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executed by: Ivan Bašták Ďurán
supported by: Jure Cedilnik, Petra Smolíkova, Peter Smerkol, Neva Pristov, and Jure Jerman

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Abstract

ALARO physics package contains horizontal turbulent diffusion scheme, which can be activated as complement to the vertical turbulent diffusion scheme, using the same stability dependency parameters. Together these two form a parametrization of 3D turbulence with independent diffusion in horizontal and vertical.

The 3D turbulence scheme was tested in cycle CY38t1 version op3, which contains ALARO physical package version ALARO1. The tests were performed in 2D model (one horizontal and one vertical dimension) for ideal case and in 3D model with high horizontal resolution (1.25km) for real case.

As expected, the tests in 2D model show that 3D turbulence reduces the horizontal variability of diffused fields.

The tests in 3D model show, that at high resolution the influence of 3D turbulence parametrization is significant and is sensitive to setup of horizontal stability dependency functions and horizontal length scales.

1 3D turbulence parametrization

Usually in NWP only vertical components of turbulent fluxes influence the evolution of prognostic variables. There are two reasons for omission of horizontal components. First, the vertical components of turbulent fluxes are dominant in current horizontal resolution of NWP models. Second, the computation in physics are done in vertical columns without consideration of horizontal effects outside the grid box, so introduction of horizontal fluxes creates technical difficulties.

However in TOUCANS there is a possibility of using 1D+2D turbulent scheme, which combines the vertical turbulent diffusion with turbulent diffusion in horizontal according to following equations (derived by assuming that $\frac{\partial K_{M/H,hor}}{\partial x} + \frac{\partial K_{M/H,hor}}{\partial y} = 0$):

$$\frac{\partial u_i}{\partial t} + ... = -K_{M,hor}\frac{\partial^2 u_i}{\partial x^2} - K_{M,hor}\frac{\partial^2 u_i}{\partial y^2} + \frac{\partial}{\partial z}\left(\overline{w'u_i'}\right) + ... \quad (1)$$

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

$$\overline{w'u_i'} = -K_M\frac{\partial u_i}{\partial z} \quad (3)$$

$$\overline{w'\Psi'} = -K_H\frac{\partial \Psi}{\partial z} + TOMs \quad (4)$$

$$K_{M,ver} = L_K\, C_K \sqrt{e_k}\chi_3(Ri), \qquad K_{H,ver} = L_K\, C_K\, C_3\sqrt{e_k}\phi_3(Ri) \quad (5)$$

$$K_{M,hor} = L_K^H\, C_K \sqrt{e_k}\chi_{3,hor}(Ri), \quad K_{H,hor} = L_K^H\, C_K\, C_3\sqrt{e_k}\phi_{3,hor}(Ri) \quad (6)$$

here Ψ stands for scalar variables temperature and moisture, u_i are horizontal wind components, χ_3 and ϕ_3 are stability dependency functions for vertical turbulent diffusion (see [1] for further details) and $\chi_{3,hor}$ and $\phi_{3,hor}$ are stability dependency functions for horizontal turbulent diffusion, L_K and L_K^H are length scales, e_k - is Turbulent Kinetic Energy (TKE), C_3 is inverse Prandtl number at neutrality and C_K is a closure constant.

The computation of horizontal operators $\nabla_H^2\Psi$ and $\nabla_H^2 u_i$ are in ALADIN evaluated by the SLHD smoother. **(Details about this can provide Filip Váňa)**.

The stability dependency functions χ_3 , ϕ_3, $\chi_{3,hor}$ and $\phi_{3,hor}$ are provided consistently by QNSE theory (see [2], Fig. 1, Fig. 3). Please note, that the horizontal stability dependency functions increase with stability while the vertical stability dependency functions decrease with stability (for more details see [2]), which is valid in stable regime (see Fig. 1) and also in weakly unstable regime (see Fig. 2).

The actual code implementation of QNSE functions is a fit of data points (QNSE theory provides only data points) with smooth and continuous extension of the functions to unstable stratification (QNSE theory provides data mostly only in stable stratification). The fitting procedure is similar to the one used for vertical stability function of QNSE in [1]. The resulting extensions(in unstable region) and fits are (see Fig. 3):

for $Ri \leq 0$:

$$\chi_{3,hor}(Ri) = \frac{1 + Ri\left(\beta_2^u + Ri\beta_1^u\right)}{1 + Ri\left(\beta_4^u + Ri\beta_3^u\right)}, \quad \phi_{3,hor}(Ri) = \frac{1 + Ri\left(\gamma_2^u + Ri\gamma_1^u\right)}{1 + Ri\left(\gamma_4^u + Ri\gamma_3^u\right)}, \quad (7)$$

for $Ri > 0$:

$$\chi_{3,hor}(Ri) = \frac{1 + Ri\left(\beta_2^s + Ri\beta_1^s\right)}{1 + Ri\left(\beta_4^s + Ri\beta_3^s\right)}, \quad \phi_{3,hor}(Ri) = \frac{1 + Ri\left(\gamma_3^s + Ri\left[\gamma_2^s + Ri\gamma_1^s\right]\right)}{1 + Ri\left(\gamma_6^s + Ri\left[\gamma_5^s + Ri\gamma_4^s\right]\right)} \quad (8)$$

with

$$\beta_1^s = 53.365, \;\; \beta_2^s = 0.5, \;\; \beta_3^s = 41.368, \;\; \beta_4^s = 0.26, \tag{9}$$

$$\beta_1^u = 5.92, \;\; \beta_2^u = 0.35, \; \beta_3^u = 11.841, \; \beta_4^u = 0.41, \tag{10}$$

$$\gamma_s^1 = 100./C_3, \; \gamma_s^2 = 29.33/C_3, \; \gamma_s^3 = 0.322/C_3, \; \gamma_s^4 = 37.507, \; \gamma_s^5 = 22.36, \; \gamma_s^6 = 0.085, \tag{11}$$

$$\gamma_u^1 = 8.962/C_3, \; \gamma_u^2 = 0.2/C_3, \; \gamma_u^3 = 7.468, \; \gamma_u^4 = 1.727. \tag{12}$$

The horizontal length scale - L_K^H is currently computed as:

$$L_K^H = \min\left(L_K, \sqrt{\Delta x \cdot \Delta y}\right) \tag{13}$$

where Δx and Δy are grid sizes.

Please note that TKE in this parametrization contains only the vertical variances of velocity. The same is valid in case of activation of prognostic Total Turbulence Energy (TTE) scheme, which affects value of the stability parameter - Ri (via appropriate conversion).

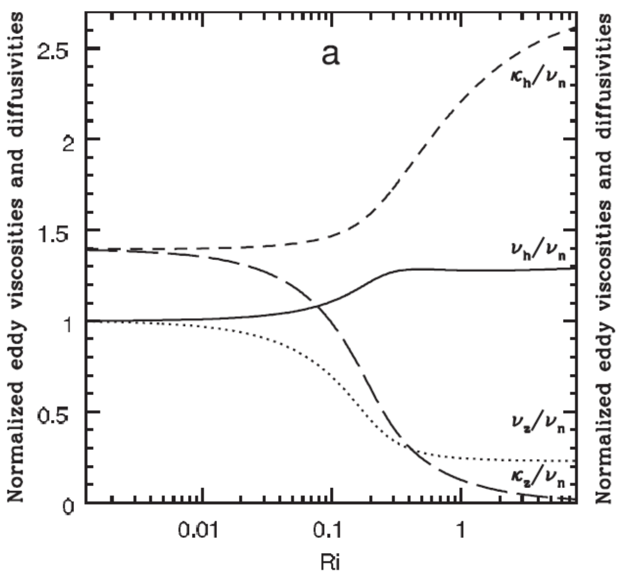

Figure 1: Stability dependency functions according to QNSE theory ([2]) in stable stratification. ν_z/ν_n, κ_z/ν_n, ν_h/ν_n, and κ_h/ν_n are χ_3 , $C_3\phi_3$, $\chi_{3,hor}$ and $C_3\phi_{3,hor}$, respectively.

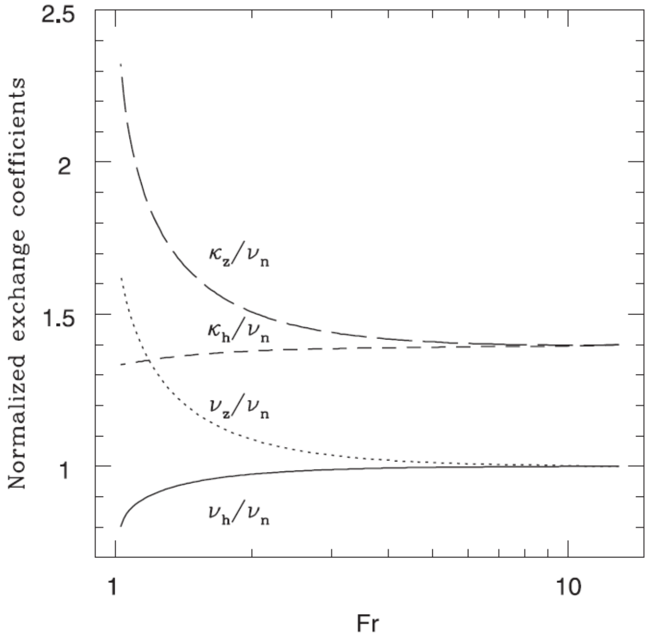

Figure 2: Stability dependency functions according to QNSE theory ([2]) in unstable stratification in terms of Froude number. ν_z/ν_n, κ_z/ν_n, ν_h/ν_n, and κ_h/ν_n are χ_3 , $C_3\phi_3$, $\chi_{3,hor}$ and $C_3\phi_{3,hor}$, respectively.

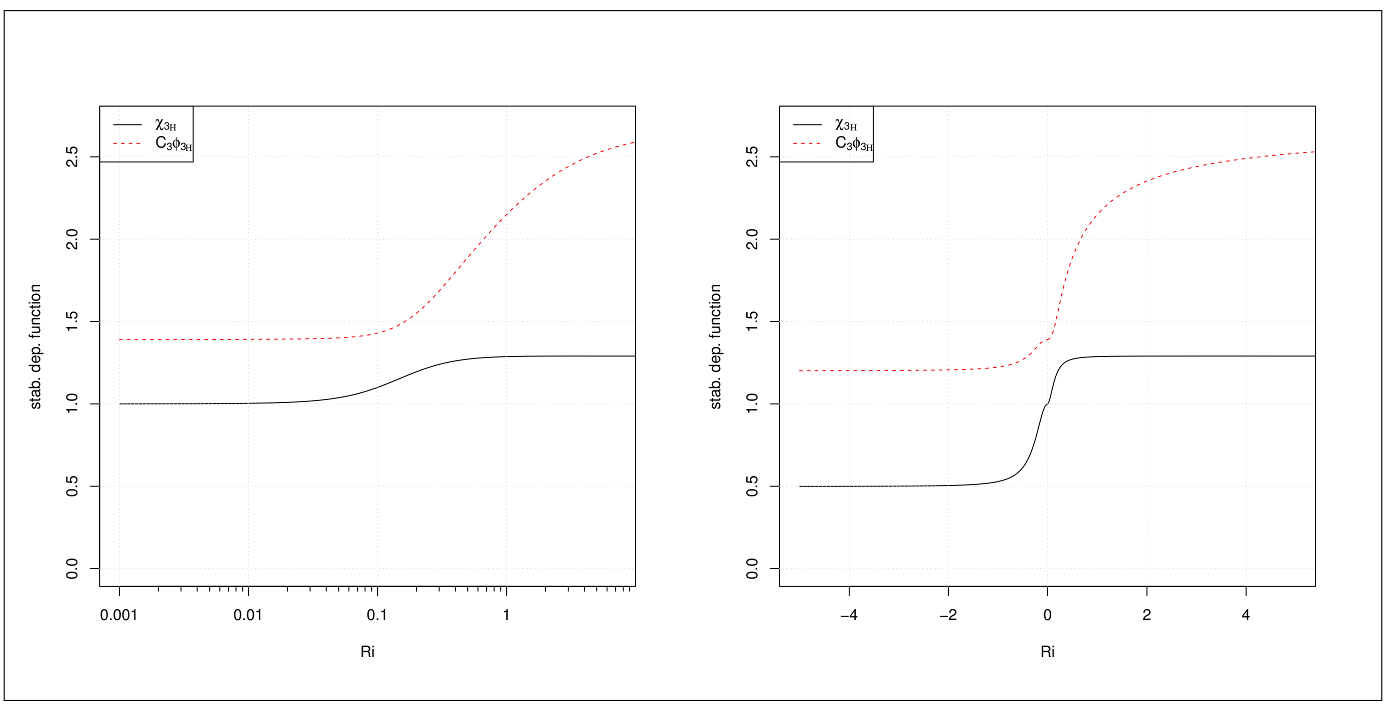

Figure 3: Fits and extension (right) of stability dependency functions - $\chi_{3,hor}$, $C_3\phi_{3,hor}$- according to QNSE theory ([2]) in stable stratification(left) and in whole range of Ri (right).

2 Experiments

We used the CY38t1_op3 version of the code (ALARO-1 physical package) for the tests of 3D turbulence parametrization. The 3D turbulence is activated by setting L3DTURB=.TRUE. . Also a local switch in ACMRIP subroutine must be set to LL3DTURB=.TRUE. in the code. The local switch should be set equal to the L3DTURB in the next version of the code.

The model was run in both experiments with a non-hydrostatic setup of the model and TOUCANS turbulent scheme was activated in physics of the model. The namelists of the experiments can be found on yaga (Prague) in /home/mma/mma199/run/2d/kh/kh3d.namel for 2D experiment and in /home/mma/mma199/run/CY38t1/1.25km/namel.e002_nhyd_s3 for 3D experiment.

2.1 2D model experiment

Domain with 800 grid-points (in y-direction) with 2km horizontal resolution and 120 vertical levels was used in the 2D experiment. As initial state of wind field was used a horizontally uniform profile with U component set to 0 m/s till level 70 and then set to 10m/s above (see Fig. 4 left), and V component set to 0m/s in all levels. The temperature field is a superposition of horizontally uniform profile: constant (281 K) from surface to 100-th level and then decreases with constant vertical gradient; and a periodic (in horizontal) perturbation function with amplitude decreasing with height (see Fig. 4 right).

The initial conditions were chosen to test the ability of 3D turbulence to decrease the variability of temperature field in horizontal direction (horizontal down-gradient diffusion). To minimize the effect of advection the V-component of wind field was set to zero (only advection in y-direction is possible in 2D model). In order to create sufficient source of turbulent flow generation, U component is initialized with large gradient (shear term in TKE equation).

The initial file for 2D model can be created by using Rfa package developed by Alex Deckmyn with additional modification by Jure Cedilnik (the modification can be found on yaga in /home/mma/mma199/run/2d/Rfa_1D.R; example can be seen in /home/mma/mma199/run/2d/m3D.R), which enables decoding and encoding of 2D fields.

The results of 2D model run after 10 h integration (with 50s time step) show that 3D turbulence parametrization decreases the horizontal variability of the diffused fields (see Figs. 5 and 6). Note that the horizontal gradients are also decreased (when compared with initial state) by horizontal advection and SLHD diffusion scheme, but the activation of 3D turbulence parametrization decreases the variability further. Tests with different perturbation functions (not shown here) for initial temperature field imply that the influence of 3D turbulence scheme is significant only when the gradients in horizontal fields are steep enough. Model can represents such gradients only when it's horizontal resolution is sufficiently high. It should be aim of further study to determine the horizontal resolution of model at which the 3D turbulence is required.

2.2 3D model experiment

Domain in Alpine region with 1.25km horizontal resolution(757x501 grid-points, see Fig. 7) and with 87 vertical levels was used for testing of 3D turbulence in chosen 3D case form 1.7.2014 (integration start at 00:00; see Fig. 8).

The results with 3D model run after 14 h integration (with 50s time step) show that 3D turbulence parametrization has significant impact on model forecast of diffused variables in regions with steep horizontal gradients (see Figs. 10, 9, and 11).

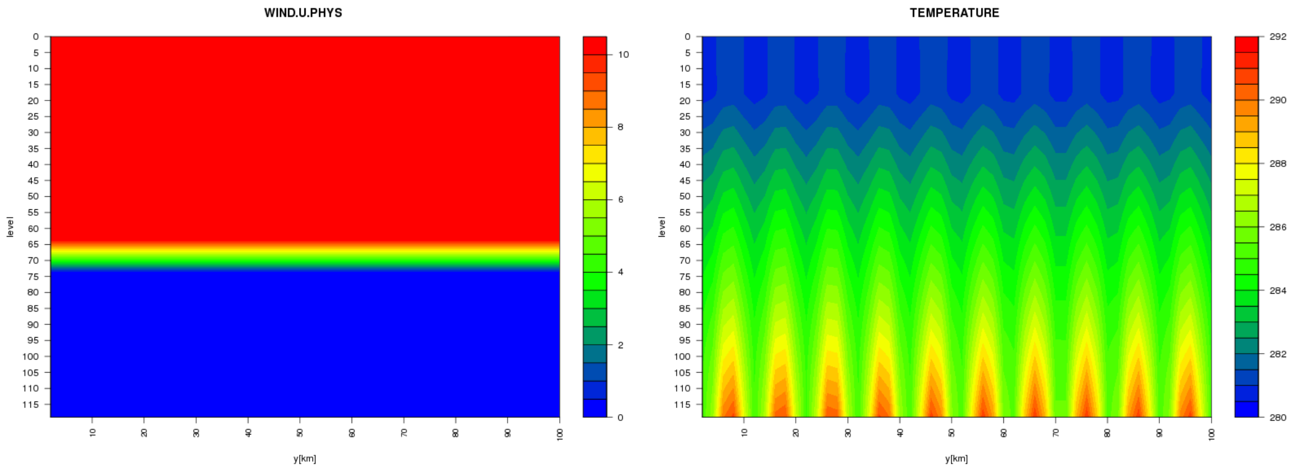

Figure 4: Initial state of U-component(left) and air temperature(right) in 2D experiment.

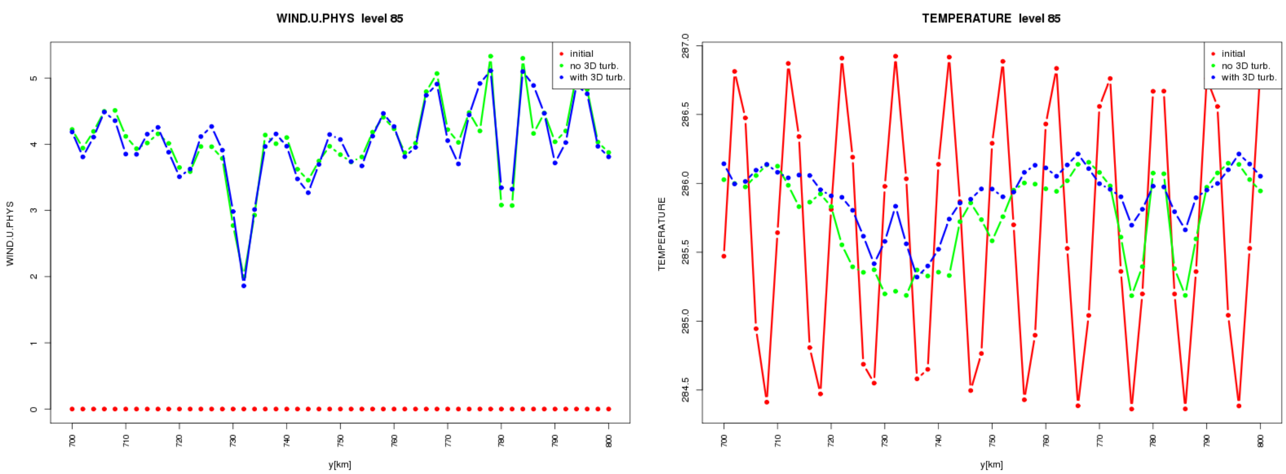

Figure 5: Comparison of 2D model runs with(blue) and without(green) 3D turbulence parametrization for U-component (left) and temperature (right) in 85th model level. The initial state is plotted with red line.

The sensitivity of 3D turbulence parametrization was tested for choice of stability dependency functions and horizontal length scales. In first case we used stability functions identical to 1.0 in whole range of Ri or fit of QNSE horizontal stability function (see 10, 9). In second case horizontal length scale was set to vertical length scale, grid size, or minimum of those two (11). Both stability functions and length scale show significant impact on 3D turbulence parametrization.

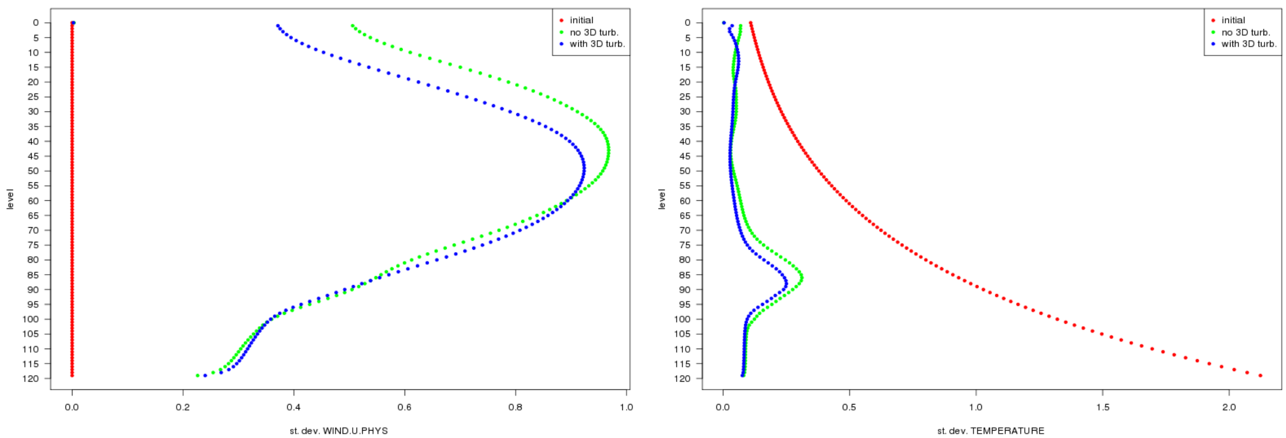

Figure 6: Comparison of standard deviation of each level(horizontal variability measure) for 2D model runs with(blue) and without(green) 3D turbulence parametrization for U-component (left) and temperature (right). The initial state is ploted with red dots.

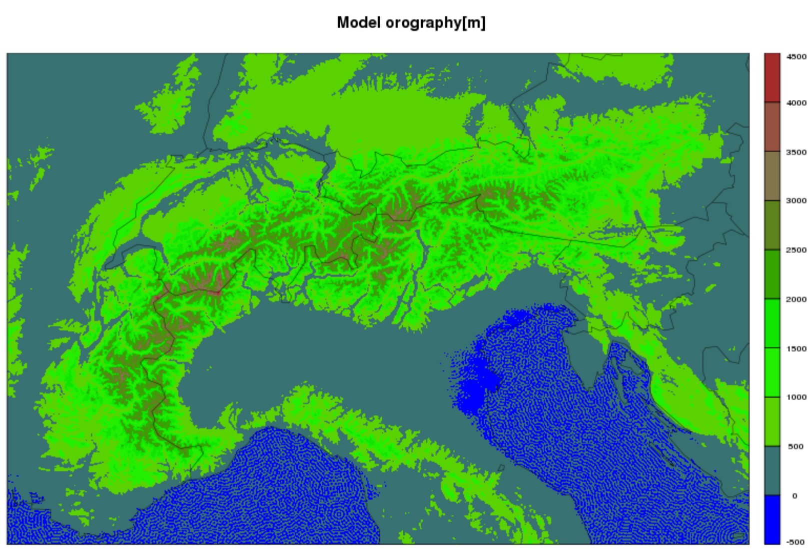

Figure 7: Model orography for 3D experiment.

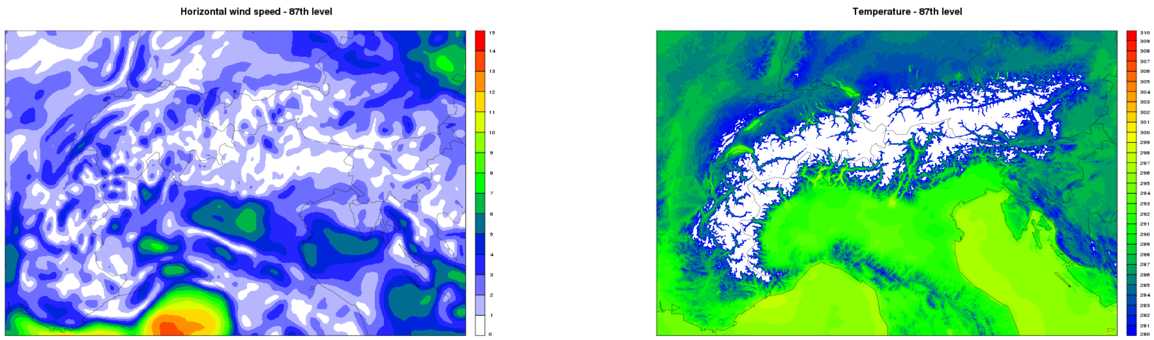

Figure 8: Initial state of horizontal wind speed (left) and temperature (right) near surface (87th model level) for 3D experiment.

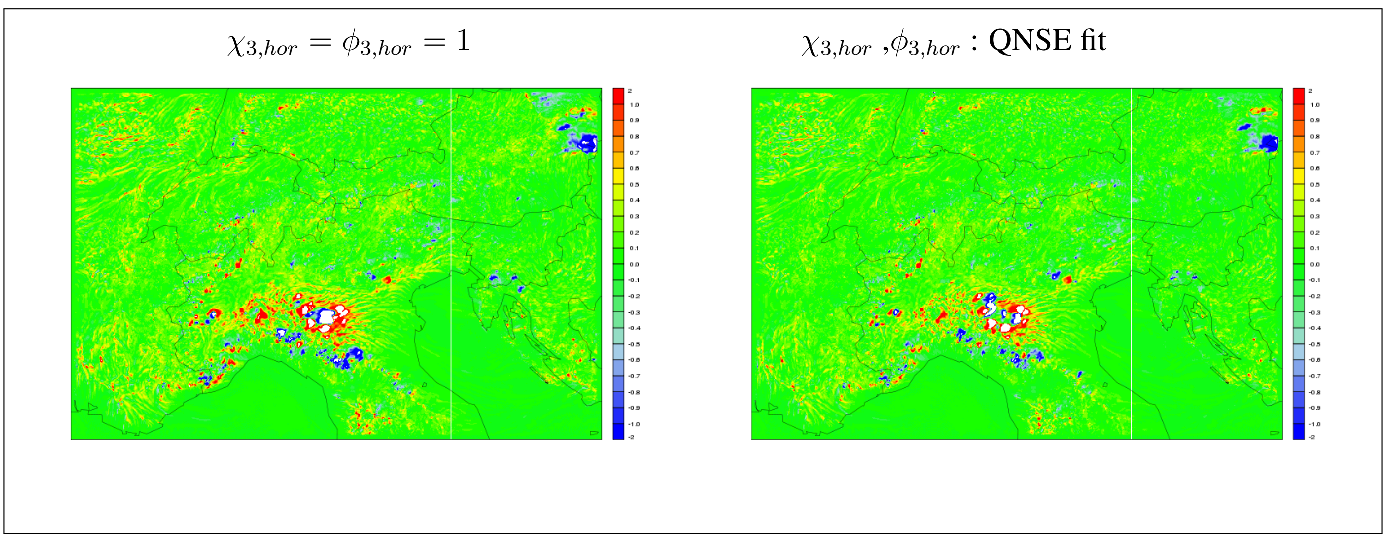

Figure 9: Differences of near surface(87th level) temperature between runs with and without 3D turbulence parametrization after 14 h of integration (50s time step) with horizontal stability dependency functions set to 1.0 (left) and according to QNSE theory (Eqs. (7) and (8))(right). Horizontal length scale set equal to horizontal grid size.

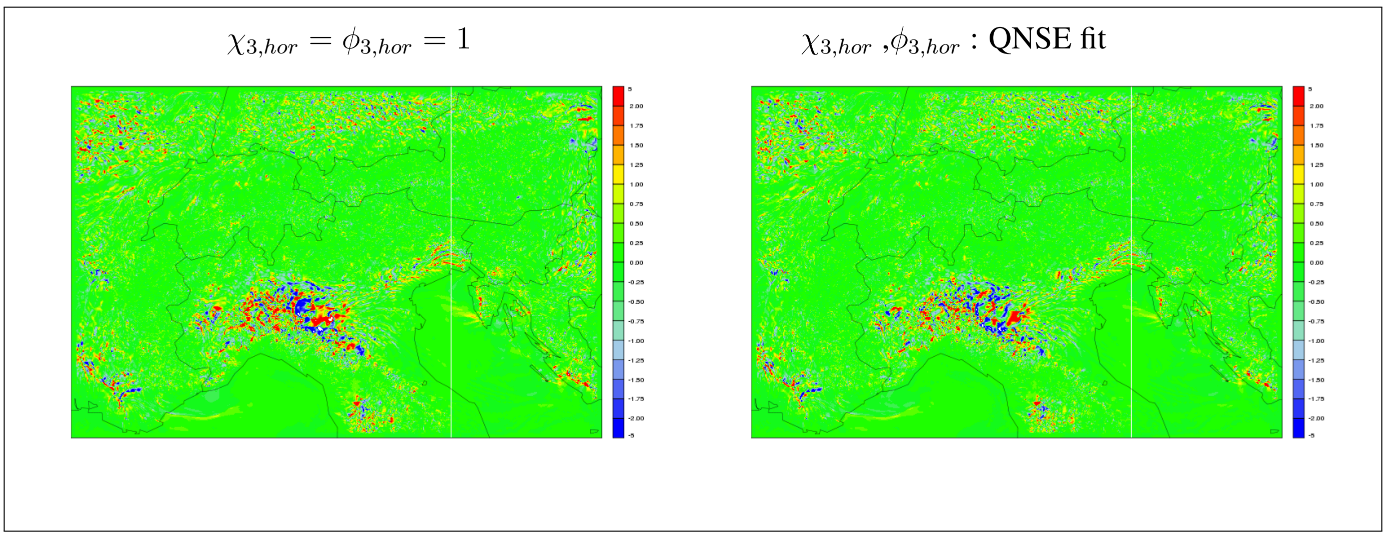

Figure 10: Same as Fig. 9, but for horizontal wind velocity near surface.

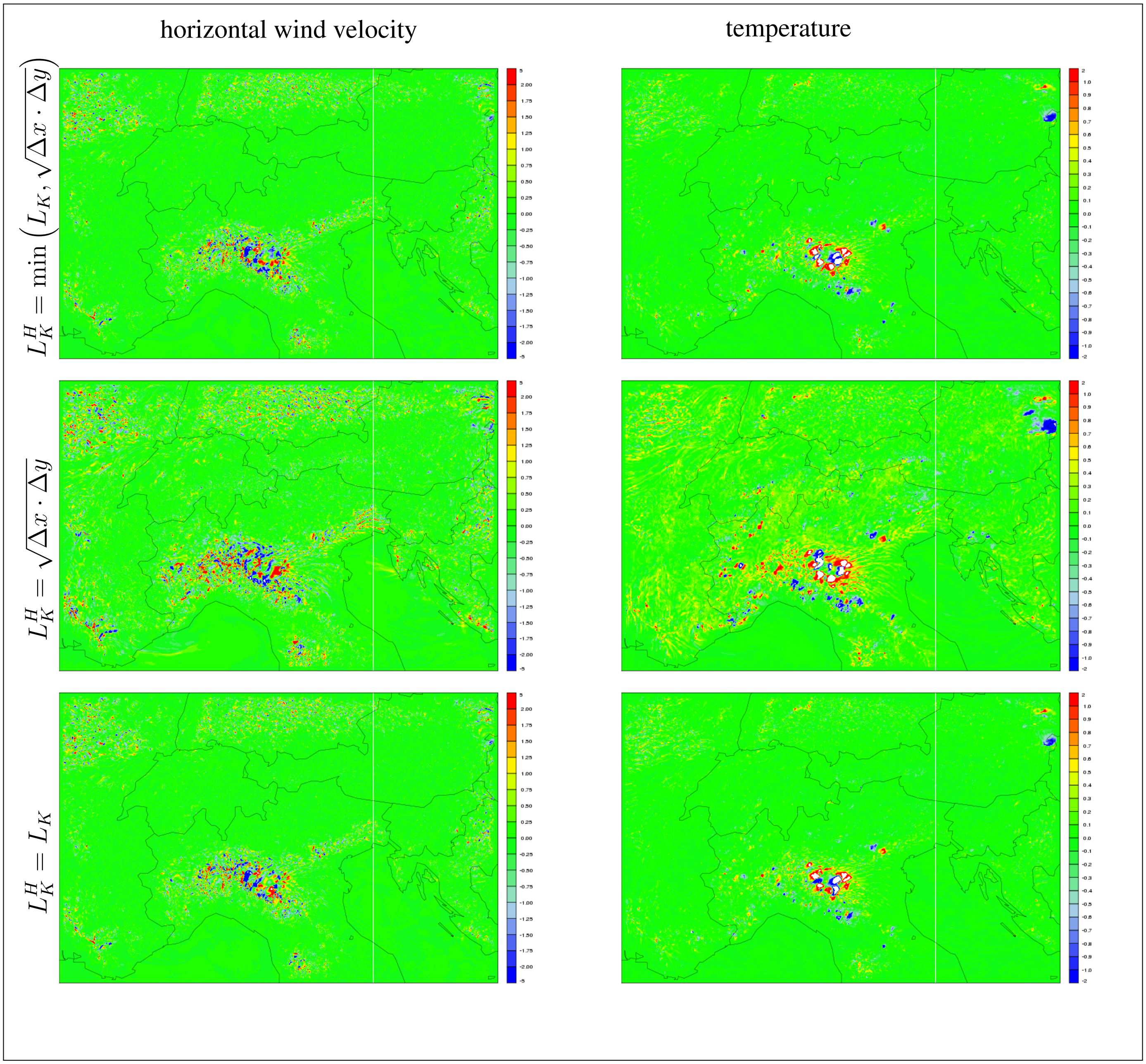

Figure 11: Differences between runs with and without 3D turbulence parametrization after 14 h of integration (50s time step) for wind velocity (left column) and surface temperature (right column) near surface (87th model level). Horizontal length scale is set according to Eq. (13) (first row), equal to grid size (second row), or equal to vertical length scale (third row). Horizontal stability dependency functions set according to QNSE theory (Eqs. (7) and (8))(right).

3 Conclusion

Tests of 3D turbulence parametrization in 2D and 3D model showed that the scheme behaves according to expectation, i.e it reduces horizontal gradients of diffused variables. Also the 3D turbulence parametrization is sensitive to choice of stability dependency functions and horizontal length scale.

However the scheme is only effective if sufficiently steep horizontal gradients are present in the model fields. This is possible only in domains with high horizontal resolution. The limiting resolution at which the 3D turbulence parametrization is still useful was not determined in this study. We would recommend to analyze the spectrum (in space) of the model fields do see where the 3D turbulence is most active in order to determine when (at which horizontal resolution) the scheme should be switched on.

The effect of 3D turbulence is similar to the horizontal diffusion scheme SLHD, but in the former the diffusion is a parametrization of physical process and in the later the diffusion is a numerical method for noise filtering in the model fields. SLHD alone partly supersedes horizontal turbulent diffusion. So when 3D turbulence parametrization is activated SLHD diffusion should be reduced. This means that optimal 'cooperation' between both schemes should be determined. We can assume the weighting between the schemes will probably depend on the horizontal resolution of the model. We recommend further study of this subject.

References

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[2] Sukoriansky, A., B. Galperin 2008. „Anisotropic turbulence and internal waves in stably stratified flows (QNSE theory)". *Physica Scripta*, **T132**, 014 036 (2008).