Regional Cooperation for Limited Area Modeling in Central Europe

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TKE-based turbulence length scale in TOUCANS: the final settings and their preliminary validation

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Outline

- Introduction: an overview of the TOUCANS scheme
- Development of the new Turbulence Length Scale (TLS) formulation
- Results:
  - 1D model validation against LES data
  - The high-impact weather situations in 3D model
  - The objective verification
- Conclusion

Introduction: an overview of the TOUCANS scheme

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- 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:

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

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

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

- Computation of turbulent fluxes in the surface layer:

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

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

Introduction: an overview of the TOUCANS scheme

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- TLS is an essential quantity in the $\mathrm{TKE}-\mathrm{L}$ type of closure representing the size (dimension) of the most energetic turbulence eddies

- TOUCANS distinguishes several TLS: $L_{K/H}$ and L_ϵ (related via the 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):

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

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

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

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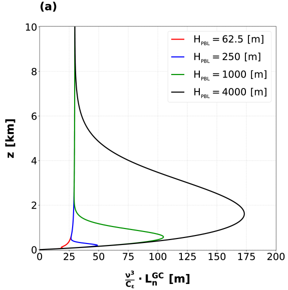
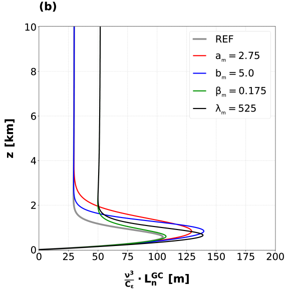
- Currently, the Geleyn-Cedilnik formulation is a default choice in TOUCANS:

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





1. Very sensitive to the H_{PBL} estimation
2. UAL=const. (should be regime-dependent)
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

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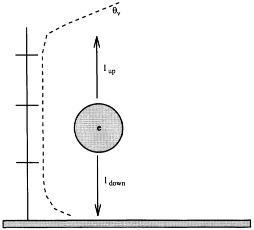
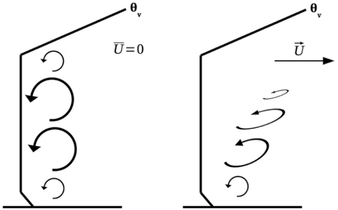
Development of the new TLS formulation

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

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

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





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

Development of the new TLS formulation

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- Can we assign L_{AVG} 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):

$$L_n = \min\left(\frac{C_\epsilon}{\nu^3}\kappa z, L_{AVG}\right) \qquad (16)$$

Problems:

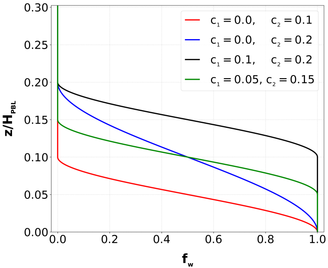
1. Obeying MOST is not ensured
2. Possibility of a "jumpy" solution
3. Insufficient mixing (overall)

Development of the new TLS formulation

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

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

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



1. Ensures obeying MOST and smooth and stable solution
2. Partly solves the problem of insufficient mixing
3. Problems in convective conditions and near PBL top

Development of the new TLS formulation

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- Few more items are needed to finalize the TLS formulation:

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

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

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

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

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

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

$$L_n^{H24} = \frac{\kappa C_\epsilon}{\nu^3}\left[f_w z + (1 - f_w) L_{TKE}\right] \quad vs. \quad L_n^{H24*} = \frac{C_\epsilon}{\nu^3} f_w \kappa z + (1 - f_w) L_{TKE} \quad (22)$$

Development of the new TLS formulation

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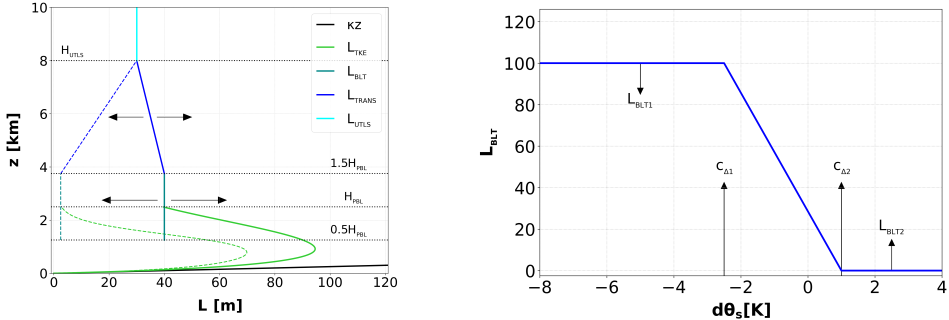
- Scheme of the final solution:



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

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

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Results: 1D model validation against LES data

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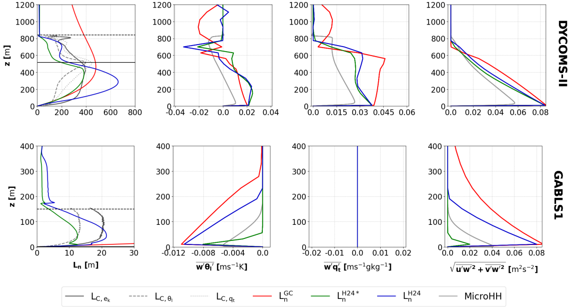
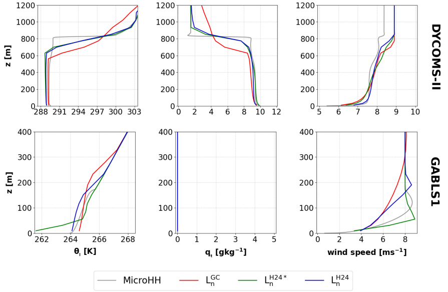
- The evaluation in idealized cases (1-h averaged profiles): (i) more stable PBL (DYCOMS-II and GABLS1; at +3-h and +4.5-h) and (ii) convective PBL (ARM and BOMEX; at +10-h and +7-h)
- TLS is diagnosed from LES budgets of e_k, s_{sL} and q_t after Bašták Ďurán et al. (2020) and Reilly et al. (2022)
- An improvement over the L_n^{GC} in DYCOMS-II and GABLS cases, particularly near the surface and the PBL top (key roles of κ scaling and $\mathrm{L_{BLT}}$)





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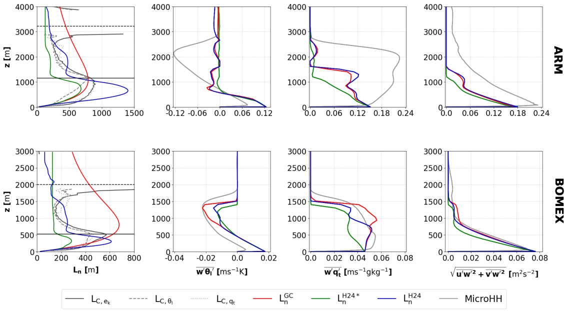
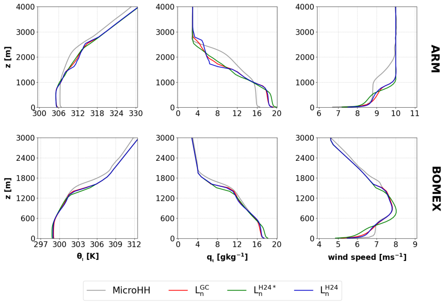
Results: 1D model validation against LES data

- In ARM and BOMEX cases, L_n^{H24} and L_n^{GC} perform similarly, while L_n^{H24*} underestimates TLS and fluxes
- Within the cloud layer and ARM case, L_n^{GC} and L_n^{H24}) considerably underestimate mixing. However, unlike L_n^{H24*}, their $\mathrm{H_{PBL}}$ is comparable to LES
- The ARM case results point to the importance of counter-gradient terms (TOMs)





Results: the high-impact weather situations in 3D model

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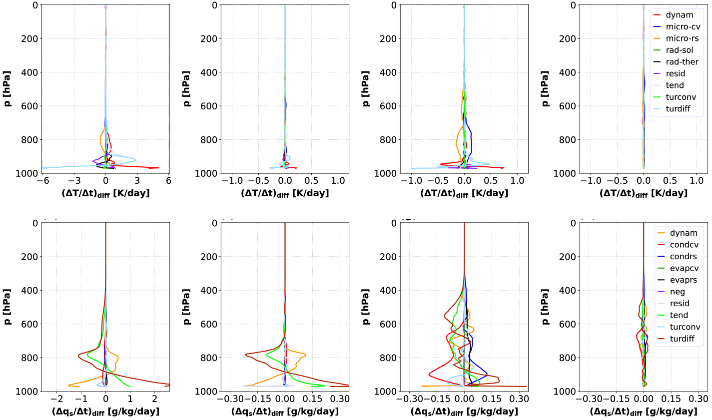
- What is the contribution of components we added to the L_n^{H24} solution?

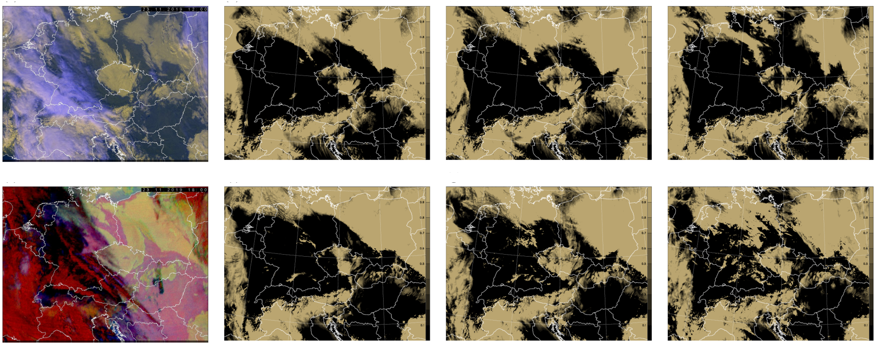


κ scaling | SL smoothing | L_{BLT} | $L_{UTLS} + L_{TRANS}$

1. The κ scaling is crucial
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
5. The impact of TLS tuning is moderate

Results: the high-impact weather situations in 3D model

- 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

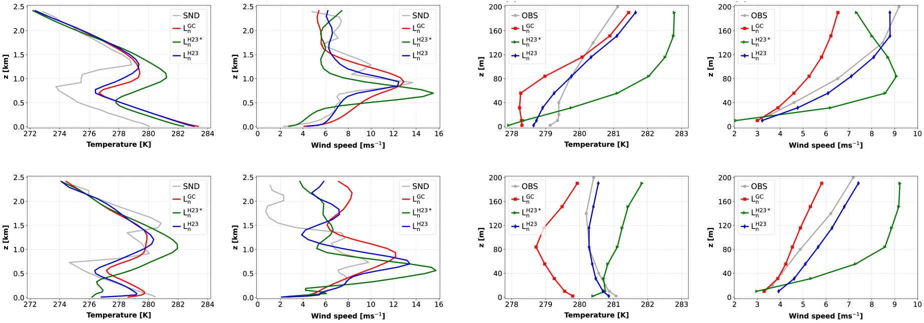
MSG | L_n^{GC} | L_n^{H24} | L_n^{H24*}

Results: the high-impact weather situations in 3D model

- Slightly improved representation of inversion (Prague-Libuš)
- Improved averaged daytime and nighttime temperature and wind profiles at Cabauw

12 UTC

24 UTC



Prague-Libuš

Cabauw

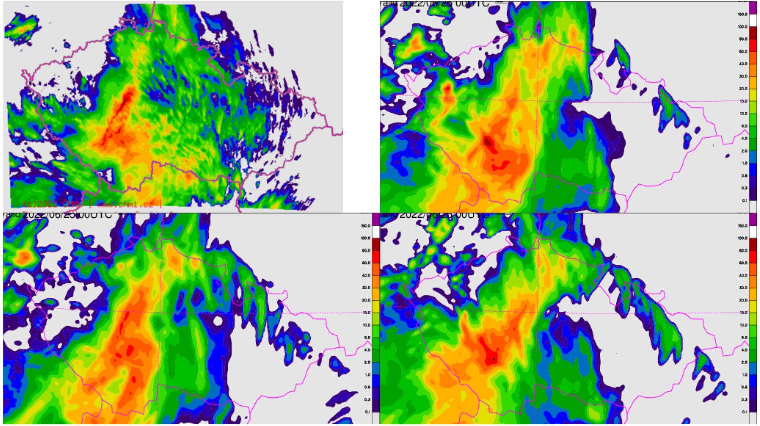
Results: the high-impact weather situations in 3D model

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

CZRAD

18-24 UTC

$\mathbf{L_n^{H24}}$



$\mathbf{L_n^{GC}}$

6h accum.

$\mathbf{L_n^{H24*}}$

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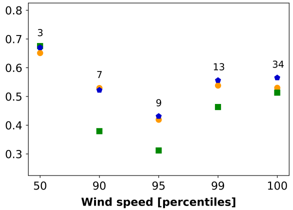
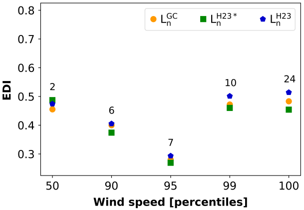
Results: the objective verification

- The L_n^{H24*} formulation (close to the initial implementation) has 15-25% larger RMSE for most of the surface and upper-air scores (up to 850-700 hPa) for two 10-day periods
- Due to κ scaling (mainly) and "internal" tuning (C_0, c_2, $c_{\Delta 1}$, $c_{\Delta 2}$ and L_{BLT1}), the statistical scores for L_n^{H24} are nearly neutral to L_n^{GC}; confirmed on additional 3-5 day periods
- However, there are also 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

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- The settings of L_n^{H24} TLS formulation are more or less confirmed by LES-diagnostics and 1D model evaluation, yielding also satisfying first results within the 3D model
- As expected, the improvement is mainly seen in statically stable conditions
- Further validation and tuning of other model components/processes is needed
- Despite similar attempts (L_{MIN} and H_{PBL} method), the L_n^{GC} formulation is not improved
- Future work aims to address: (i) the scale-awareness of TLS and TOUCANS scheme, (ii) the 3D aspects of turbulence and (iii) the treatment of the stable PBL in situatiotns with weak wind

The related manuscript is in revision at Monthly Weather Review:
Hrastinski, M., Mašek, J.,Bašták Ďurán, I., Grisogono, B. and Brožková, R., 2024: Regime-dependent turbulence length scale formulation for NWP models based on turbulence kinetic energy, shear and stratification.

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