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Towards the 3D turbulence in the ALARO CMC

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Outline

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- Introduction: addressing 3D turbulence effects
- The existing 3D approaches within the TOUCANS scheme
- Results:
  - Adjusting the 3D turbulence settings
  - The role of the deep convection scheme
- Conclusions and future steps

Motivation and objectives

- The ultimate goal is to have a $\Delta x \sim< 1$km model providing an added value to the existing operational configurations
- Therefore, we first addressed the settings of model dynamics (mostly horizontal diffusion) and concluded that its tuning is needed at these scales - not easy to achieve
- The 3D turbulence was considered a necessary addition to provide the added value but its role seems to change
- By the above increase in resolution, we move across the deep convection grey zone and enter the grey zone of shallow convection and turbulence (some adjustments are expected)

Introduction: addressing 3D effects

- There is an ongoing related activity in the ACCORD consortium (in the AROME CMC)
- Thereby, the following 3D effects are considered:
  - In production of turbulence energies after Goger et al. (2018, 2019)
  - The contribution of largest sub-filter scale eddies after Moeng et al. (2010); so-called Leonard terms (originates from LES)

$$\overline{w'\phi'} = -K_\phi \frac{\partial\overline{\phi}}{\partial z} + 2\left(\frac{\Delta_f^2}{12}\right)\left(\frac{\partial\overline{w}}{\partial x}\frac{\partial\overline{\phi}}{\partial x} + \frac{\partial\overline{w}}{\partial y}\frac{\partial\overline{\phi}}{\partial y}\right) \tag{1}$$

- Additionally, we can utilize the 1D+2D scheme in TOUCANS, solving 2D diffusion equation for the horizontal direction

The existing 3D approaches within the TOUCANS scheme

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

$$\frac{\partial e_k}{\partial t} + ADV(e_k) = \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) + I + II - \frac{2e_k}{\tau_k} \quad (2)$$

$$\frac{\partial e_t}{\partial t} + ADV(e_t) = \frac{\partial}{\partial z}\left(K_{e_t}\frac{\partial e_t}{\partial z}\right) + I - \frac{2e_t}{\tau_t} \quad (3)$$

$$I = -\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}, \qquad II = E_{s_L}\overline{s_L{}'w'} + E_{q_t}\overline{q_t{}'w'} \quad (4)$$

$$s_L = c_{pd}\left(1 + \left[\frac{c_{pv}}{c_{pd}} - 1\right]q_t\right)T + gz - (L_v q_l + L_s q_i), \qquad q_t = q_t + q_l + q_i \quad (5)$$

I, II - source terms; s_L - static energy; q_t - total specific moisture

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The existing 3D approaches within the TOUCANS scheme

- In Goger et al. (2018, 2019), the TKE/TTE shear production term (I) is extended into 3D:

$$\mathrm{I_{3D}} = \underbrace{-\overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{v'w'}\frac{\partial\overline{v}}{\partial z}}_{\mathrm{I_{vert}}} \underbrace{-\overline{u'u'}\frac{\partial\overline{u}}{\partial x} - \overline{u'v'}\frac{\partial\overline{u}}{\partial y} - \overline{u'v'}\frac{\partial\overline{v}}{\partial x} - \overline{v'v'}\frac{\partial\overline{v}}{\partial y}}_{\mathrm{I_{horiz}}} \tag{6}$$

- The $\mathrm{I_{horiz}}$ term is parameterized following Smagorinsky (1963):

$$\mathrm{I_{horiz}} = \left(\mathrm{L_K^H}\right)^2 \cdot \left[\left(\frac{\partial \mathrm{u}}{\partial \mathrm{x}}\right)^2 + \left(\frac{\partial \mathrm{v}}{\partial \mathrm{y}}\right)^2 + \frac{1}{2}\left(\frac{\partial \mathrm{u}}{\partial \mathrm{y}} + \frac{\partial \mathrm{v}}{\partial \mathrm{x}}\right)^2\right]^{\frac{3}{2}} \tag{7}$$

- The difference between Goger et al. (2018) and Goger et al. (2019) is in $\mathrm{L_K^H}$ treatment:

$$\mathrm{L^H_{K-G18}} = \mathrm{c_s}\Delta\mathrm{x}, \qquad \mathrm{L^H_{K-G19}} = \mathrm{f(U, \sigma_{u,v}, z_i)} \tag{8}$$

$\mathrm{c_s}$ - Smagorinsky's constant; U - velocity scale; $\sigma_{\mathrm{u,v}}$ - horizontal wind variances; $\mathrm{z_i}$ - PBL height

The existing 3D approaches within the TOUCANS scheme

- The 1D+2D scheme Eqs. are derived assuming $\partial K_{M/H,hor}/\partial x + \partial K_{M/H,hor}/\partial y = 0$:

$$\frac{\partial u_i}{\partial t} + \ldots = -K_{M,hor}\frac{\partial^2 u_i}{\partial x^2} - K_{M,hor}\frac{\partial^2 u_i}{\partial y^2} + \frac{\partial}{\partial z}\left(\overline{w' u_i'}\right) \tag{9}$$

$$\frac{\partial \Psi}{\partial t} + \ldots = -K_{H,hor}\frac{\partial^2 \Psi}{\partial x^2} - K_{H,hor}\frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial}{\partial z}\left(\overline{w' \Psi'}\right) \tag{10}$$

$$\overline{w' u_i'} = -K_{M,ver}\frac{\partial u_i}{\partial z}, \qquad \overline{w' \Psi'} = -K_{H,ver}\frac{\partial \Psi}{\partial z} + \mathrm{TOMs} \tag{11}$$

- The exchange coefficients for horizontal and vertical directions have the same "shape":

$$K_{M,ver} = L_K C_K \sqrt{e_k}\chi_3(Ri), \qquad K_{H,ver} = L_K C_K C_3 \sqrt{e_k}\phi_3(Ri) \tag{12}$$

$$K_{M,hor} = L_K^H C_K^H \sqrt{e_k}\chi_{3,hor}(Ri), \qquad K_{H,hor} = L_K^H C_K^H C_3 \sqrt{e_k}\phi_{3,hor}(Ri) \tag{13}$$

The existing 3D approaches within the TOUCANS scheme

- The shear and stretching HTLS are computed after Wang et al. (2021):

$$L_{Hshr} = sW\left[\left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2\right]^{-\frac{1}{2}} \tag{14}$$

$$L_{Hstr} = sW\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]^{-\frac{1}{2}}, \qquad s = \left(\frac{\Delta_0}{\Delta}\right)^{\alpha} \tag{15}$$

- The combined HTLS is obtained by averaging L_{Hstr} and L_{Hstr} and protected as follows:

$$L_K^{H'} = \sqrt{L_{Hshr} L_{Hstr}}, \qquad L_K^{H} = \max\left(L_K^{H'}, c_s\sqrt{\Delta x \Delta y}\right) \tag{16}$$

s - resolution-dependent scaling factor; $W = \sqrt{u^2 + v^2}$ - wind speed

The existing 3D approaches within the TOUCANS scheme

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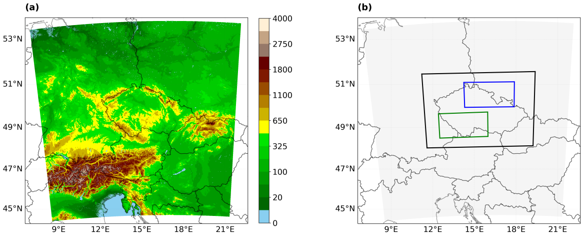
- Following the preliminary tests (small impact of 3D turbulence), we "adjusted" the 1D + 2D scheme's code:

$$\mathrm{K_{M,hor}} = \mathrm{L_K^H C'_K C_K} \sqrt{\mathrm{e_k}} \chi_{3,\mathrm{hor}}(\mathrm{Ri}), \qquad \mathrm{K_{H,hor}} = \mathrm{L_K^H C'_K C_K C_3} \sqrt{\mathrm{e_k}} \phi_{3,\mathrm{hor}}(\mathrm{Ri}) \tag{17}$$

Results: The preliminary analysis across resolutions

- Central European domain: 1024 x 1024 km, linear grid, 87 vert. lev., Δx=4, 2, 1 and 0.5 km
- NHYD dyn., ICI scheme (1 iter.), horiz. diffusion and ALARO-1 phy. (both as in operational ALADIN-CZ)
- INIT: ALADIN-CZ, LBC: ARPEGE (3-h freq.)

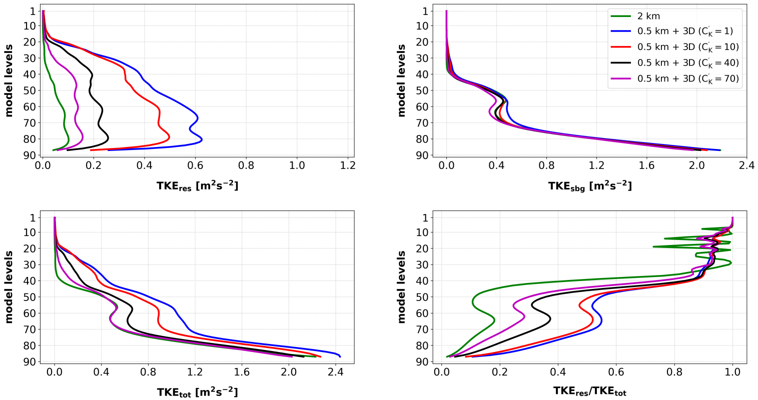


- The results from two convection cases: (i) with considerable large-scale forcing and (ii) more locally driven
- During the analysis, we rely on: KE spectra, averaged profiles of resolved and subgrid TKE ($\mathrm{TKE_{res}}$ and $\mathrm{TKE_{sbg}}$), convective fluxes and noise-indicative fields (e.g., pressure departure)
- The $\mathrm{TKE_{res}}$ is computed by applying the Reynolds averaging to predicted wind components ($\mathrm{u_i = \bar{u}_i + u'_i}$):

$$\mathrm{TKE_{res}} = \frac{1}{2}\sum_{i=1}^{3} \mathrm{u_i'^2}\,; \qquad \mathrm{\bar{u}_{i,MA}} = \frac{1}{\mathrm{N}}\sum_{\mathrm{j=n-k}}^{\mathrm{n+k}} \mathrm{u_{i,j}}\,, \quad \mathrm{N = 2k+1} \tag{18}$$

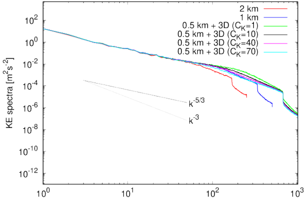
Results: Adjusting the 3D turbulence settings (case 1)

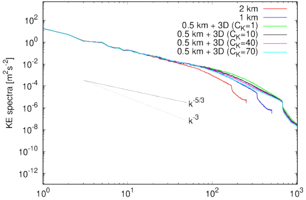
- The sensitivity tests to the C'_K parameter (the strength of the 1D+2D scheme):

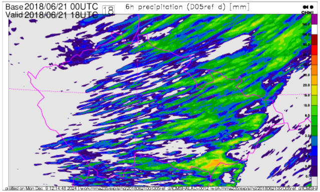


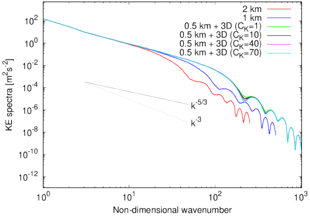
Results: Adjusting the 3D turbulence settings (case 1)

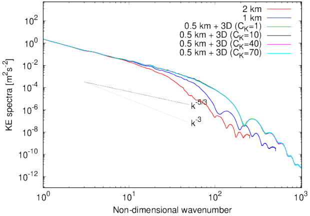
- The impact off the 3D turbulence at $\Delta x = 0.5$ km:

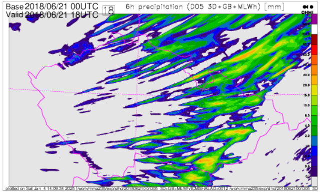












Results: Adjusting the 3D turbulence settings (case 1)

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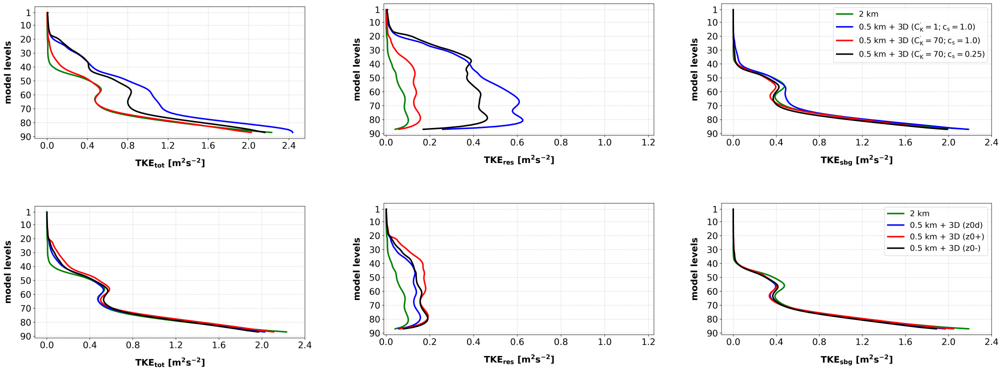
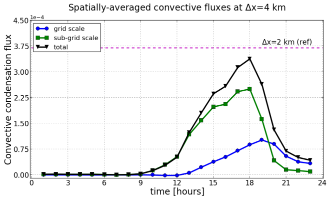
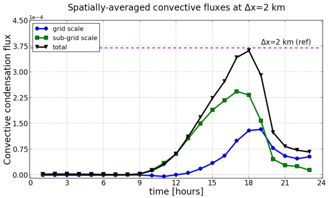
- The sensitivity of complementary diagnostics to L_K^H protection and z_{0m}^{oro}:

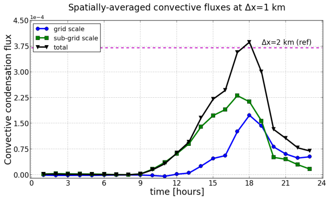


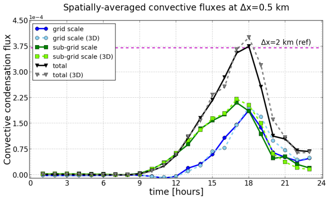
Results: The role of the deep convection scheme (3MT) - case 1

▶ How 3MT scheme adapts with a decrease in Δx?







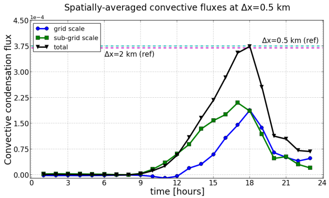


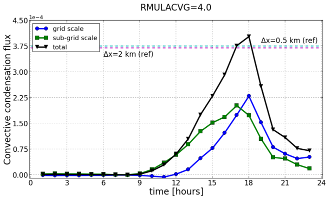
condensation fluxes in updraught

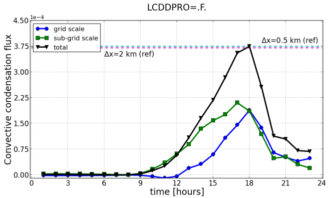
1. 3MT scheme adapts only slightly with Δx
2. Total condensation flux increases with the grid-scale part

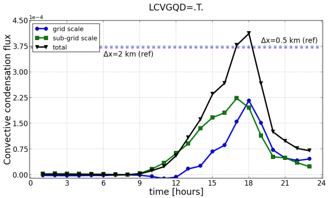
Results: The role of the deep convection scheme (3MT) - case 1

▶ Can we help the 3MT scheme to adapt a bit more?





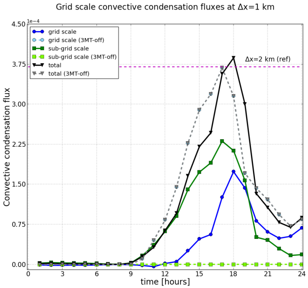


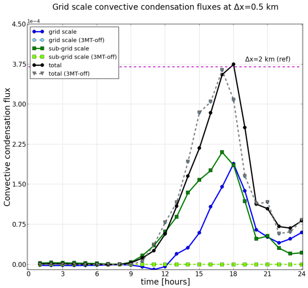


condensation fluxes
in updraught

1. The largest sensitivity is to RMULACVG↓
2. The downdraught part has very small impact

- The impact off 3MT scheme at $\Delta x = 1.0$ km and $\Delta x = 0.5$ km:





condensation fluxes in updraught

1. The maximum is shifted to one hour earlier
2. The total magnitude is comparable

Can we simply switch off the 3MT scheme?

Results: The role of the deep convection scheme (3MT) - case 1

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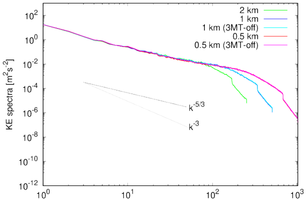
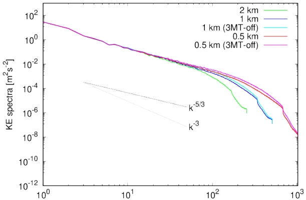
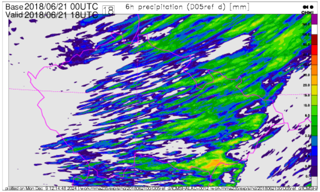
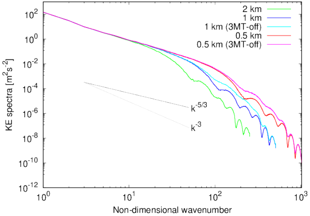
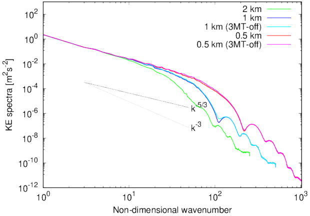
- The impact off 3MT scheme at $\Delta x = 1.0$ km and $\Delta x = 0.5$ km:

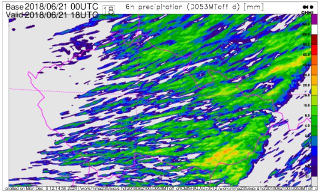












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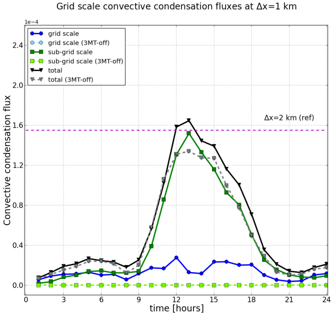
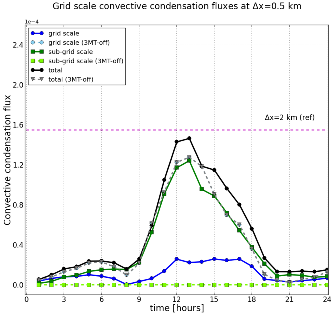
- The impact off 3MT scheme at $\Delta \mathrm{x} = 1.0$ km and $\Delta \mathrm{x} = 0.5$ km:





condensation fluxes
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1. The contribution from sub-grid- and grid-scale different than in case 1

2. The total flux is $\sim$ 20% smaller without the 3MT

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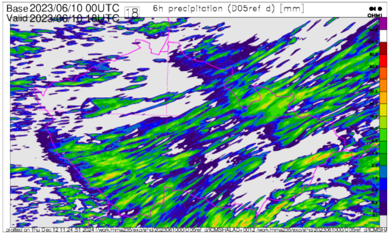
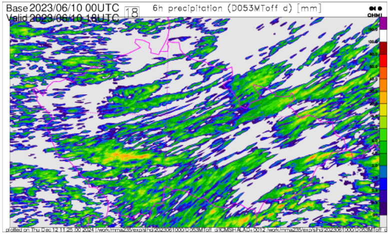
- The impact off 3MT scheme at $\Delta x = 0.5$ km:





Conclusions

- The default model settings at $\Delta \mathrm{x} = 1.0$ km and $\Delta \mathrm{x} = 0.5$ produce progressively increasing noisy patterns
- Stronger horizontal diffusion is needed but the existing components (SLHD + 2 spectral) seem hard to tune
- The 3D turbulence helps to reduce the noise and make precipitation forecast closer to observations; further inspection is needed on the values of closure parameters and $\mathrm{L}_{\mathrm{K}}^{\mathrm{H}}$
- The 3MT scheme should not be switched off for $\Delta \mathrm{x} \sim< 1.0$ km but its adjustment/tuning is required
- More extensive validation is needed

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