Hectometric-Scales in NWP AROME System

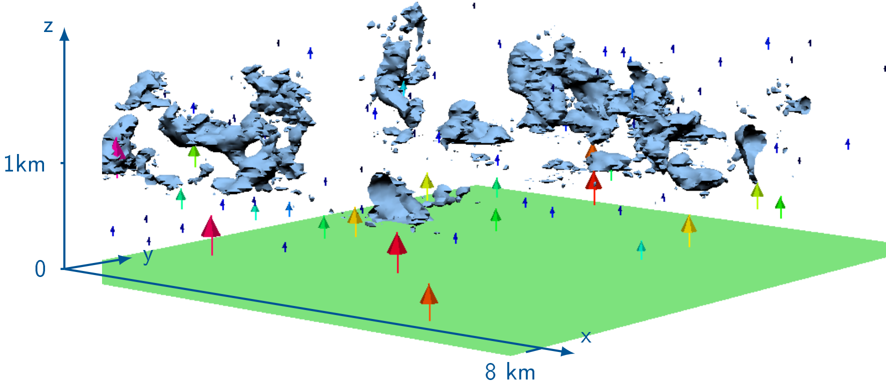
Rachel Honnert (Météo-France/CNRM)
ECMWF Annual Seminar 2022
September 2022

Convective boundary-layer : processes

- Clouds at the top of the Boundary Layer
- Updrafts in the boundary layer

ARM simulation at 12h at 62,5 m resolution (*Honnert (2012)*).

→ Wind > 2 $m.s^{-1}$
🟪 Water mixing ratio liquid > 0,05 $g.kg^{-1}$



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■■■■ Passiv Scalar *Couvreux et al. (2010)*

→ Wind > 2 $m.s^{-1}$

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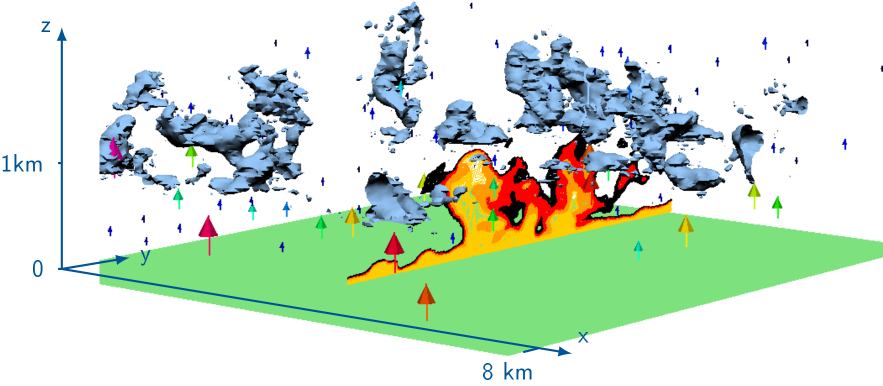
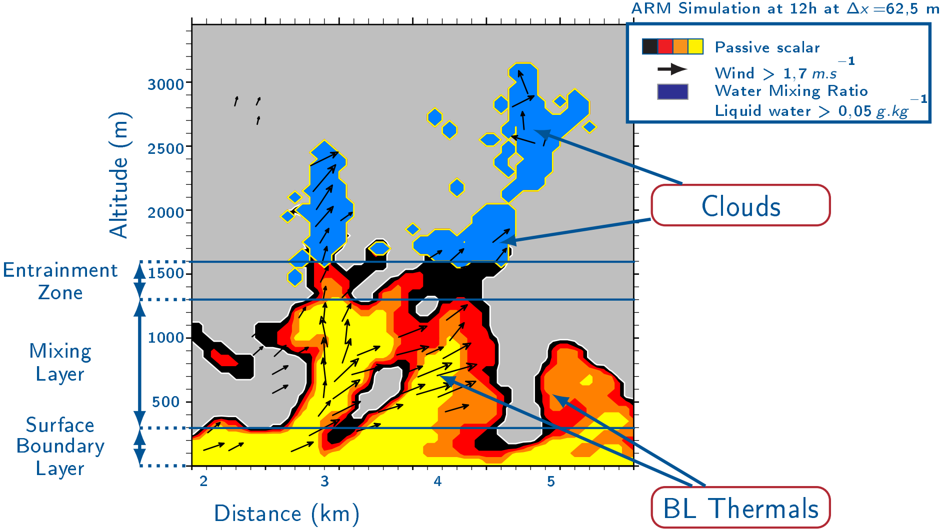
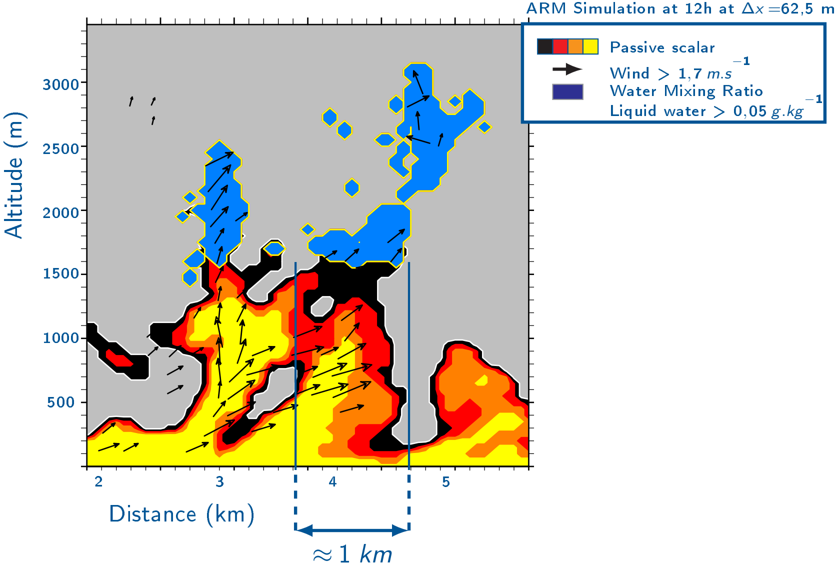


Convective boundary-layer : processes

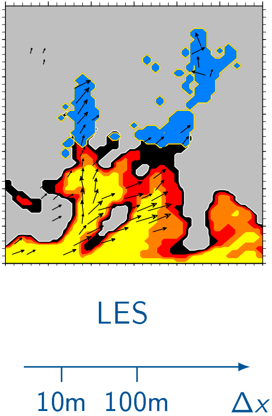


Convective boundary-layer : processes



ARM Simulation at 12h at $\Delta x = 62{,}5$ m

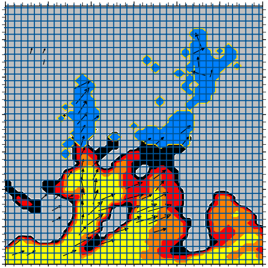
Atmospheric Models : Large-Eddy Simulations



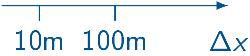
Large-Eddy Simulation (LES) :

- Research Model,
  dedicated to turbulence studies

Atmospheric Models : Large-Eddy Simulations



LES



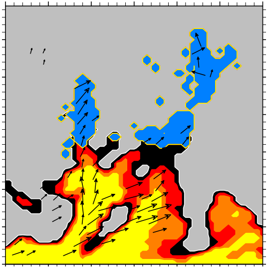
Large-Eddy Simulation (LES) :

- Research Model,
  dedicated to turbulence studies
- Main part of the eddies are resolved
  (very fine resolution)
- Sub-grid turbulence weak and 3D

Atmospheric Models : Large scales

NWP, climate or research
at meso-scale models :

- Entirely subgrid Eddies ($\Delta x \geq 1$km)

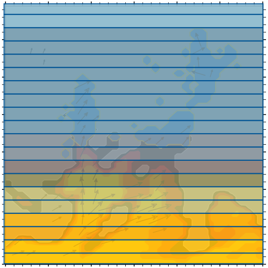


Meso-scale

Atmospheric Models : Large scales

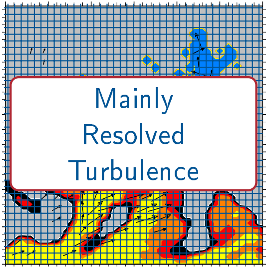
NWP, climate or research
at meso-scale models :

- Entirely subgrid Eddies ($\Delta x \geq 1$km)
- Entirely parameterised turbulence
- Only vertical exchanges



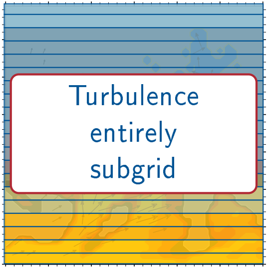
Meso-scale

Atmospheric Models : gray zone



Mainly
Resolved
Turbulence

GREY ZONE
Close to energy
containing scale
Wyngaard (2004)

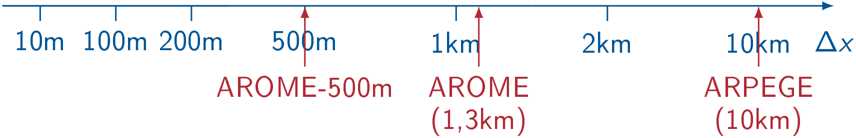


Turbulence
entirely
subgrid

LES

Increasing
computational resources

Meso-scale



10m 100m 200m 500m 1km 2km 10km Δx

AROME-500m

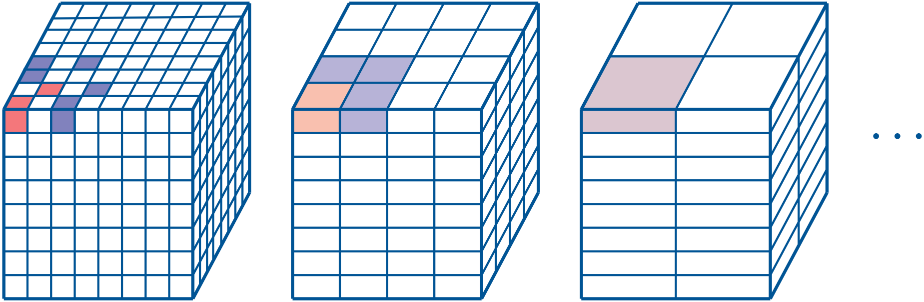
AROME
(1,3km)

ARPEGE
(10km)

Contents

Reference : coarse-graining

Step by step average of an LES Meso-NH field :



LES Field

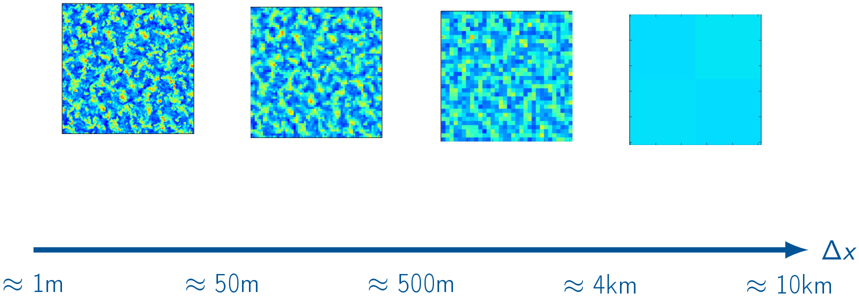
Average on
4 cells
of the LES field

Average on
16 cells
of the LES field

. . .

Gray zone of turbulence

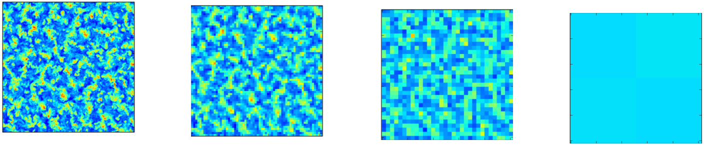
Horizontal cross-sections of vertical velocity by coarse-graining from IHOP LES:



Honnert, Efstathiou, Beare, Ito, Lock,
Neggers, Plant, Shin, Tomassini et Zhou (2020)

Gray zone of turbulence

Horizontal cross-sections of vertical velocity by coarse-graining from IHOP LES:



Resolved Large eddies	Mainly resolved turbulence	Partly resolved turbulence	No resolved turbulence
$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 1$		$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 0.5$	$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 0$

$\frac{\Delta x}{l}$: 0.02, 0.4, 4

l:scale of the most energetic structures

Honnert, Efstathiou, Beare, Ito, Lock, Neggers, Plant, Shin, Tomassini et Zhou (2020)

Gray zone of turbulence

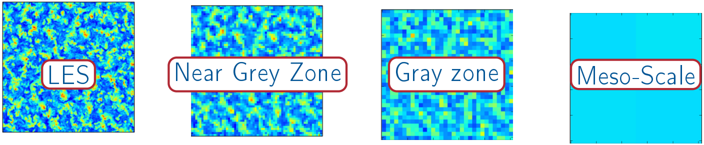
Horizontal cross-sections of vertical velocity by coarse-graining from IHOP LES:

Resolved Large eddies

Mainly resolved turbulence

Partly resolved turbulence

No resolved turbulence



$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 1$

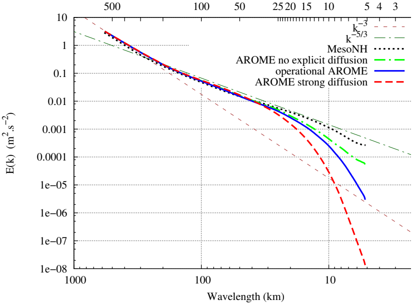
$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 0.5$

$\frac{e_{\text{res}}}{e_{\text{tot}}} \approx 0$

0.02 0.4 4 → $\frac{\Delta x}{l}$

Honnert, Efstathiou, Beare, Ito, Lock, Neggers, Plant, Shin, Tomassini et Zhou (2020)

Other representations (1/2)



Ricard et al. (2012)

$\Delta x \Rightarrow$ Effective resolution

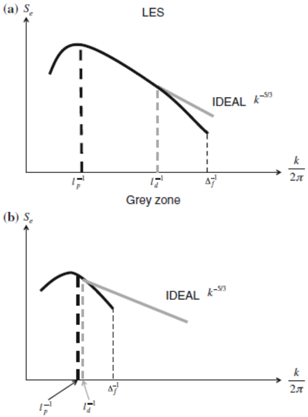
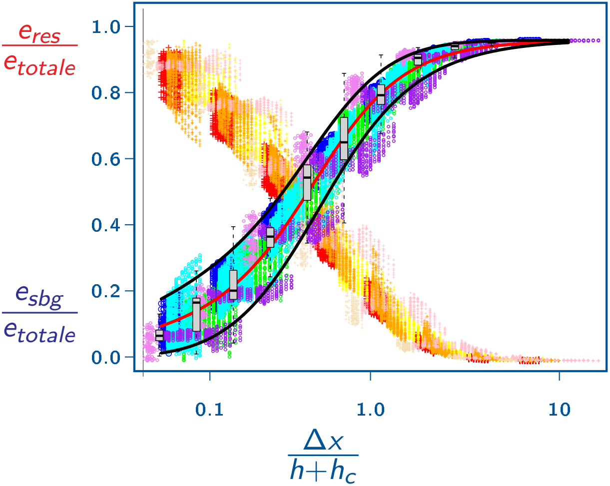


Fig. 1 A schematic showing the TKE spectrum (S_e) against horizontal wavenumber (k) for a simulation (*black line*) and an ideal $k^{-5/3}$ law (*grey line*). The length-scales annotated are: the spectral peak (l_p), the dissipation length scale (l_d) and the filter width (Δ_f). Illustrations of these are given for: **a** a large-eddy simulation, **b** a simulation in the grey zone

Beare (2014)

Other representations (2/2)

Partial similarity functions:



Honnert et al. (2011)

Turbulence scheme

K-gradient :

$$\overline{w'\phi'} = -K_\phi \frac{\partial \overline{\phi}}{\partial z}$$

with $\overline{w'\phi'}$, turbulence flux and K_ϕ, eddy-diffusivity

Eddy-diffusivity :

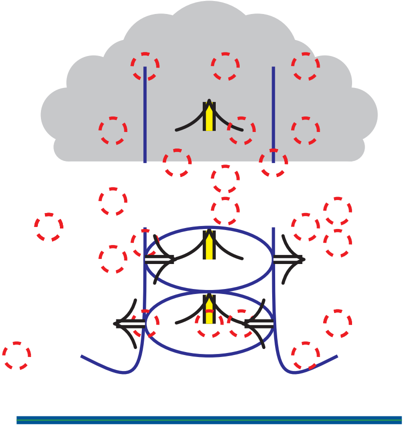
$$K_\phi = c_\phi \; f_\phi \; l \; \sqrt{e}$$

with e TKE, l mixing length, f_ϕ stability function and c_ϕ a constant.

TKE prognostic equation (*Cuxart et al., 2000*) :

$$\frac{\partial e}{\partial t} = Tr + P_d + P_T - \varepsilon$$

EDMF scheme in Meso-NH and AROME



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

- EDMF :
  Siebesma and Texeira (2000),
  Hourdin et al. (2002),
  Soares et al. (2004)
- CBR (K-gradient) :
  Cuxart et al. (2000)
- PM09 (flux de masse) :
  Pergaud et al. (2009)

Boundary-layer scheme at Météo-France

Meso-NH : research model with various configurations at meso-scale or in LES.

- Mixing length :
  - BL89, RM17 : size of the largest eddies at a given altitude (*Bougeault et Lacarrère, 1989*, *Rodier et al., 2017*).
  - DEAR : grid size (*Deardorff, 1972*)
- Dimension :
  - 1D Turbulence scheme
  - 3D Turbulence scheme

- Shallow convection scheme (PM09) :
  - Switched on
  - Switched off

Boundary-layer scheme at Météo-France

AROME : Meso-scale NWP model (*Seity et al., 2010*).

- Mixing length :
  - BL89, RM17 : size of the largest eddies at a given altitude (*Bougeault et Lacarrère, 1989*, *Rodier et al., 2017*).
  - DEAR : grid size (*Deardorff, 1972*)
- Dimension :
  - 1D Turbulence scheme
  - 3D Turbulence scheme

- Shallow convection scheme (PM09) :
  - Switched on
  - Switched off

Boundary-layer scheme at Météo-France

Gray Zone : micro-scale scheme.

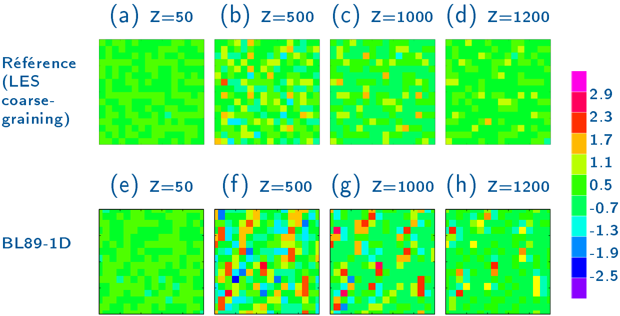
- Mixing length :
    - RM17 : size of the largest eddies at a given altitude (*Rodier et al., 2017*)
    - Adapt to Δx (*Honnert et al., 2020*)
    - DEAR : grid size (*Deardorff, 1972*)
- Dimension :
    - Schéma turbulence 1D
    - 3D in AROME (work in progress)
    - Schéma turbulence 3D
- Shallow convection scheme (PM09) :
    - Switched on
    - Function of Δx (*Honnert et al., 2016*)
    - Switched off

METEO FRANCE

Contents

Grey Zone Impact on Mass-Flux

IHOP : vertical velocity, 1 km résolution, 'z' : altitude



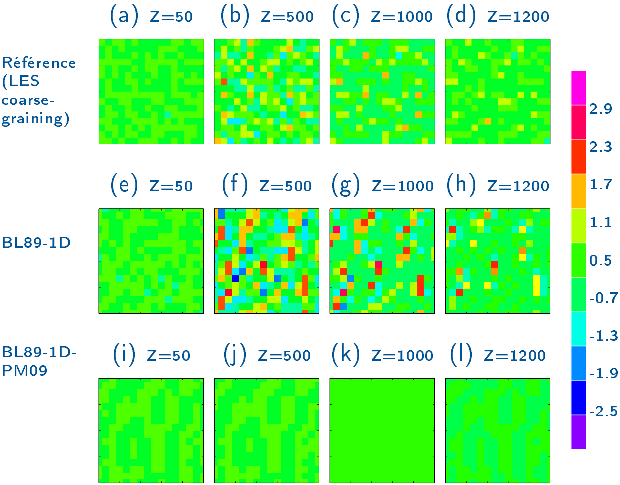
Without Mass-Flux

- Too strong resolved movements
- Too large Structures

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

Grey Zone Impact on Mass-Flux

IHOP : vertical velocity, 1 km résolution, 'z' : altitude



Without Mass-Flux

- Too strong resolved movements
- Too large Structures

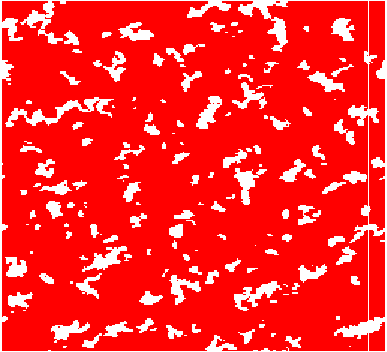
With Mass-Flux

- No resolved structures

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

What is the problem in the grey zone ?

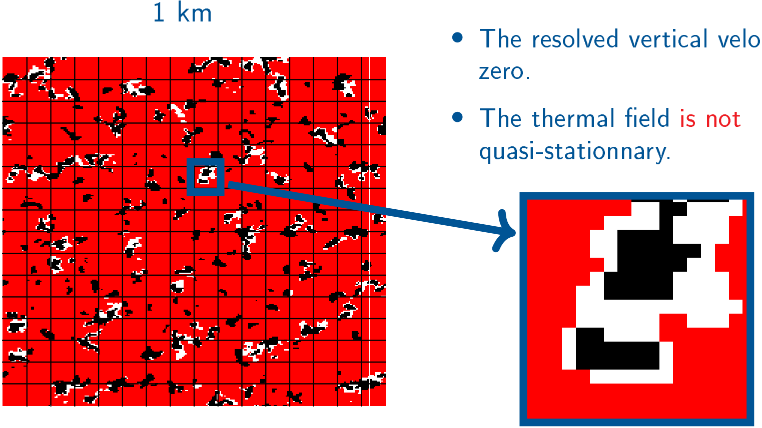
16 km



- The surface occupied by BL thermals is small.
- The resolved vertical velocity is zero.
- The thermal field is quasi-stationnary.

Honnert et al. (2016)

What is the problem in the grey zone ?



- The surface occupied by BL thermals is not small.
- The resolved vertical velocity is not zero.
- The thermal field is not quasi-stationnary.

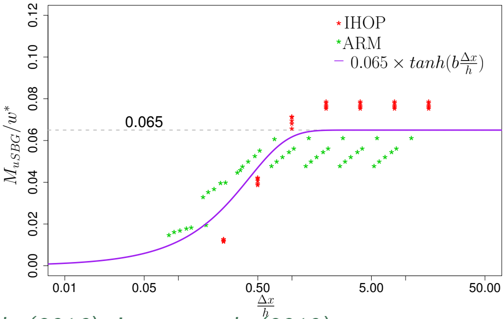
Honnert et al. (2016)

Modification for hectometric scales

Work with Dàvid Lancz and Balázs Szintai (HMS) : Surface closure from LES analysis

$$\frac{M_u(z=0)}{w*} = \text{Cst} \Rightarrow \frac{M_u(z=0)}{w*} = f\left(\frac{\Delta x}{h}\right)$$

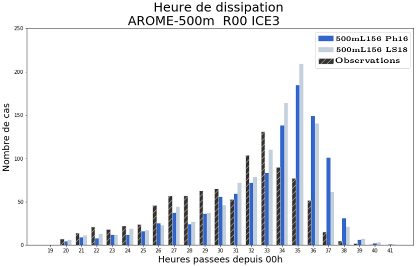
with $w*$, convective velocity, Δx resolution and h thermals height.



Honnert et al. (2016); Lancz et al. (2018)

Results in AROME-500 m

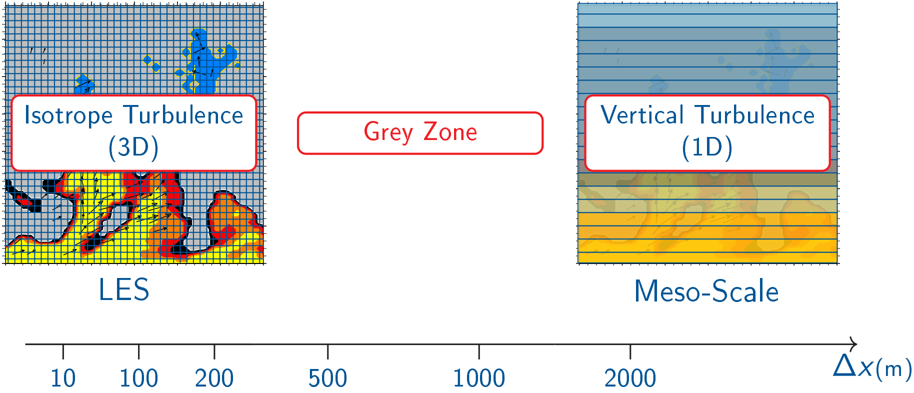
- LS18 by default in Meso-NH.
- <u>Summer :</u> *Lancz et al.(2018)* scores over Hongary during one summer : neutral except for rain and gusts. Deep convective case study : more small rain
- <u>Winter :</u> PM09 too strong in winter conditions. Night fog benefit from the good representation of CBL of the day before by LS18, but no reduction of the delay in fog dissipation.



Sommaire

1. What is new in the grey zone of turbulence ?
2. Which convection in the turbulence grey zone of turbulence ?
3. From 1D to 3D turbulence
4. Mixing length in the grey zone
5. AROME-500 m

From 1D to 3D turbulence



Isotrope Turbulence (3D)

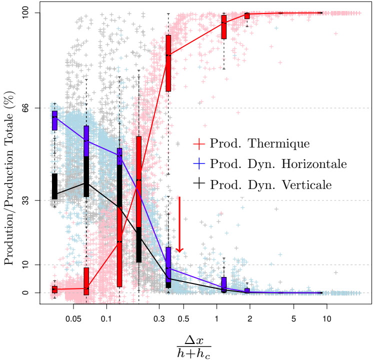
Grey Zone

Vertical Turbulence (1D)

LES

Meso-Scale

1D/3D limit in the grey zone

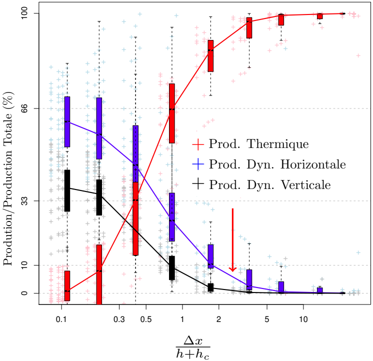


- At which resolution, horizontal turbulence movements are not negligeable anymore ?
- 3D schemes are necessary for resolution finer than $0.5\left(h+h_c\right)$ in free convection

Production Terms of TKE computed from 5 free convective LES as a fonction of the resolution normalised by the BL height (h) plus the depth of the cloud layer (h_c).

Honnert and Masson (2014)

1D/3D limit in the grey zone



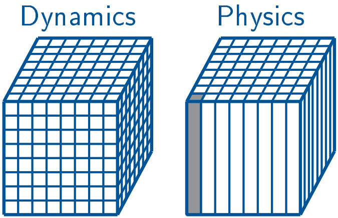
Production Terms of TKE computed from TRAC forced convective LES as a fonction of the resolution normalised by the BL height (h) plus the depth of the cloud layer (h_c).

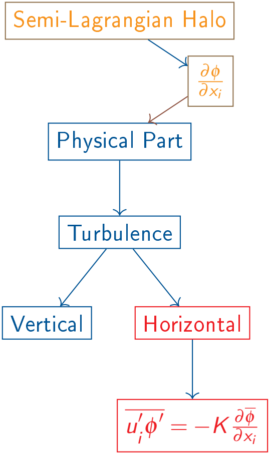
Honnert and Masson (2014)

- At which resolution, horizontal turbulence movements are not negligeable anymore ?
- 3D schemes are necessary for resolution finer than $0.5\left(h+h_c\right)$ in free convection
- 3D schemes are necessary for resolution finer than $3\left(h+h_c\right)$ in forced convection
- See also *Arnold (2014)*, *Göger et al. (2018)*

Horizontal gradients in AROME physics

AROME parametrizations are all 1D.





Semi-Lagrangian Halo

$\frac{\partial\phi}{\partial x_i}$

Physical Part

Turbulence

Vertical

Horizontal

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

We have to compute the horizontal gradients in the dynamics.

Honnert and El Khatib (2020)

Semi-Lagrangian halos for gradients

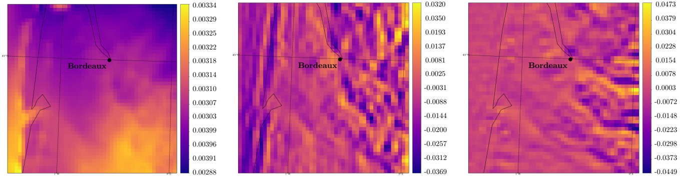


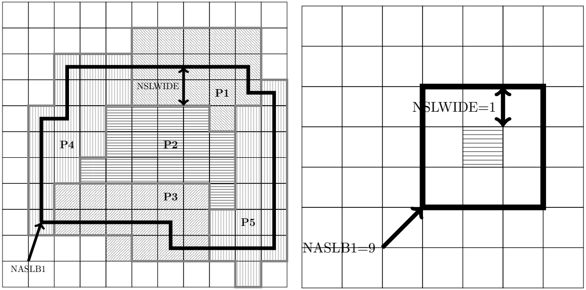
Figure: **Temperature (T), $\frac{\partial T}{\partial x}$ and $\frac{\partial T}{\partial y}$ at the first level of the domain (April, 21st 2020)**

"Semi-Lagrangian" halos also used for :

- Interpolations at observation points
- Interpolations at post-processing point
- Now used to compute gradients for 3D physics

Honnert and El Khatib (2020)

Semi-Lagrangian halos for gradients



- Potentially large width of the halo (⇒ expensive) in Semi-Lagrangian scheme
- Small for interpolations and gradients computation (1 or 2 rows only ⇒ cheap)
- Available in Cy48t1

Honnert and El Khatib (2020)

3D Turbulence in Deep Convection

Work with Samy Gallego (ENM) and Didier Ricard (CNRM/GMME) :

- *Verrelle et al. (2015)* : a lake of turbulence inside deep clouds.
- Increase the mixing by *Leonard (1997)*, *Moeng et al.(2010)*
- MesoNH (*Verrelle et al., 2017*), MetOffice (*Hanley et al., 2019*)
- ⇒ AROME cy49t1

$$\overline{w's'} = -K_s \frac{\partial \overline{s}}{\partial z} + K_L \frac{(\Delta x)^2}{12} \left(\frac{\partial w}{\partial x}\frac{\partial s}{\partial x} + \frac{\partial w}{\partial y}\frac{\partial s}{\partial y} \right),$$

where s may be θ_l, rv or rc, with $K_L = 5$ and $\Delta x = 1300$ in AROME

.

⇒ see Didier Ricard's presentation

Shear in Complex Terrain

- In 1D scheme, production from vertical gradients of horizontal winds
- In complex terrain, the 3D effects ⇒ 3D turbulence scheme
- *Goger et al. (2018)* pseudo-3D on vertical fluxes only.

$$\left.\frac{\partial \overline{e}}{\partial t}\right|_{\text{shear}} = (C_s \Delta x)^2 \left[\left(\frac{\partial \overline{u}}{\partial x}\right)^2 + \left(\frac{\partial \overline{v}}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right)^2 \right]^{\frac{3}{2}}$$

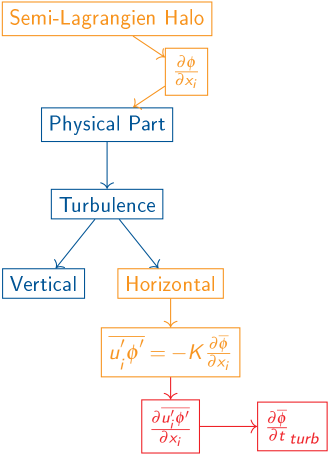
where C_s is chosen to be the Smagorinsky constant.
Goger et al. (2018) tested it over the Alps for a grid length of 1.1 km and had beneficial effects. ⇒ Evaluation in **TeamX (... 2024)**

3D Turbulence in AROME

Work with Fabrice Voitus :

- Solve stability issues
- Toy model (no need for a halo) to evaluate the benefice of 3D turbulence
- Then, complete 3D turbulence in AROME

⇒ PhD Position in 2023



Semi-Lagrangien Halo

$\frac{\partial \phi}{\partial x_i}$

Physical Part

Turbulence

Vertical

Horizontal

$\overline{u'_i \phi'} = -K \frac{\partial \overline{\phi}}{\partial x_i}$

$\frac{\partial \overline{u'_i \phi'}}{\partial x_i}$

$\frac{\partial \overline{\phi}}{\partial t}_{turb}$

Contents

"True" mixing lengths

Work with Xavier Lamboley and Pascal Marquet :

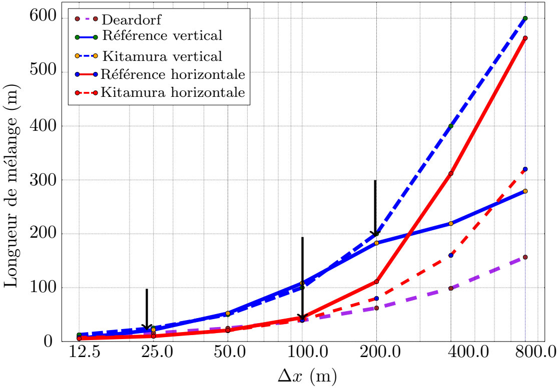
$$\begin{cases} \overline{u'v'} = -K_{u,v}\left(\frac{\partial\overline{u}}{\partial y}+\frac{\partial\overline{v}}{\partial x}\right) \\ \overline{u'w'} = -K_{u,w}\left(\frac{\partial\overline{u}}{\partial z}+\frac{\partial\overline{w}}{\partial x}\right) \\ \overline{v'w'} = -K_{v,w}\left(\frac{\partial\overline{v}}{\partial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

Local mixing lengths

Work with Xavier Lamboley and Pascal Marquet :

- $l_{DEAR} = (\Delta x \Delta y \Delta z)^{\frac{1}{3}}$: Isotropic Turbulence
- *Kitamura (2015)*

$$\begin{cases} l_{h,M} & = & min(max((\Delta x \Delta z^2)^{\frac{1}{3}}, 0,4\Delta x), l_\infty) \\ l_{z,M} & = & min(\Delta x, l_\infty) \end{cases}$$



METEO FRANCE

New blend mixing length

LES, cubic cells ⇒ Meso-scale, flat cells. *Deardorff (1972)*

$$L_{DELT} = (\Delta x \Delta y \Delta z)^{1/3}$$
$$L_{\Delta} = (\Delta x \Delta y)^{1/2}$$

Rodier et al. (2017)

$$e(z) = \int_{z}^{z+l_{up}} \beta \left(\theta_v(z') - \theta_v(z) + C_0 \sqrt{e}\, \sigma(z') \right) dz'$$

$$e(z) = \int_{z-l_{down}}^{z} \beta \left(\theta_v(z') - \theta_v(z) + C_0 \sqrt{e}\, \sigma(z') \right) dz'$$

with C_0 a constant and $\sigma = \frac{\partial ||U||}{\partial x_j}$ local wind shear.

$$L_{RM17} = \left(\frac{l_{up}{}^{-2/3} + l_{down}{}^{-2/3}}{2} \right)^{-3/2}$$

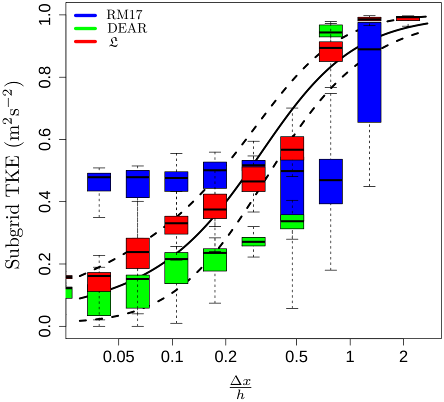
New blend mixing length

$$\boxed{\mathfrak{L} = min(\gamma L_{\Delta}, L_{RM17})}$$

avec $\gamma = 0.5$ a constant

Honnert, Masson, Lac et Nagel (2020)

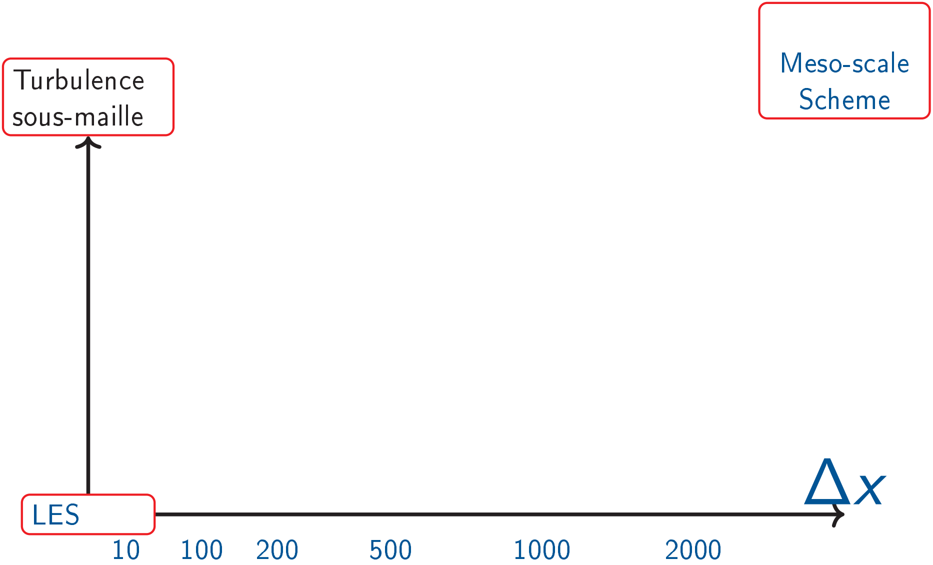
$\Rightarrow$ cy49t1



Subgrid TKE as a function of the normalised resolution.

Similitude Function from *Honnert et al. (2011)* (black solid line) and incertitude (black dashed lines).

Summary

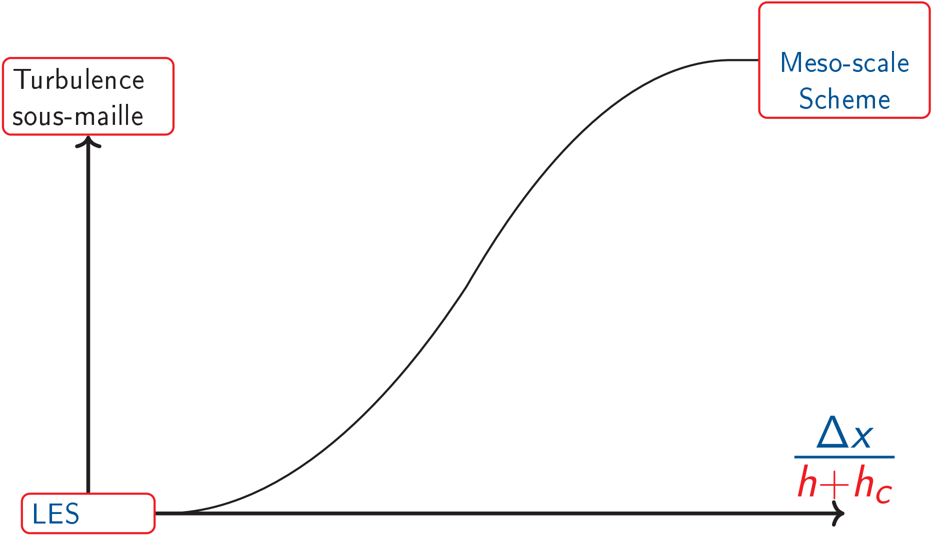


Turbulence
sous-maille

Meso-scale
Scheme

LES

Summary



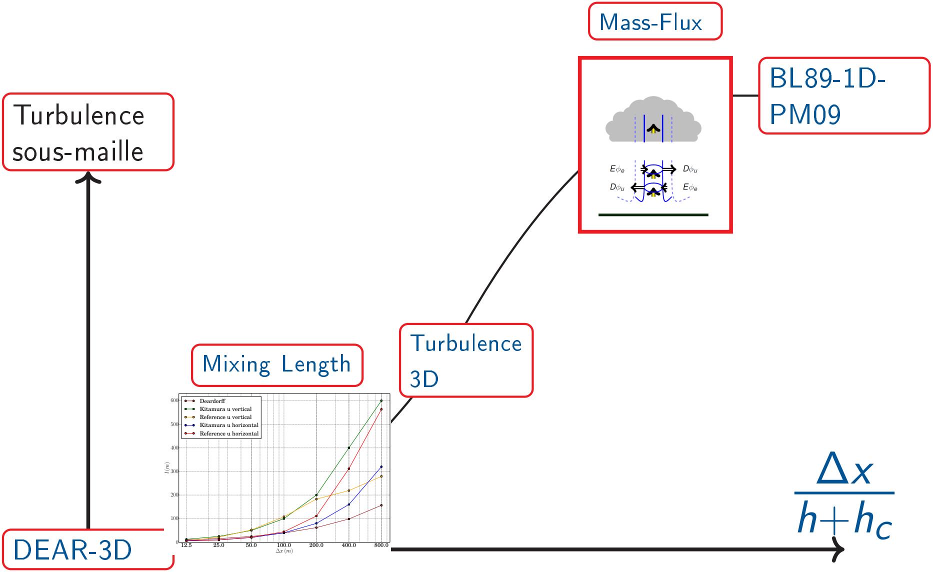
Turbulence sous-maille

Meso-scale Scheme

LES

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

Summary



Mass-Flux

BL89-1D-PM09

Turbulence sous-maille

Mixing Length

Turbulence 3D

DEAR-3D

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

Contents

METEO FRANCE

AROME-500m : Goals

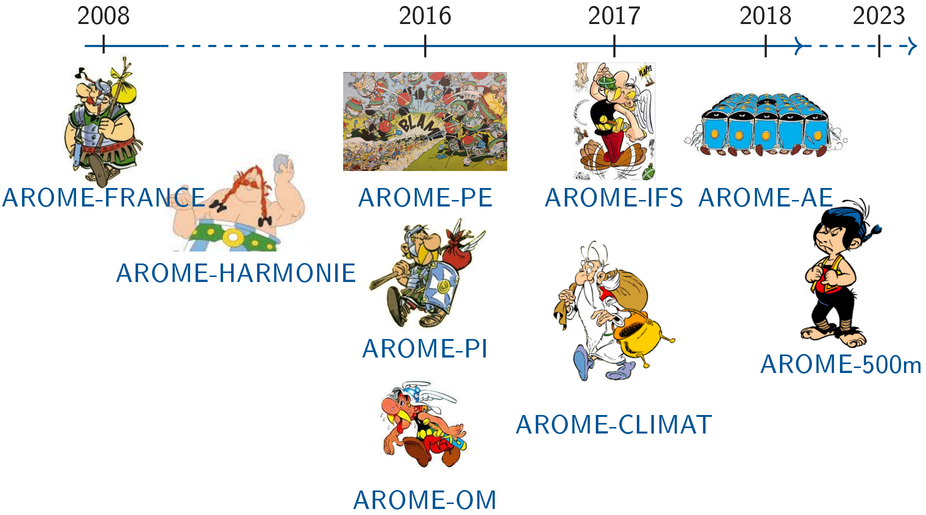
COP 2022-2026 :

- 500 m resolution models over specific areas : Paris **airports**, **mountains**, **Mediterranean regions** by 2024.
- **Urban Heat Island** : High Impact Weather and its socio-economic effect in the context of global change : Urban (Sub-department) heat alerts
- RDP Paris 2024 (WMO) : High resolution observation and modelling during the **Paris 2024** Olympic Games

AROME-500m : Challenges

- Turbulence and Shallow convection
- Dynamics : noise and oscillations coming from the orographic resonance
- Radiation, topography-radiation & clouds-radiation interaction, and 3D effects therein
- Physiography data & description of continental land covers

AROME-500m : AROME family



2008 2016 2017 2018 2023

AROME-FRANCE

AROME-HARMONIE

AROME-PE

AROME-PI

AROME-OM

AROME-IFS

AROME-CLIMAT

AROME-AE

AROME-500m

Seity et al. (2011), Brousseau et al. (2015)

AROME-500m : Previous experiments

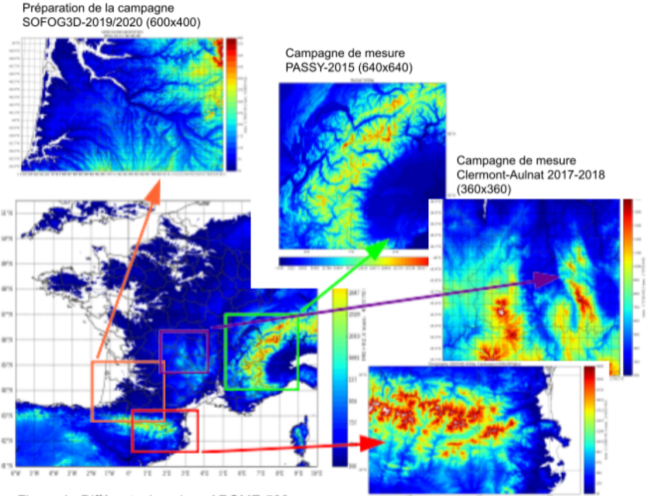
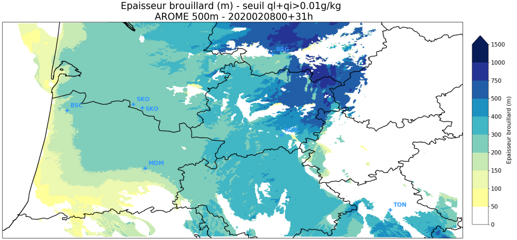


Figure 4 : Différents domaines AROME-500m mis en place dans le cadre de campagnes de mesures.

Fog forecasts in AROME-500 m

Work with Salomé Antoine and Y. Seity (PhD, AROME-500 m, Sofog3D) : Evaluations Δx and Δz (from 90 to 156 or 120 levels) ; LIMA (a 2-moment scheme, *Vié et al., 2016*) ; Deposition (*Mazoyer et al., 2016*)



Fog Depth South-West of France during 6 months of SoFog3D

Statistical valuation of AROME-500m

- Under estimation of fog events early in the night
- Delay at the fog dissipation in the morning
- Fogs too thick
- Fog with too much water content

How to improve fog forecast ?

A missing physical process : deposition

Take account the deposition term : should reduce liquid water content over estimation in fog (*Mazoyer et al. 2016; Zhang, 2014*)

Flux of deposition :

$$F_{DEP} = LWC.V_{DEP}. \qquad (1)$$

+ Decrease visibility bias, less water content in fog
Greater impact on 1250L90 grid (due to first model level height)

A new microphysical scheme

ICE3 (1-moment - *Pinty and Jabouille, 1998*)
vs
LIMA (2-moment - *Vié et al., 2016*)

Droplet concentration impacts fog sedimentation and radiative budgets : LIMA (2 prognostic variables) mass mixing ratios and their concentration. (*Duconge et al., 2020*)

+/− More fog events forecast with LIMA
+ Decrease visibility bias - Less water content in LIMA fogs than in ICE3 fogs
+ Reduce fog dissipation delay in the morning ⇒ Salomé Antoine's defence in December 2022.

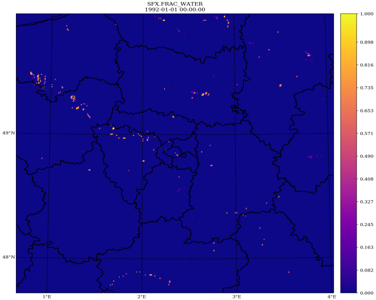
PANAME-2022 : Urban Meteorology

Ten research projects grouped together to **acquire observations** in order to better understand the mechanisms responsible for **air pollution**, the **urban heat island**, **extreme weather events** in the city, and their consequences. (Valéry Masson and Aude Lemonsu)

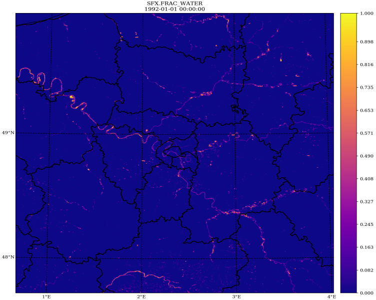
ACROSS experimental device on the roof of the Paris Cité University (Aline Gratien)

Conventional meteorological balloon launch at Quai de Bercy at sunset (Cyril Frésillon)

Enhanced Surface Database



"Water" fraction with Ecoclimap-I

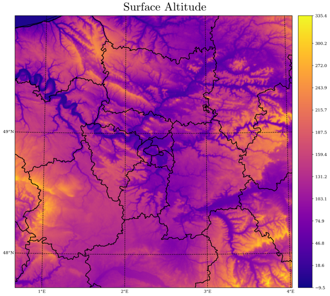


"Water" fraction with OpenStreetMap (J. Wurtz)

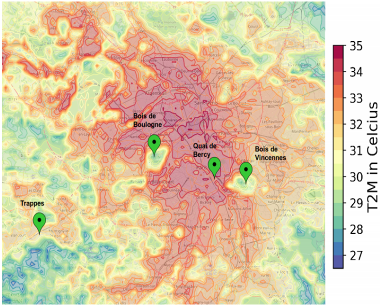
- Update representation of the surface
- More Water, More Town, less Nature

AROME-PARIS-500m

AROME-500 m run in real time during the campaign



AROME-500 m Domain Surface Altitude

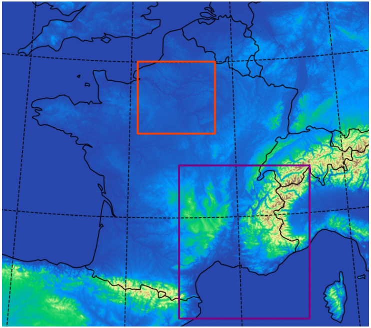


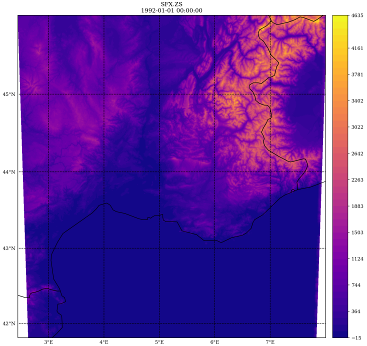
Air temperature with the AROME-500 m resolution, June 17, 2022 at 20 UTC. (plot : Jean Wurtz).

The simulated temperature difference between the city center and the outlying areas reaches 5 to 7°C. The two cooler areas to the east and west of Paris correspond to the Bois de Vincennes and Boulogne, respectively.

Objectives

COP 2022-2026 : LAM 500 m domains for 2024.





Deode : LAM sub-kilometer domains.

- First models around 500 m : shallow convection (LS18), ecRad, TEB (Garden, BEM), CMO (cy48t1)
- Models finer resolutions : 3D effects and mixing length (cy49t1)

Thank you for your attention !