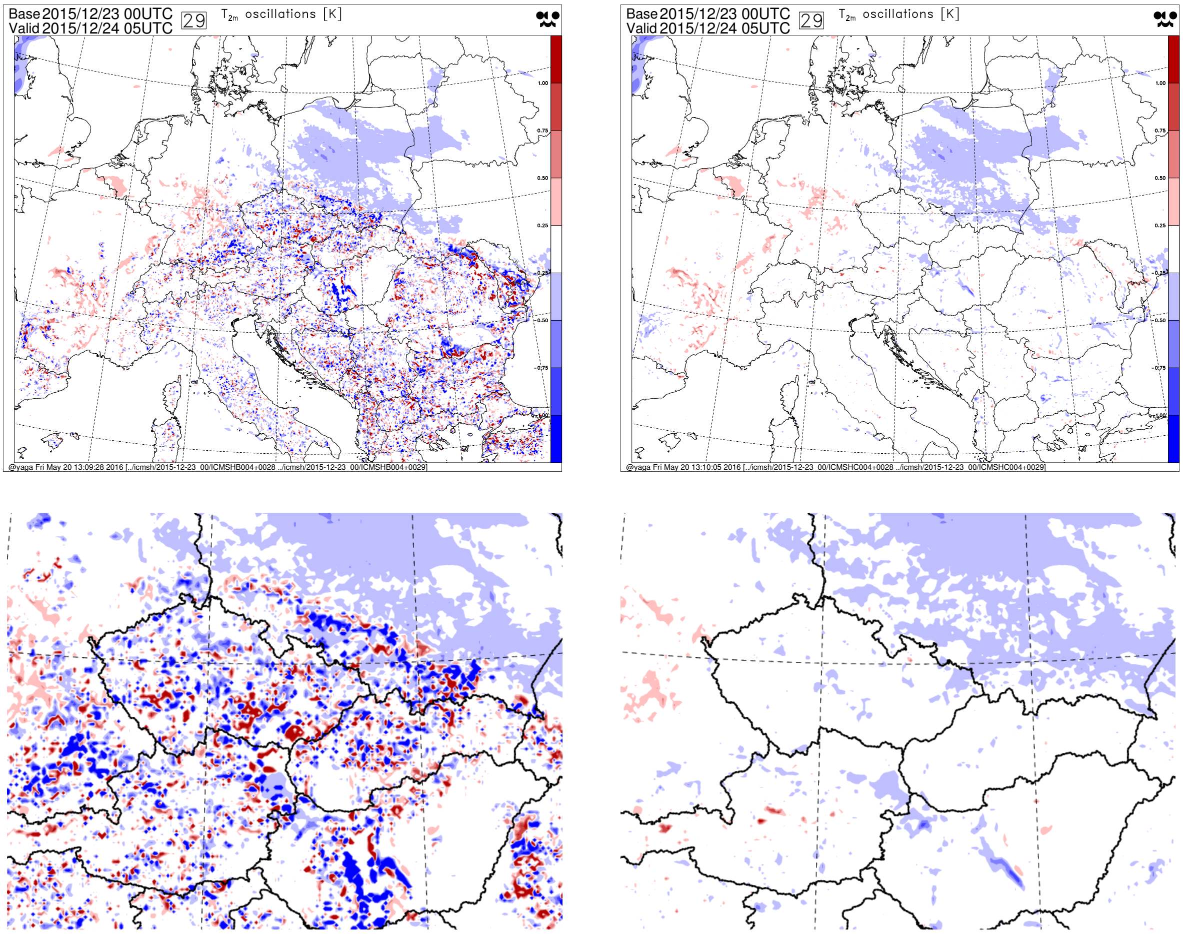

Fig. 4.2: T_{2m} difference 29h - 28h of forecast. Left column: Reference mixed solution (2.19). Right column: New interpolation formula (3.2). Top row: Whole domain. Bottom row: Zoom over Central Europe.

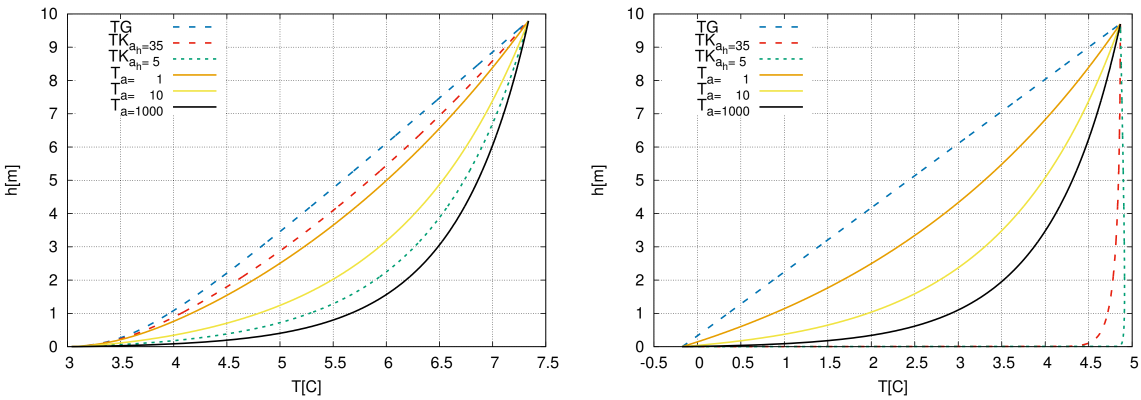

Fig. 4.3: Vertical temperature profile as function of height z: +25h (left); +31h (right). Blue dashed line: Geleyn formula (2.12). Red dashed line: Kullmann formula (2.15) for $a_K = 35$. Green dashed line: Kullmann formula (2.15) for $a_K = 5$. Orange, yellow and black solid lines: New revised formula (3.2) for $a = 1$, $a = 10$ and $a = 1000$ respectively.

night, average difference between warmest and coldest solutions reaches 1K. Order of curves for 2m relative humidity bias is reversed (right panel), reflecting decrease of relative humidity with increasing temperature when specific humidity remains nearly the same. All the curves meet at +12 and +36 hours, since in unstable conditions occurring around noon the same interpolation formula is used in all cases.

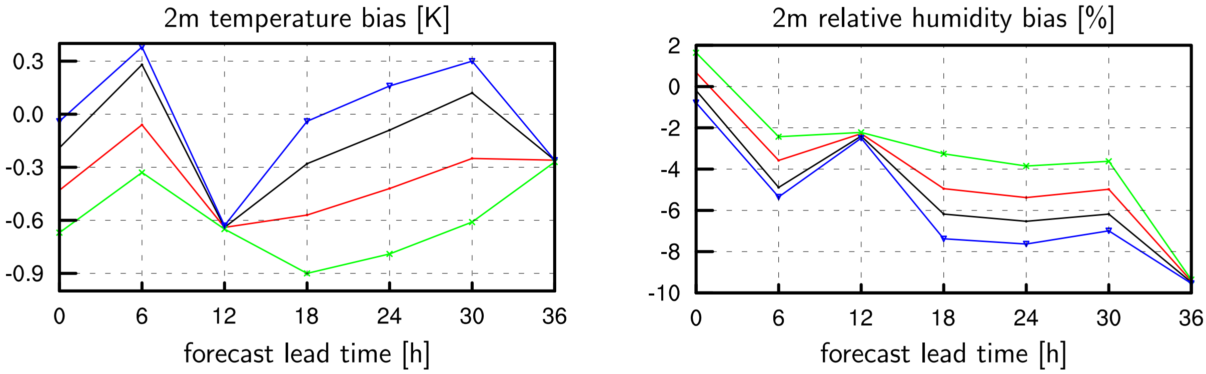

Fig. 4.4: BIAS for T_{2m} (left) and RH_{2m} (right) calculated for model run starting 00 UTC 23th December 2015 (forecast length 36h). Black: Reference (mixed Geleyn Kullmann solution). Green: Pure Geleyn solution. Red and Blue: New interpolation formula $a = 1$ and $a = 10$ respectively.

5. Conclusions

In this work we proposed the new 2m interpolation of the temperature and humidity in stable conditions. Solution of Geleyn 1988 was smooth but too cold in winter. Solution of Kullmann 2009 was warmer, but followed lowest model level too closely and sometimes oscillated. Mixture of the two introduced in TOUCANS reduced T_{2m} bias but oscillated even more, switching abruptly between the too cold (Geleyn 1988) and too warm (Kullmann 2009) solutions.

We introduce revised Kullmann 2009 solution, obtained by consistent application of Geleyn 1988 methodology to simplified Gratchev et al. 2007 stability function. New solution is smooth (non-oscillating), with one tunable parameter a alias ACLS_HS, see Appendix. Setting $a = 0$ gives back Geleyn 1988 solution (lower T_{2m} limit), $a = 1$ corresponds to unmodified stability function (recommended) and $a \to \infty$ gives the upper T_{2m} limit. Interpolation in unstable conditions is not influenced, here the Geleyn 1988 solution seems satisfactory.

6. Appendix

We worked in Prague on the local cycle 38t1tr_op4, which contains ALARO-1. Then was code phasing for c43t1 in Toulouse and was made modset also on cycle cy40t1 (last cycle, which can be compilable by fortran 90).

Phasing contribution for cy43t1

Content:	New 2m interpol. in stab. conditions. Affects only TOUCANS turb.
Contributors:	M. Dian, J. Masek
GIT branch:	masekj_CY43_t2m
Base cycle:	cy43_t1.01
Target cycle:	cy43_t1.02
List of modified files (4):	
	arpifs/module/yomphy1.F90, see fig.6.1.
	arpifs/namelist/namphy1.nam.h, see fig.6.2.
	arpifs/phys_dmn/actkecls.F90, see fig.6.3.
	arpifs/phys_dmn/suphy1.F90, see fig.6.4.

Desc. of modifications:

arpifs/module/yomphy1.F90
Added variables LCLS_HS, ACLS_HS.

arpifs/namelist/namphy1.nam.h
Added variables LCLS_HS, ACLS_HS.

arpifs/phys_dmn/actkecls.F90
New 2m interpolation of temperature and humidity for stable case, kept under key LCLS_HS. ACLS_HS is free parameter a defined in eq. (3.1). Subroutine is specific for TOUCANS turbulence.

arpifs/phys_dmn/suphy1.F90
Setting default values of LCLS_HS, ACLS_HS and reading their actual values from the namelist &NAMPHY1.

Interpolation routine ACTKECLS is called only from TOUCANS, i.e. when there is LCOEFK-SURF=.T. in namelist &NAMPHY. New interpolation is activated by setting:

```
&NAMPHY1
LCLS_HS=.T., (default .F.)
ACLS_HS=1., (default, recommended)
/
```

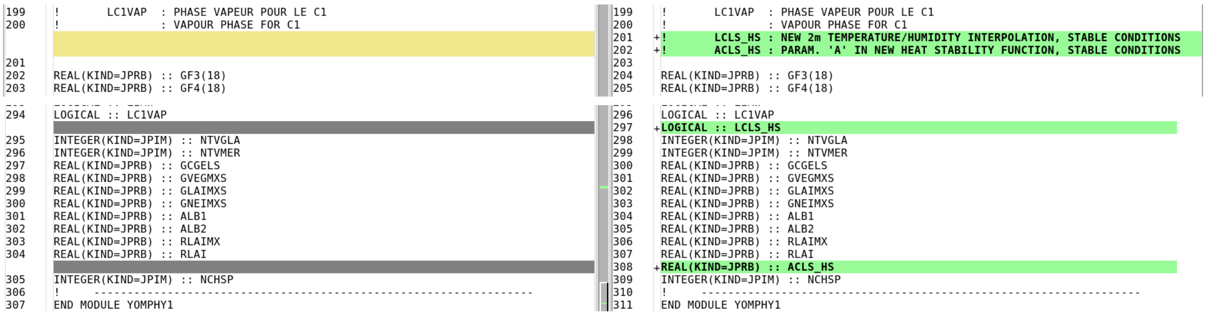

Fig. 6.1: Modification in arpifs/module/yomphy1.F90. left: reference. right: modified.

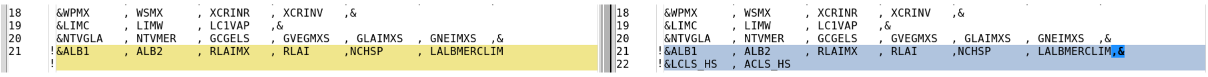

Fig. 6.2: Modification in arpifs/namelist/namphy1.nam.h. left: reference. right: modified.

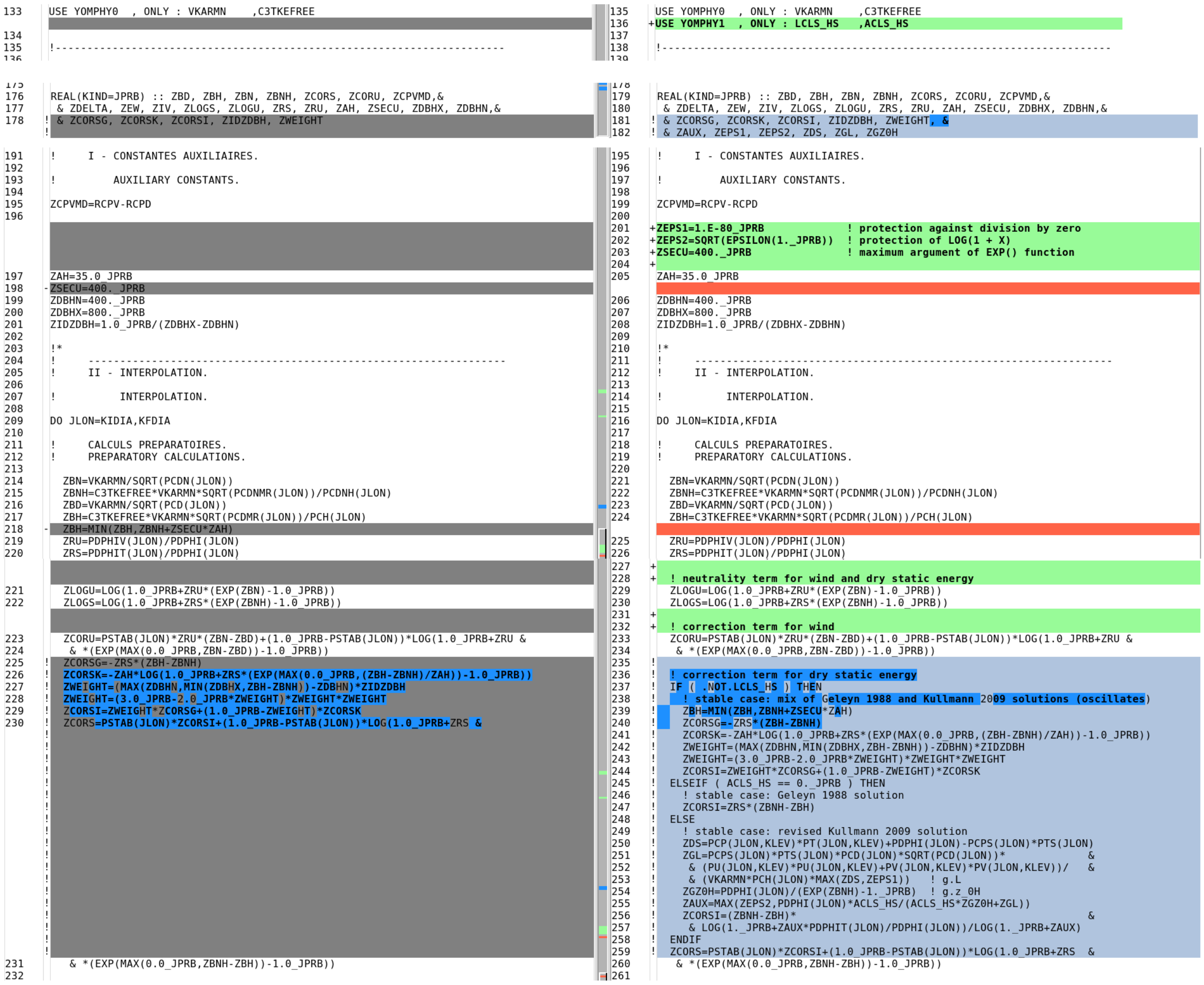

Fig. 6.3: Modification in arpifs/phys_dmn/actkecls.F90. left: reference. right: modified.

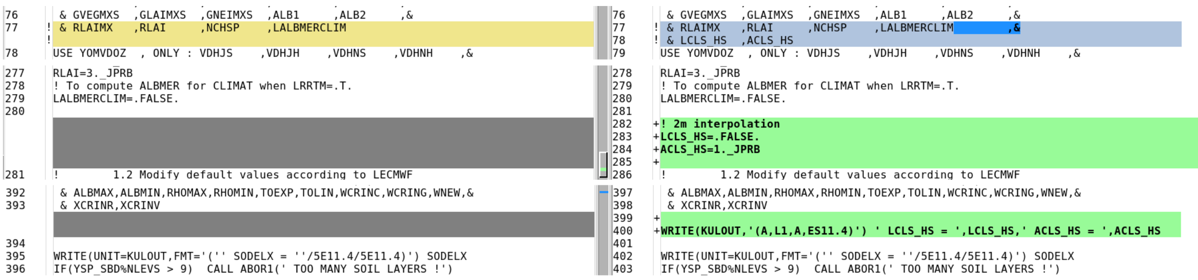

Fig. 6.4: Modification in arpifs/phys_dmn/suphy1.F90. left: reference. right: modified..

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