Regional Cooperation for
Limited Area Modeling in Central Europe

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First attempts to implement horizontal features to the turbulence scheme TOUCANS of ACCORD/ALARO

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Outline

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The turbulence scheme TOUCANS

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(J.F.Geleyn, I.Bašták Ďurán et al.)

T - Third

O - Order moments

U - Unified

C - Condensation

A - Accounting and

N - N-dependent

S - Solver for turbulence and diffusion

The turbulence scheme TOUCANS

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- uses two prognostic energies - TKE and TTE=TKE+TPE
- TPE is used only for a modification of the stability parameters
- the vertical turbulent fluxes are proportional to the local gradients of the diffused variables, but the stability parameters and the turbulent exchange coefficients are not strictly local anymore and have a prognostic character
- these characteristics enable the scheme to model both turbulence and clouds in the planetary boundary layer

The turbulence scheme TOUCANS

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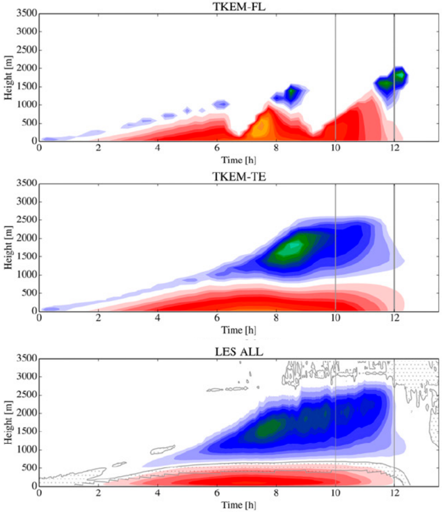
TKE

TKE
+TTE

LES



The two-energy scheme shows a more continuous behavior in time and space and mixes deeper in accordance with the LES results.

(courtesy of I.Bašták)

Towards the 3D turbulence and grey zone

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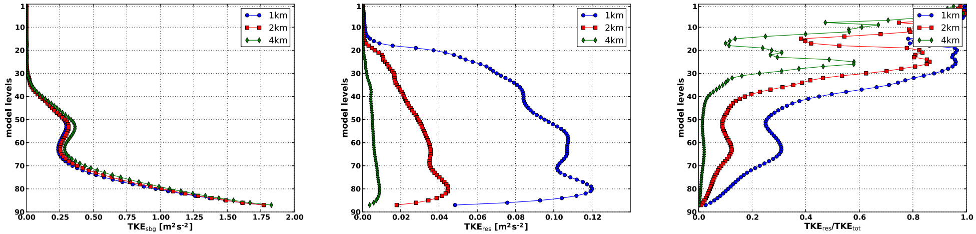
- The existing turbulence schemes in NWP models are intended for use in horizontally homogeneous and flat terrain (1D)
- At $\Delta x \approx 1$ km and in complex (mountainous) terrain the turbulence intensity is typically underestimated - need for 3D effects
- Furthermore, at $\Delta x \approx 1$ km we are within the gray zone (turb. is partly resolved) - need to take care of partitioning between TKE_{res} and TKE_{sbg}



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Prognostic equations in TOUCANS

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for the turbulent kinetic and the turbulent total energy [Ďurán et al. (2018)]

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

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

The shear production term

$$I = -\overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{v'w'}\frac{\partial\overline{v}}{\partial z}$$

The buoyancy production/destruction term

$$II = E_{s_{sL}}\overline{s_{sL}'w'} + E_{q_t}\overline{q_t'w'}$$

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Horizontal features in TOUCANS

in the turbulent kinetic and the turbulent total energy prognostic equations [Goger et al. (2018, 2019)]

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

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

The shear production term

$$I = -\overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{v'w'}\frac{\partial\overline{v}}{\partial z} - \overline{u'u'}\frac{\partial\overline{u}}{\partial x} - \overline{u'v'}\frac{\partial\overline{u}}{\partial y} - \overline{u'v'}\frac{\partial\overline{v}}{\partial x} - \overline{v'v'}\frac{\partial\overline{v}}{\partial y}$$

The buoyancy production/destruction term

$$II = E_{s_{sL}}\overline{s_{sL}'w'} + E_{q_t}\overline{q_t'w'}$$

Horizontal turbulent length scale L_H

The horizontal shear production term

$$HSP = L_H^2 \cdot \left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 \right]^{\frac{3}{2}}$$

APPROACH 1: Constant horizontal length scale
[Smagorinski (1963), Goger (2018)]

$$L_H = c_s \Delta x, \quad c_s = 0.2.$$

It is too simple and appropriate only for small scale processes which are isotropic.

Horizontal turbulent length scale L_H

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APPROACH 2: Variable horizontal length scale [Goger et al. (2019)]

$$L_H = W \cdot T_{L,u,v}, \qquad T_{L,u,v} = 0.15\frac{H_{PBL}}{\sigma_{u,v}}$$

W - mean horizontal wind speed, $T_{\mathrm{L,u,v}}$ - Lagrangian integral time scale
H_{PBL} - the height of PBL, $\sigma_{u,v}$ - the zonal and meridional wind variances

$$\sigma_u^2 = u_*^2\left(5 - 4\frac{z}{H_{PBL}}\right) + 0.35u_*^2\left(\frac{H_{PBL}}{\kappa L}\right)^{\frac{2}{3}}$$

$$\sigma_v^2 = u_*^2\left(2 - 2\frac{z}{H_{PBL}}\right)$$

inapplicable above the PBL + based on a specific dataset
* additional term in statically unstable conditions

Computation of the PBL height

None of the existing methods estimates the H_{PBL} accurately enough for different stability conditions

Weak-capping-inversion (WCI)
[Ayotte et al. (1996)]

$$\langle\theta(z)\rangle_L \geq \frac{1}{z}\int_0^{z_i} \langle\theta(z)\rangle dz + 0.25$$

is appropriate for convective and near-neutral PBL

TKE-based method
[Kosović and Curry (2000)]

$$H_{PBL} = \frac{z_{05}}{0.95}$$

is more general (suitable for statically stable conditions)

Computation of the PBL height

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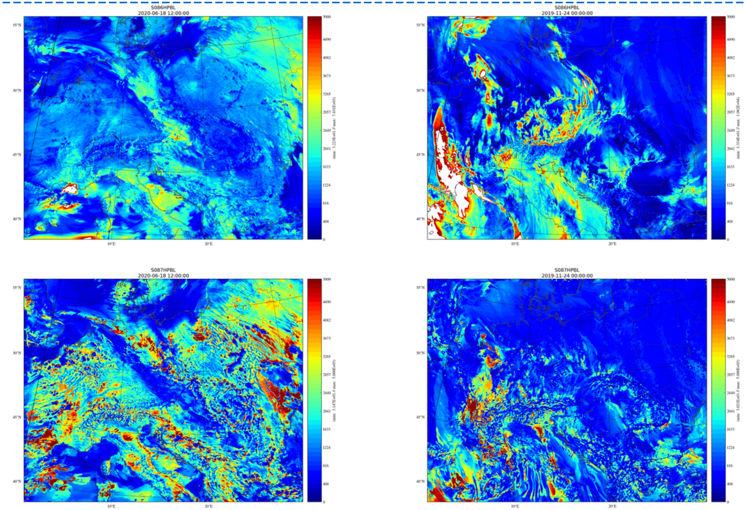

WCIM method

TKE-based method

(courtesy of M.Hrastinski)

Computation of the PBL height

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- WCIM provides unrealistic values in statically stable conditions, while TKE-based method is characterized by grainy patterns
- Can a combination of two methods work?
- We need a more robust method, e.g. [Bašták et al. (2022)]

$$H_{PBL} = c_{pblh} \cdot \sqrt{\int_{z=0}^{z_{top}} L_{up} \cdot dz}, \qquad c_{pblh} = 1.75$$

L_{up} depends on stratification and turbulence within the entire model column

Horizontal turbulent length scale L_H

APPROACH 3: Horizontal length scale depending on properties of the local flow [Wang et al. (2021)] based on the length scales for shear and stretching

$$L_{Hshr} = sW\left[\left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}^2\right)\right]^{-\frac{1}{2}}, \quad L_{Hstr} = sW\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}^2\right)\right]^{-\frac{1}{2}}$$

$$s = \left(\frac{\Delta_0}{\Delta x}\right)^{\alpha}, \quad L_H = \sqrt{L_{Hshr} L_{Hstr}}$$

where Δ_0 is the grid spacing at which the model can resolve the most energetic turbulent eddies and $\alpha = 1.45$ is an empirical constant based on the fit with observations.

Current status of the implementation in ACCORD/ALARO and future plans

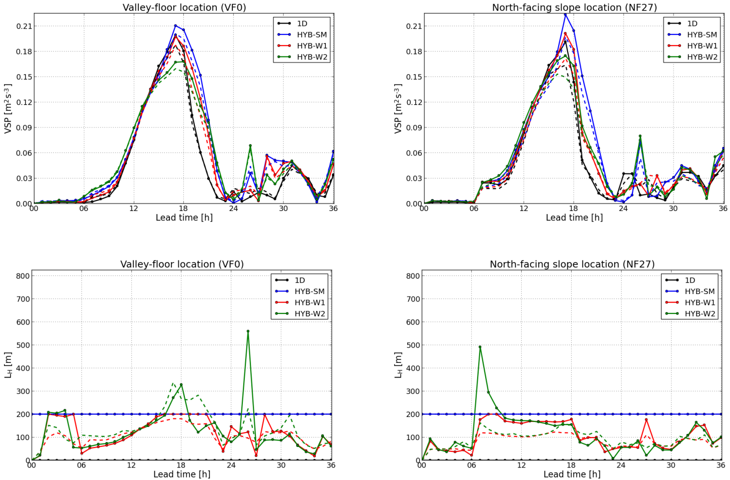
- APPROACH 1 [Goger (2018)] and APPROACH 3 [Wang (2021)] are coded and validation is ongoing
- we do not have satisfactory results with the APPROACH 2 so far; we plan to implement APPROACH 2 [Goger (2019)] with $\sigma_{\mathrm{u,v}}$ computed from TOUCANS
- we plan to implement the optimal $\mathrm{L_H}$ option into 1D+2D turbulence scheme based on SLHD
- we plan the adaptation of TOUCANS for the grey zone (scale-aware scheme) following [Boutle et al. (2014), Honnert (2011, 2019, 2020)]

Real case study

A case of 1 July 2015, 00 UTC

- forecast for 72 hours in the cascade of resolutions 4km, 2km, 1km approximately over the same domain covering Central Europe
- 87 vertical levels
- ALARO configuration
- coupling to ARPEGE in 3h coupling frequency

VSP and L_H @1km



Vertical shear production

1D
APPROACH 1
APPROACH 3
APPROACH 3 bounded

Turbulent horizontal length scale L_H @1km

(courtesy of M.Hrastinski)

HSP and TKE @1km

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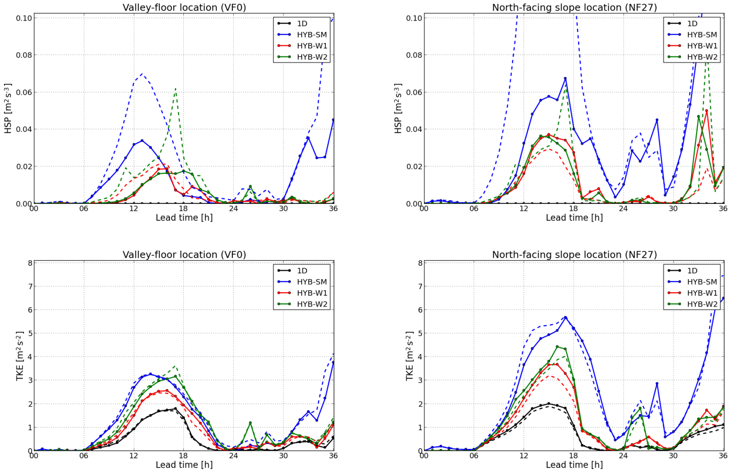

Horizontal shear production

1D
APPROACH 1
APPROACH 3
APPROACH 3 bounded

Turbulent kinetic energy @1km

(courtesy of M.Hrastinski)

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HSP and TKE @2km

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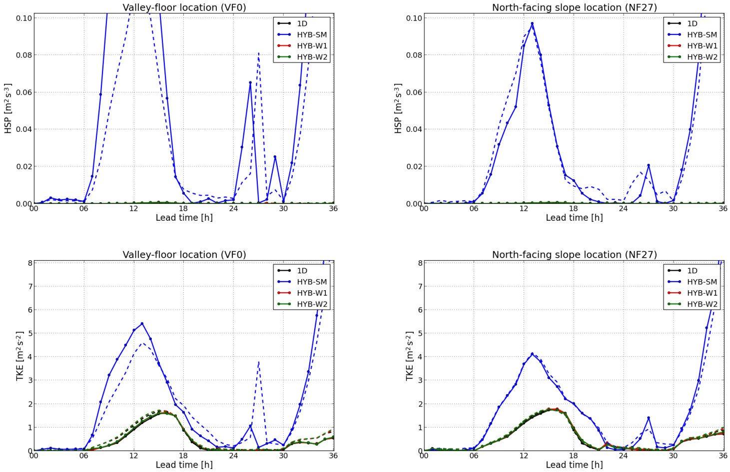

Horizontal shear production

1D
APPROACH 1
APPROACH 3
APPROACH 3
bounded

Turbulent kinetic energy @2km

(courtesy of M.Hrastinski)

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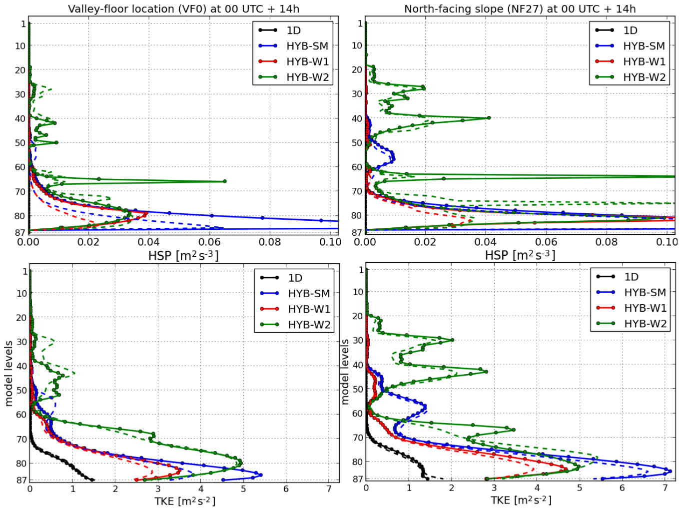
Vertical profiles @1km



Horizontal shear production

1D
APPROACH 1
APPROACH 3
APPROACH 3 bounded

Turbulent kinetic energy @1km

(courtesy of M.Hrastinski)

Conclusions

- There were no problems with numerical instability with any of the three tested L_H options. Spectral norms gradually develop within the first few hours of the forecast with no significant differences between 1D and quasi-3D until the intensity of turbulence reaches its maximum (early afternoon).
- The impact of the quasi-3D turbulence scheme at coarser horizontal resolution ($\Delta x = 2\,km$ and $\Delta x = 4\,km$) is almost negligible.
- The performance of constant L_H worsens as Δx increases. The Horizontal Shear Production (HSP) values are too high for the north-facing slope location and even comparable with the Vertical Shear Production (VSP).

Conclusions

- When variable L_H is employed, the values become comparable, pronounced daily variability is shown, with maxima near the sunrise and noon. The TKE values are slightly higher with the variable L_H formulations than for 1D. Strong HSP appears near the surface and the turbulence intensity is higher throughout the whole model column for both the valley-floor and the north-facing slope locations than for the 1D scheme.
- The third approach to L_H, which allows stronger horizontal mixing, is also able to produce a secondary and a tertiary maxima in the middle and the upper troposphere. Further research will aim on the potential benefit for the simulation of the jet stream related turbulence, as well as for lateral mixing at the edges of atmospheric fronts.

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