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Representation of the grey zone of turbulence in the atmospheric boundary layer

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Abstract. Numerical weather prediction model forecasts at horizontal grid lengths in the range of 100 to 1 km are now possible. This range of scales is the “grey zone of turbulence”. Previous studies, based on large-eddy simulation (LES) analysis from the MésoNH model, showed that some assumptions of some turbulence schemes on boundary-layer structures are not valid. Indeed, boundary-layer thermals are now partly resolved, and the subgrid remaining part of the thermals is possibly largely or completely absent from the model columns. First, some modifications of the equations of the shallow convection scheme have been tested in the MésoNH model and in an idealized version of the operational AROME model at resolutions coarser than 500 m. Secondly, although the turbulence is mainly vertical at mesoscale ($>$ 2 km resolution), it is isotropic in LES ($<$ 100 m resolution). It has been proved by LES analysis that, in convective boundary layers, the horizontal production of turbulence cannot be neglected at resolutions finer than half of the boundary-layer height. Thus, in the grey zone, fully unidirectional turbulence scheme should become tridirectional around 500 m resolution. At Météo-France, the dynamical turbulence is modelled by a K-gradient in LES as well as at mesoscale in both MésoNH and AROME, which needs mixing lengths in the formulation. Vertical and horizontal mixing lengths have been calculated from LES of neutral and convective cases at resolutions in the grey zone.

1 Introduction

The grey zone of turbulence is defined by Wyngaard (2004) as the scales on the order of the energy-containing turbulence scale. At these resolutions, the turbulence structures are neither entirely subgrid scale (as in global and mesoscale models) nor largely resolved (as in large-eddy simulations – LESs). Honnert et al. (2011) used LES coarse-graining to produce similarity functions linking the subgrid or resolved part of the turbulent fluxes and the horizontal resolution of the model out of the height of the thermals. They indicated that the grey zone exists from resolutions smaller than 2 times the boundary-layer height in convective boundary layers (CBLs). Regional models are now approaching the sub-kilometre scales, and Honnert et al. (2011) showed that neither unidirectional (1-D) non-local mesoscale boundary-layer (BL) turbulence scheme nor isotropic (3-D) LES schemes are appropriate at these scales. That is why the turbulence schemes have to be adapted to the grey zone of turbulence.

Boutle et al. (2014) blended a 3-D-Smagorinsky with a 1-D non-local BL scheme with the help of the similarity functions proposed by Honnert et al. (2011). Ito et al. (2015) extended the Mellor and Yamada scheme by modifying the length scales using statistics obtained from LES coarse-graining. Shin and Hong (2015) quantified the local and non-local turbulence at scales in the grey zone to adjust the vertical profiles resulting from their non-local K-gradient scheme.

These adaptations strongly depend on the schemes which are currently used at mesoscale or LES. At Météo-France, the turbulence in the atmospheric BL is represented by an eddy-diffusivity/mass-flux parameterization (EDMF; Hourdin et al., 2002; Soares et al., 2004). The updraughts are represented by the mass-flux scheme which starts at the ground (hereafter PM_{09}; Pergaud et al., 2009) and represents the shallow convection, while the rest of the turbulence is represented by a K-gradient scheme (hereafter CBR; Cuxart et al., 2000). Both parts of this scheme are being modified to adapt Météo-France models to the grey zone of turbulence. In this article, modifications of PM_{09} are presented in the second section as well as preliminary results in the third section. As perspective, the "true" CBR mixing lengths in the grey zone are presented.

2 A new mass-flux scheme

As many mass-flux schemes, PM_{09} is based on several assumptions which are valid at large scales. It assumes in particular that the thermal surface is small, the resolved vertical velocity is zero, and the thermal field is quasi-stationary.

Honnert et al. (2016) determined the characteristics of the non-local turbulence (BL thermals) in the grey zone by means of a conditional sampling. Figure 1 shows a 16 km long horizontal cross section of an LES. The thermals (in white) and the part of the thermals which impact the subgrid mass-flux scheme at 1 km resolution (in black) have been determined by the conditional sampling of Honnert et al. (2016). The environment of the structures is in red. Figure 1 shows that at 16 km resolution, PM_{09}'s assumptions are valid: the thermal surface is small, the resolved vertical velocity is zero, as the grid cell contains both the updraughts and the compensatory subsidence, and the thermal field is quasi-stationary. However, in the grey zone, they are not verified. Indeed, as seen on the 1 km zoom of Fig. 1, the thermal surface (in black) may be large, the resolved vertical velocity is not zero, as one thermal can fill the grid cell, and the thermal field is probably not quasi-stationary.

However, mass-flux schemes can be developed without the three assumptions presented before. The initial schemes (PM_{09}; Rio and Hourdin, 2008) describe the behaviour of parameters of one unique thermal in the mesh (the vertical velocity w_u, the mass-flux M_u, the total potential temperature θ_{l_u}, the thermal surface area α, the buoyancy inside the thermal B_u and the pressure and the entrainment (ϵ)/detrainment (δ) lateral closure). a_1 and b_1 are constant. Equations (1)–(4) show the modifications (in red) of PM_{09}. The non-negligible resolved vertical velocity ($\overline{w}^{\Delta x}$) is added in Eqs. (1), (3), and (4). The thermal surface is not negligible and appears at the denominator in Eqs. (3)–(4). The surface triggering of the mass flux ($M_{u_{z=0}}$, Eq. 5) depends on the resolution.

$$M_u = \rho\alpha\left(w_u - \overline{w}^{\Delta x}\right) \tag{1}$$

$$\frac{1}{M_u}\frac{\partial M_u}{\partial z} = \epsilon - \delta \tag{2}$$

$$\frac{\partial \theta_{l_u}}{\partial z} = -\frac{\epsilon}{1-\alpha}\left(\theta_{l_u} - \overline{\theta_l}^{\Delta x}\right) \tag{3}$$

$$\frac{1}{2}\frac{\partial\left(w_u - \overline{w}^{\Delta x}\right)^2}{\partial z} = a_1 B_u - b_1\frac{\epsilon}{1-\alpha}\left(w_u - \overline{w}^{\Delta x}\right)^2 \tag{4}$$

$$\frac{M_{u_{z=0}}}{w*} = 0.075 \times \left(1 + \tanh\left(\ln\left(\frac{\Delta x}{h+h_c}\right) + 0.8\right)\right) \tag{5}$$

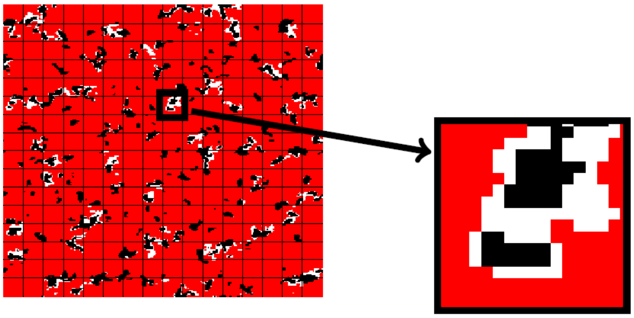


Figure 1. 16 km long horizontal cross section of an LES (IHOP case, 14:00 LT, 500 m altitude) and 1 km long zoom. The thermal fraction is in white, the core of the thermals (strong vertical velocity) is in black, and the environment is in red (see Honnert et al., 2016).

Then, the finer the resolution or the smaller the BL height, the smaller the subgrid turbulent flux. The scheme produces less subgrid turbulence. Consequently, resolved BL thermals are created.

3 Results

The results presented in this section compare model simulations and coarse-grained LES of a dry CBL (hereafter IHOP). This case has been performed using radio soundings collected during the International H_2O Project (IHOP_{2002}) campaign (Weckwerth et al., 2004). This field experiment took place in the US Southern Great Plains from 13 May to 25 June 2002. Here, we used the 14 June 2002 case corresponding to a growing CBL near Homestead, Oklahoma (cf. Couvreux et al., 2015). This day was characterized by high pressure (1016 hPa or more) and light wind (less than 5 m s^{-1}). The vertical shear was weak. The well-mixed boundary layer reached 1.5 km in the beginning of the afternoon. The radio soundings were made in the morning from 14:00 to 18:00 UTC (09:00 to 13:00 LT – local time). This case was chosen as it presented a relatively uniform site topography and a typical development of continental convective boundary layer. The simulations lasted for 7 h.

Méso-NH (Lafore et al., 1998) is the research model at Météo France. It can be used in various configurations of the turbulence scheme (from LES to synoptic), in idealized cases, as well as in real cases. In Fig. 2a and b, the resolved turbulent kinetic energy (TKE) of the new parameterization (in green) is compared at 500 m and 1 km resolution with the results of the LES coarse-graining (in black), those of simulations with PM_{09} (in blue), and without mass flux at all (in red). The new parameterization is scale-adaptive and produces the resolved TKE calculated from the LES, even if it produces a bit too much TKE at 500 m and not enough at 1 km resolution.

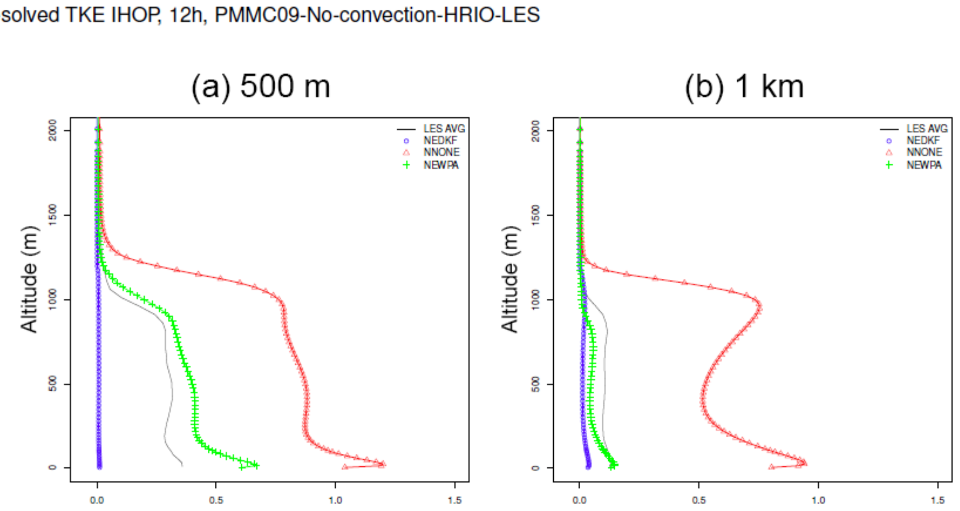


Figure 2. Resolved TKE in Méso-NH at **(a)** 500 m and **(b)** 1 km resolution in IHOP. The reference (coarse-grained LES) is in black, and the parameterization in green. The blue lines are results of simulations with PM_{09}, and the red ones result from simulations without shallow convection.

AROME (Seity et al., 2010) is the operational regional model at Météo France. Its turbulence scheme is the same as Méso-NH, but the configuration is fixed (for mesoscale simulations) and it simulates real cases only. It is challenging to test a new turbulence parameterization in the operational AROME as there is no reference. That is why, in these tests, we used idealized-AROME. This model has no land surface or lateral coupling and no surface scheme. The imposed boundary conditions allow us to reproduce in AROME the idealized cases previously studied in LES.

Figure 3 shows subgrid TKE produced by the new parameterization at resolutions from 500 m to 2 km (dotted lines) and the subgrid TKE at resolutions from 62.5 m to 8 km calculated from LES. In the middle of the BL, the parameterization follows the LES reference. However, in the surface layer, the turbulence is underestimated. This default is not due to the mass-flux parameterization, but it results from limits of the K-gradient scheme. Indeed, it is purely 1-D in AROME, while in the surface layer, a 3-D dynamical turbulence is required.

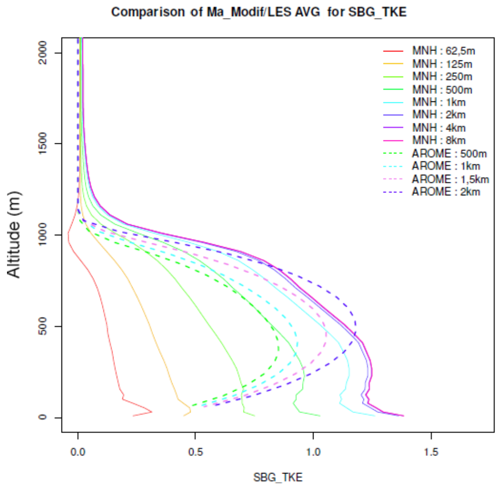
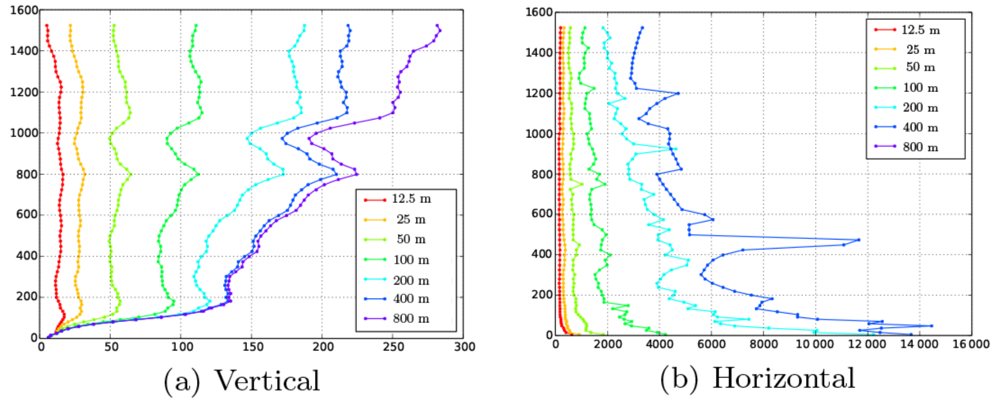


Figure 3. Subgrid TKE in AROME at 500 m and 1 km resolution in the IHOP. "MNH" means the reference LES (in full lines) and AROME means the new parameterization (in dotted lines).

4 Limits of the mass-flux modifications: from 1-D to 3-D turbulence scheme

A second problem appears in the grey zone of turbulence: the dimensionality of the scheme. At mesoscale, the horizontal homogeneity assumption allows the computation of the vertical (1-D) turbulent flux only. On the contrary, in LES, the turbulence is assumed isotropic, thus 3-D. The limit resolution at which the horizontal turbulent movements are not negligible is in the grey zone. Honnert and Masson (2014) quantified the production terms of the TKE at grey-zone resolutions from LES coarse-graining. At mesoscale, the turbulence is mainly produced by thermals; thus the (vertical) mass-flux scheme has the most impact. However thermal production of TKE is reduced in the grey zone, as the thermals are partly resolved, and the vertical and horizontal components of the dynamical production of TKE become larger; thus the 3-D K-gradient scheme becomes critical.

Honnert and Masson (2014) have proved that the limit resolution at which the horizontal turbulent movements are not negligible is about 0.5 times the size of the energy-containing structures in free CBL (about 500 m resolution). So, the modifications made in the mass-flux part impact the scheme until about 500 m resolution. The K-gradient scheme has to



(a) Vertical (b) Horizontal

Figure 4. **(a)** Vertical and **(b)** horizontal mixing lengths computed at resolutions from 12.5 to 800 m. CASES-99 (neutral BL).

be modified for finer resolutions. Firstly, a 3-D K gradient is necessary. AROME, for instance, has no 3-D turbulence scheme. This limits the modelling of the smallest scales of the grey zone of the turbulence with AROME. Secondly, the subgrid turbulence is not isotropic in the grey zone (as proved in Honnert and Masson, 2014). Méso-NH, for instance, possesses a 3-D turbulence scheme. However, the turbulence is always assumed isotropic. In particular, the LES scheme uses a unique mixing length on the horizontal and on the vertical. Finally, the mixing length is on the order of the boundary-layer height at mesoscale (Bougeault and Lacarrère, 1989) and on the order of the mesh size in LES.

The size of the vertical and horizontal mixing lengths is studied in the grey zone. The eddy diffusivity (K) is calculated from the fluxes ($\overline{u'v'}$, $\overline{v'w'}$, $\overline{u'w'}$ in Eqs. 6–8) and gradients (e.g. $\frac{\partial \overline{u}}{\partial y}$ in Eqs. 6–8) computed by LES coarse-graining of IHOP and an additional neutral case at several resolution in the grey zone (Eqs. 6–8). The mixing lengths (L) are computed from the eddy diffusivity and the TKE (e) (Eqs. 9–11) in the CBR equations (C is a constant).

$$\overline{u'v'} = -K_{u,v}\left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right) \tag{6}$$

$$\overline{u'w'} = -K_{u,w}\left(\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x}\right) \tag{7}$$

$$\overline{v'w'} = -K_{v,w}\left(\frac{\partial \overline{v}}{\partial z} + \frac{\partial \overline{w}}{\partial y}\right) \tag{8}$$

$$K_{u,v} = -CL_{u,v}\sqrt{e} \tag{9}$$

$$K_{u,w} = -CL_{u,w}\sqrt{e} \tag{10}$$

$$K_{v,w} = -CL_{v,w}\sqrt{e} \tag{11}$$

Figure 4 shows the mixing lengths in the neutral BL (CASES-99) based on the CASES-99 experiment which took place from 1 to 31 October 1999 near Leon, Kansas. It was first designed to study stable BL, morning and evening transitions periods. Measurements were taken during neutral conditions. Drobinski et al. (2007) first described this LES. The rugosity length of the site is 0.1 m, and the friction velocity is 0.42 m s^{-1}. A constant (293.15 K) potential temperature is imposed until 750 m altitude (Drobinski et al., 2007) and then a constant adiabatic gradient until 1500 m altitude. The stable boundary layer kills the turbulence above 750 m altitude and limits the size of the eddies. Thus, the eddies remain small enough to be contained in the LES domain. The heat flux at the surface is zero along the simulations, as well as the humidity flux at the surface. The simulations are dry. Thus, the buoyancy flux is zero during the simulations and the production of turbulence is purely dynamical. The geostrophic wind is zonal and prescribed at 10 m s^{-1}.

Figure 4 shows vertical and horizontal mixing lengths computed by Eqs. (6)–(11). Both vertical and horizontal mixing lengths are larger at mesoscale. Under 1000 m altitude, the vertical mixing lengths are consistent with the literature: at mesoscale, they behave as in Bougeault and Lacarrère (1989) with a maximum of a few hundred metres in the BL, while at small scale, they behave as the Deardorff mixing length (the size of the grid cell) with a relatively constant value in the BL of a few tens of metres. Above the BL, the method reaches its limits as the fluxes and gradients are very small. The horizontal mixing lengths are larger at the surface, where there is a maximum of horizontal movements. At mesoscale, the very large horizontal mixing lengths may result from small horizontal gradients at these scales. The fine resolutions present horizontal mixing lengths on the order of the vertical lengths as turbulence is isotropic at those scales.

5 Conclusions

Numerical weather prediction model forecasts at horizontal grid lengths in the range of 100 m to 1 km are now possible. This range of scales is in the “grey zone of turbulence”. Previous studies, based on LES analysis from the MésoNH model, showed that some assumptions of turbulence schemes on BL structures are not valid. Indeed, BL thermals are now partly resolved and the subgrid remaining part of the thermals is possibly largely or completely absent from the model columns. Moreover, although the turbulence is mainly vertical at mesoscale, it is isotropic in LES. It has been proved by LES analysis that, in CBL, the turbulence is neither 1-D nor isotropic in the grey zone.

At Météo-France, the turbulence scheme is an EDMF. In this study, in order to model the turbulence at all scales, both the mass flux and the K-gradient part of the scheme are examined. Firstly, the equations of the shallow convection (mass flux) scheme have been modified in order to remove the mesoscale assumptions, which are not valid in the grey zone. These modifications have been tested in the MésoNH model and in an idealized version of the operational AROME model. Secondly, horizontal and vertical mixing lengths have been calculated from LES of neutral and CBL cases at resolutions in the grey zone. These mixing lengths will be introduced in 3-D CBR, which will amend the K-gradient scheme in the grey zone.

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