6A.3

WHICH TURBULENCE IN ATMOSPHERIC MODEL AT THE KILOMETRIC SCALE ?

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Abstract

This study focuses on the sub-grid/resolved partitioning of boundary-layer thermals in the grey zone of turbulence. A conditional sampling is developed which detects sub-grid thermals. It is used to analyse the sensibility to the grid spacing of the thermal structures, such as the sub-grid thermal fraction. The analysis proves that some assumptions of the mass-flux scheme are not valid in the grey zone. In particular, the thermal fraction is not weak and the averaged vertical velocity is not negligible. A mass-flux parameterization is proposed here.

1 Introduction

In current operational forecasting models, the boundary-layer thermals are entirely parameterized by methods such as the counter-gradient (Deardorff (1972)), the transient matrix (Stull (1984)) or the mass-flux (Hourdin et al. (2002), Siebesma et al. (2007)). For instance, the Meso-NH model (Lafore et al. (1998)) possesses a EDMF scheme (cf. Pergaud et al. (2009), hereafter PM09) which models numerous entirely sub-grid boundary-layer thermals. Thanks to increasing computational resources, in a near future, limited area NWP models will reach grid spacing on the order of 1 km or even 500 m. Honnert et al. (2011) proved that, at these grid spacings, boundary-layer thermals are partly resolved, partly sub-grid. So NWP models enter the grey zone of turbulence and new parameterization are needed to properly represent this range of scale, called "*terra incognita*" by Wyngaard (2004). The manuscript introduces a study made in Météo France, whose goal is to develop a parameterization which provides adequate turbulence to the new generation, high resolution models in the grey zone of turbulence.

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2 Gray zone of turbulence

The first step is to clarify which part of turbulence should be parameterized at kilometric scales.

In Honnert et al. (2011), the Meso-NH model (Lafore et al. (1998)) is used to simulate five Large-Eddy Simulation (LES) cases from field campaigns : three dry and two cumulus non-drizzling topped boundary layers, which represent a large range of convective cases. These LES are used here.

The figure 1 shows an example of 62.5 m resolution LES cross-sections of potential temperature, vertical velocity and water vapor mixing ratio. We get reference resolved fields at coarser grid spacing by horizontally averaging the LES fields. They show that the resolved structures are very fine in the LES. As the grid size increases, the resolved structures become smoother and finally vanish at meso-scale mesh size. They disappear more rapidly in the surface boundary layer (SBL), where the eddy size is smaller than in the mixed layer (ML) (not shown). They also vanish more rapidly for the potential temperature field than for the water vapor mixing ratio field as the characteristic size of the structures is larger than those for potential temperature and vertical velocity. Finally, at

1 km grid spacing, some structures are resolved : so 1 km resolution belongs to the grey zone.

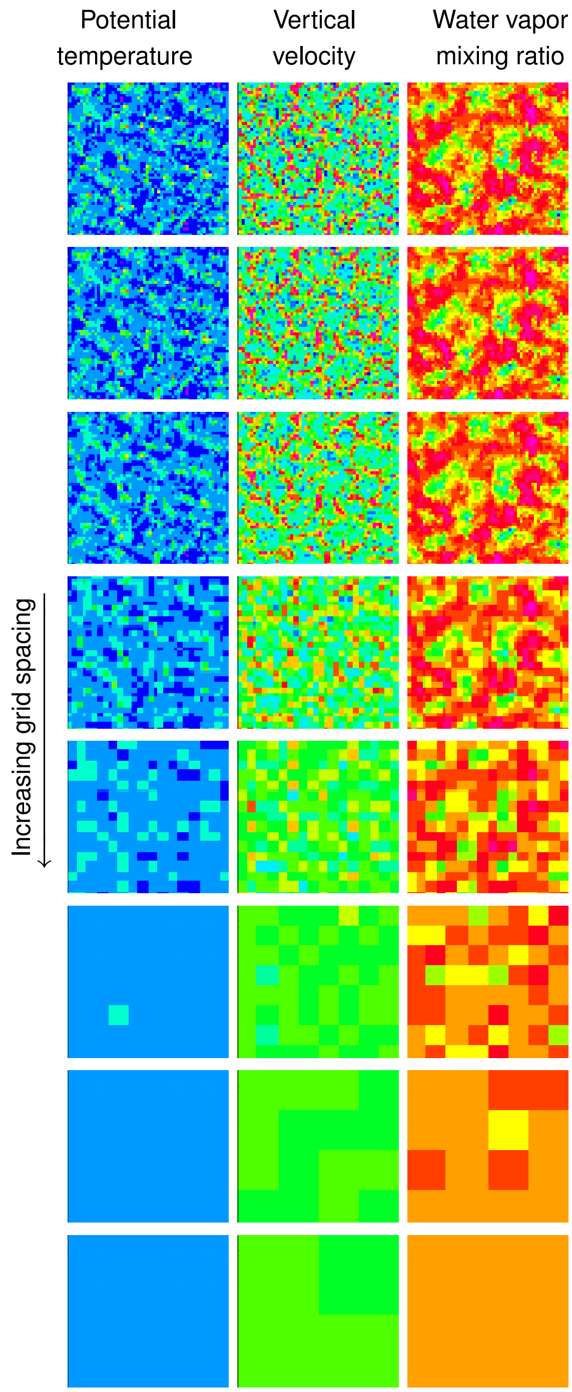

Fig. 1: 62.5 m resolution LES cross-sections of potential temperature, vertical velocity and water vapor mixing ratio. Averaged LES fields at coarser resolutions.

These results are only valid for the convective boundary layer case used in the LES and for the grid spacings at which the LES fields are averaged. To generalize those conclusions to the whole of the grey-zone scales and of the convective boundary layers, we have developed “partial simulation functions“. Thanks to the theorem of similarity, we proved that the sub-grid/resolved partitioning in the mixed layer only depends on the grid spacing normalized by the height of the coarsest boundary layer eddies. As an example, the figure 2 shows the partial similarity function of the TKE.

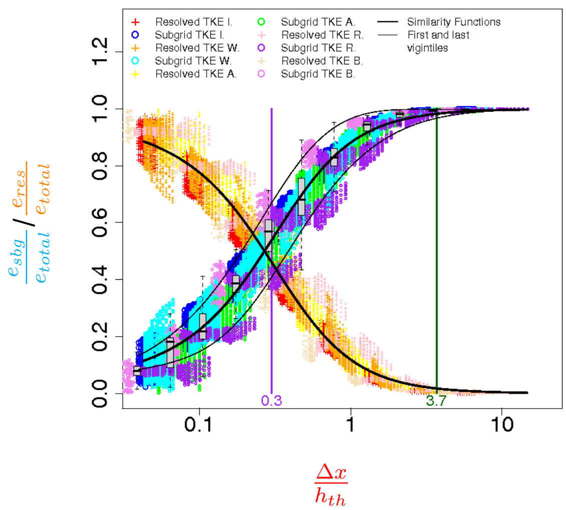

Fig. 2: Partial similarity function of the TKE in the mixed layer.The resolved part is plotted in warm colors and sub-grid part is in cold colors.

The data of the five LES are used to produce the figure 2. Whatever the simulation the data follow the partial similarity function. For the fine meshes (near the LES resolution), the sub-grid part is smaller than the resolved one. When the mesh becomes coarser, the sub-grid part grows up. Finally, for the coarsest meshes, the TKE is entirely sub-grid. This reference is valid for any dry and cumulus-topped free convective boundary layer. See Honnert et al. (2011) for the method to get them and their mathematical form. As a reference function, the partial similarity functions can be used to test model parameterizations.

3 Defaults of the current parameterizations

The partial similarity functions (cf. Fig. 2) are a precious tool to quantify the errors made by atmospheric models when running at kilometric scales. These errors are quantified for the state-of-the-art meso-scale model Meso-NH with several turbulence mixing options : a 1D or a 3D dimensionality, a Deardorff (DEAR, Deardorff (1972)) or a Bougeault-Lacarrère mixing length (BL89, Bougeault et Lacarrère (1989)) and a K-gradient scheme or an EDMF (K-gradient with a mass-flux scheme, Pergaud et al. (2009)). The mass-flux scheme activation has the most significant effect.

The figure 3 presents horizontal cross-sections of vertical velocity at several altitudes in the boundary layer with a 1 km grid spacing. The reference fields calculated by LES averaging are at the top. A simulation without the mass-flux scheme is in the middle and a simulation with it is at the bottom.

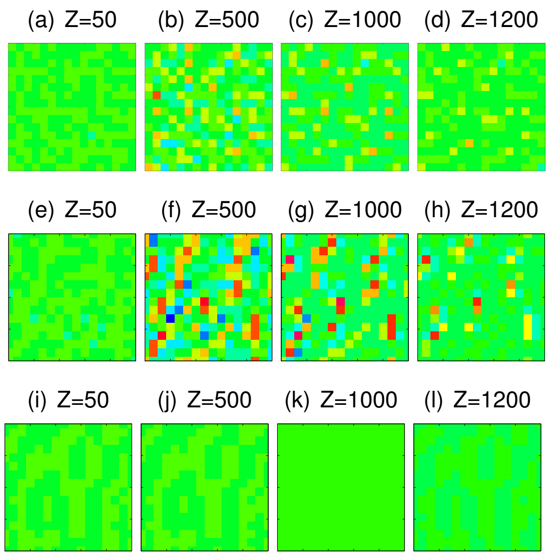

Fig. 3: Horizontal cross-sections of vertical velocity at 50 m, 500 m, 1 km, 1.2 km altitude with a 1 km grid spacing (see text).

Without the mass-flux scheme, the resolved movements are too important and the structures are too large. In contrast, when it is activated, the variability disappears. The defaults results from the representation of the non-local turbulence. Indeed, K-gradient turbulence schemes are unable to reproduce the counter-gradient zone due to the thermals. In the grey-zone of turbulence, this characteristic has a disastrous effect : as the instability is too large and the sub-grid mixing is too weak, the boundary layer is mainly mixed by the dynamic of the model. Then, the turbulent mixing is too strong and the structures too large. An EDMF can reproduce the counter gradient zone. However the mass-flux scheme in its original form only produced entirely sub-grid thermals at a grid spacing for which boundary-layer thermals should be partly resolved. In this case, the sub-grid mixing is too strong and no resolved structure is produced. Everything suggests that the mass-flux is the part of the turbulence scheme to improve.

4 Sub-grid thermals in the grey zone

4.1 Issue

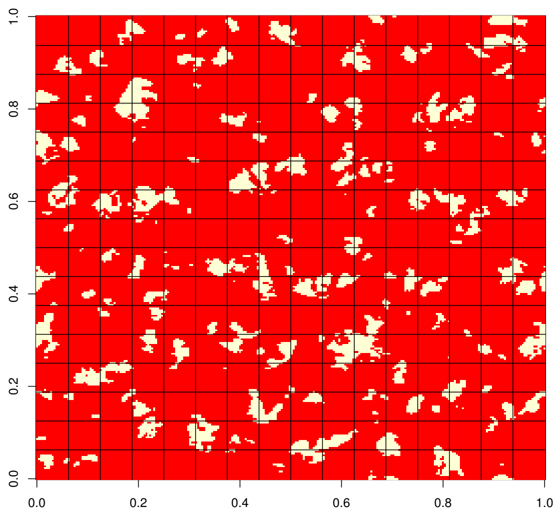

Fig. 4: Horizontal cross-section over a 16 km long LES thermal field. The thermal plumes are in white, the environment is in red.

If the cross section of the figure 4 is a unique mesh, the parameterization has to represent the characteristics of all the thermals presented. They are numerous and the thermal area is small. This allows some assumptions at meso-scale.

- The thermal plume fraction is small.
- The resolved vertical velocity is negligible.
- The tendency term is null.
- The intra-thermal term is negligible.

But when the mesh is 1 km square (cf. Fig. 5), there is one thermal at the most, which possibly can occupy a large area and so can be resolved.

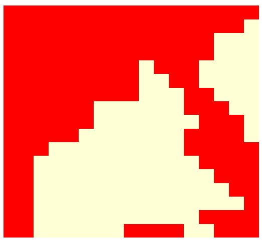

Fig. 5: 1 km^2 detail of the figure 5.

So the question arises as what is a sub-grid thermal in the grey-zone of turbulence, when the mesh contains one thermal at the most and a part of the thermal has to be resolved by the advection scheme of the model. Conditional samplings make it possible to separate the thermals from their environment in LES. A conditional sampling has been adapted to detect the sub-grid thermals in the grey zone of turbulence.

4.2 Conditional Sampling

The most common method to detect the thermal plumes in LES is the conditional sampling. Couvreux et al. (2010) proposes to use a tracer (of concentration sv) emitted at the surface. In this case, a LES mesh belongs to a thermal plume when the concentration anomaly of the tracer $(sv_i - <sv>)$ is larger than the standard deviation (σ_{sv}) and a minimum threshold (σ_{min}) and when the vertical velocity (w_i) is positive :

$$\begin{array}{lll} \mathcal{A}_i = 1 \quad if\ sv_i - <sv> & > & max(\sigma_{sv}, \sigma_{min}) \\ \qquad\qquad\quad w_i & > & 0 \\ \mathcal{A}_i = 0 \quad otherwise & & \end{array}$$

(a) Horizontal (b) Vertical

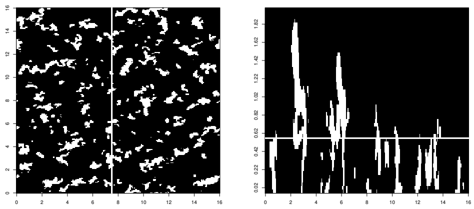

Fig. 6: (a) Horizontal and (b) vertical cross-sections of a thermal field (in white).

But what we want is not the whole thermal, but the sub-grid part of it. A LES mesh belongs to a sub-grid thermal plume in a Δx grid spacing when the concentration anomaly between the LES mesh and the resolved concentration of a Δx mesh which includes the concerned LES mesh $(sv_i - \overline{sv}^{\Delta x})$ is larger than the standard deviation calculated into the Δx mesh (σ_{svi}) and a minimum threshold and when the vertical velocity w_i is positive and larger than the resolved vertical velocity ($\overline{w}^{\Delta x}$).

$$\begin{array}{lll} \mathcal{A}_u(\Delta x)_i & = & 1\ if\ sv_i - \overline{sv}^{\Delta x} \ > \ max(\sigma_{svi}, \sigma_{min}) \\ \qquad w_i & > & 0 \\ w_i - \overline{w}^{\Delta x} & > & 0 \\ \mathcal{A}_u(\Delta x)_i & = & 0\ otherwise \end{array}$$

(a) Horizontal (b) Vertical

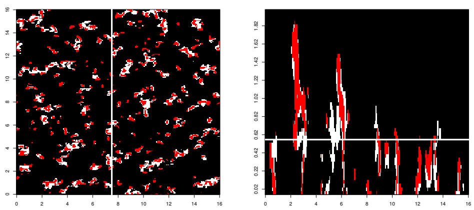

Fig. 7: (a) Horizontal and (b) vertical cross-sections of a sub-grid thermal field (in red) at 500 m resolution in ARM.

Thanks to this new conditional sampling, we can calculate the characteristics of the sub-grid thermals as a function of the grid spacing.

4.3 Sub-grid thermal characteristics

4.3.1 Thermal Fraction

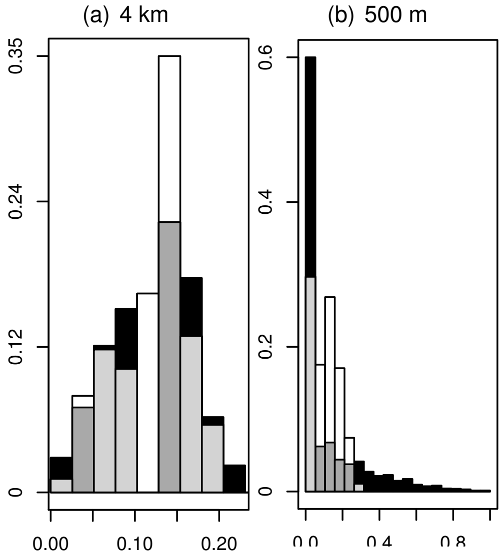

Fig. 8: Average of the thermal fraction (in black) over the Δx mesh and average of the sub-grid thermal fraction (in white) at (a) 4 km resolution and (b) 500 m resolution in ARM.

The figures 8 (a-b) present histograms of the thermal and sub-grid thermal fraction at meso-scale (a) and in the gray zone (b). The average of the thermal fraction over the Δx mesh is in black and the average of the sub-grid thermal fraction is in white. In the figure 8(a) (at meso-scale), the thermals are entirely sub-grid, the thermal fraction is $\alpha \approx 0.12$. In the figure 8(b) (in the grey zone), α not negligible, but α remains inferior to 0.4.

4.3.2 Updraft vertical velocity

The figures 9 (a-b) present histograms of vertical velocity at meso-scale (a) and in the gray zone (b). The vertical velocity of the sub-gird updraft is in white, while the resolved vertical velocity is in black. In the figure 9(a), the meso-scale resolved velocity is null as the mesh contains both the updraught and the compensatory subsidence. In the figure 9(b) (in the grey zone), the resolved velocity is not negligible compared to the velocity of the sub-grid updraft.

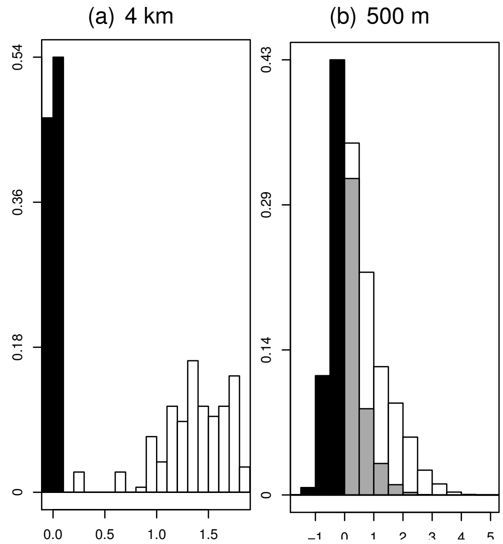

Fig. 9: Average of the vertical velocity over the sub-grid thermal (in white) and resolved vertical velocity (in black) at (a) 4 km resolution and (b) 500 m resolution.

4.3.3 Tendency term

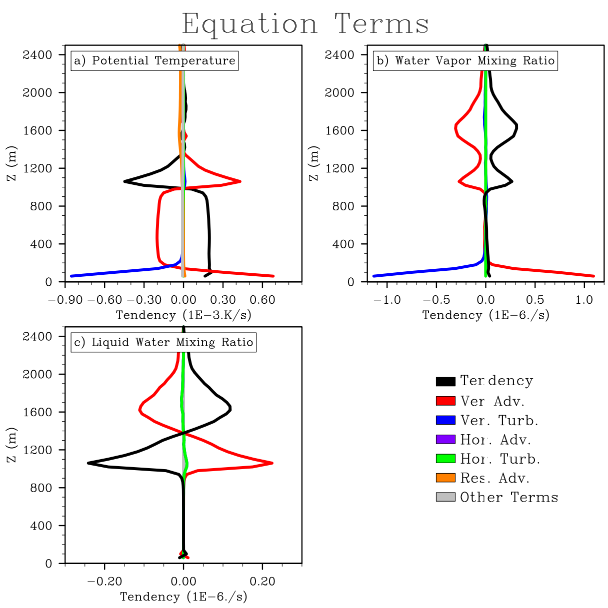

Fig. 10: Vertical profiles of updraft tendency (in black), of updraft vertical advection (in red), of updraft horizontal advection (in violet), of up-

draft vertical turbulence (in blue), of updraft horizontal turbulence (in green), of updraft resolved advection (in orange), of other minor terms including large scale forcing and pressure terms (in grey) for (a) potential temperature, (b) water vapor mixing ratio, (c) liquid water mixing ratio in ARM.

At meso-scale, the tendency terms are null as the mesh contains the same amount of thermal even if the sub-grid thermals evolve inside the mesh. In the gray zone, the thermal area can radically change in a time step. So the tendency term is not negligible anymore as seen in figure 10.

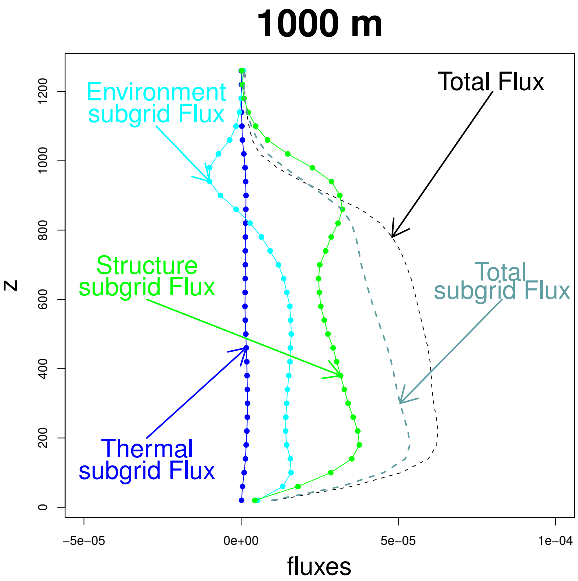

Fig. 11: Vertical profile of the humidity flux of ARM after 6 hours divided into total flux (Total) in black, resolved flux (Res.) in red, sub-grid flux (Sbg) in blue, sub-grid intra-thermal flux (Intra-th.) violet pointed line, sub-grid intra-environment flux (Intra-env.) in cyan dot-point line,sub-grid structure flux (Str.) in green line.

4.3.4 Intra-thermal terms

The total flux is divided into resolved and sub-grid flux. The sub-grid flux is divided into the intra-thermal, intra-environment and structure fluxes as in Eq. 1.

$$\begin{aligned}\underbrace{\overline{(w-\overline{w})(\phi-\overline{\phi})}}_{\text{sub-grid flux}} &= \underbrace{\alpha\overline{(w-w_u)(\phi-\phi_u)}^u}_{\text{sub-grid intra-thermal variability}} \\ &+ \underbrace{(1-\alpha)\overline{(w-w_e)(\phi-\phi_e)}^e}_{\text{sub-grid intra-environment variability}} \\ &+ \underbrace{\alpha(1-\alpha)(w_u-w_e)(\phi_u-\phi_e)}_{\text{structure flux}}\end{aligned} \tag{1}$$

where ϕ is a parameter, w is the vertical velocity, $\overline{w}$ is the average value of w over the Δx mesh, w_u or $\overline{w}^u$ (respectively w_e or $\overline{w}^e$) is the average value of the vertical velocity over the updraft (respectively the environment) of the Δx mesh and α is the thermal fraction in a Δx mesh.

Whatever the grid spacing and the simulation (only ARM is shown), the intra-thermal flux is negligible by comparison with the structure flux (cf. Fig. 11).

4.3.5 Validity of the mass-flux assumptions

In fact, only the fourth mass-flux assumption is valid in the grey zone.

- The thermal plume fraction is small => False
- The resolved vertical velocity is negligible => False
- The tendency term is null => False
- The intra-thermal term is negligible => True

The mass-flux equations have to be re-established in the grey zone.

5 New Mass-Flux scheme

The wrongly neglected terms are introduced in the mass-flux system of equations.

Mass-flux definition :

$$M_u = \rho\alpha(w_u - \overline{w}^{\Delta x})$$

The red terms are the change into the system of equations of Pergaud et al. (2009). The mass-flux (M_u) definition takes now into account the resolved vertical velocity.

Continuity equation :

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

The continuity equation depends on the entrainment (ϵ) and detrainment (δ) rates which now take into account the tendency of the updraft.

Thermal equation :

$$\frac{\partial \theta_{lu}}{\partial z} = -\frac{\epsilon}{1-\alpha}(\theta_{lu} - \overline{\theta_l}^{\Delta x})$$

In the thermal equation, the thermal fraction (α) is not neglected. In this equation, θ_l, the liquid potential temperature can be replaced by the total water mixing ratio, in order to get the humidity equation.

Dynamic equation :

$$\frac{1}{2}\frac{\partial (w_u - \overline{w}^{\Delta x})^2)}{\partial z} = (B_u - \overline{B}^{\Delta x})$$

$$-\frac{\epsilon}{1-\alpha}(w_u - \overline{w}^{\Delta x})^2$$

$$-(\mathcal{P}_u - \overline{\mathcal{P}}^{\Delta x}) - \frac{1}{\alpha}\frac{\partial \alpha \overline{w'^2}^u}{\partial z} - (w_u - \overline{w}^{\Delta x})\frac{\partial \overline{w}}{\partial z}$$

The dynamic equation is the evolution equation of the square of the sub-grid updraft vertical velocity $(w_u - \overline{w}^{\Delta x})^2$. It depends on the buoyancy of the sub-grid updraft ($B_u - \overline{B}^{\Delta x}$), of the lateral entrainment ($-\frac{\epsilon}{1-\alpha}(w_u - \overline{w}^{\Delta x})^2$), of the pressure term (($\mathcal{P}_u - \overline{\mathcal{P}}^{\Delta x}$)), of the intra-thermal term ($-\frac{1}{\alpha}\frac{\partial \alpha \overline{w'^2}^u}{\partial z}$) and of the resolved velocity term ($-(w_u - \overline{w}^{\Delta x})\frac{\partial \overline{w}}{\partial z}$). The last three terms have to be parameterized.

A paper has been submitted on the topic : Honnert R., V. Masson, and F. Couvreux : A parameterization of the turbulence at the kilometric scales. What is a sub-grid thermal at the Kilometric Scale ? *QJRMS*.

6 Conclusion and perspectives

To conclude, the grey zone of turbulence has been studied. By the mean of partial similarity function, we now know at which scales the turbulence is partly resolved and what is the true resolved/sub-grid partitioning in this range of scale. This reference has be used to quantify the defaults of a current model. In the grey zone, the turbulence is ill-represented whatever the configuration of the scheme, the non local turbulence is the main problem. An article has been published on the topic. Finally a conditional sampling is created to detect the sub-grid thermal plumes and study their characteristics in the grey zone. As mass-flux current assumptions are not true in the grey zone, a new parameterization is develop. An article has been submitted to the QJRMS on the topic. Subsequently, The parameterization is going to be closed and tested.

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