Some Light Shed on the Grey Zone of Turbulence

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Grey Zone of turbulence

Turbulence mainly resolved

GREY ZONE
(Wyngaard, 2004)

Turbulence entirely subgrid

LES

Increasing resources

10 100 200 500 1000 2000 1.3 km 10 km

MésoNH AROME ARPEGE
Turbulence scheme

\[ u_i' \phi' = -K\phi \frac{\partial \phi}{\partial x_i} \]

\[ K\phi = C_\phi \times l \times \sqrt{e} \]

with:
- \( u_i' \phi' \) turbulent flux
- \( l \) mixing length
- \( e \) prognostic TKE
Méso-NH and AROME mass-flux scheme

\[ w' \phi' = -K \frac{\partial \phi}{\partial z} + \frac{M_u}{\rho} \left( \phi_u - \phi \right) \]

- **Turbulence**
- **Shallow convection**

- **CBR**: K-gradient scheme (Cuxart et al (2000))
- **PM09**: Mass-Flux scheme (Pergaud et al (2009))
- Updraft starts at the surface \( \Rightarrow \) BL thermals.
Turbulence scheme at Météo-France

Méso-NH : research model used in various configurations : meso-scale, CRM or LES. (Cuxart et al. (2000))

- Mixing length
  - BL89 : Size of the coarsest eddies at a given altitude. (Bougeault et Lacarrère (1989)).
  - DEAR : Size of the mesh (Deardorff (1972)).

- Dimensionnality
  - 1D turbulence scheme
  - 3D turbulence scheme

- Thermal scheme (PM09)
  - activated
  - deactivated
Turbulence scheme at Météo-France

AROME-FRANCE NWP meso-scale model (*Seity et al. (2010)*)

- **Mixing length**
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1. Which turbulence in the Grey Zone?
2. Mass-Flux scheme in the Grey Zone
3. From 1D turbulence scheme to 3D
4. Mixing lengths in the Grey Zone
Method

Goal
Get a true subgrid-resolved distribution of the turbulence in the grey zone.

![Diagram showing the comparison between LES and NWP models for turbulent parameter distribution.](image)
Method

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Get a true subgrid-resolved distribution of the turbulence in the grey zone.

Method:

- LES of several BL cases
- Coarse-graining of LES fields
  → get true resolved fields
- Compute resolved and subgrid turbulence fluxes
- Generalisation
  → Π theorem (E. Buckingham (1914))
Well-documented BL cases

Dry Boundary Layers

(a) IHOP  
(b) AMMA  
(c) Wangara

Cumulus-topped Boundary Layers

(d) ARM  
(e) BOMEX
Horizontal Coarse Graining

LES resolution: 62.5 m

Average on 4 cells of the LES: 125 m resolution

Average on 16 cells of the LES: 250 m resolution
Get a reference

- Fines structures vanish at meso-scale
- Size of the structures depends on the parameter
- Structures visible at 1 km resolution → grey zone
Computation of turbulent parameters

TKE, humidity and heat fluxes, variances of potential temperature and total water mixing ratio
Computation of turbulent parameters

TKE, humidity and heat fluxes, variances of potential temperature and total water mixing ratio

Resolved TKE at $\Delta x$ resolution:

$$e_{res}(\Delta x) = \frac{1}{2} \left\langle \left( \frac{u^{\Delta x} - \langle u \rangle}{\Delta x} \right)^2 + \left( \frac{v^{\Delta x} - \langle v \rangle}{\Delta x} \right)^2 + \left( \frac{w^{\Delta x} - \langle w \rangle}{\Delta x} \right)^2 \right\rangle$$
Computation of turbulent parameters

TKE, humidity and heat fluxes, variances of potential temperature and total water mixing ratio

Resolved TKE at $\Delta x$ resolution:

$$e_{\text{res}}(\Delta x) = \frac{1}{2} \left\langle \left( \frac{u}{u} \Delta x - \langle u \rangle \right)^2 + \left( \frac{v}{v} \Delta x - \langle v \rangle \right)^2 + \left( \frac{w}{w} \Delta x - \langle w \rangle \right)^2 \right\rangle$$
Computation of turbulent parameters

TKE, humidity and heat fluxes, variances of potential temperature and total water mixing ratio

Resolved TKE at $\Delta x$ resolution:

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Computation of turbulent parameters

TKE, humidity and heat fluxes, variances of potential temperature and total water mixing ratio

Resolved TKE at $\Delta x$ resolution:

$$e_{\text{res}}(\Delta x) = \frac{1}{2} \left\langle \left( \frac{u^2}{\Delta x} - \langle u \rangle \right)^2 + \left( \frac{v^2}{\Delta x} - \langle v \rangle \right)^2 + \left( \frac{w^2}{\Delta x} - \langle w \rangle \right)^2 \right\rangle$$

Subgrid TKE at $\Delta x$ resolution:

$$e_{\text{sbg}}(\Delta x) = e_{\text{res}}(62, 5m) + e_{\text{sbg}}(62, 5m) - e_{\text{res}}(\Delta x)$$

$$e_{\text{total}}$$
Similarity function

Example: TKE in CBL

Similarity functions of Total TKE \( (Lenshow(1980), Sorbjan(1991)) \):

\[
\frac{e_{\text{total}}}{w^*} = F_{e_{\text{total}}} \left( \frac{z}{h} \right)
\]

\( w^* \): convective velocity scale

\( h \): BL height
Similarity function

Example: TKE in CBL

Similarity functions of Total TKE \( \text{(Lenshow}(1980), \text{Sorbian}(1991)) \):

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\frac{e_{\text{total}}}{w^*^2} = F_{e_{\text{total}}}(\frac{z}{h})
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\( w^* \): convective velocity scale

\( h \): BL height

Dimensional analysis:

\[
\frac{e_{\text{sbg}}}{w^*^2} = F_{e_{\text{sbg}}}(\frac{z}{h}, \frac{\Delta x}{h+h_c}) = F_{e_{\text{total}}}(\frac{z}{h}) \times P_{e_{\text{sbg}}}(\frac{\Delta x}{h+h_c})
\]

\( h_c \): cloud depth

\( h+h_c \): thermal plume depth
Similarity function

Example: TKE in CBL

Similarity functions of Total TKE \((\text{Lenshow}(1980), \text{Sorbian}(1991))\):

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\]

\(h\) : cloud depth

\(h + h_c\) : thermal plume depth

What we need: partial similarity function

\[
\frac{e_{\text{sbg}}}{e_{\text{total}}} = P_{e_{\text{sbg}}} \left( \frac{\Delta x}{h + h_c} \right)
\]
Partial similarity function

\[ 0.05 \leq \frac{z}{h} \leq 0.85 \]

- Whatever the case:
  - Data follow one unique function
  - In LES, the resolved part is majoritary.
  - In the grey zone, the subgrid part increases.
  - At meso-scale, resolved part is null.
Partial similarity function

\[ 0.05 \leq \frac{z}{h} \leq 0.85 \]

- Whatever the case:
  - In LES, the resolved part is majoritary.
  - In the grey zone, the subgrid part increases.
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The "true" resolved-subgrid distribution in the grey-zone!

Defaults of the parameterization

Without Mass-Flux

DEAR
BL89

With Mass-Flux

DEAR
BL89

The grey zone is ill-represented
Most significant impact: Mass-Flux

IHOP: Vertical velocity, 1 km resolution

Without Mass-flux scheme
- Too strong resolved movements
- Too wide structures

PM09: Mass-flux scheme
BL89: Bougeault-Lacarrère (1989) mixing length
1D: scheme dimensionality
Most significant impact: Mass-Flux

IHOP: Vertical velocity, 1 km resolution

Reference (LES)

Without Mass-flux scheme
- Too strong resolved movements
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With Mass-flux scheme
- No resolved structures

PM09: Mass-flux scheme
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Table of contents

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3. From 1D turbulence scheme to 3D
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Conditional Sampling

LES grid cell = a cell of thermal or a cell of environment

Couvreux et al. (2010): a passive tracer emitted at the surface
How to detect a subgrid thermal?

Conditional sampling of Couvreux et al. (2010)
a grid cell of thermal is defined as:

\[
sv_i - \langle sv \rangle > \max (\sigma_{sv}, \sigma_{min})
\]

\[
w_i > 0
\]

\[w\]: vertical wind speed.
\[sv\]: concentration of the passive tracer emitted at the surface.
Thermals (in white). ARM 14 h.
How to detect a subgrid thermal?

New conditional sampling
A grid cell of subgrid thermal is defined as:

\[ \text{sv}_i - \text{sv} \Delta x > \max(\sigma_{\text{sv}_i}, \sigma_{\min}) \]

\[ w_i > 0 \]

\[ w_i - w \Delta x > 0 \]

\( w \): vertical wind speed.
\( \text{sv} \): concentration of the passive tracer emitted at the surface.

Subgrid Thermals at 500 m resolution (in red). ARM 14 h.
Example: Vertical velocity of the thermals

\[ \Delta x = 4 \text{ km} \]

- Meso-scale: \( \bar{w} \) negligible
- \( M_u = \alpha (w_u - \bar{w}) \approx \alpha w_u \)

\( w \) (black), \( \bar{w} \) (white)

ARM, 8 h simulation, all boundary-layer levels
Example: Vertical velocity of the thermals

\[ \Delta x = 500 \text{ m} \]

- Meso-scale: \( \overline{w} \) negligible
- \( M_u = \alpha(\overline{w}_u - \overline{w}) \approx \alpha \overline{w}_u \)
- Grey Zone: \( \overline{w} \) not negligible

ARM, 8 h simulation, all boundary-layer levels
\( \overline{w} \) (black), \( \overline{w}_u \) (white)
Mass-flux scheme: defaults in the grey zone

16 km

- Small thermal area
- Zero vertical velocity
- Quasi-stationary thermal field
Mass-flux scheme: defaults in the grey zone

- Not necessarily small thermal area
- Non zero vertical velocity
- Non quasi-stationary thermal field

1 km
Mass-Flux scheme: PM09 (Pergaud et al. 2009)

At mesoscale (Siebesma (2007)):

\[
\frac{\partial M_u \phi_u}{\partial z} = E\phi - D\phi_u
\]

where

- \( \phi \) is a variable
- \( M_u \) is the mass-flux
- \( E \) is the lateral entrainment
- \( D \) is the lateral detrainment
- \( \alpha \) is the thermal fraction

\[
M_u = \alpha w_u
\]
In the grey zone:

\[
\frac{\partial M_u \phi_u}{\partial z} = \tilde{E} \phi_e - \tilde{D} \phi_u
\]

Similar to meso-scale equations...

\[
M_u = \alpha (w_u - \bar{w})
\]

Same entrainment in dry and cloudy thermal (cf. Rio et al. (2010))

- Smaller thermal area
- \(\Rightarrow\) less mixing
- \(\Rightarrow\) resolved structures

In the grey zone:

- **David Lancz** (PhD Thesis at HMS): computed $M_u$ as a function of the resolution from Meso-NH LES.

- **Surface closure**:
  \[
  \frac{M_u(z=0)}{w^*} = \text{Cst} \\
  \Rightarrow \frac{M_u(z=0)}{w^*} = f\left(\frac{\Delta x}{h}\right)
  \]

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Dávid Lancz, Balázs Szintai, Rachel Honnert, 2017: Modification of shallow convection parametrization in the grey zone in a mesoscale model, Boundary-layer Meteorol., accepted

Results in Méso-NH

Resolved TKE IHOP, 12h, PM09-No-convection-HRIO-LES

(a) 500 m

(b) 1 km
Results

- Fields on the order of the reference
- It follows the law by $0.5(h + h_c)$
- But not to the smallest scales
1. Which turbulence in the Grey Zone?
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Turbulence scheme: from 1D to 3D

What is the resolution limit at which the horizontal turbulent movements are not negligible?
From 1D to 3D : method

At which resolution the horizontal movements are not negligible anymore? What is the value of the horizontal production?

Method

- Use LES $\rightarrow$ coarse-graining
- Computation of the fluxes at $\Delta x$ resolution
- Computation of the production terms: $-u_i' u_j' \Delta x \partial u_i/\partial X_j$ and $\beta w' \theta_v' \Delta x$
- Plot the production as a function of $\Delta x / (h + h_c)$
From 1D to 3D: limit resolution

Thermal (red), dynamic horizontal (blue) and dynamic vertical (grey) as a function of normalized resolution in free CBL.
From 1D to 3D: limit resolution

Thermal (red), dynamic horizontal (blue) and dynamic vertical (grey) as a function of normalized resolution in forced CBL.

Honnert and Masson (2014)
What is the resolution limit at which the horizontal turbulent movements are not negligible? → $0.5(h + h_c)$ in free CBL

Honnert R and Masson V (2014) What is the smallest physically acceptable scale for 1D turbulence
Anisotropy in the grey zone

The turbulence is anisotropic when $\Delta x \geq 0.05 \, h$

**Figure 1:** Zonal (black), meridian (red) and vertical (blue) dynamic production terms. CASES-99 (neutral BL), 5h.
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K-gradient and mixing lengths

Anisotropic turbulence in the Grey Zone \( \Rightarrow \) Which horizontal mixing lengths in the grey-zone?

\[
\begin{align*}
\bar{u}'v' &= -K_{u,v} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \\
\bar{u}'w' &= -K_{u,w} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
\bar{v}'w' &= -K_{v,w} \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)
\end{align*}
\]

\[
\begin{align*}
K_{u,v} &= CL_{u,v} \sqrt{e} \\
K_{u,w} &= CL_{u,w} \sqrt{e} \\
K_{v,w} &= CL_{v,w} \sqrt{e}
\end{align*}
\]

- Computation of the fluxes and gradients by coarse-graining \( \rightarrow \) eddy-diffusivity and vertical and horizontal mixing lengths at all scales.
Comparison with mixing lengths in NWP

- \( l_{\text{DEAR}} = (\Delta x \Delta y \Delta z)^{\frac{1}{3}} \) : Isotropic Turbulence.
- *Kitamura (2015)* mixing lengths established in dry CBL.

"True" vertical and horizontal mixing lengths, Deardorff and Kitamura at 400 m altitude as a function of resolution in CASES-99. (Xavier Lamboley)
The moist-air entropy, $\theta_s$, (Marquet, 2011) improvement of the Betts potential temperature, $\theta$, to be used in moist air turbulence.

- The impact on turbulent fluxes might be specially important if the turbulent Lewis number $Le_t$ would be different from unity.

\[
Le_{st} = \frac{K_\theta^s}{K_q^t}
\]

- Investigation of the hypothesis “$Le_t \neq 1$” by using observations\(^1\) and LES\(^2\).

- Need a “back to basic” analysis of CBR scheme

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\(^1\) Daily measurements of eddy-correlation flux of moist entropy with CNRM-FLUXNET devices

\(^2\) High-Tune submitted ANR
Figure 2: Number of Lewis and $Le_{st}$. IHOP in the grey zone. (Xavier Lamboley)
Summary

Subgrid Turbulence

 LES

\[ \Delta x \]

Mesoscale scheme

Mixing Lengths

Do wndraft

3D turbulence

Mass-Flux \approx 500 \text{ m}

Non Vertical plumes

Mesoscale scheme

Dynamics
Subgrid Turbulence

\[
\frac{\Delta x}{h + h_c}
\]

Les

Mesoscale scheme
Summary

Subgrid Turbulence

DEAR-3D

Mixing Lengths

3D turbulence

Mass-Flux

BL89-1D-PM09

\[ \frac{\Delta x}{h + h_c} \]
Thank you for your attention!