Regional Cooperation for
Limited Area Modeling in Central Europe

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Overview of turbulence length scale developments in TOUCANS

Mario Hrastinski, Ján Mašek, Ivan Bašták Ďurán, Branko Grisogono and Radmila Brožková

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Outline

- Introduction: an overview of the TOUCANS scheme
- Development of the new Turbulence Length Scale (TLS) formulation
- Results:
  - Comparison with LES-diagnosed TLS and preliminary 3D model validation
  - Analysis of inversion and convection cases
  - Objective verification
- Conclusion

Introduction: an overview of the TOUCANS scheme

- TOUCANS is a two prognostic energy scheme (Baštak Ďuran et al. 2014, 2018):

$$\frac{de_k}{dt} = -g\frac{\partial}{\partial p}\left(\rho K_{e_k}\frac{\partial e_k}{\partial z}\right) + I + II - \frac{e_k^{\frac{3}{2}}}{\tau_k} \quad (1)$$

$$\frac{de_t}{dt} = -g\frac{\partial}{\partial p}\left(\rho K_{e_t}\frac{\partial e_t}{\partial z}\right) + I - \frac{e_t^{\frac{3}{2}}}{\tau_t} \quad (2)$$

$$I = -\overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{v'w'}\frac{\partial\overline{v}}{\partial z}, \qquad II = E_{s_{sL}}\overline{s_{sL}'w'} + E_{q_t}\overline{q_t'w'} \quad (3)$$

$$s_{sL} = c_{pd}\left(1 + \left[\frac{c_{pv}}{c_{pd}} - 1\right]q_t\right)T + gz - (L_v q_l + L_s q_i), \qquad q_t = q_t + q_l + q_i \quad (4)$$

Introduction: an overview of the TOUCANS scheme

- Computation of turbulent fluxes above the surface layer:

$$\overline{u'w'} = -K_M \frac{\partial u}{\partial z}, \qquad \overline{v'w'} = -K_M \frac{\partial v}{\partial z} \qquad (5)$$

$$\overline{s'_L w'} = -K_H \frac{\partial s_L}{\partial z} + TOMs, \qquad \overline{q'_t w'} = -K_H \frac{\partial q_t}{\partial z} + TOMs \qquad (6)$$

$$K_M = C_K L_K \chi_3 \sqrt{e_k}, \qquad K_H = C_K L_H \phi_3 \sqrt{e_k}, \qquad L_H = C_3 L_K \qquad (7)$$

- Computation of turbulent fluxes in the surface layer:

$$\overline{(w'\phi')}_s = C_\phi \sqrt{(u^2 + v^2)}[\phi(z) - \phi_s], \qquad C_{M/H} = C_{M/HN} F_{M/H}(Ri) \qquad (8)$$

$$C_{MN} = \left[\frac{\kappa}{ln\left(1 + \frac{z}{z_0 m}\right)}\right]^2, \qquad C_{HN} = \left[\frac{\kappa^2}{ln\left(1 + \frac{z}{z_0 m}\right) ln\left(1 + \frac{z}{z_0 h}\right)}\right] \qquad (9)$$

Introduction: an overview of the TOUCANS scheme

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- TLS is an essential quantity in the $e_k - L$ type of closure representing the size (dimension) of the most energetic turbulence eddies
- TOUCANS distinguishes several TLS: L_K, L_H and L_ϵ (related through the main/master TLS - L_n)
- Following Redelsperger et al. (2001), the relationship between L_K, L_ϵ and L_n is stability-dependent (cf. Mašek et. al. (2022) for details):

$$L_K = L_n F_\epsilon^{\frac{1}{3}}, \qquad L_\epsilon = \frac{L_n}{F_\epsilon}, \qquad F_\epsilon = \left[\frac{1 - Ri_f}{\chi_3(Ri_f)}\right]^{\frac{3}{4}} \tag{10}$$

- For consistency with previous pTKE scheme, it is assumed:

$$l_m = \frac{\nu^3}{C_\epsilon}\left(L_K^3 \cdot L_\epsilon\right)^{\frac{1}{4}} \quad \longrightarrow \quad L_n = \frac{C_\epsilon}{\nu^3} l_m, \qquad \nu = (C_K C_\epsilon)^{\frac{1}{4}} \tag{11}$$

l_m - Prandtl type mixing length; $C_\epsilon/\nu^3 \approx 6$ (prone to tuning)

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Introduction: an overview of the TOUCANS scheme

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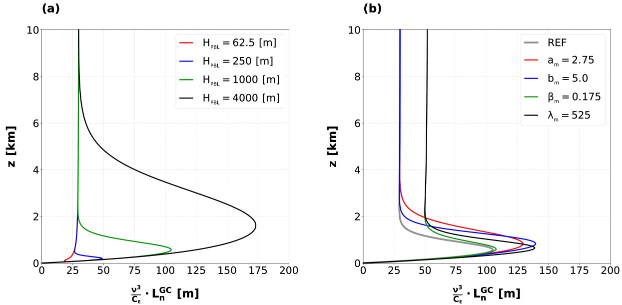
- Currently, the Geleyn-Cedilnik formulation is a default choice in TOUCANS:

$$L_n^{GC} = \frac{C_\epsilon}{\nu^3} \frac{\kappa z}{1 + \frac{\kappa z}{\lambda_m}\left[\frac{1+\exp\left(-a_m\sqrt{\frac{z}{H_{PBL}}}+b_m\right)}{\beta_m+\exp\left(-a_m\sqrt{\frac{z}{H_{PBL}}}+b_m\right)}\right]} \quad (12)$$



1. Very sensitive to the H_{PBL} est.
2. UAL=const. may be a problem
3. Small variability (in practice)
4. Too strong mixing in SABL

REF: a_m=4.5, b_m=3.0, β_m=0.1 and λ_m=300

Development of the new TLS formulation

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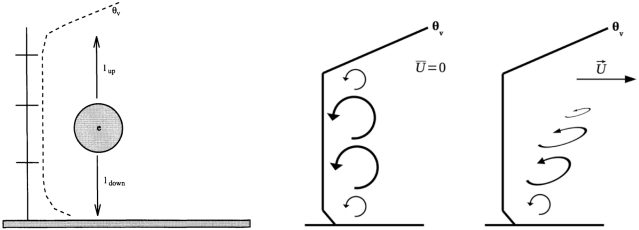
- We start from the generalized version of BL89 TLS following Rodier et al. (2017):

$$\int_{z}^{z+L_{up}} \left\{ \frac{g}{\theta_v(z')} \left[\theta_v(z') - \theta_v(z)\right] + c_0\sqrt{e(z')}S(z') \right\} dz' = e(z) \tag{13}$$

$$\int_{z-L_{down}}^{z} \left\{ \frac{g}{\theta_v(z')} \left[\theta_v(z) - \theta_v(z')\right] + c_0\sqrt{e(z')}S(z') \right\} dz' = e(z) \tag{14}$$



$$L_{TKE} = \left(\frac{L_{up}^{p} + L_{down}^{p}}{2} \right)^{\frac{1}{p}} \tag{15}$$

Development of the new TLS formulation

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- Can we assign L_{TKE} directly to any of TLS options within TOUCANS?
  1. Obey similarity laws in the surface layer: ~~L_K~~ and ~~L_ϵ~~
  2. Ensure numerically stable solution: ~~l_m~~

- Initial attempt with the remaining option (L_n):

$$\mathrm{L_n} = \min\left(\frac{\mathrm{C}_\epsilon}{\nu^3}\kappa \mathrm{z}, \mathrm{L_{TKE}}\right) \qquad (16)$$

Problems:

1. Obeying MOST is not ensured
2. Possibility of a "jumpy" solution
3. Insufficient mixing (overall)

Development of the new TLS formulation

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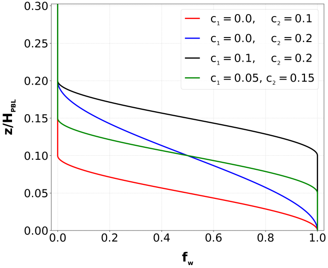
- Smoothing the transition between two solutions in the surface layer:

$$f_w = 3 \cdot {f'_w}^2 - 2 \cdot {f'_w}^3; \qquad f'_w = \max\left[0, \min\left(1, \frac{c_2 - \frac{z}{H_{PBL}}}{c_2 - c_1}\right)\right], \quad c_2 > c_1 \tag{17}$$

$$L_n = \kappa z \frac{C_\epsilon}{\nu^3} f_w + L_{TKE} (1 - f_w) \tag{18}$$



1. Partly solves the problem of insufficient mixing
2. Problems in convective conditions and near PBL top
3. Can crossing parcels help (e.g., Golaz et al. 2002)?

Development of the new TLS formulation

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- Few more items are needed to finalize the solution:

1) Regime-dependent minimum TLS near the PBL top (Bechtold and Marquet 2020):

$$\mathrm{L_{BLT}} = \min\left\{\max\left[\mathrm{L_{BLT2}} + \frac{\mathrm{L_{BLT2}} - \mathrm{L_{BLT1}}}{\mathrm{C_{\Delta 2}} - \mathrm{C_{\Delta 1}}}\left(\Delta\theta_{\mathrm{s}} - \mathrm{C_{\Delta 2}}\right), \mathrm{L_{BLT1}}\right], \mathrm{L_{BLT2}}\right\} \quad (19)$$

$$\Delta\theta_{\mathrm{s}} = \theta_{\mathrm{s}}(\mathrm{z} = 1.5 \cdot \mathrm{H_{PBL}}) - \theta_{\mathrm{s}}(\mathrm{z} = 0) \quad (20)$$

2) Minimum allowed upper-air TLS ($\mathrm{L_{UTLS}}$ + $\mathrm{L_{TRANS}}$):

$$\mathrm{L_{TKE}} = \max(\mathrm{L'_{TKE}}, \mathrm{L_{MIN}}), \quad \mathrm{L_{MIN}} = \mathrm{f}\left(\mathrm{L_{BLT}}, \mathrm{L_{TRANS}}, \mathrm{L_{UTLS}}\right) \quad (21)$$

3) Introduction of global scaling with κ (even smoother transition in the surface layer):

$$\mathrm{L_n} = \frac{\kappa \mathrm{C}_{\epsilon}}{\nu^3}\left[\mathrm{f_w} \mathrm{z} + (1 - \mathrm{f_w}) \mathrm{L_{TKE}}\right] \quad (22)$$

Development of the new TLS formulation

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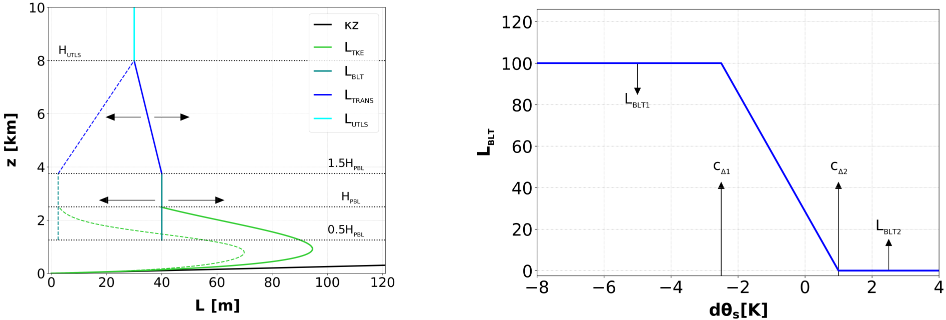
- Scheme of the final solution:



We need a reliable "tool" to validate this → LES-based TLS diagnostics

MicroHH DNS and LES model (van Heerwaarden et al. 2017)

Results (LES diagnostics)

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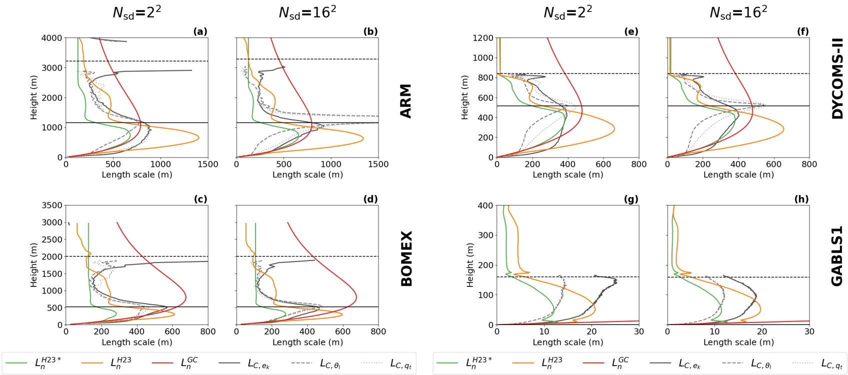
- TLS is diagnosed from LES budgets of e_k, s_{sL} and q_t after Bašták Ďurán et al. (2020) and Reilly et al. (2022) - four idealized cases



L_n^{GC} - reference

L_n^{H23} - our proposal with global κ scaling and L_{MIN}

L_n^{H23*} - as L_n^{H23} + local κ scaling + minor tuning + crossing parcels

ARM - continental Cu; BOMEX - trade wind Cu; DYCOMS-II - drizzling Sc; GABLS1 - very stable

Results (preliminary 3D model validation)

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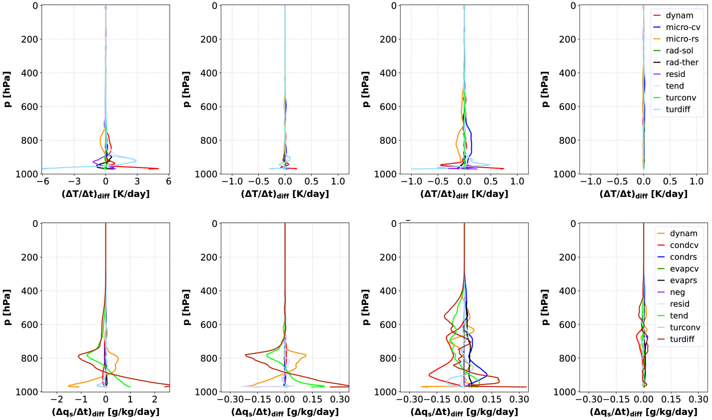
- What is the contribution of components we added to the L_n^{H23} solution?



κ scaling | SL smoothing | L_{BLT} | L_{UTLS} + L_{TRANS}

1. κ scaling is essential
2. Smoothing diminishes the impact of L_{up}
3. The impact of L_{BLT} is important in all cond.
4. The impact of L_{UTLS} + L_{TRANS} is small

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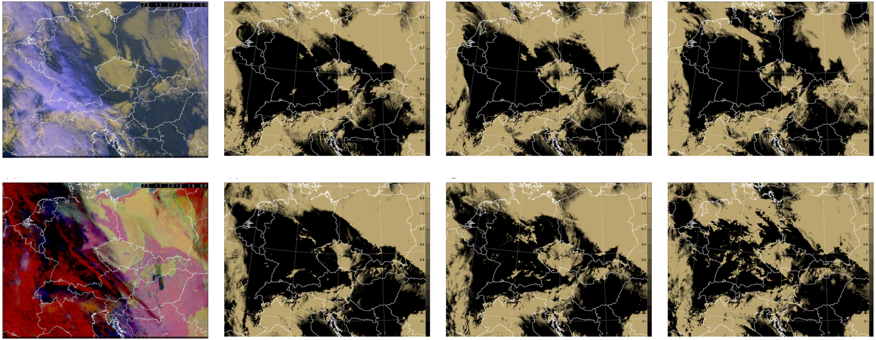
Results (analysis of the inversion case)

- ALADIN-CZ at Δx=2.3125 km and 87 levels, NH-dynamics and ALARO-1 physics
- Anticyclonic period with persistent inversion over Czechia (23 November 2019 case)

12 UTC

18 UTC



MSG | L_n^{GC} | L_n^{H23} | L_n^{H23*}

Results (analysis of the inversion case)

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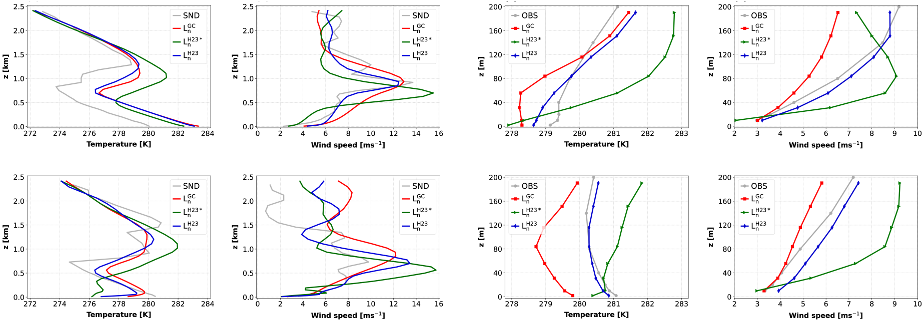
- Slightly improved representation of inversion (Prague-Libuš)
- Improved temperature and wind profiles at Cabauw (heat and moisture fluxes as well)

12 UTC

24 UTC



Prague-Libuš

Cabauw

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Results (analysis of the convection case)

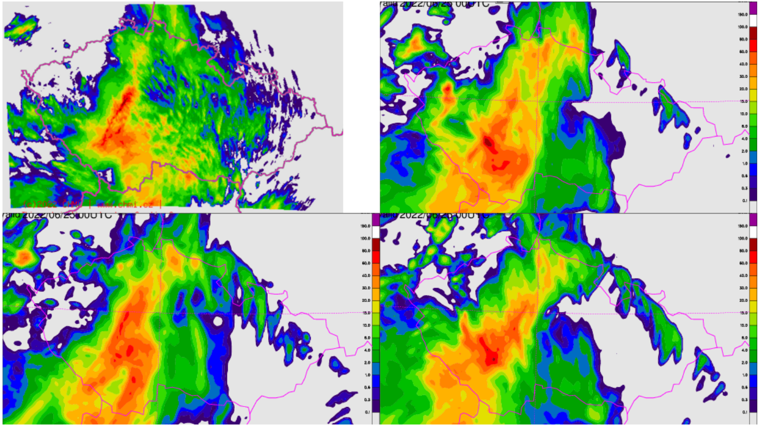
- Mesoscale Convective System - 24th June 2022 ($>$ 100 mm of precipitation in Prague)

CZRAD

18-24 UTC

L_n^{GC}

6h accum.



L_n^{H23}

L_n^{H23*}

Results (objective scores)

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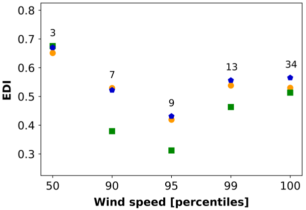
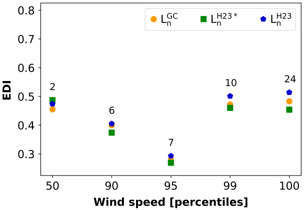
- The L_n^{H23*} option (very close to initial implementation) had 15-25% larger RMSE for most of the surface and upper-air scores (up to 850-700 hPa)
- Due to κ scaling (mainly) and "internal" tuning (C_0, c_2, $c_{\Delta 1}$, $c_{\Delta 2}$ and L_{BLT1}), the statistical performance is now nearly neutral with the reference (L_n^{GC})
- However, there are some improvements:

1. BIAS and RMSE of cloudiness ($\sim$ 2%)
2. STD of T2m ($\sim$ 1.5-2%)
3. Extreme 10-m wind (FB and EDI $\sim$ 3.5-6.5%)
4. Upper-air rel. humidity



winter



summer

Conclusions

- The settings of L_n^{H23} TLS formulation are more or less confirmed by LES-diagnostics and it gives satisfying first results within the 3D model
- As expected, the improvement is mainly seen in statically stable conditions
- Further validation and tuning of other components/processes are needed
- Despite similar attempts (L_{MIN} and H_{PBL} method), the L_n^{GC} formulation was not improved
- The L_n^{H23} TLS formulation is not scale-aware (obvious from LES results), neither the TOUCANS scheme (at least not fully) - further work is aimed in that direction

There is a related publication in preparation!

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Thank you for your attention.

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