Modified PM09 parameterizations in the shallow convection grey zone

LACE stay report
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1) Introduction

AROME (Application of Research to Operations at MesoscalE) is a limited area model. Its usual resolution is around 2.5 km (1.3 km), which allows to simulate most of the atmospheric phenomena. However, it has to parametrize a lot of remaining subgrid processes, one of which is the shallow convection.

The current shallow convection parameterization in AROME is the PM09 (Pergaud Masson Malardelle and Couvreux 2009, Pergaud (2009), note: in the previous reports we refered to this parametrization as EDKF), which works well outside the grey zone of turbulence. The grey zone is the range of scales, where the non-local eddies (due to the shallow convection) are partly resolved and thus should be handled by the model's dynamics. However, the resolutions in the grey zone are not fine enough for the shallow convection to be entirely resolved and the parameterization of the vertical fluxes caused by these non-local eddies is still needed.

In this work, as the continuation of the previous LACE stay in September 2014, we attempted to modify the PM09 and make it scale-adaptive so it can work in the grey zone of turbulence too. We tried four new changes in the code:

1/ We computed the "true" mass-flux values at various resolutions based on MesoNH LES (Large-Eddy Simulation) results. According to these values, we modified the initialization of the PM09 parametrization.

1bis/ Randomization of the initialisation at the surface (by Rachel Honnert).

2/ We introduced the modifications from Boutle at al. (2014), where the subgrid fluxes were multiplied by a coefficient, which was based on the work of Honnert at al. (2011).

3/ We introduced the modifications by Rachel Honnert's work, in which the used mass-flux equations do not neglect the resolved velocity and the thermal fraction.

The new PM09 parameterizations were tested with the idealised AROME on the IHOP (International H_2O Project) case and the results were compared to the reference (original) PM09.

2) The modified initialization of the PM09

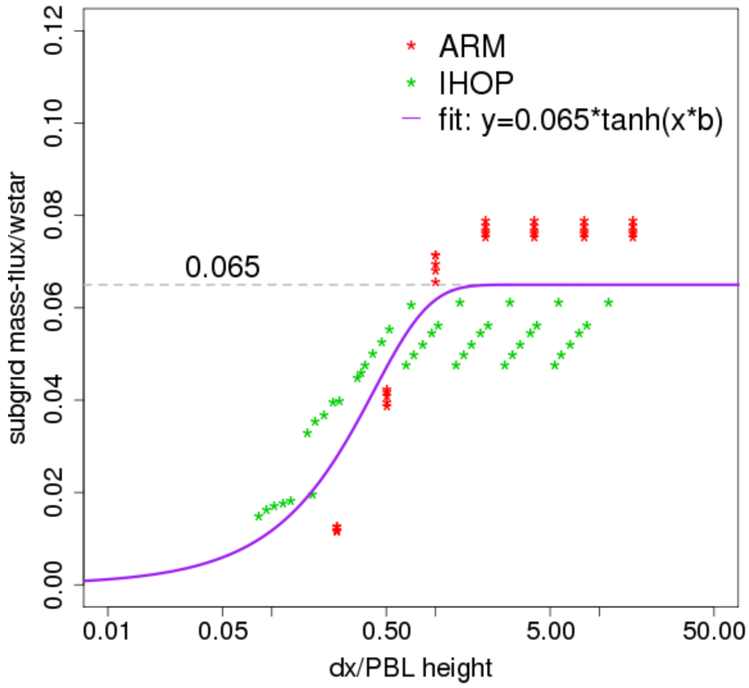
The PM09 parameterization is meant to handle the vertical fluxes caused by the shallow convection. Its algorithm follows Pergaud et al. (2009). It begins with the initialization of the mass-flux (M_u), vertical velocity (w_u), updraft fraction (α) and arbitrary variables (ϕ_u , the subscipt *u* points to the values in the subgrid thermal) at the surface and then integrates them upward until the mass-flux or the vertical velocity disappears. The current initialization of the mass-flux at the surface ($M_u(z_{grd})$) is made by the equation

$$M_u(z_{grd}) = C_M \left(\frac{g}{\overline{\theta_{vref}}} \overline{w'\theta'_{vs}} L_{up} \right)^{1/3}$$

where g is the gravity acceleration [m/s^2], $\overline{\theta_{vref}}$ is the mean virtual temperature [K], $\overline{w'\theta'_{vs}}$ is the surface buoyancy flux [Km/s] and L_{up} is the Bougeault and Lacarrère upward mixing length [m]. The C_M coefficients value is 0.065 and it was estimated from LES results using the conditional sampling method (Pergaud et al. (2009)).

On the previous LACE stay (see the LACE report from September 2014 - Toulouse), we also used MesoNH LES results to estimate the dependency of $M_u(z_{grd})$ on the resolution. In figure 1 one can see the surface mass-fluxes normalized by the vertical velocity scale (w_*) as a function of the resolution normalized by the PBL (Planetary Boundary-Layer) height in the IHOP

(International H2O Project in green) and ARM (Atmospheric Radiation Measurement in red) cases (see Honnert et al. (2011) for more details). The ratio of these values gives us the C_M coefficient. At mesoscale (>2km) it is constant and equal to 0.065. In the grey zone it falls down, because the subgrid mass-flux becomes resolved. The fitted function (purple line) is a tangent hyperbolic with the *b* parameter: f(x)=0.065*tanh(x*b). After the least-squares fitting the *b* parameter got the value 1.86. The idea of using the tangent hyperbolic function comes from Boutle at al. (2014). This function was then built in the code and tested. Series of idealized AROME simulations were made of the IHOP case at various grid-sizes: 2000 m, 1500 m, 1000 m, 500 m.



1) The ratio of subgrid mass-flux and the vertical velocity as a function of the ratio of the horizontal grid-size and the PBL (Planetary Boundary-Layer) height from the ARM (red) and IHOP (green) case at different times. The grey dashed line shows the currently used C_M = 0.065 value. The purple line shows the fitted tangent hyperbolic function.

Notice that the horizontal resolution depends on the grid-lengths *dx* and *dy*, the used grid-size factor in the code was: $\sqrt{dx*dy}$. Although the parameter *b* in the fitted function is based on the $\sqrt{dx*dy}$ grid-size values normalised by the PBL height, we also tested the alternative version of this modification, when the $\sqrt{dx*dy}$ is divided by the L_{up} at the surface.

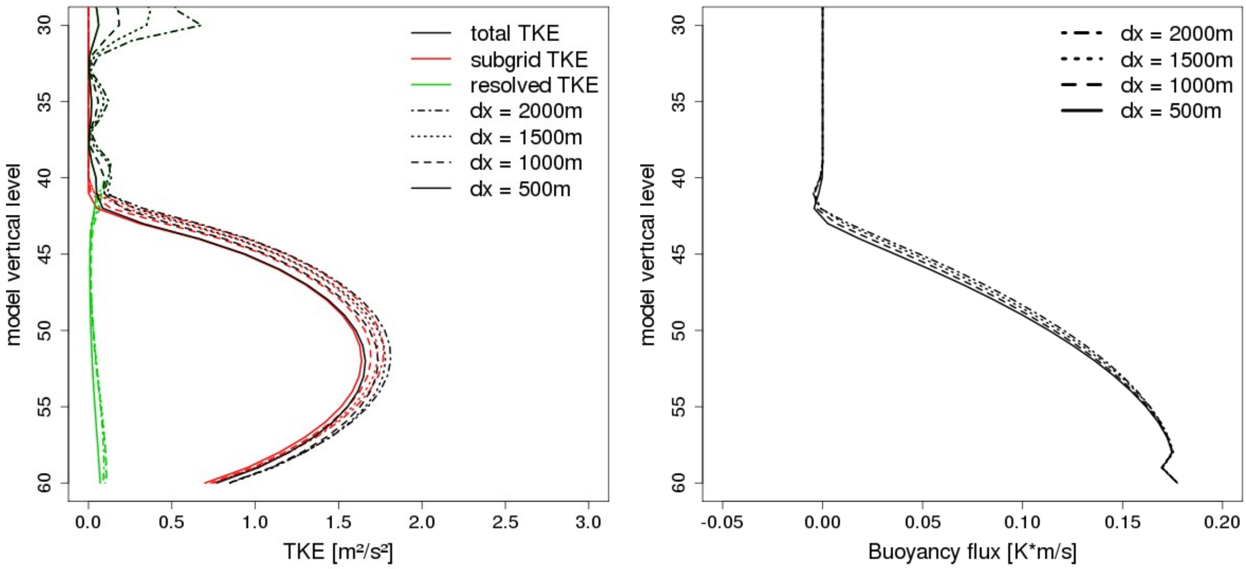
These changes can be turned on by the switch LSAEDKF in the namelist. By another switch (LUPBLH) we can chose the normalization factor (TRUE - PBL height, FALSE - L_{up}).

Figures 2 and 3 show the subgrid and resolved TKE (turbulent kinetic energy [m^2/s^2]) and subgrid buoyancy flux (vertical turbulent flux of virtual potential temperature - wthv [Km/s]) values of the idealized AROME (cycle 38) runs (with and without PM09) of the IHOP case after 415 minutes long simulation. The subgrid TKE and the subgrid buoyancy flux are from the history files. The resolved TKE was computed by the equation:

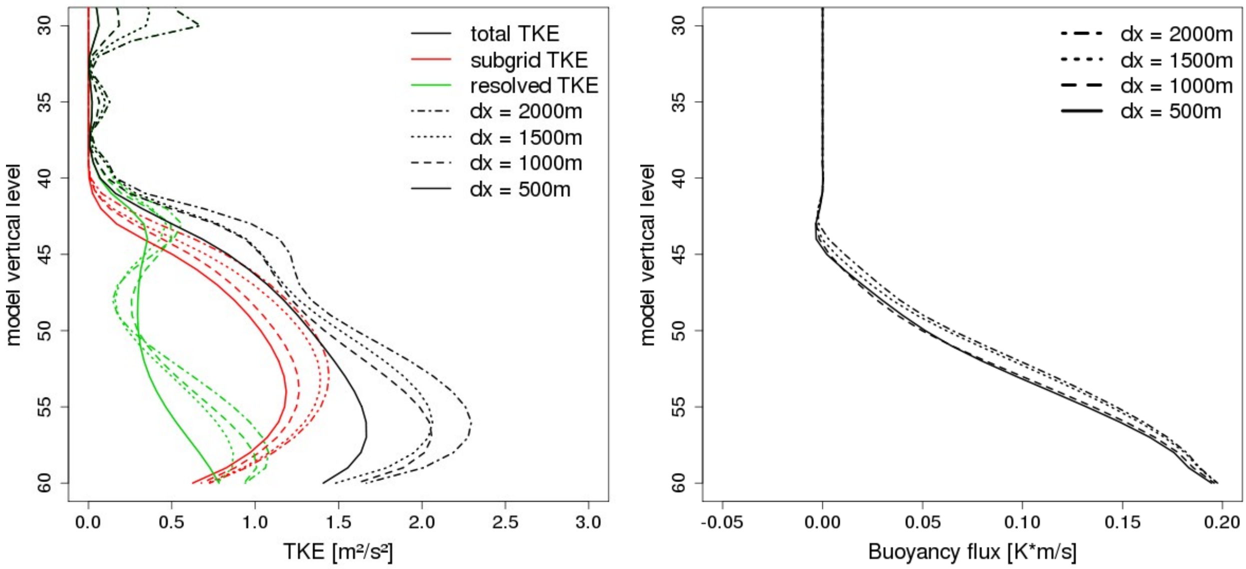
$$TKE_{res}=\frac{1}{2}[(u-\langle u\rangle)^2+(v-\langle v\rangle)^2+(w-\langle w\rangle)^2] \quad ,$$

where u,v are the horizontal wind components [m/s], w is the vertical velocity [m/s] and the $\langle\ \rangle$ symbol means the average in space for the given vertical level. The total TKE is the sum of the subgrid and resolved TKE.

These simulations (figure 4 and 5) were used as references in the comparison of the experiments with the original and the modified parameterizations.

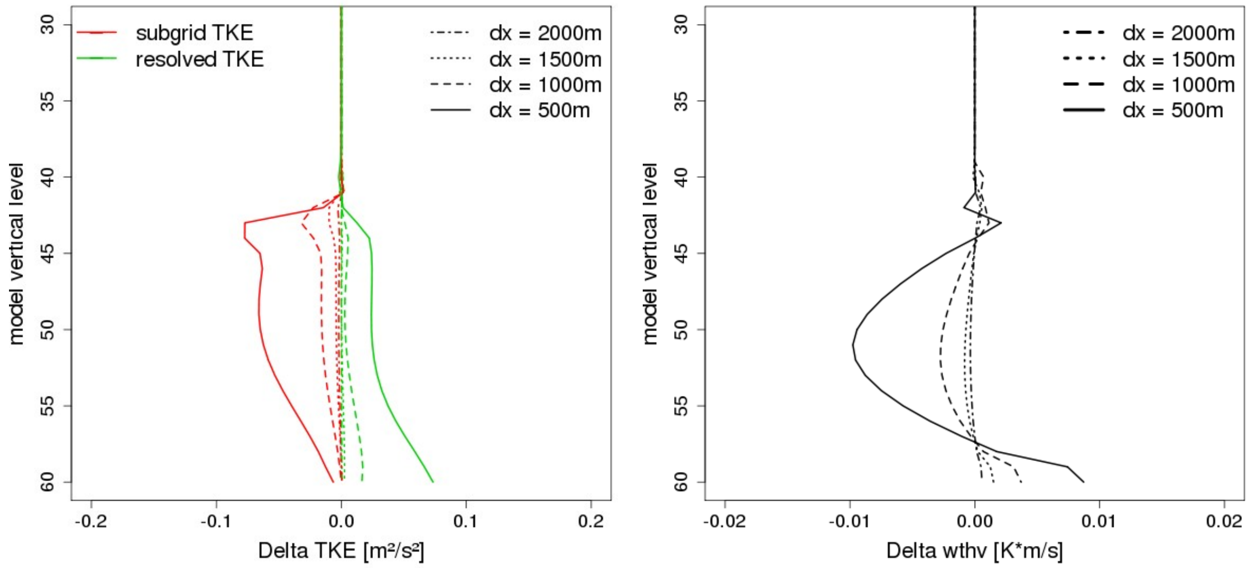


2) The mean total, subgrid and resolved TKE [m^2/s^2] (left) and subgrid buoyancy flux [Km/s] (right) values of the reference idealized AROME runs with PM09 at different resolutions.

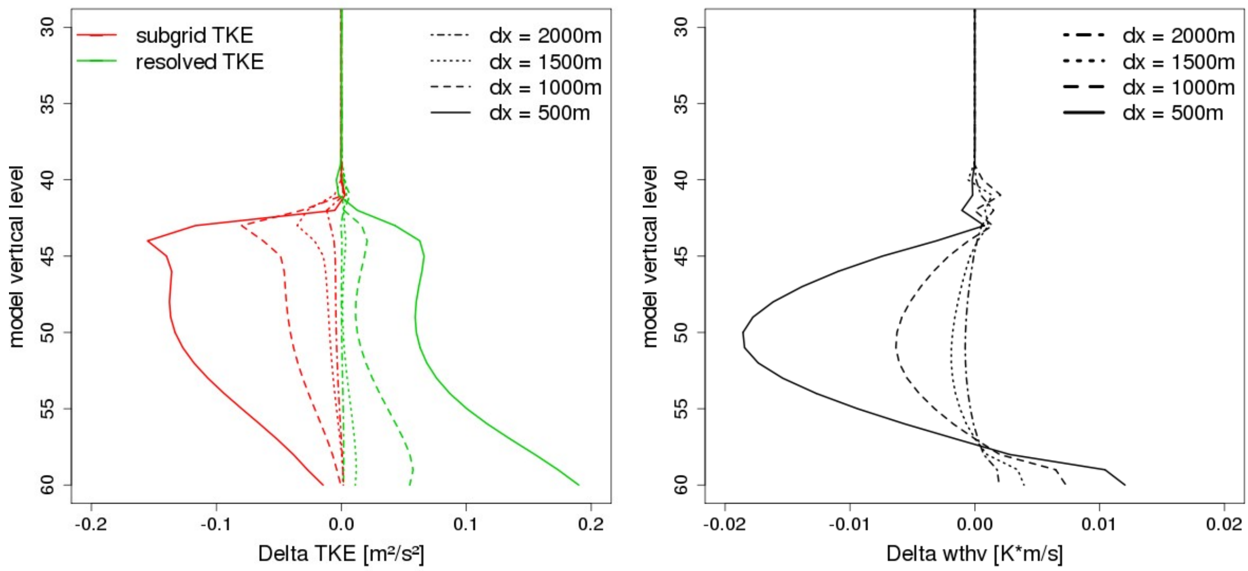


3) The mean total, subgrid and resolved TKE [m^2/s^2] (left) and subgrid buoyancy flux [Km/s] (right) values of the reference idealized AROME runs without PM09 at different resolutions.

Figure 4 and 5 show how our modification influenced (LSAEDKF=TRUE, LRANDOM=FALSE) the results. As expected, the finer the resolution, the stronger the effect. The subgrid TKE and the subgrid buoyancy flux decreases more and the resolved TKE increases more.



4) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the modified and original PM09 when LUPBLH=TRUE (modified-original PM09).



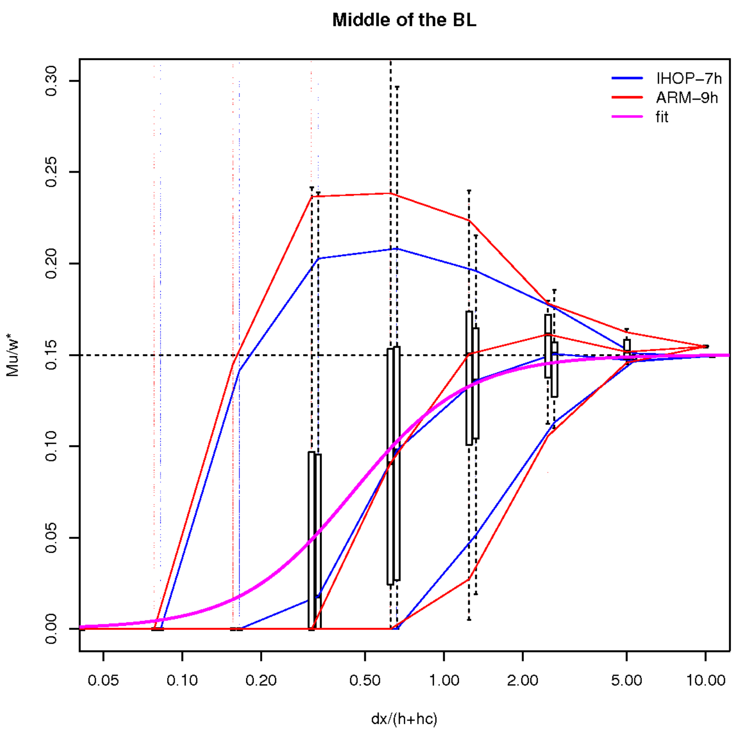
5) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the modified and original PM09 when LUPBLH=FALSE (modified-original PM09).

3) Randomization of the initialisation at the surface

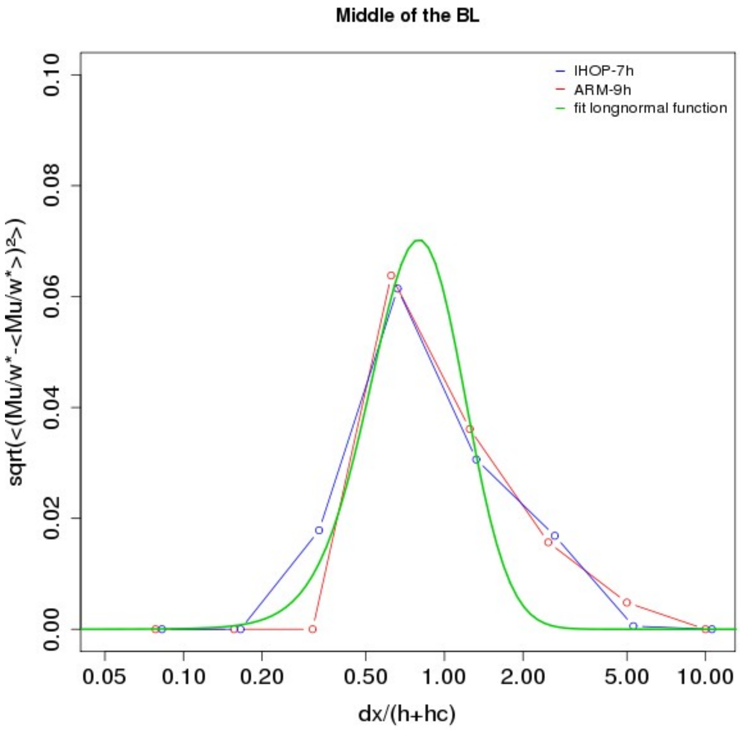
An extra modification, originated by Rachel Honnert, adds a perturbation to the mass-flux initialization. At large scale each cell of the model has statistically the same thermal for the same forcings. In the grey zone, for the same forcings, some cells have thermals triggering while the others have no thermal. This behaviour can only be simulated by random triggering of the parametrization which is the modification added.

In the figure 6 can be seen normalized subgrid mass-fluxes in middle of the PBL when the thermals are well developed (case ARM and IHOP). This time the subgrid mass-flux values were computed for every single grid-point of the spatially averaged fields of the LES, which are the theoretical values of an ideal model (Honnert at al. 2011). The points represent the subgrid mass-fluxes with box-plots and the lines are the 5% and 95% quantiles and the median. The magenta line is the fitted tangent hyperbolic function. In the figure *7* is the dispersion of these mass-fluxes, which are obviously not independent on the resolution. We fitted a log-normal function on these dispersions. Whereas they are not at the surface, we implemented this estimated relation into our modification. So when the switch LRANDOM is TRUE in the namelist, the initialized mass-fluxes are randomly perturbated in the range of this fitted function.

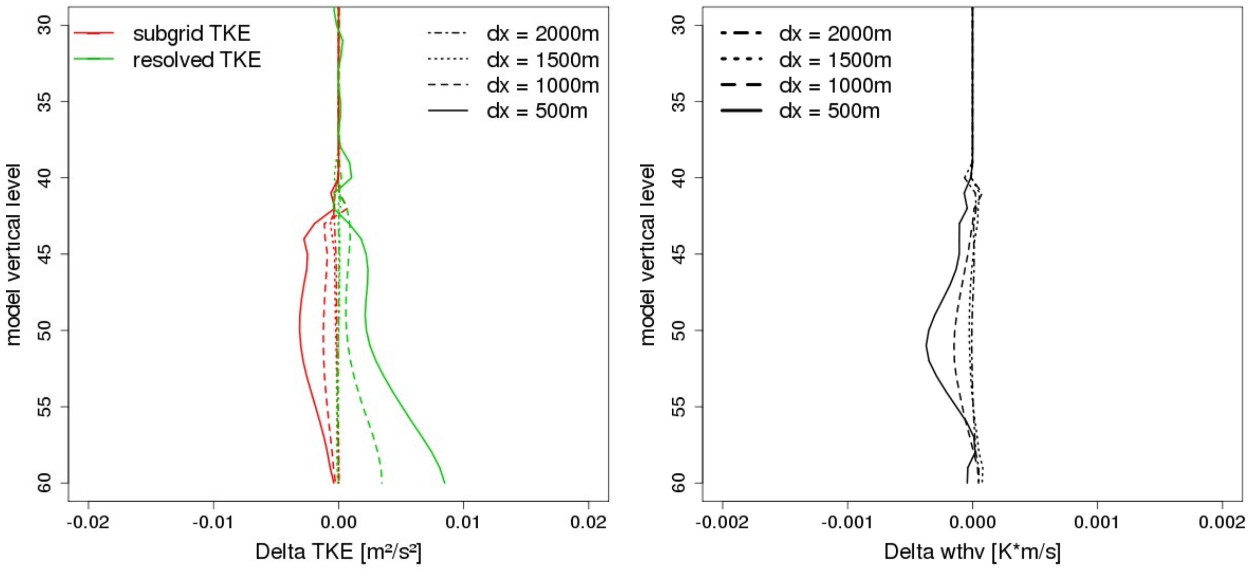
The effect of the perturbation of the initialization of the mass-flux (LRANDOM=TRUE) are shown in the figures 8 and 9. When the randomization is turned on the results do not differ very much from the case when it is turned off, the differences in the mean values are in order of 1% of the differences in the mean values between the cases LSAEDKF=TRUE and LSAEDKF=FALSE. However the structures of the vertical velocity fields are different (figure 10).



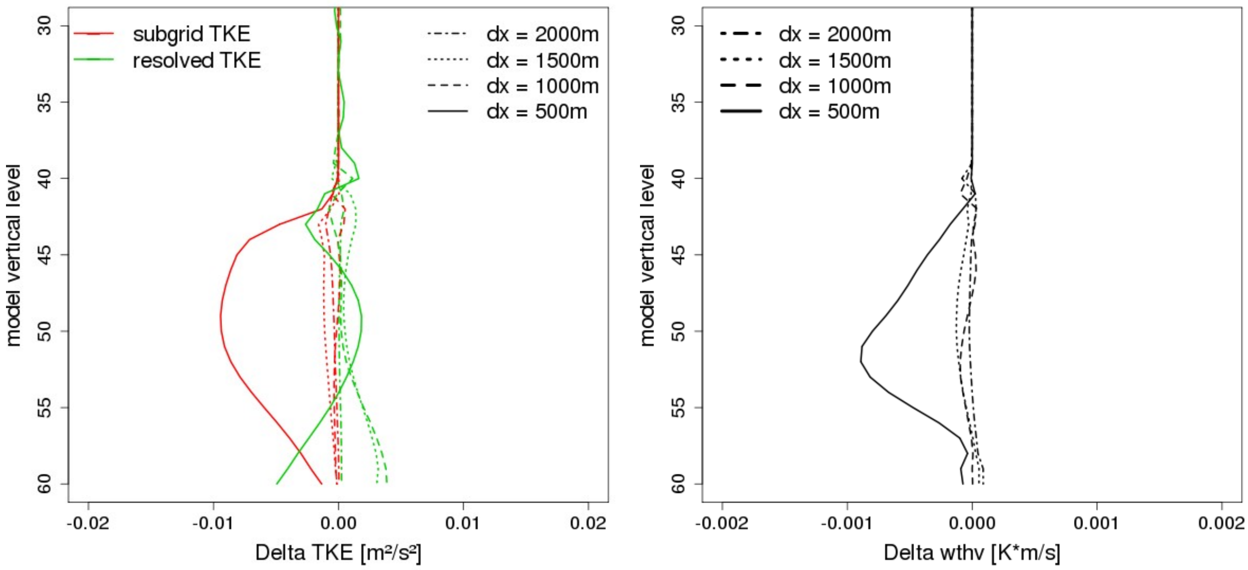
6) Normalized subgrid mass-fluxes (ARM - red, IHOP - blue) as a function of the normalised resolution (h+hc is the PBL height + the cloud layer height) in middle of the PBL with box-plots and the 5% and 95% quantiles and the median, when the thermals are well developed. The magenta line is the fitted tangent hyperbolic function.



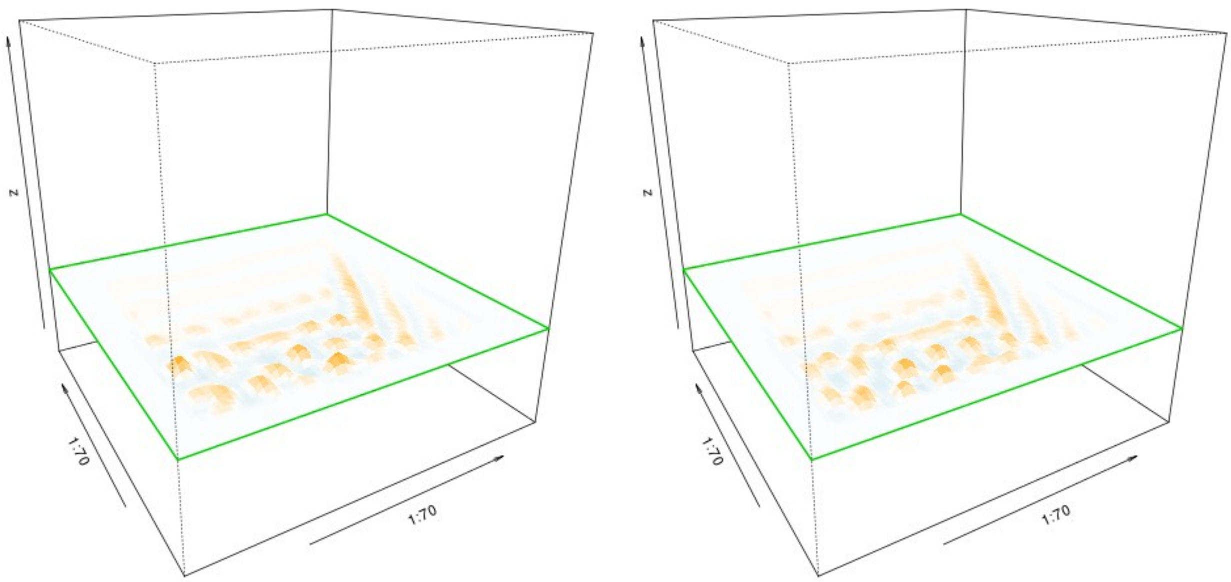
7) Dispersion of the normalized subgrid mass-fluxes (ARM - red, IHOP - blue) as a function of the normalised resolution (h+hc is the PBL height + the cloud layer height) in middle of the PBL, when the thermals are well developed. The green line is the fitted log-normal function.



8) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the cases LRANDOM=TRUE and LRANDOM=FALSE when LUPBLH=TRUE, LSAEDKF=TRUE (case$_{LRANDOM=TRUE}$-case$_{LRANDOM=FALSE}$).



9) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the cases LRANDOM=TRUE and LRANDOM=FALSE when LUPBLH=FALSE, LSAEDKF=TRUE (case$_{LRANDOM=TRUE}$-case$_{LRANDOM=FALSE}$).



10) Structure of the vertical velocity (blue - downdraft, orange - updraft) fields at the 47. model level of the simulations with PM09 when dx=500 m, LSAEDKF=TRUE, LUPBLH=FALSE. Left: LRANDOM=FALSE , right: LRANDOM=TRUE.

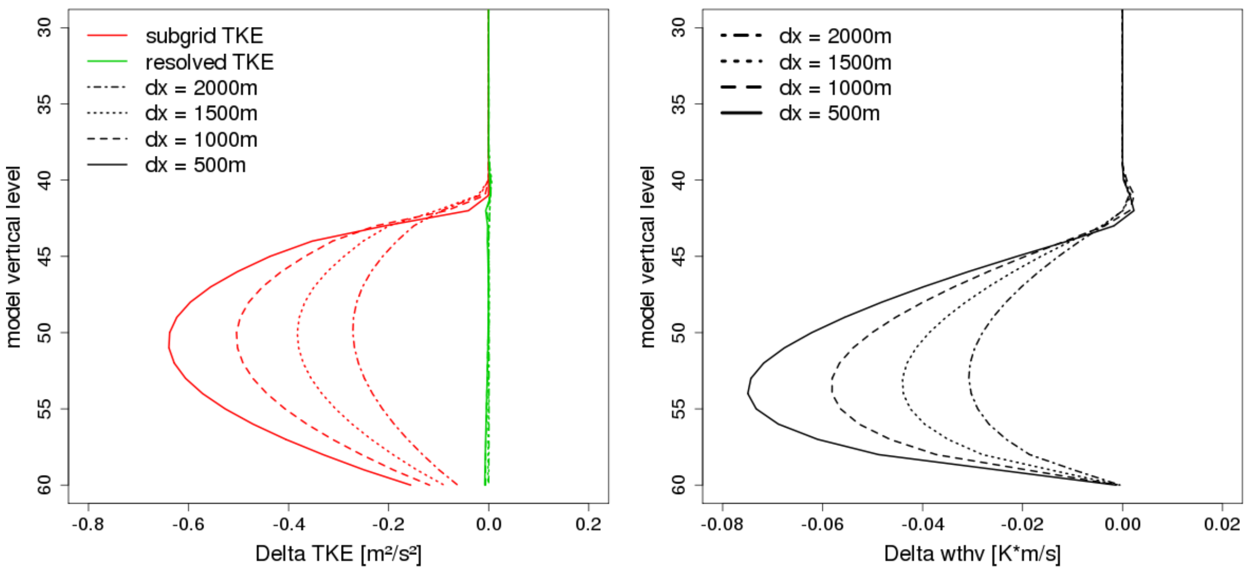
4) The modification of the PM09 by Boutle

In Boutle at al. (2014) a simple solution was suggested to decrease the subgrid turbulent fluxes by a coefficient which depends on the normalized resolution. The equation of this coefficient ZPLAW, which we implemented into the AROME, is based on the work of Honnert at al. (2011):

$$X=\frac{\sqrt{dx*dy}}{L_{up}}$$

$$ZPLAW=\frac{X^2+0.19*X^{2/3}}{X^2+0.15*X^{2/3}+0.33}$$

The figure 11 shows the differences in the mean subgrid and resolved TKE and buoyancy fluxes between Boutle's and the original PM09 parametrization. The influence of this modification is strong, but it effects only on the subgrid TKE and buoyancy flux and only minimal on the resolved TKE.



11) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the modified (by Boutle) and original PM09 (modified-original PM09).

5) The modification of the PM09 by Honnert

In the PM09 modifications by Honnert the used mass-flux equations do not neglect the resolved vertical velocity or the subgrid thermal fraction, as it is the case in mass-flux schemes as PM09. The new equations are:

$$\overline{w'\theta'}_{lMF}=M_u\left(\theta_{lu}-\overline{\theta}_l\right)\frac{1}{1-\alpha}$$

$$\overline{w'r'}_{tMF}=M_u\left(r_{tu}-\overline{r}_t\right)\frac{1}{1-\alpha}$$

$$\alpha = \frac{M_u}{w_u - \overline{w}}$$

$$\frac{1}{M_u}\frac{\partial M_u}{\partial z} = \epsilon - \delta$$

$$\frac{1}{2}\frac{\partial (w_u - \overline{w})^2}{\partial z} = -\epsilon (w_u - \overline{w})^2 \frac{1}{1-\alpha} - (w_u - \overline{w})\frac{\partial \overline{w}}{\partial z} + B_u - \overline{B} - (P_u - \overline{P}) - \frac{1}{\alpha}\frac{\partial \alpha \overline{w'^2} u}{\partial z}$$

$$B_u = g \times \frac{\theta_{vu} - \overline{\theta}_v}{\overline{\theta}_v}$$

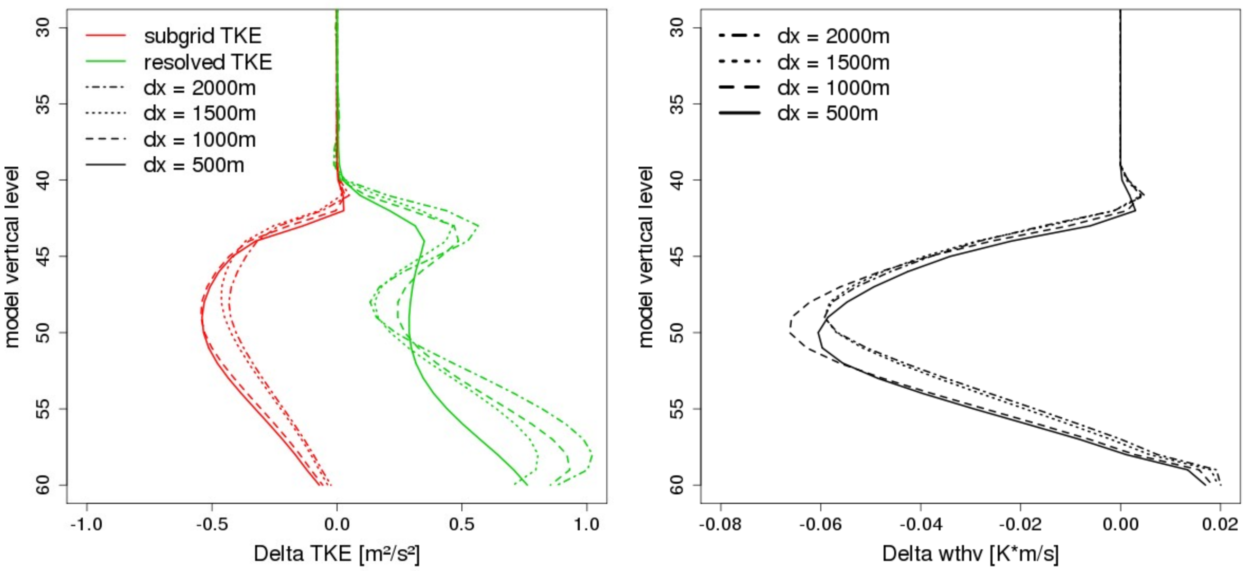
$$\theta_{vu} = f(\theta_{lu}, r_{tu})$$

$$\frac{\partial \theta_{lu}}{\partial z} = -\epsilon (\theta_{lu} - \overline{\theta}_l)\frac{1}{1-\alpha}$$

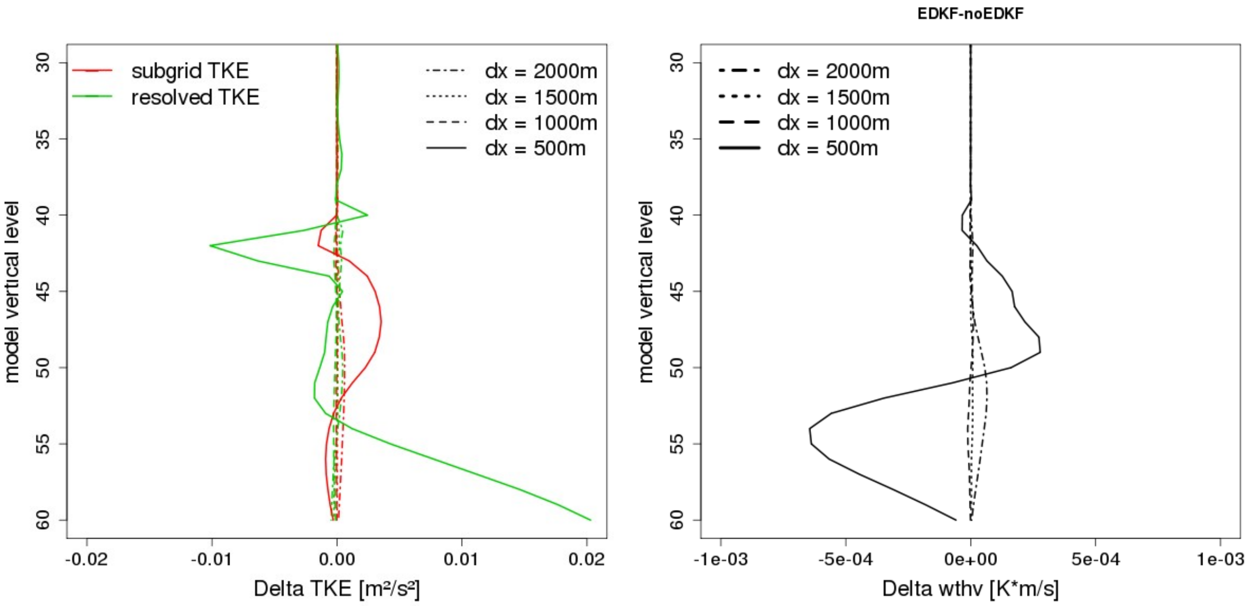
$$\frac{\partial r_{tu}}{\partial z} = -\epsilon (r_{tu} - \overline{r}_t)\frac{1}{1-\alpha}$$

where θ_l is the liquid potential temperature, r_t is the total water content, θ_v is the virtual potential temperature, the overline means the spatial average (with *u* it means over the thermal area), *ε* is the entrainment, *δ* is the detrainment, *B* is the buoyancy and *P* is the pressure.

In the figure 12 the change caused by this modification in the PM09 can be seen. The differences in the mean subgrid and resolved TKE and buoyancy fluxes between the modified and original PM09 are quite big. If we look at the figure 13, where the differences are between the simulations with this new PM09 and without PM09, we can see that they are very close, and the differences are minimal.



12) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the modified (by Honnert) and original PM09 (modified-original PM09).



13) Differences in the mean subgrid and resolved TKE (left) and subgrid buoyancy fluxes (right) between the simulations with modified (by Honnert) PM09 and without PM09 (modified PM09-no PM09).

6) Summary and future plans

In our work we tried four new versions of the PM09 parametrization, which are meant to handle the shallow convection in the grey zone, and compared them to the original version. We used for this idealized AROME simulations of the IHOP case at resolutions 2000 m, 1500 m, 1000 m and 500 m. The examined variables were the subgrid and resolved TKE and the subgrid buoyancy flux.

The first modification changes the initial mass-flux in the PM09 according to the normalized horizontal resolution. This way the subgrid TKE and the buoyancy flux decreases and the resolved TKE rises as we use finer resolution. It is possible to use the PBL height or the L_{up} to normalize the resolution. With L_{up} the effect of the modification doubles. It is also possible to randomize the mass-flux initialization, which does not modify the mean profiles but changes the locations of the thermals.

The parameterization by Boutle has a strong influence, but it only affects the subgrid TKE and buoyancy flux while the changes are minimal on the resolved TKE.

The parameterization by Honnert uses a new set of equations of the mass-flux, in which the currently neglected resolved vertical velocity and thermal fraction is used in the equations. When this type of parametrization is turned on, the results are very close to the results without any PM09 parametrization.

Our future plan is to validate the new parameterization, where the initial mass-flux is resolution-adaptive first on idealised dry and cloudy cases with idealised AROME (thanks to MesoNH LES data) and then on real cases in the operational model.

7) Acknowledgement

I want to thank for all the help I got in Toulouse at CNRM, especially to Rachel Honnert, who leaded my work there.

8) References

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