Some Light Shed on the Grey Zone of Turbulence

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Workshop ECMWF

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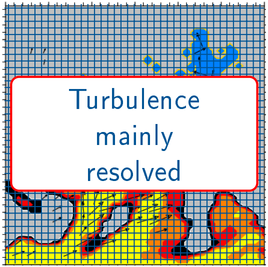
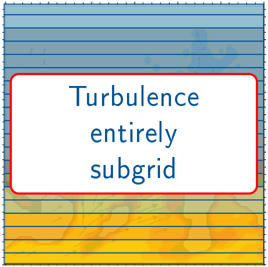
Grey Zone of turbulence



LES

GREY ZONE

(Wyngaard,2004)



1,3 km

10 km

10 100 200 500 1000 2000

MésoNH

AROME

ARPEGE

Increasing resources

Turbulence scheme

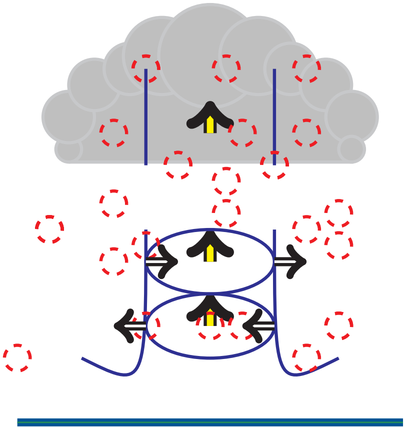
$$\overline{u_i'\phi'} = -K_\phi \frac{\partial \overline{\phi}}{\partial x_i}$$

$$K_\phi = C_\phi \times l \times \sqrt{e}$$

with:

- $\overline{u_i'\phi'}$ turbulent flux
- l mixing length
- e prognostic TKE

Méso-NH and AROME mass-flux scheme



$$\overline{w'\phi'} = \underbrace{-K\frac{\partial\overline{\phi}}{\partial z}}_{\text{Turbulence}} + \underbrace{\frac{M_u}{\rho}\left(\phi_u - \overline{\phi}\right)}_{\text{Shallow convection}}$$

- EDMF (Eddy-Diffusivity/Mass-Flux) : *Siebesma et Texeira (2000), Hourdin et al (2002), Soares et al (2004)*
- CBR : K-gradient scheme (*Cuxart et al (2000)*)
- PM09 : Mass-Flux scheme (*Pergaud et al (2009)*)
- Updraft starts at the surface ⇒ 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
  - BL89 : Size of the coarsest eddies at a given altitude.(*Bougeault et Lacarrère* (1989)).
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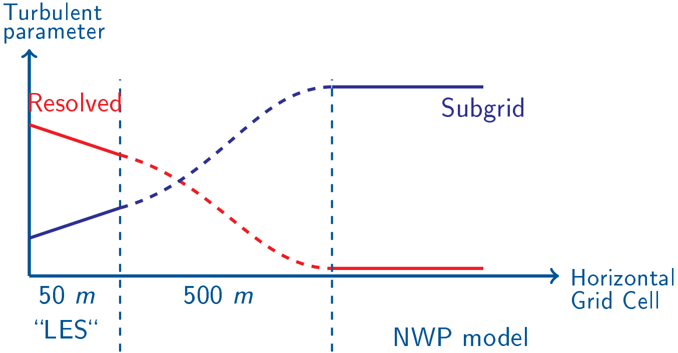
Method

Goal

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



Method

Goal

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

Method :

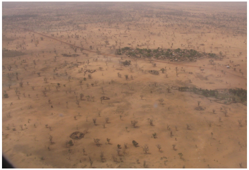
- LES of several BL cases
- Coarse-graining of LES fields
  $\rightarrow$ get true resolved fields
- Compute resolved and subgrid turbulence fluxes
- Generalisation
  $\rightarrow$ Π theorem (*E. Buckingham (1914)*)

Well-documented BL cases

Dry Boundary Layers

(a) IHOP

(b) AMMA



(c) Wangara

Cumulus-topped Boundary Layers

(d) ARM

(e) BOMEX

Horizontal Coarse Graining

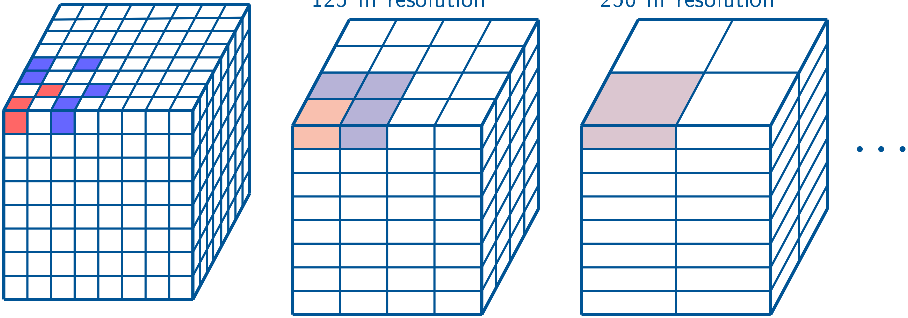
Meso-NH
mesoscale non-hydrostatic model

DIAGNOSTICS

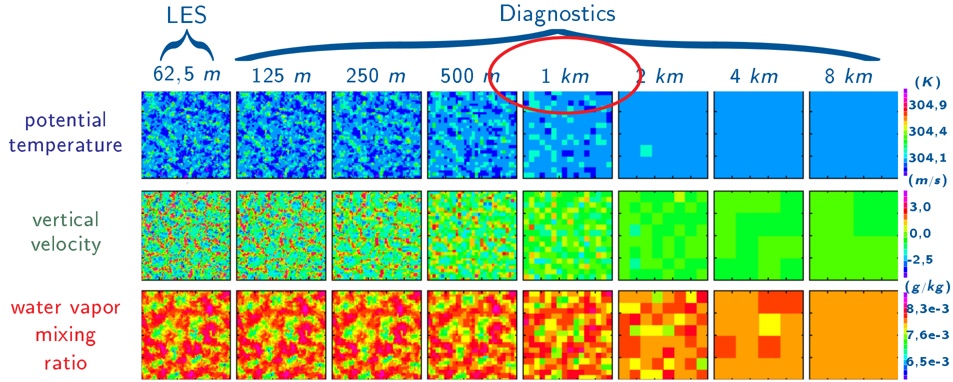
LES
resolution : 62,5 m

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 Δx resolution :

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

Computation of turbulent parameters

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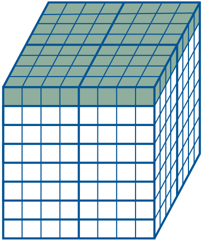

Computation of turbulent parameters

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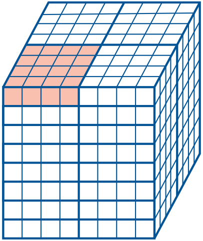

Computation of turbulent parameters

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

Resolved TKE at Δx resolution :

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Subgrid TKE at Δx resolution :

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

Similarity function

Example : TKE in CBL

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

$$\frac{e_{total}}{w^{*2}} = F_{e_{total}}\left(\frac{z}{h}\right)$$

w^* : *convective velocity scale*

h : *BL height*

Similarity function

Example : TKE in CBL

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

$$\frac{e_{total}}{w^{*2}} = F_{e_{total}}\left(\frac{z}{h}\right)$$

w^* : *convective velocity scale*

h : *BL height*

Dimensional analysis :

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

h_c: *cloud depth*

$h+h_c$: *thermal plume depth*

Similarity function

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h_c : *cloud depth*

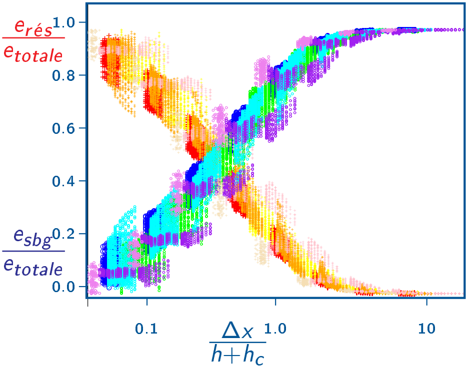
$h+h_c$: *thermal plume depth*

What we need : partial similarity function

$$\frac{e_{sbg}}{e_{total}} = P_{e_{sbg}}\left(\frac{\Delta x}{h+h_c}\right)$$

Partial similarity function

$$0,05 \leq \frac{z}{h} \leq 0,85$$



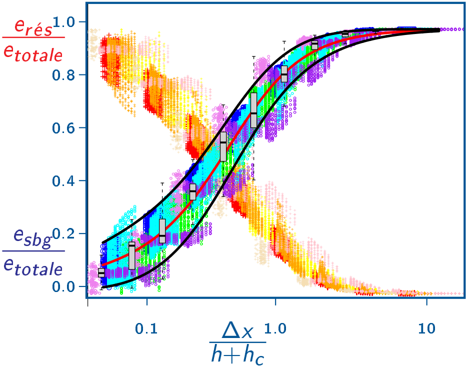
- Whatever the case :

data follow one unique function

- In LES,
  the resolved part is majortary.
- 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 :

data follow one unique function

- In LES,
  the resolved part is majortary.
- In the grey zone,
  the subgrid part increases.
- At meso-scale,
  resolved part is null.

The "true" resolved-subgrid distribution in the grey-zone !

Honnert R., V. Masson, and F. Couvreux, 2011 : A diagnostic for Evaluating the Representation of Turbulence in Atmospheric Models at the Kilometric Scale. *J. Atmos. Sci.*, 68(12), 3112-3131, doi : 10.1175/JAS-D-11-061.1

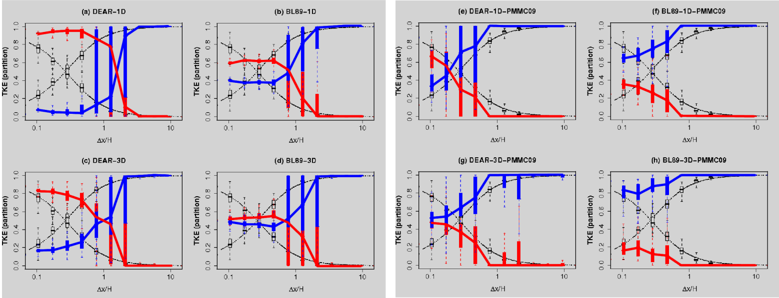
Defaults of the parameterization

Without Mass-Flux — With Mass-Flux

DEAR — BL89 — DEAR — BL89

1D scheme

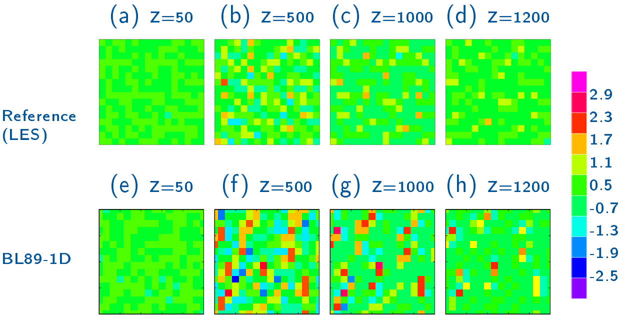
3D scheme



The grey zone is ill-represented

Most significant impact : Mass-Flux

IHOP : Vertical velocity, 1 km resolution



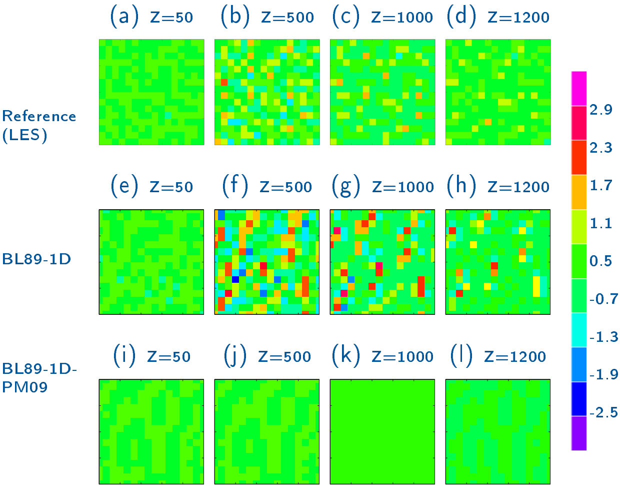
Without Mass-flux scheme

- 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



Without Mass-flux scheme

- Too strong resolved movements
- Too wide structures

With Mass-flux scheme

- No resolved structures

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

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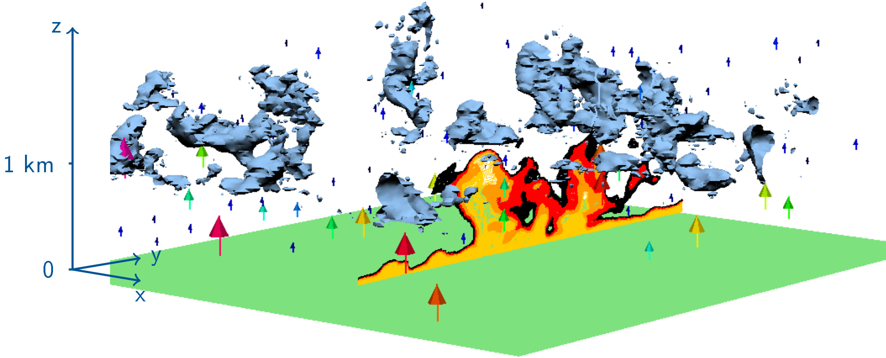
Conditional Sampling

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

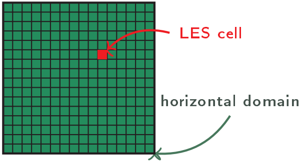
Couvreux et al. (2010) : a passive tracer emitted at the surface



How to detect a subgrid thermal ?

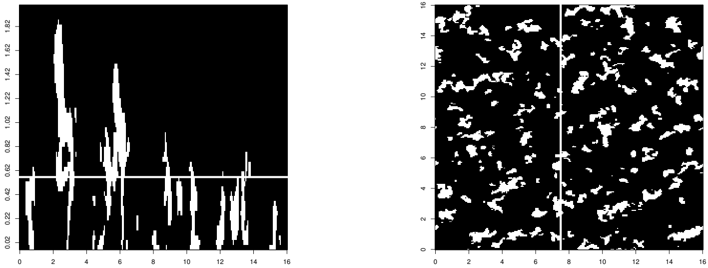
Conditional sampling of *Couvreux et al. (2010)*
a grid cell of thermal is defined as :

$$
\begin{aligned}
sv_i - \langle sv \rangle &> \max(\sigma_{sv}, \sigma_{min}) \\
w_i &> 0
\end{aligned}
$$



w : vertical wind speed.
sv : concentration of the passive tracer emitted at the surface.

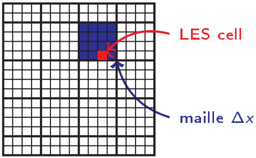
Thermals (in white) . ARM 14 h.



How to detect a subgrid thermal ?

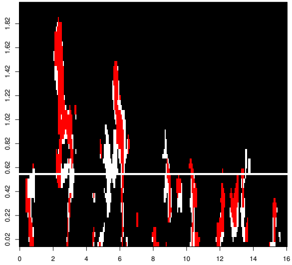
New conditional sampling
a grid cell of subgrid thermal is defined as :

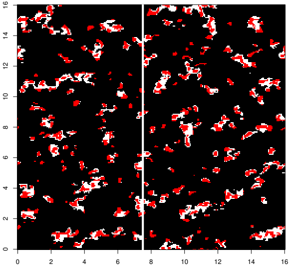
$$
\begin{aligned}
sv_i - \overline{sv}^{\Delta x} &> max(\sigma_{sv\,i}, \sigma_{min}) \\
w_i &> 0 \\
w_i - \overline{w}^{\Delta x} &> 0
\end{aligned}
$$



w : vertical wind speed.
sv : concentration of the passive tracer emitted at the surface.

subgrid Thermals at 500 m resolution (in red). ARM 14 h.

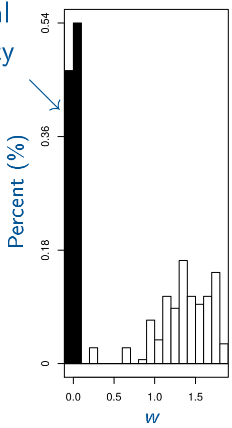




Example : Vertical velocity of the thermals

Resolved vertical velocity

Δx=4 km



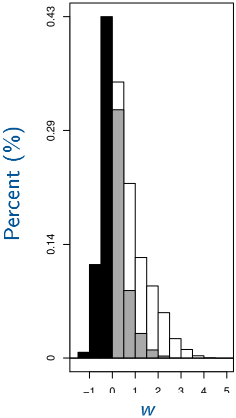
Velocity of the thermal

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

ARM, 8 h simulation, all boundary-layer levels
$\overline{w}$ (black), W_u (white)

Example : Vertical velocity of the thermals

Δx=500 m

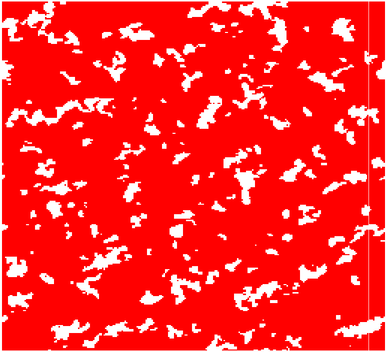


- Meso-scale : $\overline{w}$ negligible
- $M_u = \alpha(w_u - \overline{w}) \approx \alpha w_u$
- Grey Zone : $\overline{w}$ not negligeable

ARM, 8 h simulation, all boundary-layer levels
$\overline{w}$ (black), W_u (white)

Mass-flux scheme : defaults in the grey zone

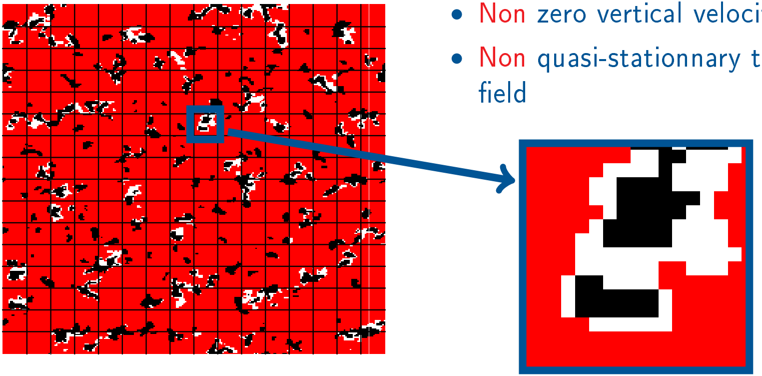
16 km



- Small thermal area
- Zero vertical velocity
- Quasi-stationnary thermal field

Mass-flux scheme : defaults in the grey zone

1 km



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

Mass-Flux scheme : PM09 (Pergaud at al. 2009)

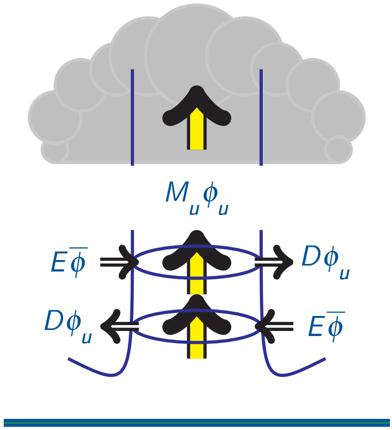
At mesoscale *(Siebesma (2007))* :

$$\frac{\partial M_u \phi_u}{\partial z} = E\overline{\phi} - D\phi_u$$

where

- ϕ is a variable
- M_u is the mass-flux
- E is the lateral entrainment
- D is the lateral detrainment
- α is the thermal fraction

$$M_u = \alpha w_u$$



Scale-Aware scheme

In the grey zone :

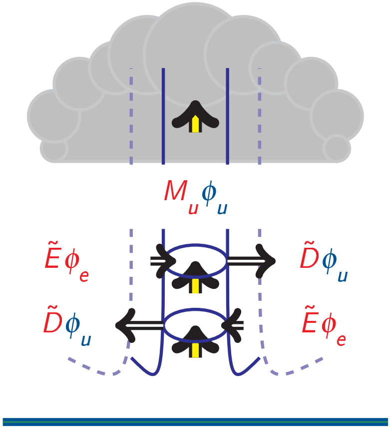
$$\frac{\partial M_u \phi_u}{\partial z} = \tilde{E}\phi_e - \tilde{D}\phi_u$$

Similar to meso-scale equations . . .

$$M_u = \alpha(w_u - \overline{w})$$

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

- Smaller thermal area
- $\Rightarrow$ less mixing
- $\Rightarrow$ resolved structures

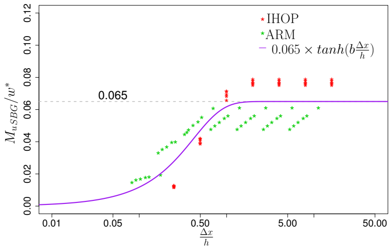


Honnert, R., F. Couvreux, V. Masson and D. Lancz, 2016 : Sampling the structure of convective turbulence and implications for grey-zone parametrizations. 133. doi:10.1007/s10546-016-0130-4

Scale-Aware scheme

In the grey zone :

- Dàvid Lancz (PhD Thesis at HMS) : computed M_u as a function of the resolution from Méso-NH LES.
- Surface closure : $\frac{M_u(z=0)}{w*} = \text{Cst}$ $\Rightarrow \frac{M_u(z=0)}{w*} = f\left(\frac{\Delta x}{h}\right)$



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

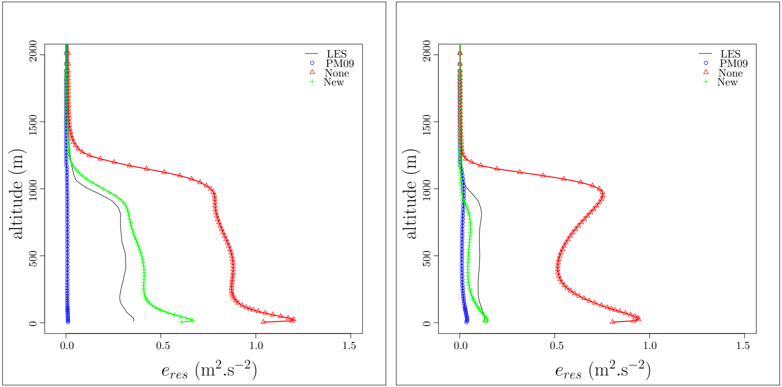
Honnert, R., F. Couvreux, V. Masson and D. Lancz, 2016 : Sampling the structure of convective

turbulence and implications for grey-zone parametrizations. 133. doi:10.1007/s10546-016-0130-4

Results in Méso-NH

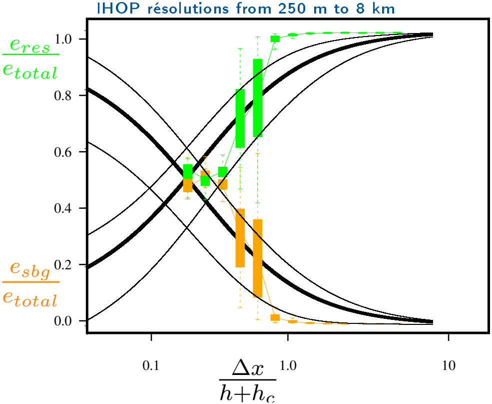
Resolved TKE IHOP, 12h, PM09-No-convection-HRIO-LES

(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



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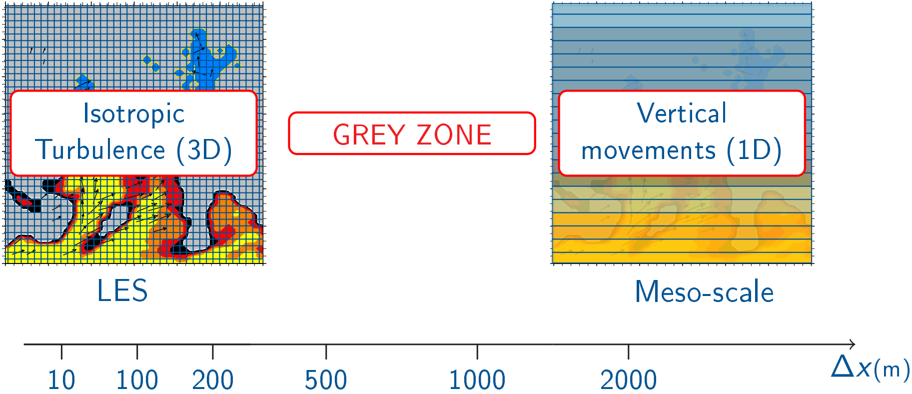
Turbulence scheme : from 1D to 3D



What is the resolution limit at which the horizontal turbulent movements are not negligible ?

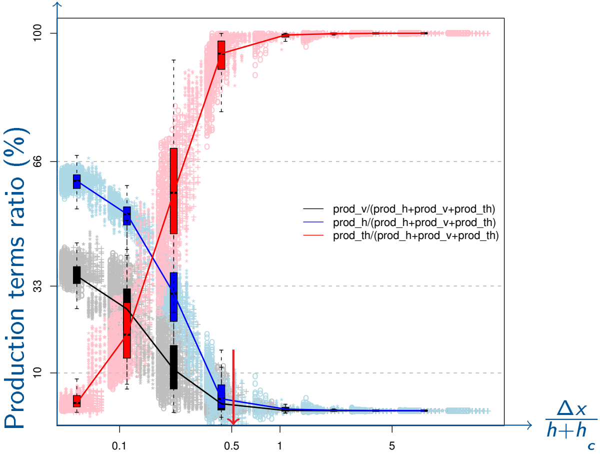
From 1D to 3D : method

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

Method

- Use LES $\Longrightarrow$ coarse-graining
- Computation of the fluxes at Δx resolution
- Computation of the production termes : $-\overline{u_i' u_j'}^{\Delta x} \dfrac{\partial \overline{u_i}^{\Delta x}}{\partial X_j}$ and $\beta \overline{w' \theta_v'}^{\Delta x}$
- Plot the production as a function of $\dfrac{\Delta x}{h + h_c}$

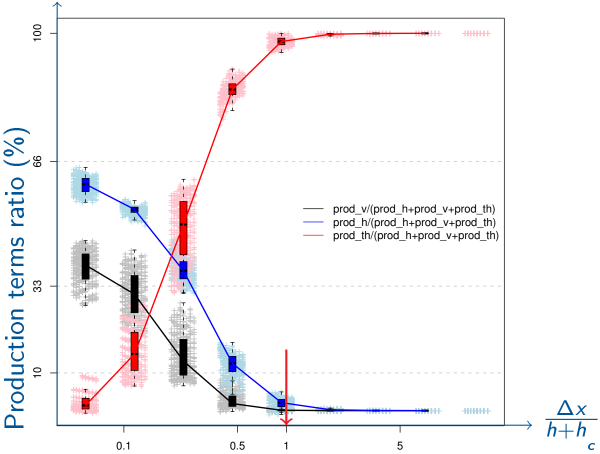
From 1D to 3D : limit resolution



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

Honnert and Masson (2014)

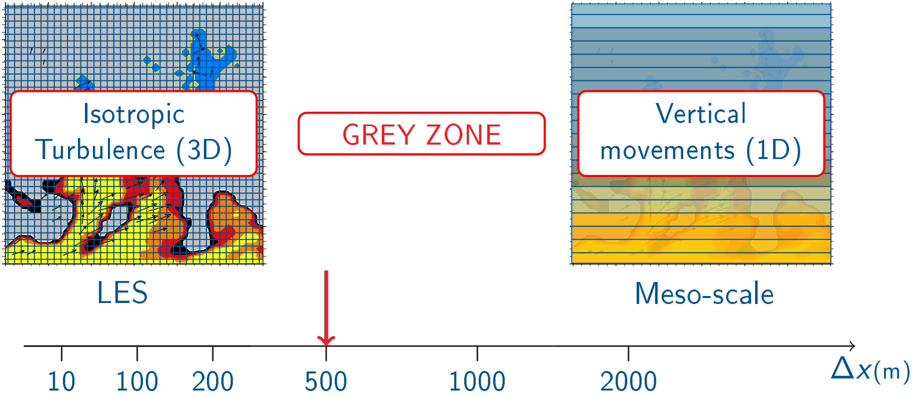
From 1D to 3D : limit resolution



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

 Honnert and Masson (2014)

Turbulence scheme : from 1D to 3D



What is the resolution limit at which the horizontal turbulent movements are not negligible ? $\rightarrow$ $0.5(h + h_c)$ in free CBL

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

Anisotropy in the grey zone

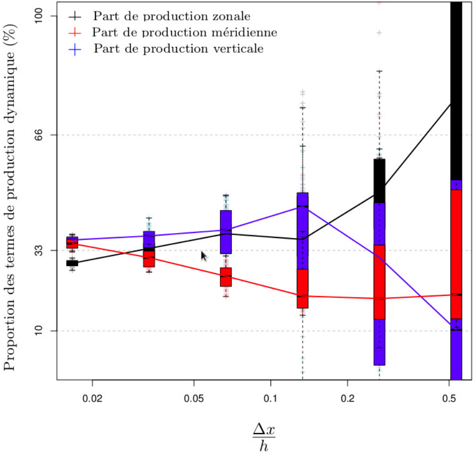


Figure 1: Zonal (black), meridian (red) and vertical (blue) dynamic production terms. CASES-99 (neutral BL), 5h.

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

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METEO FRANCE

K-gradient and mixing lengths

Anisotropic turbulence in the Grey Zone $\Longrightarrow$ Which horizontal mixing lengths in the grey-zone ?

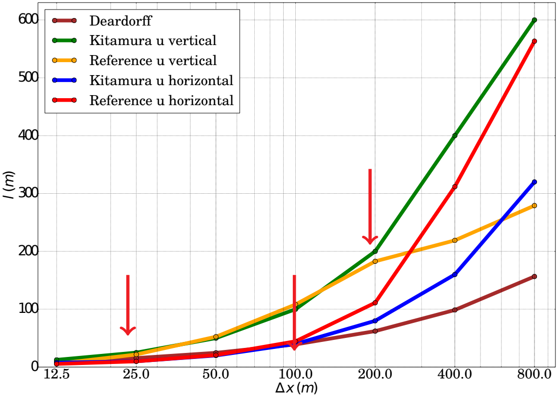
$$\begin{cases} \overline{\mathbf{u'v'}} & = -K_{u,v}\left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right) \\ \overline{\mathbf{u'w'}} & = -K_{u,w}\left(\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x}\right) \\ \overline{\mathbf{v'w'}} & = -K_{v,w}\left(\frac{\partial \overline{v}}{\partial z} + \frac{\partial \overline{w}}{\partial y}\right) \end{cases}$$

$$\begin{cases} \mathrm{K}_{\mathbf{u,v}} & = & C L_{u,v}\sqrt{e} \\ \mathrm{K}_{\mathbf{u,w}} & = & C L_{u,w}\sqrt{e} \\ \mathrm{K}_{\mathbf{v,w}} & = & C L_{v,w}\sqrt{e} \end{cases}$$

- Neutral BL (CASES-99, *Drobinski (2006)*) and CBL (IHOP_{2002}, *Weckwerth (2002)*)
- 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

- $l_{DEAR} = (\Delta x \Delta y \Delta z)^{\frac{1}{3}}$: 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)

METEO FRANCE

Moist-Air Entropy (P. Marquet)

The **moist-air entropy**, θ_s, (Marquet, 2011) improvement of the Betts potential temperature, θ, 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 "$\mathbf{Le_t \neq 1}$"** by using observations[1] and LES[2] .
- Need a "back to basic" analysis of CBR scheme

[1] Daily measurements of eddy-correlation flux of moist entropy with CNRM-FLUXNET devices

[2] High-Tune submitted ANR

METEO FRANCE

Number of Lewis

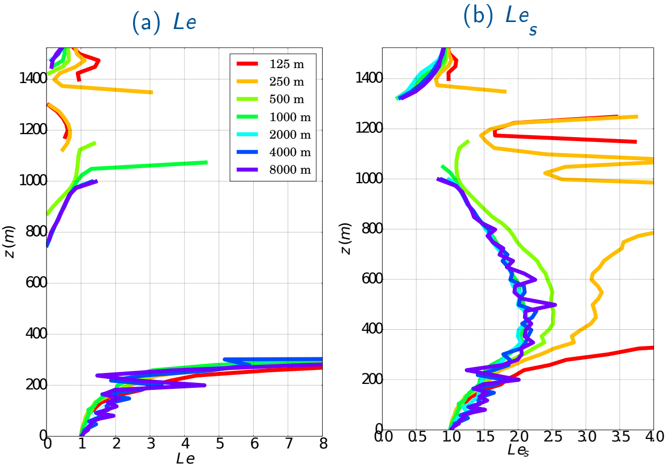
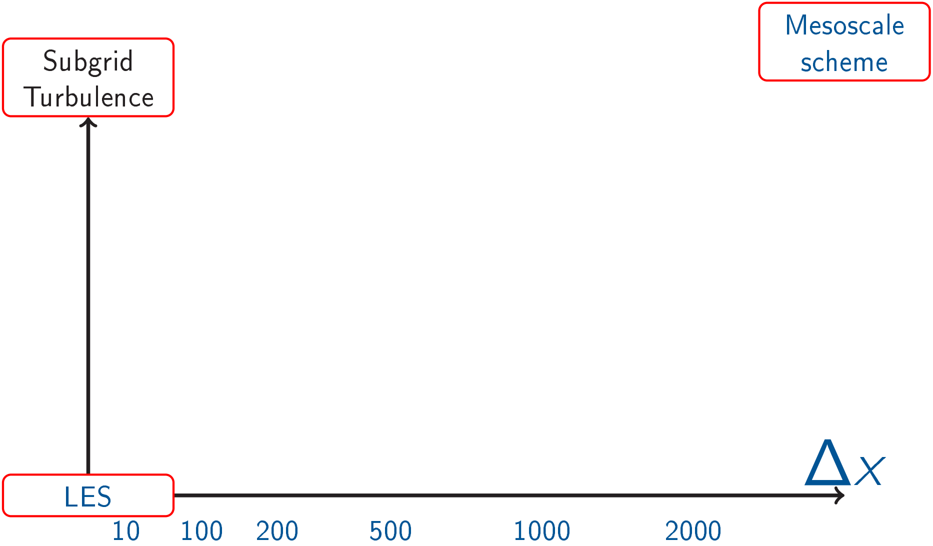
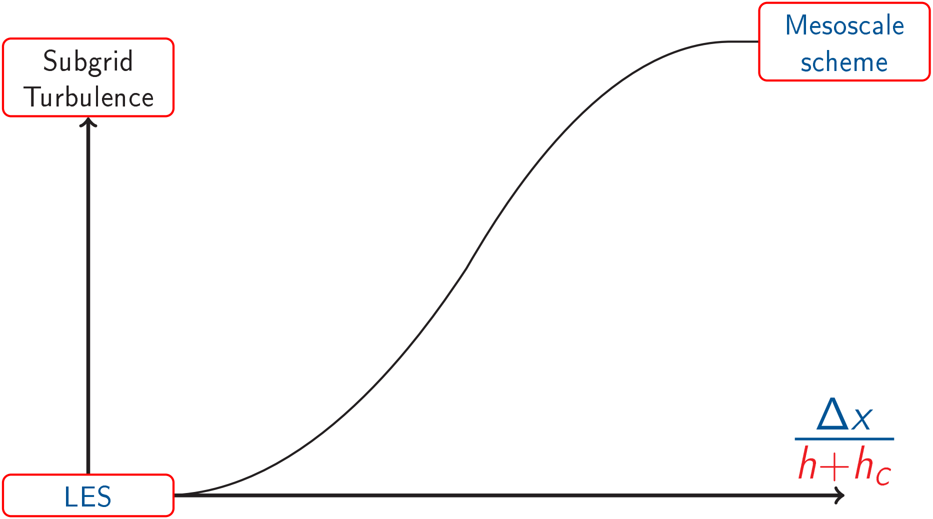


Figure 2: Number of Lewis and Le_{st}. IHOP in the grey zone.(Xavier Lamboley)

Summary

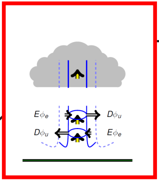

Mesoscale
scheme
Subgrid
Turbulence
LES
Δx
10
100
200
500
1000
2000

Summary



Summary

Mass-Flux

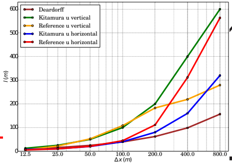


BL89-1D-PM09

Subgrid Turbulence

Mixing Lengths

3D turbulence



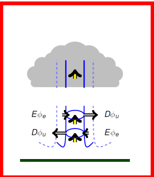
DEAR-3D

$$\frac{\Delta x}{h+h_c}$$

Summary and perspectives

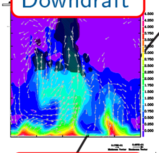
Subgrid Turbulence

Mass-Flux



BL89-1D-PM09

Downdraft

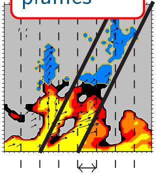


Dynamics

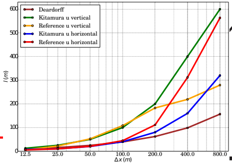
Mixing Lengths

Non Vertical plumes

3D turbulence



$\approx 500\ m$



DEAR-3D

$$\frac{\Delta x}{h+h_c}$$

Thank you for your attention !