RC LACE research stay report

Topic: Mixing length computation
Executed by: Mario Hrastinski
Supported by: Radmila Brožkova
Prague, 29th February – 24th March 2016

1. Introduction

1.1. TOUCANS

TOUCANS (**T**hird **O**rder moments (TOMs) **U**nified **C**ondenstation **A**ccounting and **N**-dependent **S**olver for (for turbulence and diffusion)) turbulence parametrization is based on the framework of stability dependency functions[1,2]. This framework is build on the basis of four free parameters (influence the basic properties of the scheme): C_3 (ratio between heat and momentum transport), ν (overall intensity of turbulence), O_λ (conversion between kinetic and potential turbulence energy) and C_ϵ (intensity of turbulent disipation), as well as on three functional dependencies: P, R and Q (determine the level of complexity of the scheme; more details in[1,2]). By selecting different values of free paramaters and more complex forms of P, Q and R functional dependencies we may emulate various turbulence parameterizations. Namely those are: model I, model II, eeQNSE and eeEFB (more details in[1,2]). Common feature of all four schemes is that there is no critical Richardson number (Ri_{cr}), i.e. turbulence exists even for strongly stable flows. TOUCANS parametrization is implemented within the CY38t1(tr).

Here we will verify the performance of model II, wich has fixed values of free parameters (no stability dependance), constant P and R functional dependencies, while Q is a function of gradient Richardson number (Ri_g). In case of the most complex scheme (eeEFB), P, R and Q are all functions of Ri_g.

1.2. Mixing length

Length scale is one of crucial parameters in the parametrization of turbulence as it directly influences the intensity of exchange processes for momentum, heat and moisture. TOUCANS parametrization differs between the length scale for exchange processes (L_K) and dissipation length scale (L_ϵ), although due to consistency with previous turbulence parameterization (pTKE) a combined length scale is used as a main length scale[2]:

$$L = (L_K^3 \cdot L_\epsilon)^{\frac{1}{4}} \tag{1}$$

In current operational setup we use L_{GC} length scale (CGMIXELEN='EL0' option) which is of Prandtl type ($L_{GC} \rightarrow l_{GC}$), i.e. necessary compatibility between the free atmosphere and surface layer computations is directly ensured by its definition[2]:

$$l_{GC} = \frac{\kappa z}{1+\frac{\kappa z}{\lambda_m}\left[\frac{1+exp\left(-a_m\sqrt{\frac{z}{H_{ABL}}}+b_m\right)}{\beta_m+exp\left(-a_m\sqrt{\frac{z}{H_{ABL}}}+b_m\right)}\right]} \quad (2)$$

where κ is Von Karman constant, a_m, b_m and β_m are tuning constants, and H_{ABL} is the height of the atmospheric boundary layer (ABL).

Another option within the TOUCANS parametrization is to use more physical, but still general and unique length scale formulation like Bougeault and Lacarrere (1989)[3] (hereafter BL89). This formulation postulates that for each level in the atmosphere L_K and L_ϵ can be related to the distance which air parcel originating from this level, and having initial kinetic energy equal to the mean TKE of the layer, can travel upwards (L_{up}) and downwards (L_{down}) before being stopped by buoyancy effects (process is adiabatic)[4]:

$$\int_z^{z+L_{up}} \frac{g}{\overline{\theta_v}}\left(\overline{\theta_v}(z') - \overline{\theta_v}(z)\right) dz' = e(z) \quad (3a)$$

$$\int_{z-L_{down}}^{z} \frac{g}{\overline{\theta_v}}\left(\overline{\theta_v}(z) - \overline{\theta_v}(z')\right) dz' = e(z) \quad (3b)$$

where $\overline{\theta_v}$ and g are virtual potential temperature and gravity constant, while e is turbulent kinetic energy (TKE). In this formulation L_K and L_ϵ have to be related to same average value between L_{up} and L_{down}. The main benefit of this method is that it gives a non-local length scale, affected not only by stability at a given model level but also by remote stable zones. Notice that in uniformly stratified atmosphere (3a) and (3b) converge towards the well known Deardorff (1980) length scale[4]:

$$L_{up} = L_{down} = \sqrt{\frac{2e}{N^2}} \quad (4)$$

where N is a Brunt-Vaisla frequency.

Within the TOUCANS parametrization contribution of moist processes is included in terms of (non-saturated moist) Brunt-Väisälä frequency (N_v^2) related to modified Richardson number (Ri'') through shear (S) ($N_v^2 = Ri'' \cdot S$). Keeping the same formulation as within (3a) and (3b), we may calculate L_{up} and L_{down}[4]:

$$\int_z^{z+L_{up}} N_v^2(z'-z)\, dz' = e(z) \quad (5a)$$

$$\int_{z-L_{down}}^{z} N_v^2(z-z')\, dz' = e(z) \quad (5a)$$

where N_v^2 is[5]:

$$N_v^2 = \frac{g}{\theta_v}\frac{\partial\theta_v}{\partial z} \quad (6)$$

Virtual potential temperature is calculated using[5]:

$$\theta_v = T_v \left(\frac{p_r}{p}\right)^{R_d/c_{pd}} \tag{7}$$

where $p_r = 1013.25$ hPa is reference pressure, R_d is gas constant for dry air, while c_{pd} is specific capacity at constant pressure (also for dry air).

Virtual temperature is to the high accuracy given by[5]:

$$T_v \approx (1 + 0.61r)\, T \tag{8}$$

where r is mixing ratio given as a function of specific humidity (q):

$$r = \frac{q}{1-q} \tag{9}$$

In case of saturated moist air, Brunt-Väisälä frequency is calculated by using the moist antifibrilation scheme (this option is currently not included).

Once when L_{up} and L_{down} are known there are variety of options to calculate the main length scale. The original BL89 length expression (L_{BL-OR}) is[3]:

$$L_{BL-OR}(e, N^2) = min(L_{up}, L_{down}) \tag{10}$$

although Sanchez and Cuxart (2004) (hereafter SC04) suggest different expression (L_{BL-SC}) for non-saturated conditions:

$$L_{BL-SC}(e, N^2) = \sqrt{L_{up} \cdot L_{down}} \tag{11}$$

In current TOUCANS setup, there is an option (CGMIXELEN='EL1') to calculate the main length scale (L) using modified BL89 approach (L_{BL-TO})[2]:

$$L_{BL-TO}(e, N^2) = \left(\frac{L_{up}^{-\frac{4}{5}} + L_{down}^{-\frac{4}{5}}}{2}\right)^{-\frac{5}{4}} \tag{12}$$

but we will also work with another option which uses higher of the BL89 displacement values:

$$L_{BL-MAX}(e, N^2) = max(L_{up}, L_{down}) \tag{13}$$

To be consistent with the Monin-Obuhkov similarity theory, TKE-based length scale (L) has to be converted to the Prandtl type mixing length (l_m):

$$l_m = \frac{\upsilon^3}{C_\epsilon} L = A_1 \cdot L \tag{14}$$

where $\upsilon = (C_K \cdot C_\epsilon)^{\frac{1}{4}}$, i.e. conversion coefficient (A_1) depends on intensities of exchange processes (C_K) and turbulent dissipation (C_ϵ).

Besides currently operational mixing length given by (2) and BL89-TO mixing length given by (12) and (14), within TOUCANS parametrization there are another four options based on the combination of those two soley or joined with (4) or (13) (more details within the Table 1. of [2]).

1.3. Problem, assignment and work plan

It has been reported that all TKE based mixning lengths and their combinations produce too small mixing near the surface. Consequently, the forecast is deteriorated when compared to the one obtained by using (2). So, the main focus of this research will be on the review and optimization of ***acmixelen.F90*** subroutine, as well as on testing the model performance when using L_{GC} and L_{BL-TO}. We will also implement and test other BL89 main length scale options given by (11), (12) and (14), and eventually (or after the stay) some of the combinations.

Evaluation of forecasts obtained by using the above mentioned length scale options will be performed on a two week period of intensive summer convection (June 21th – July 5th 2009) over Central Europe. The forecasts will be initialized at 00 UTC, with the length of forecast window of 54 hours.

2. Code modifications

acmixelen.F90 subroutine:

- is optimized, i.e. some unnecessary calculations (like shear, change of geopotential with height, etc.) are removed and number of computing operations is reduced.
- calculation of virtual temperature (T_v) and virtual potential temperature (θ_v) is modified according to (7)-(9).
- calculation of 'dry' (or precisely moist without phase changes) Brunt-Väisälä frequency (N_v) is modified according to (6) and minor bug regarding the lower limit of absolute value of N_v was fixed (in prior version the sign was not preserved).
- CGMIXELEN='EL6' option was implemented. This option calculates the main length scale (L) by using BL89 original approach given by (10), or its modifications given by (12) or (13). Default setup uses (10) and depending on preferences, it can be manually changed to (12) or (13).

aplpar.F90 subroutine:

- call of ***acmixelen.F90*** subroutine was modified to include 'EL6' option.

3. Results

Table1. List of experiments with short description

Name of the experiment	Short description
'EL0a'	Using l_{GC}mixing length given by (2)
'EL1a'	Using l_{BL-TO} mixing length given by (12) and (14)
'EL1b'	Same as 'EL1b', but with new Brunt-Väisälä frequency (N_v) calculation given by (6)-(9)
'EL1c'	Same as 'EL1b', but without $L \to l$ conversion ($A_1 = 1$ in (14))
'EL1i'	Same as 'EL1c', but without 'harsh' lower limit on absolute value of Brunt-Väisälä frequency (N_v)[1]
'EL1l'	Same as 'EL1i', but with modified TKEMULT pamareter which was set to TKEMULT=2 (by default it was set TKEMULT=1)

Within the Table1. we have summarized the experiments performed with the goal of improving the forecast built on the BL89 mixing length formulation which was described in the introduction part. The same experiments were also performed for a newly implemented 'EL6' mixing length based on (10)-(11) and (13)-(14), as well as for 'EL2' (mix of Prandtl and TKE based approaches; details in [1] and [2]). As there are no major differences between forecasts obtained with all these approaches, we will stick here to the 'EL1' which was originally implemented within the TOUCANS. Later on we may switch to 'EL2' or 'EL6' if they provide smaller error for longer period(s) covering various stability regimes.

3.1. The effect of increasing the mixing length (L -> l_m conversion)

Analysis of vertical profiles of turbulent diffusion for zonal and meridional momentum, temperature and specific humidity was made using the DDH. Here are presented an averaged results for the whole domain of the ALADIN/ALARO1-CZ model. When comparing L_{GC} (EL0a; red) and L_{BL-TO} (EL1a; blue) based turbulent diffusion profiles (Fig 1.) we can see different signals for near surface zonal and meridional momentum diffusion, which overall resuts in higher near surface wind speed (not shown here) as meridional momentum diffusion is larger. Slightly above, both meridional and zonal diffusion become smaller for EL1a than for the reference (EL0a) which results in mostly weaker winds throughout the entire troposphere (not shown). When mixing length is increased six times (EL1c; orange) L_{BL-TO} turbulent momentum diffusion profiles come closer towards the reference.

[1] In old setup, lower limit of Brunt-Väisälä frequency (N_v) was set to 10^{-6} [s^{-2}], and here it is set to 10^{-8} [s^{-2}] which is the smallest number to be written in current precision (zeroes are not allowed as mixing length obtained from (5a), (5b) and (14) would be unity).

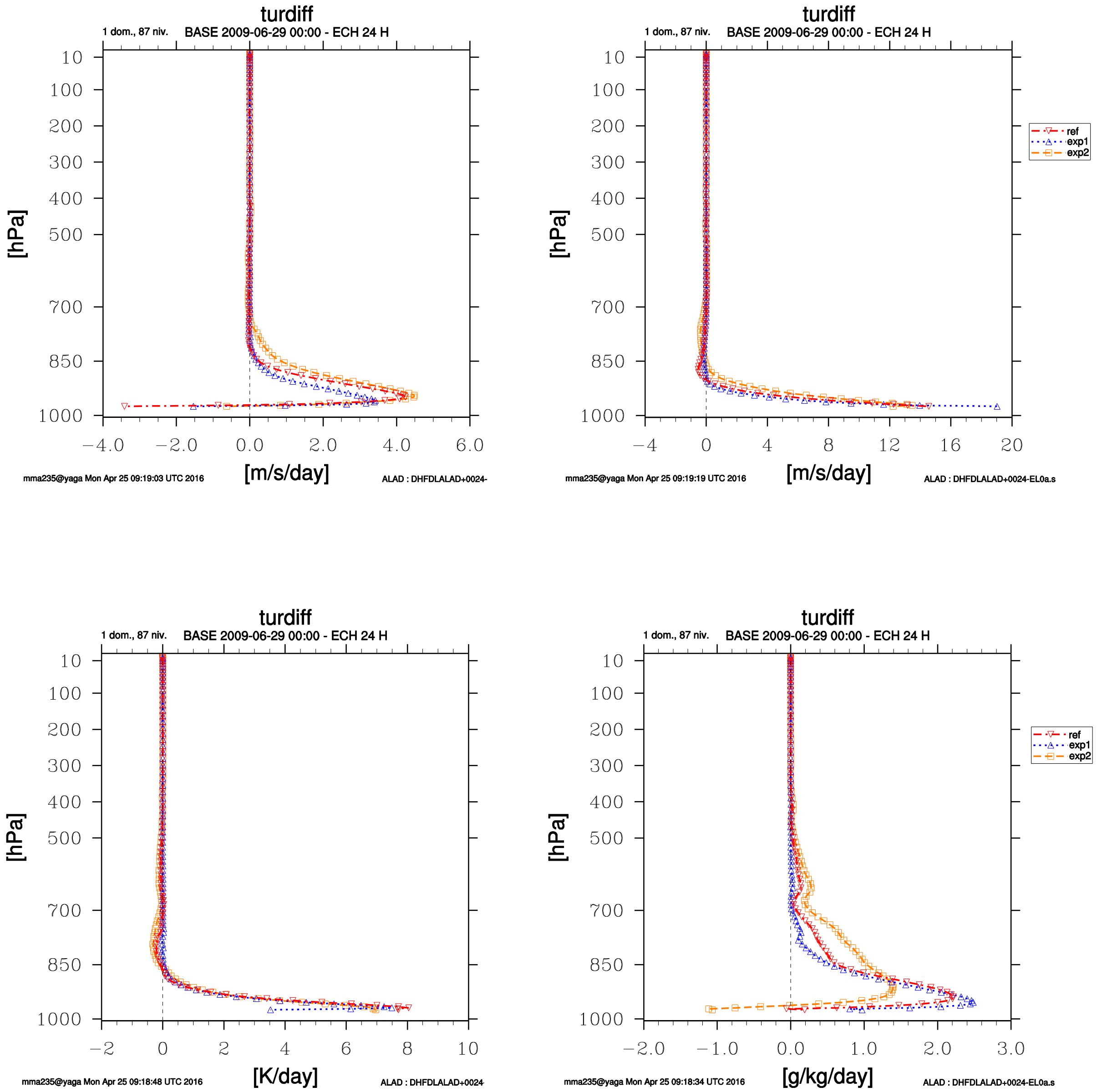

Fig 1. Vertical profile of turbulent diffusion for zonal (upper left panel) and meridional (upper right panel) momentum, temperature (lower left panel) and specific humidity (lower right panel) at 00 UTC on June 30th 2009. (29th June 00 UTC forecast + 0024 hrs). Red line with upright oriented triangles denotes reference (EL0a), blue line with downward oriented triangles denotes experiment 1 (EL1a), while orange line with squares denotes experiment 2 (EL1i). For explanation of experiment abbreviations please check Table1.

Major differences in turbulent diffusion profiles are observed for near surface and lower troposphere heat and moisture diffusion (Fig 1. lower panels) with significant impact on near surface fields of temperature and relative humidity (Fig 2. and Fig 3.). Very low contribution of turbulence term to near surface temperature budget (Fig 1.) results in appearence of a cold layer of air for the EL1a experiment (L_{BL-TO} based forecast). As contribution of turbulence term within the L_{GC} based forecast (EL0a) decreases, at some point it becomes significantly smaller than the same for the L_{BL-TO} based forecast which results in appearence of relatively warmer layer of air between 850 hPa and 700 hPa pressure levels (Fig 2.). Results for relative humidity show strong temperature signal in it, with the exception within the layer between 850 and 700 hPa pressure levels where the reference is more humid (Fig 3.). When mixing length is increased six times (EL1c; orange), near surface cold layer in L_{BL-TO} based forecast vanishes (Fig 4.). Except for the surface level, the temperature BIAS has significantly decreased in most of the lower troposphere (Fig 4.). It has decreased both over the L_{BL-TO} forecast with lower mixing and L_{GC}, which is currently used operationally. Unfortunately, the standard deviation (not shown) is significantly higher for both L_{BL-TO} based forecasts. This results in higher RMSE (not shown), although the increased mixing has significantly improved the results for the L_{BL-TO} based forecast. In the case of humidity increasing the mixing length resulted in smaller contribution of turbulence below the 850 hPa level and higher above it (Fig 1.; lower right panels). The overall effect on the relative humidity profile (Fig 5.) is mixed, i.e. positive near the surface, but negative around the 850 hPa pressure level. Further research is mandatory.

In general, we can say that mixing in current BL89 formulation is to small, but increasing it the way we did still leaves the problem of variability near the surface. At this point it seems that this may be caused either by: i) definition of the main length scale (eq. (1)) which removes the stability dependence between the L and l_m (eq. (14)), ii) putting the equality sign between the L_{BL-TO} and L or iii) some of the reported problems of the BL89 formulation near the surface and near neutrality (Lenderink and Holtslag (2004)).

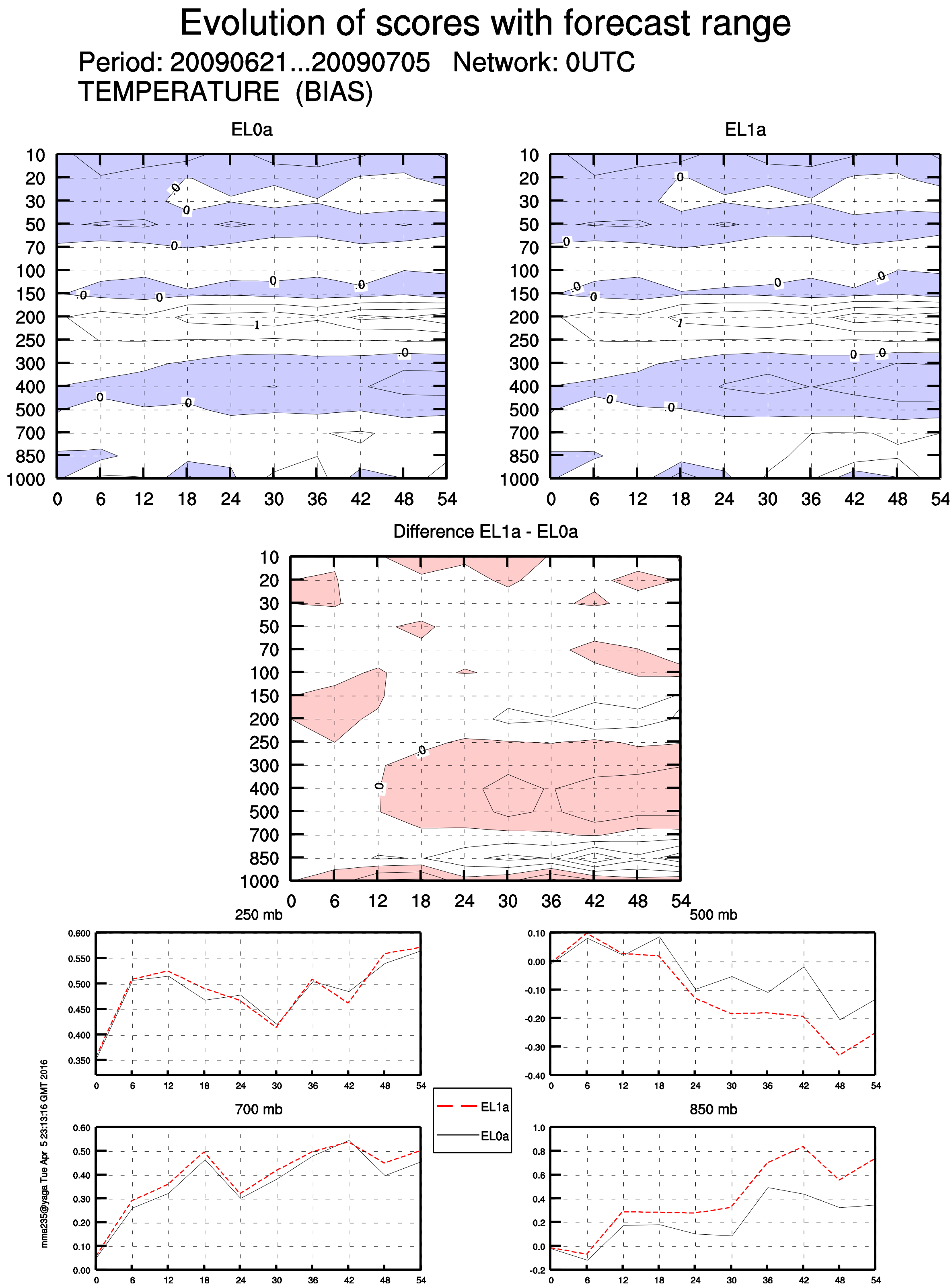

Fig 2. Time evolution of the BIAS of temperature for the reference (EL0a) and experiment (EL1a) throughout 54-hours forecast window; (1) averaged and height dependant – upper panels, (2) averaged and height dependent difference – middle panel and (3) at specific pressure levels – lower panels (for explanation of experiment abbreviations please check Table 1.).

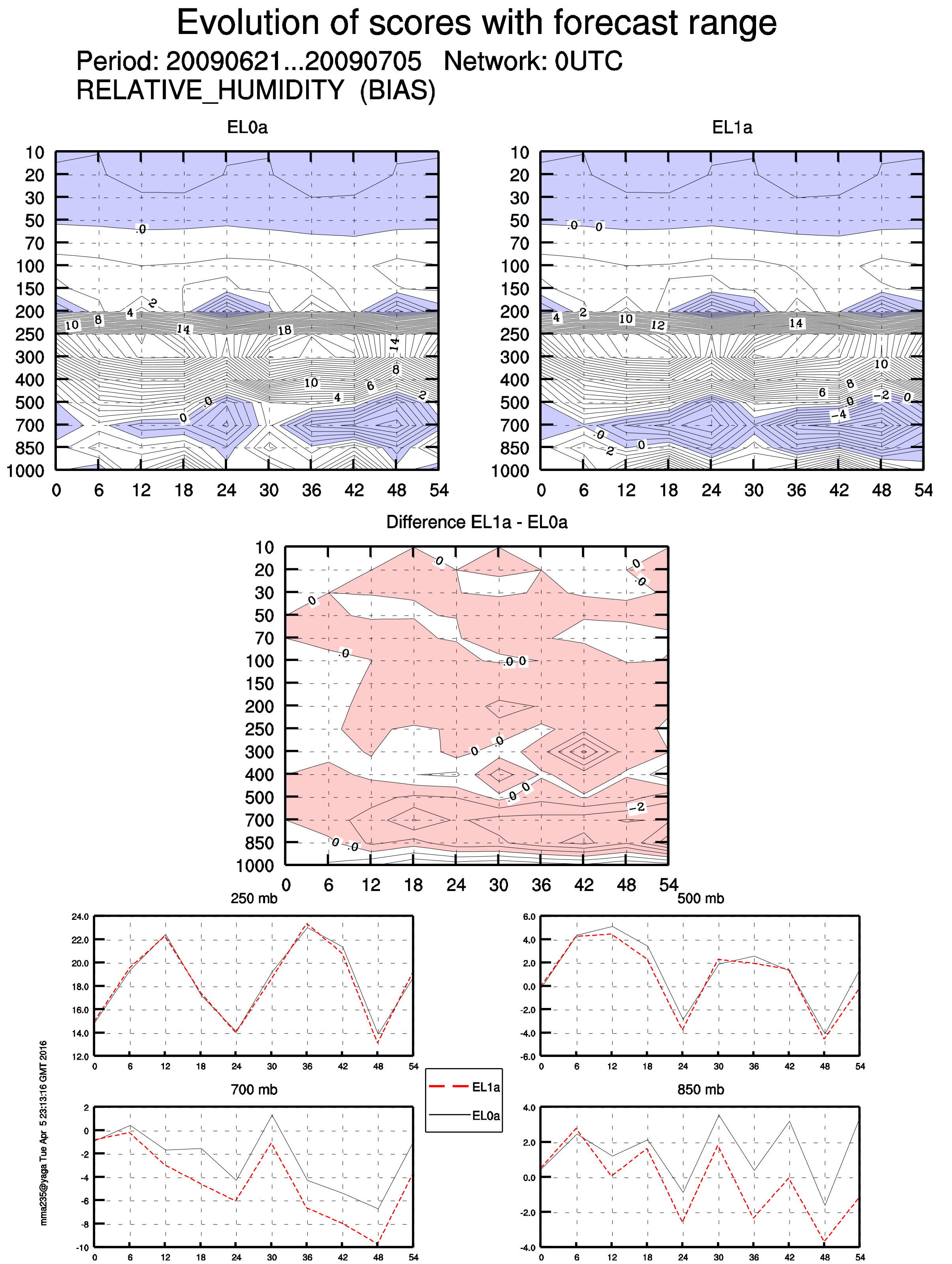

Fig 3. Time evolution of the BIAS of relative humidity for the reference (EL0a) and experiment (EL1a) throughout 54-hours forecast window; (1) averaged and height dependant – upper panels, (2) averaged and height dependent difference – middle panel and (3) at specific pressure levels – lower panels (for explanation of experiment abbreviations please check Table 1.).

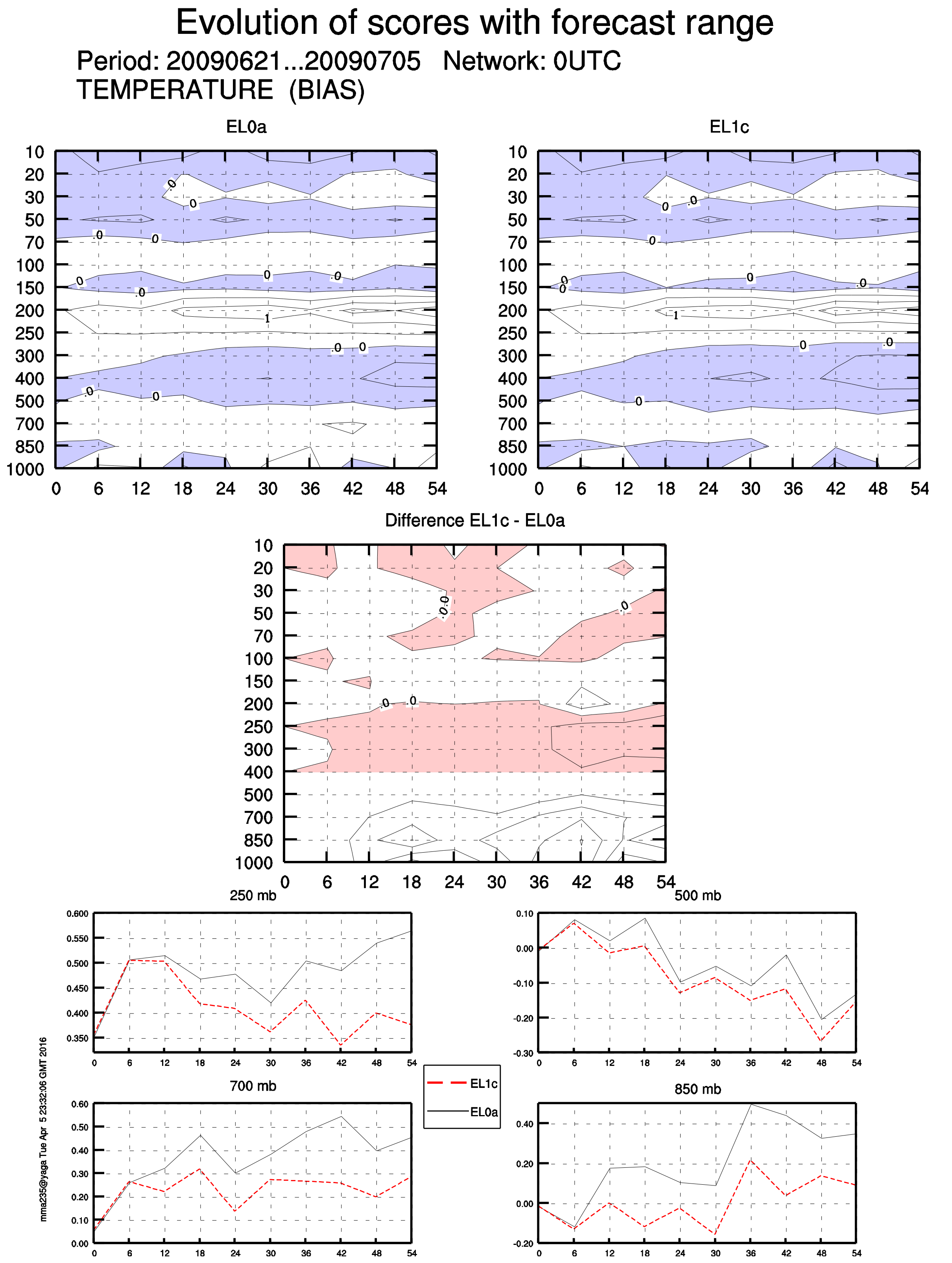

Fig 4. Time evolution of the BIAS of temperature for the reference (EL0a) and experiment (EL1c) throughout 54-hours forecast window; (1) averaged and height dependant – upper panels, (2) averaged and height dependent difference – middle panel and (3) at specific pressure levels – lower panels (for explanation of experiment abbreviations please check Table 1.).

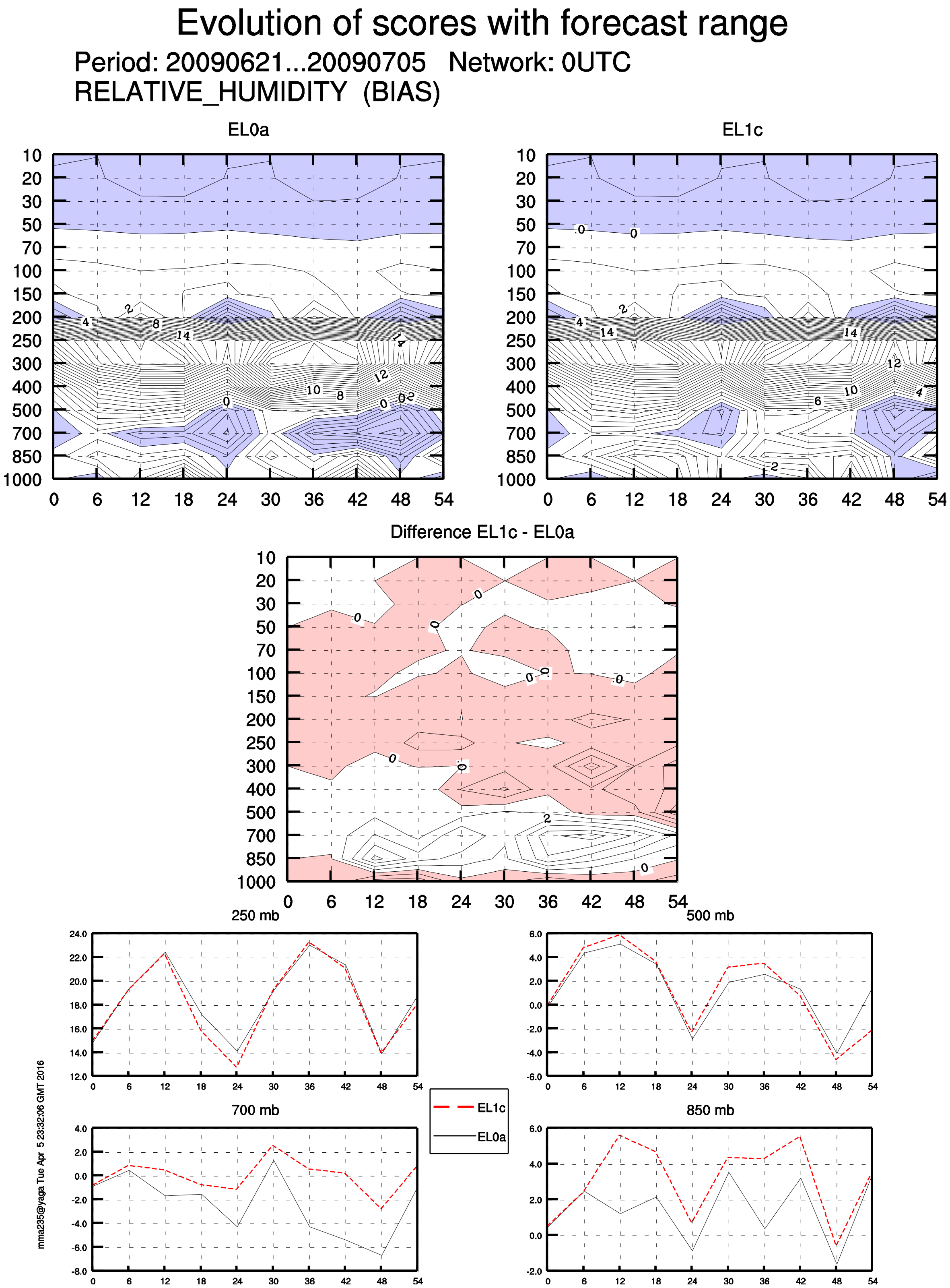

Fig 5. Time evolution of the BIAS of relative humidity for the reference (EL0a) and experiment (EL1c) throughout 54-hours forecast window; (1) averaged and height dependant – upper panels, (2) averaged and height dependent difference – middle panel and (3) at specific pressure levels – lower panels (for explanation of experiment abbreviations please check Table 1.).

3.2. Other experiments

Computation of Brunt-Väisälä frequency was modified according to (6)-(9). Overall effect on most of the parameters (wind speed, temperature, relative humidity, etc.) was mixed or increased BIAS and slightly decreased standard deviation (STD). Compared to the effect of increasing the mixing length, the impact was minor.

We have also experimented with different computations of L_{BL} from L_{up} and L_{down} according to (10)-(13). Option (13) resulted in increased both BIAS and STD, while option (11) led to mixed results. Other two options were almost equally successful, wherein the option (10) resulted in lower STD and (12) in lower BIAS.

Finally, we have increased the TKEMULT parameter to TKEMULT=2. By doing so we have increased the TKE which air parcel has at disposal to work against stratification, starting from a specific model level in the BL89 approach. Consequently, the main length scale is increased too. Compared to the experiment in previous chapter this effect was minor while overall results were mixed.

4. Conclusion

By increasing the conversion coefficient (A_1) between the main length scale and Prandtl type mixing length (eq. (14)), we have shown that turbulent mixing is way to low in the present BL89 main length scale formulation. When the conversion coefficient was increased to A_1=1 near surface BIAS of temperature and relative humidity were significantly decreased, both over the starting BL89 formulation ($L_{BL\text{-}TO}$) and the reference (L_{GC}). When different options for calculation of the main length scale from (BL89 formulation) L_{up} and L_{down} were compared, the original BL89 proposal (10) and currently used option within TOUCANS (12) were almost equally successful. Using the option (13) significantly increased both the BIAS and STD. Several other experiments were performed, but joint effect of those was almost negligible.

With the experiments performed here we have confirmed that the mixing within the present BL89 main length scale formulation is too low. By increasing it artificialy we have reduced the problematic BIAS of temperature and relative humidity near the surface, but have increased the relative humidity BIAS around 850 hPa level. The problem with standard deviation still persists and further diagnostic is mandatory. It should certainly include the analysis of mixing length stability dependance for L_{GC} and $L_{BL\text{-}TO}$ formulations. If such an analysis would have shown that there are significant discrepancies between the two options, the STD problem could be reduced by: i) modifying the definition of main length scale (eq. (1)), i.e. including the stability dependence between L and l_m, ii) modifying the relationship between the L_{BL} and L which are currently equal (this leads to different relationship between the L and L_K than proposed by Bougeault and Lacarrere (1989)) or iii) completely removing the computational main length scale (L) from the code.

5. References

[1] Bastak Duran, I., J.-F. Geleyn and F. Vana, 2014: A Compact Model for the Stability Dependency of TKE Production–Destruction– Conversion Terms Valid for the Whole Range of Richardson Numbers, *J. Atmos. Sci.,* **71***,* 3004-3026, doi:10.1175/JAS-D-13-0203.1*.*

[2] Bastak Duran, I.,2015: TOUCANS documentation

[3] Bougeault, P. and P. Lacarrere, 1989: Parametrization of Orography-Induced Turbulence in a Mesobeta-Scale Model, *Mon. Wea. Rev.*, **117**, 1872-1890.

[4] Vana, F., I. Bastak Duran, and J.-F. Geleyn, 2011: Turbulence length scale formulated as a function of moist Brunt-Väisälä frequency. *WGNE Blue Book*, chap. 4, 9-10.

[5] Lin, Y.-L., 2007: Mesoscale Dynamics, Cambridge Univ. Press, Cambridge, 630 pp.

[6] Sanchez, E. and J. Cuxart, 2004: A buoyancy-based mixing-length proposal for cloudy boundary layers, *Q. J. R. Meteorol. Soc.*, **130**, 3385-3404. doi: 10.1256/qj.03.121

[7] Lenderink, G., and A. A. M., Holtslag, 2004: An updated length-scale formulation for turbulent mixing in clear and cloudy boundary layers., *Quart. J. Roy. Meteorol. Soc.*, **130**, 3405–3427, doi: 10.1256/qj.03.117

Contents

1. Introduction 1

1.1. TOUCANS *1*

1.2. Mixing length *1*

1.3. Problem, assignment and work plan *4*

2. Code modifications 4

3. Results 5

3.1. The effect of increasing the mixing length (L -> l_m conversion) *5*

3.2. Other experiments *12*

4. Conclusion 12

5. References 13