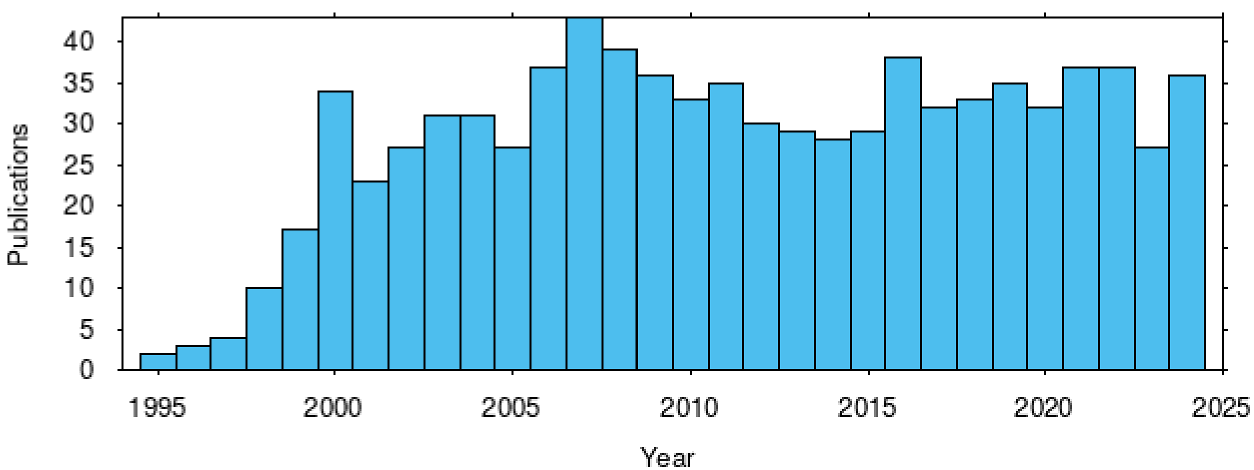
Meso-NH
mesoscale non-hydrostatic model

A research model, initially jointly developped by Meteo-France and Laboratoire d'Aérologie (CNRS/UPS)

+ LACy, CERFACS, LOPS (Brest), SPE (Corsica) ...

http://mesonh.aero.obs-mip.fr/mesonh57

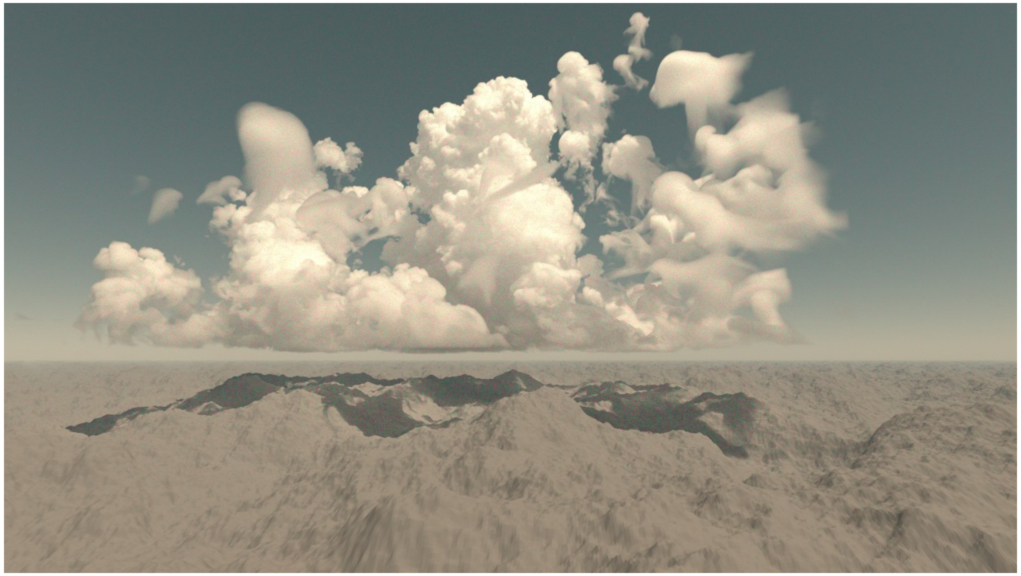


674 articles
181 thesis

<u>References</u> : *Lafore et al., 1998 – Lac et al., 2018, GMD*

Outline

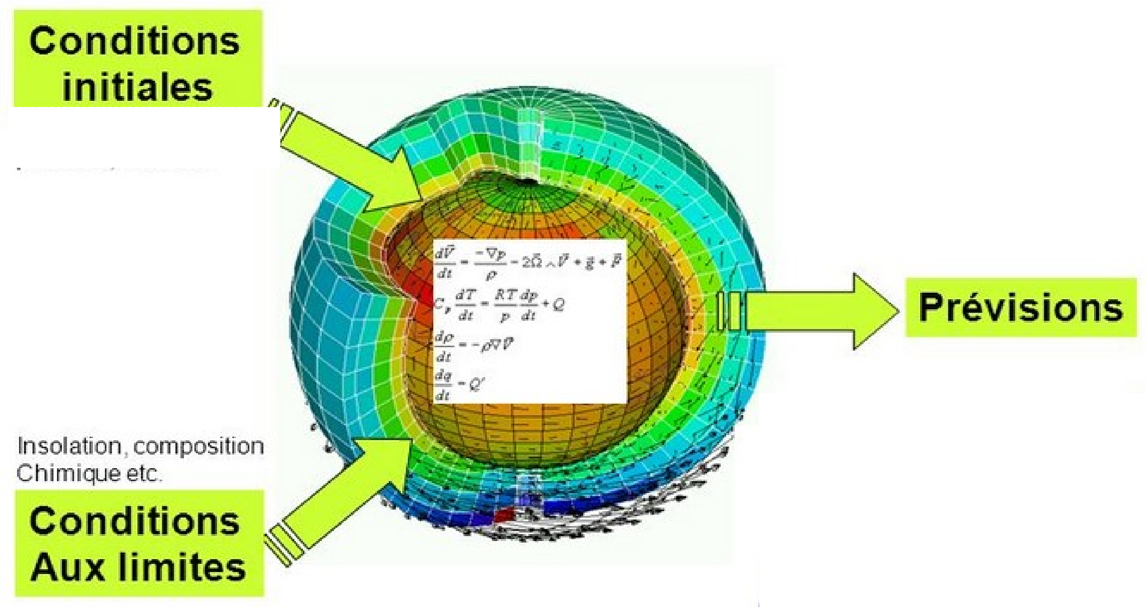
1. Introduction (a few illustrations)
2. Dynamics
3. Physics (without SURFEX)
4. A few words about on-line couplings : electricity, fire, chemistry/aerosols ...

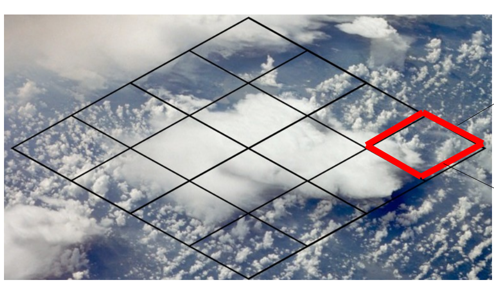


Najda Villefranque – Clément Strauss

What is an atmospheric model ?

It predicts the atmospheric state evolution represented with a spatio-temporal discretization

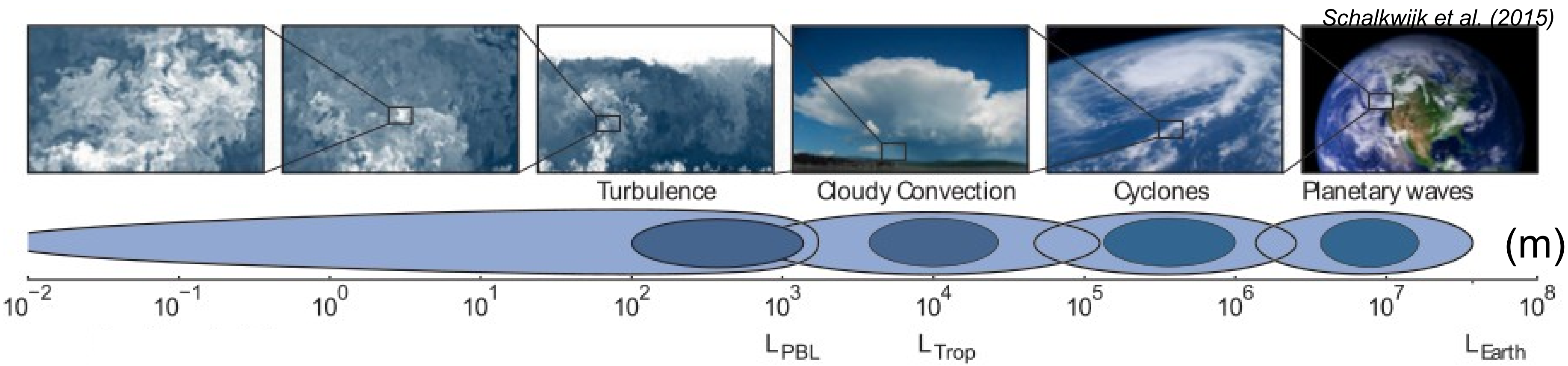




Resolved processes : **dynamical** core

Subgrid processes : **physical** parametrizations

Space and time scales



« Direct Numerical » (DNS)

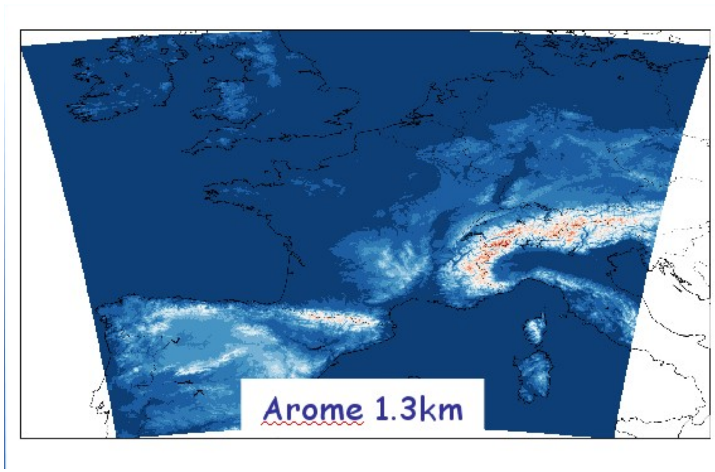
« Large-Eddy Simulation » (LES)

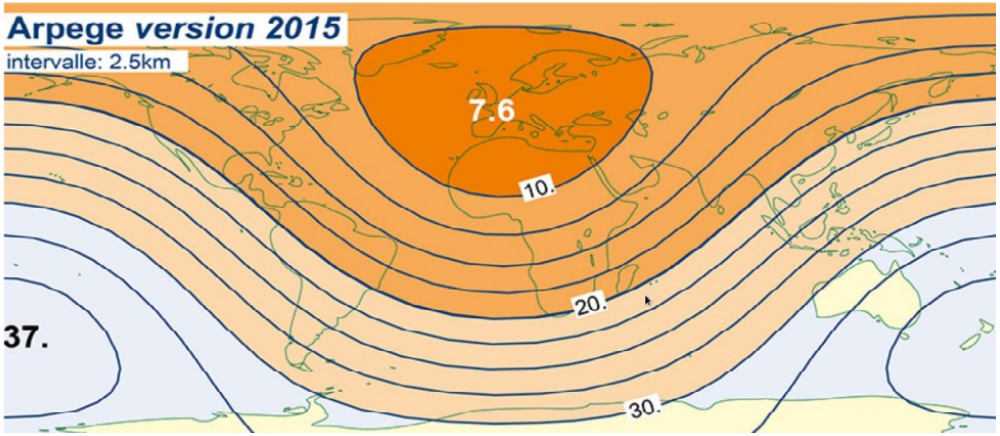
« Cloud System Resolving Model » (CSRM)

Méso-NH

Different meteorological models at Meteo-France

- **Global Climate Model (GCM) : ARPEGE Climat**
- **NWP at synoptic scale : ECMWF, ARPEGE (Δx ~5km over France, ~24 km over the Antipodes 105 vertical levels)**





- **NWP at meso-β scale : AROME (2008) (Δx=1.3km 90L)**
  - **AROME Climat (Δx=2.5km 60L)**
- **Research model for synoptic to meso-γ scale : Méso-NH (Δx=50km to cm) : AROME physics comes from Meso-NH**

Other equivalent meso-scale models elsewhere : WRF, RAMS, LM, UM …

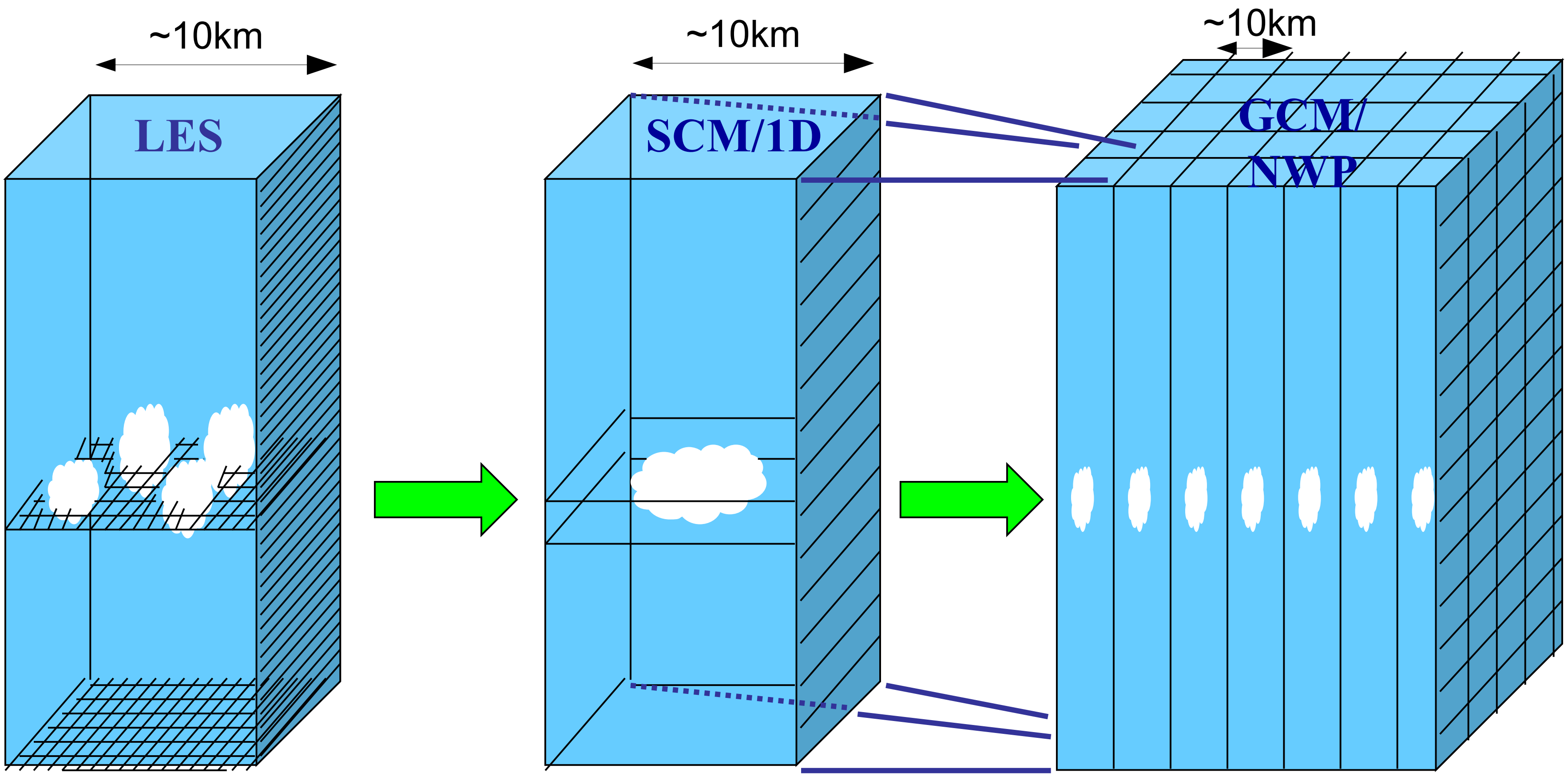
LAM

Why do we need a high resolution research model like Meso-NH ?

- To improve parameterizations for Large Scale models : fine resolution simulations allow to resolve the main coherent patterns and inform on fine scale variability.

- To help the evaluation and the improvement of NWP models like AROME (High resolution capability, Grid Nesting)

METHODOLOGY to improve PARAMETRIZATIONS

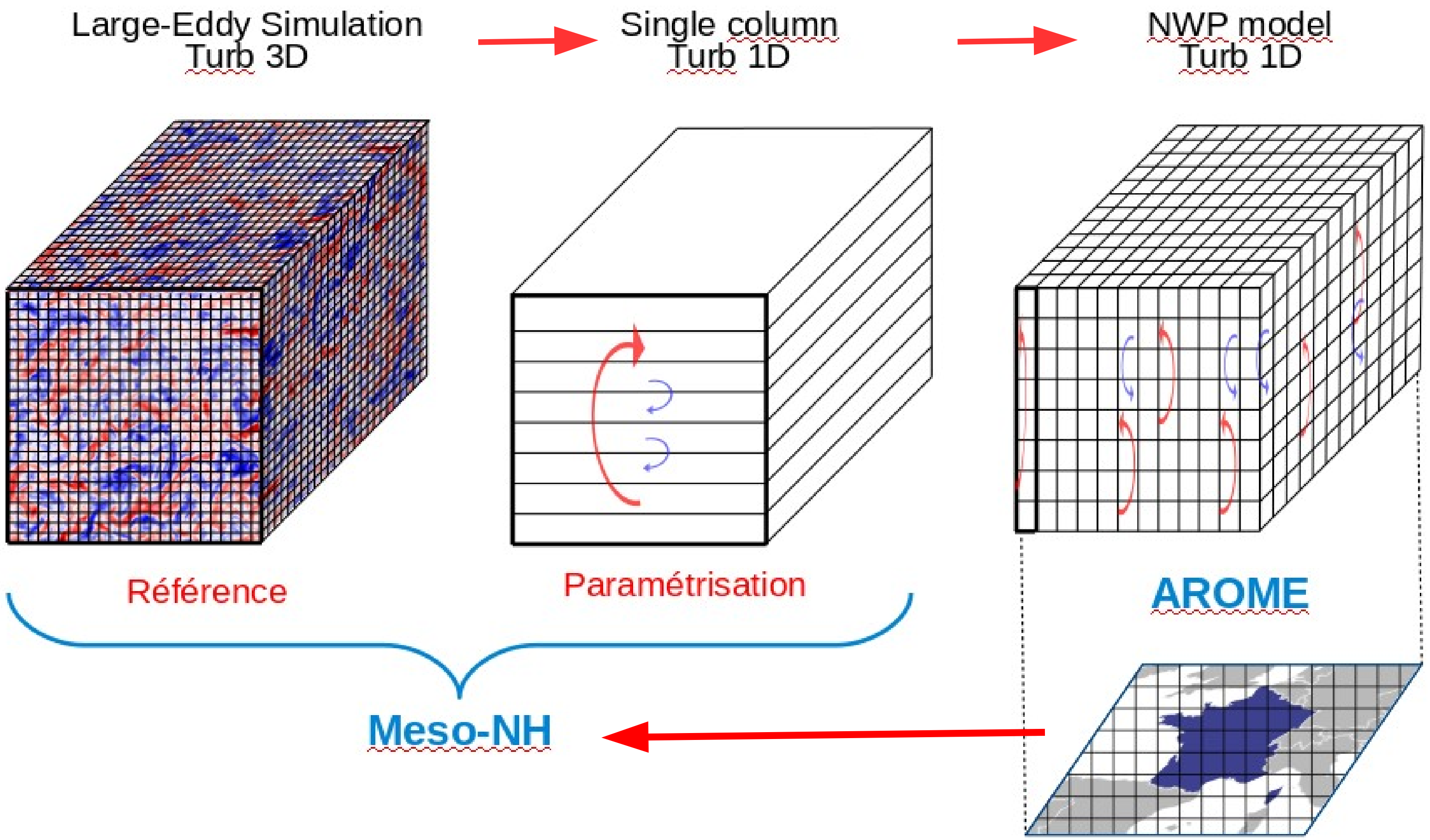


LES : Subgrid Kinetic Energy < 20 % Total Kinetic Energy
Dx depends on the motions : ~100m for convection, ~ 1m for stable boundary layer

The mean and the PDF fields of the LES constitute the reference for the 1D and 3D NWP fields

Meso-NH : The same set-up in 1D and LES (initial conditions , flux, large scale forcings)

A virtuous cycle between Meso-NH and AROME for physical parametrizations



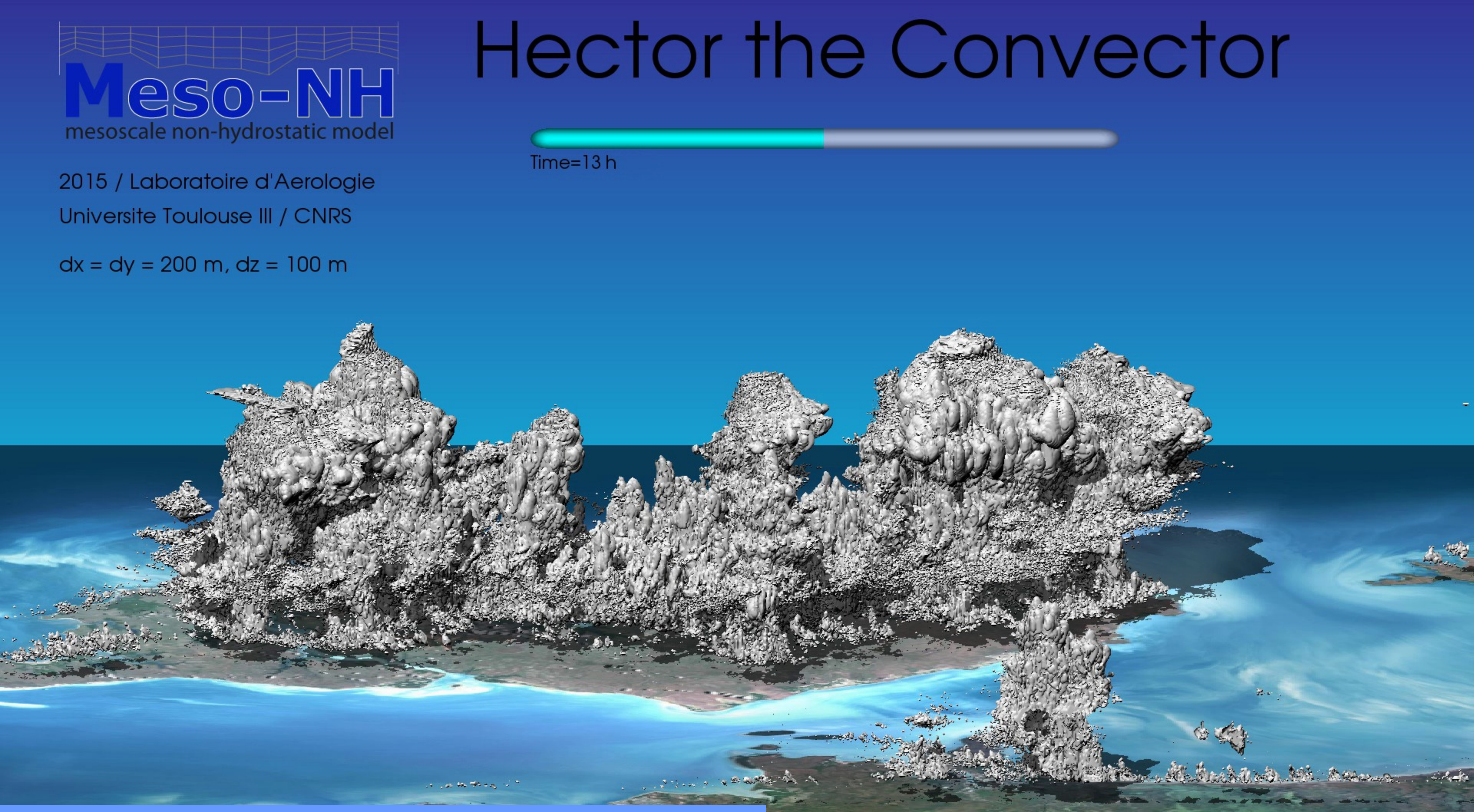
Why do we need a high resolution research model like Meso-NH ?

- To improve parameterizations for Large Scale models : fine resolution simulations allow to resolve the main coherent patterns and inform on fine scale variability.

- To help the evaluation and the improvement of NWP models like AROME (High resolution capability, Grid Nesting)

- **To better understand complex processes (e.g. cloud processes), to characterize local effects : meso-scale to large eddy simulations**

Hector the Convector



- 2560 x 2048 x 256, 1.34 billion gridpoints
  Δx=100 m and Δz=40 – 100 m : **1st Giga-LES**
- 10-h simulation on IBM BlueGene-Q
  8 million CPU h, 16 kcores, 20 Tb data
- Initial field from Darwin sounding

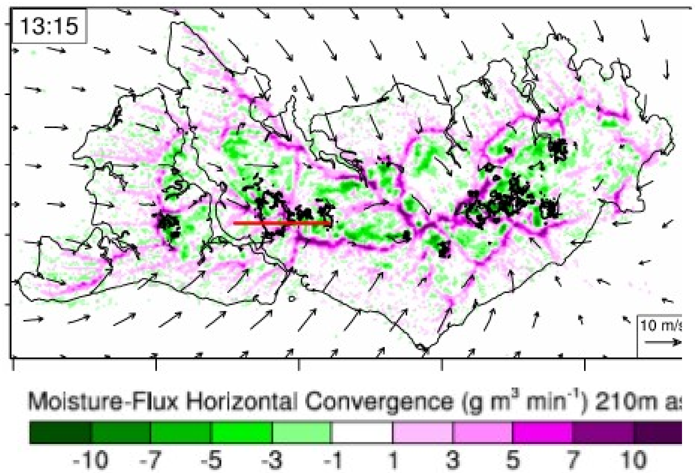
A storm that grew daily during pre-monsoon on the Tiwi Islands north of Darwin

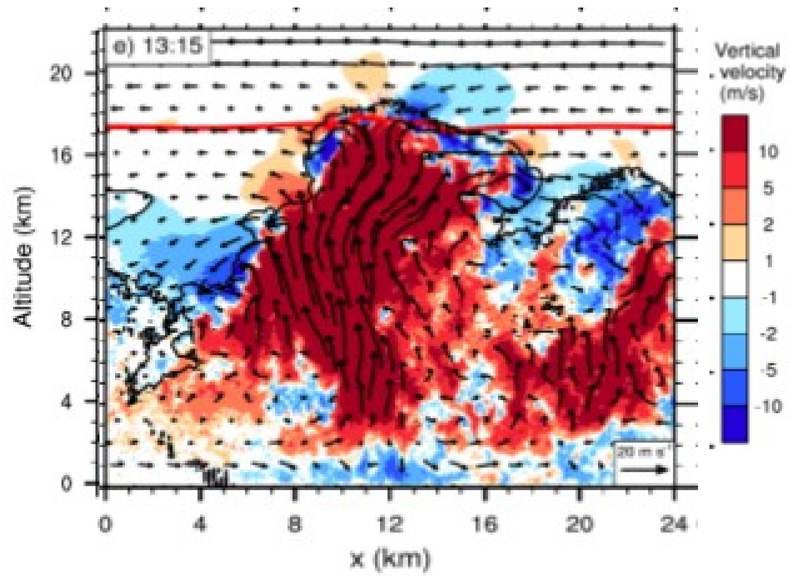
Dauhut et al., Atmos. Sci. Lett. 2015

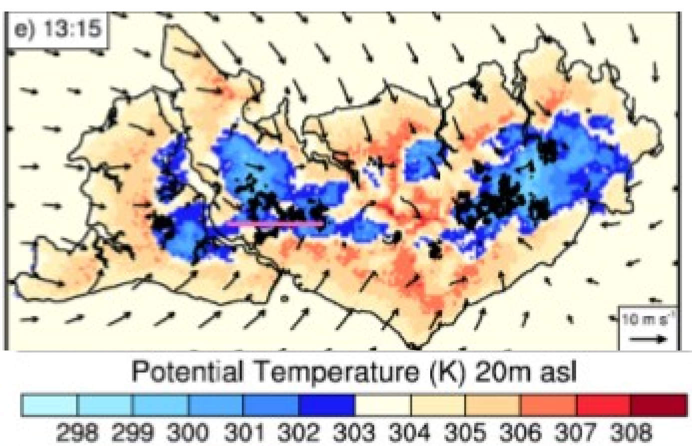
Video on https://youtu.be/xjPumywGaAU

Formation of the tallest updrafts

13:15 Very Deep Convection





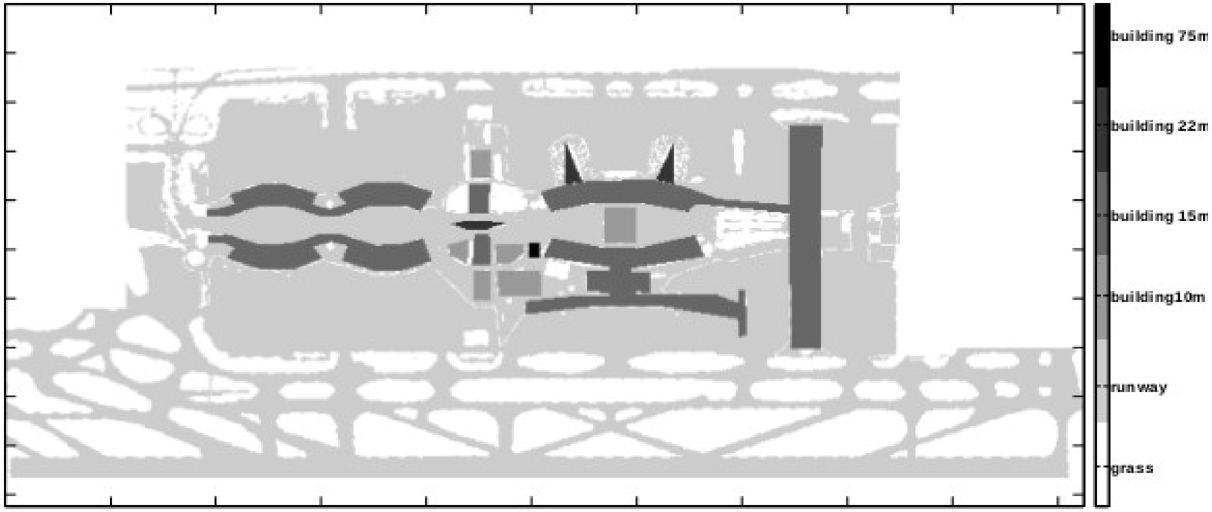


- Humidity convergence lines advected inland by the sea breeze
- Cold pools pushed the convergence lines inland
- Tallest updrafts reached 18km and inhibited the other updrafts by detraining subsiding air

Convergence intensified by cold pools

Effects of small-scale surface heterogeneities on radiation fog : LES at Paris CDG airport

Database from Aéroports de Paris
Surface elements have been built

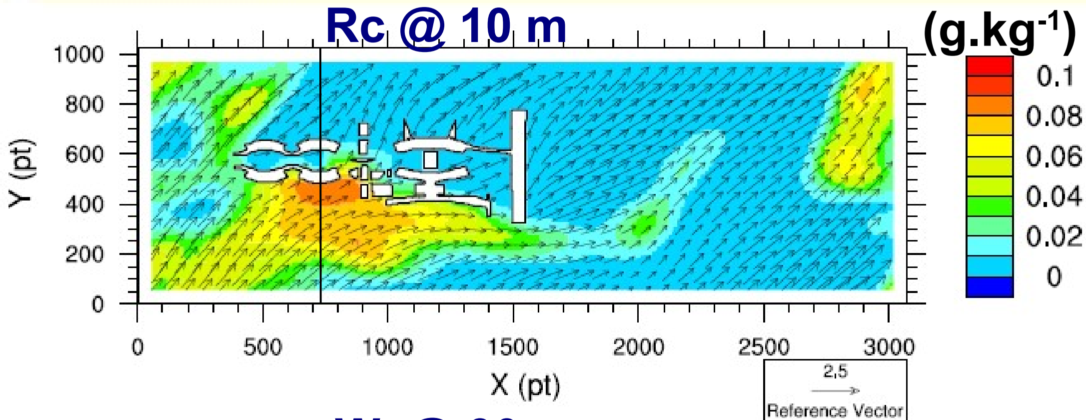


3000×1000 ×135
Δx=1.5m
Δz=1m
Flat terrain
Building drag effect

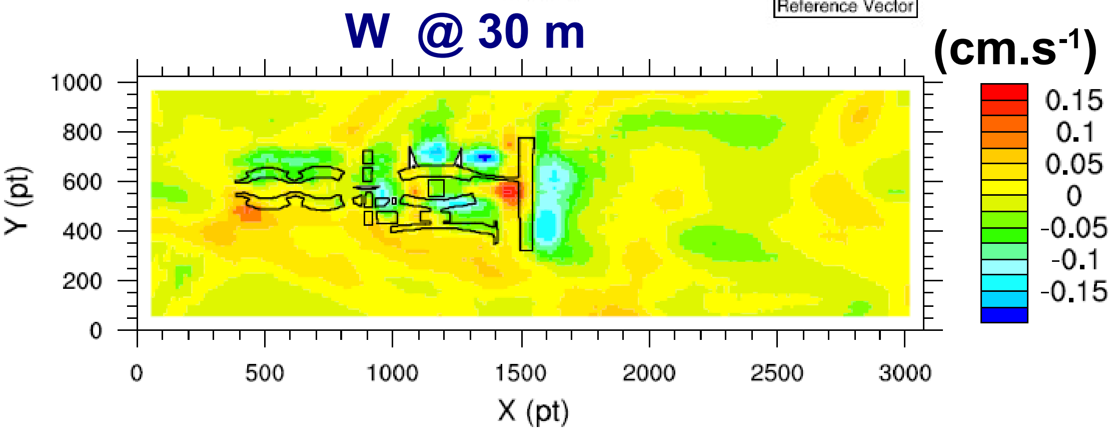
Bergot et al., 2015, QJRMS

CNRM-GAME

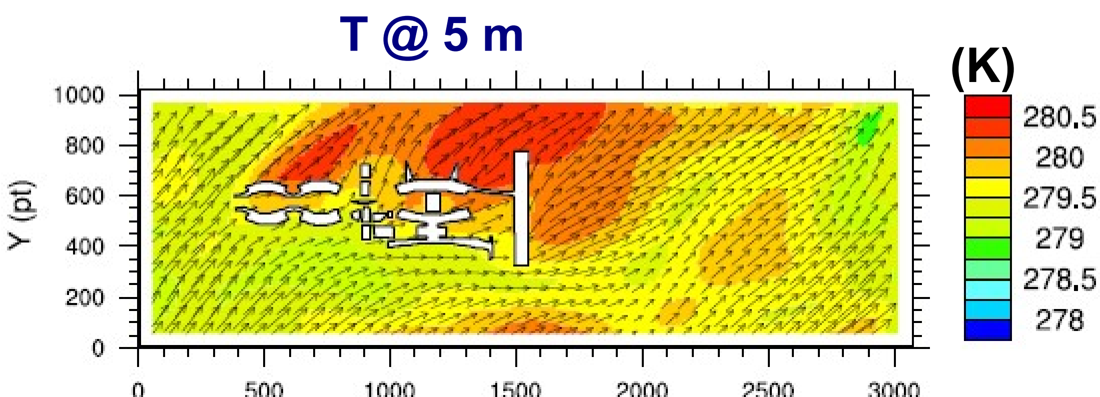
23h15 UTC — Development of the fog — DRAG



Very heterogeneous fog formation (~1.5 h)
No fog downstream



Ascendance ($0.1 cm.s^{-1}$) upstream and subsidence ($-0.1 cm.s^{-1}$) downstream



Heating (1K) downstream due to subsidence (adding to anthopogenic heating) delays fog formation

Why do we need a high resolution research model like Meso-NH ?

- To improve parameterizations for Large Scale models : fine resolution simulations allow to resolve the main coherent patterns and inform on fine scale variability.

- To help the evaluation and the improvement of NWP models like AROME (High resolution capability, Grid Nesting)

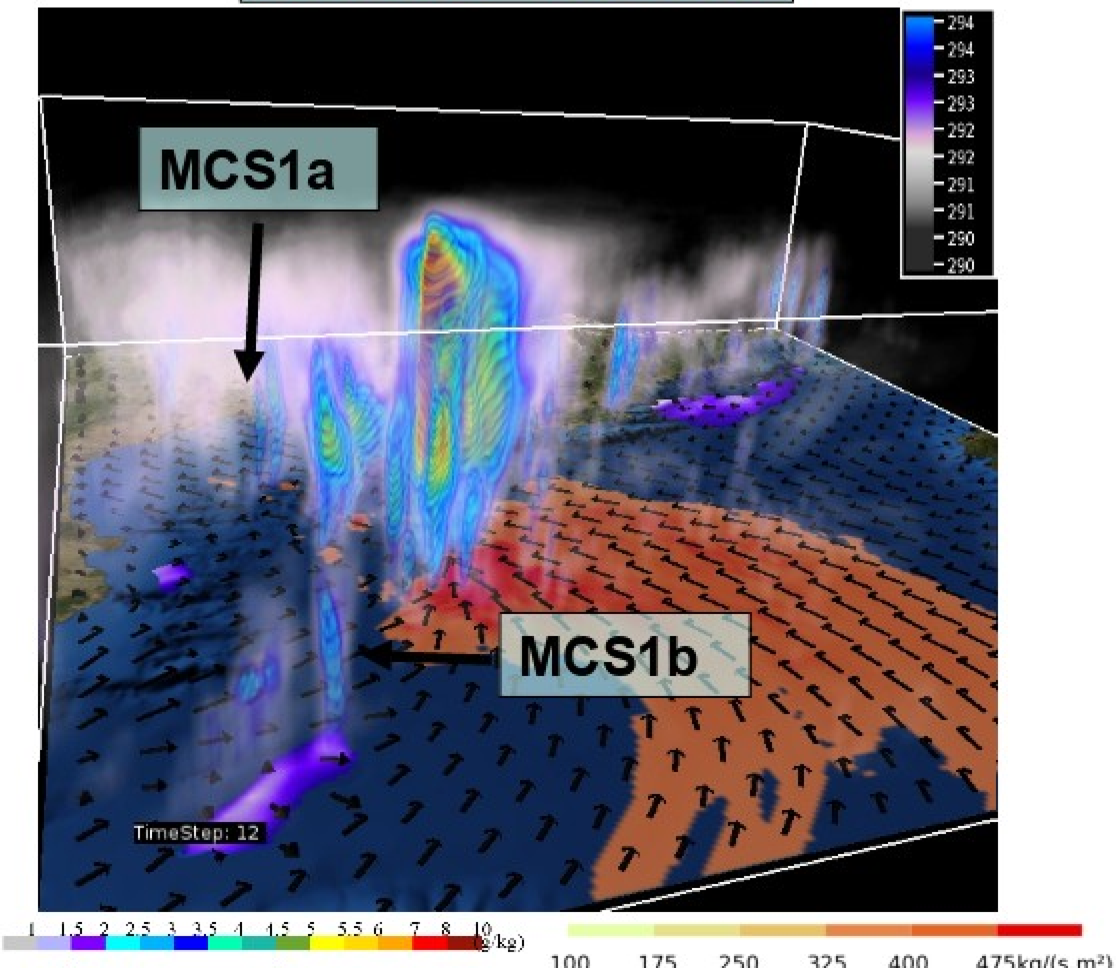
- To better understand complex processes (e.g. cloud processes), to characterize local effects : meso-scale to large eddy simulations

- **To carry out impact studies and use the model as a laboratory**

- **To develop Diagnostics : budgets, LES diagnostics ; observation simulators : satellite, radar, lidar, scintillometer, to validate the model and to develop new data assimilation**

Diagnostics to study key physical processes

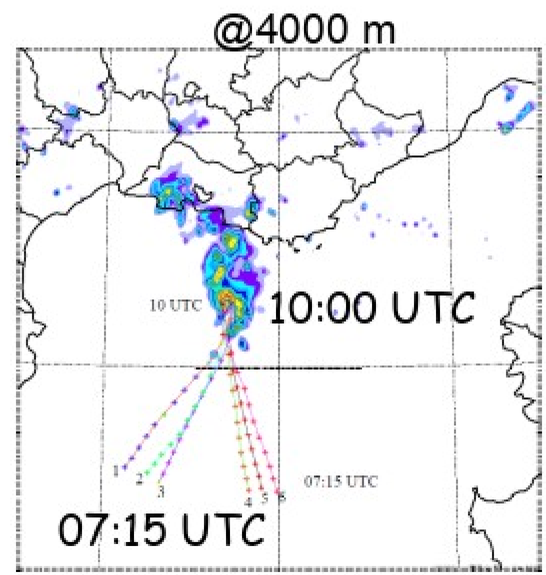
Vizualisation 3D with VAPOR

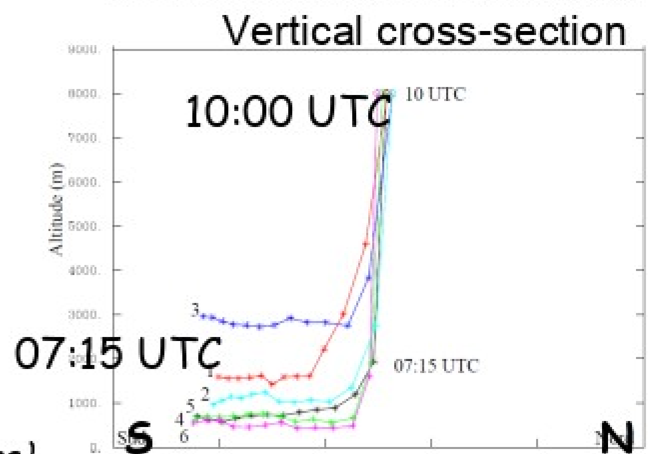


Hydrometeor total content (volume coloré)

Integrated humidity flux 0→3km (color surface)

→ Wind 10-m





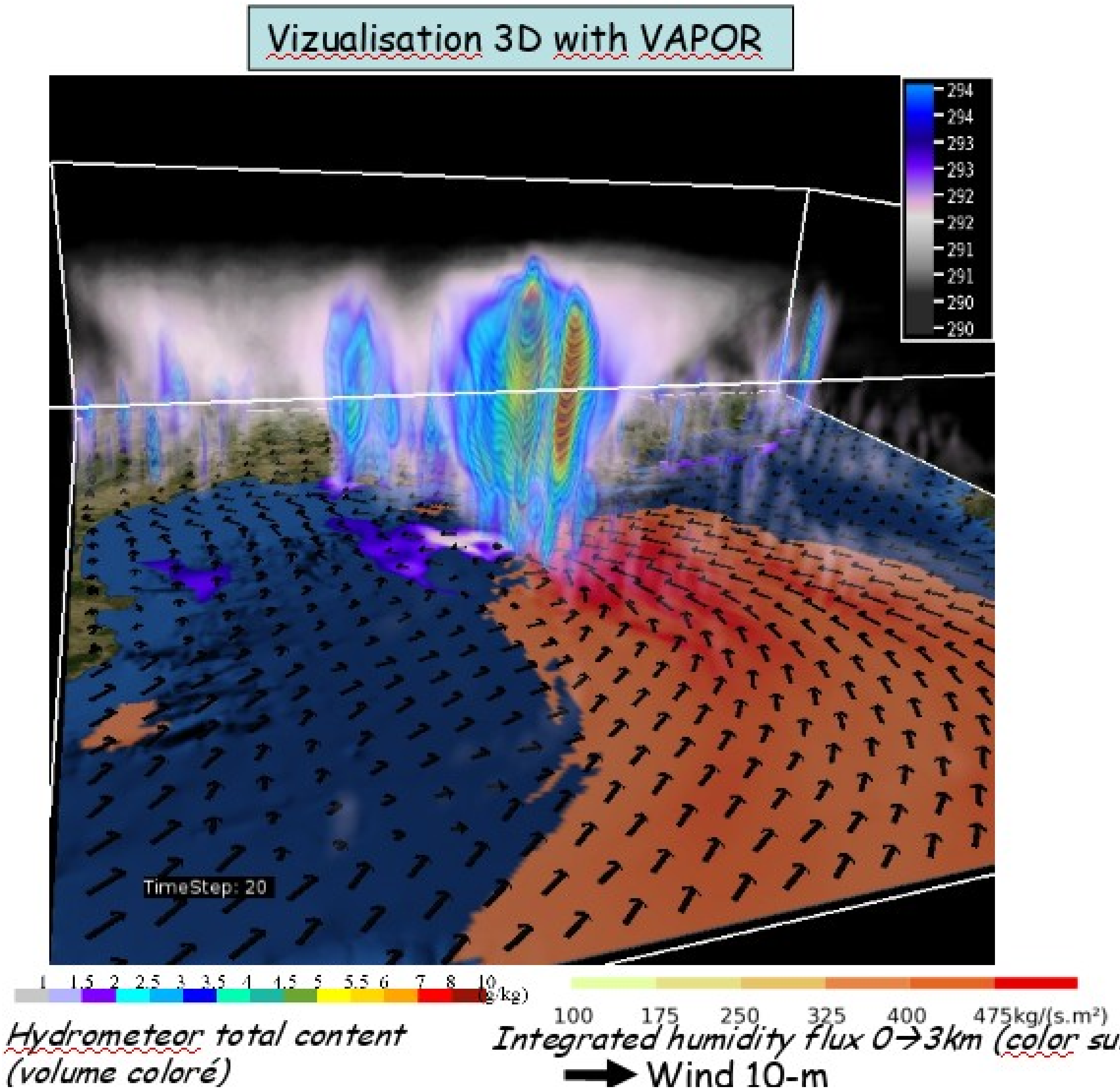
Retro-trajectories 10:00 UTC → 7:15 UTC

- Humidity advection and low-level convergence !

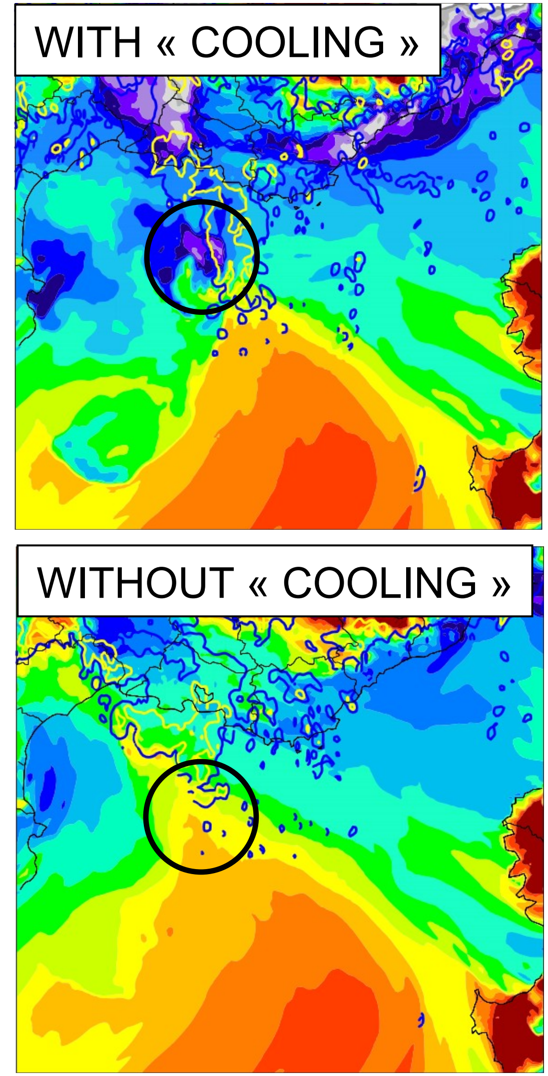
Nuissier et Civiate, 2013

Key physical processes

Nuissier et Civiate, 2013



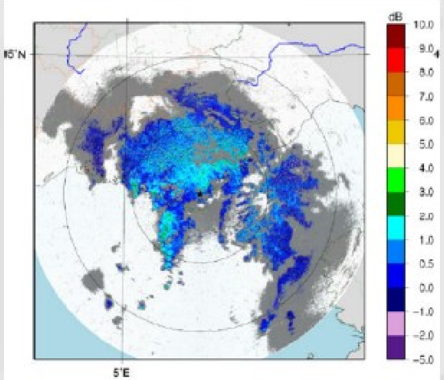
Theta$_v$



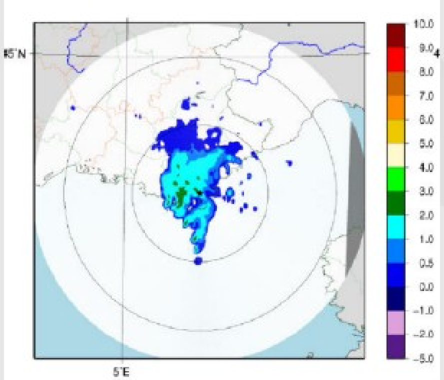
- Lifting on the leading edge of the cold pool
- MCS1b quickly advected to the north without cooling

Observation simulators

- Polarimetric radar

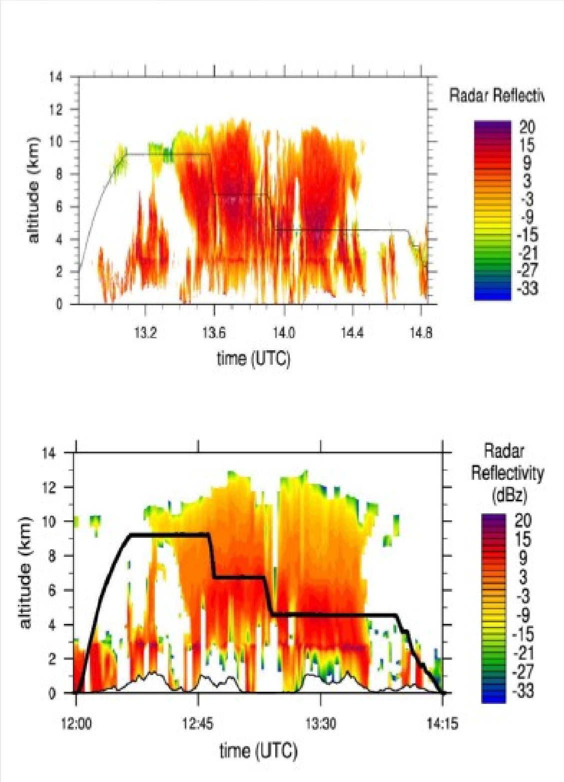


Zdr radar (dB)

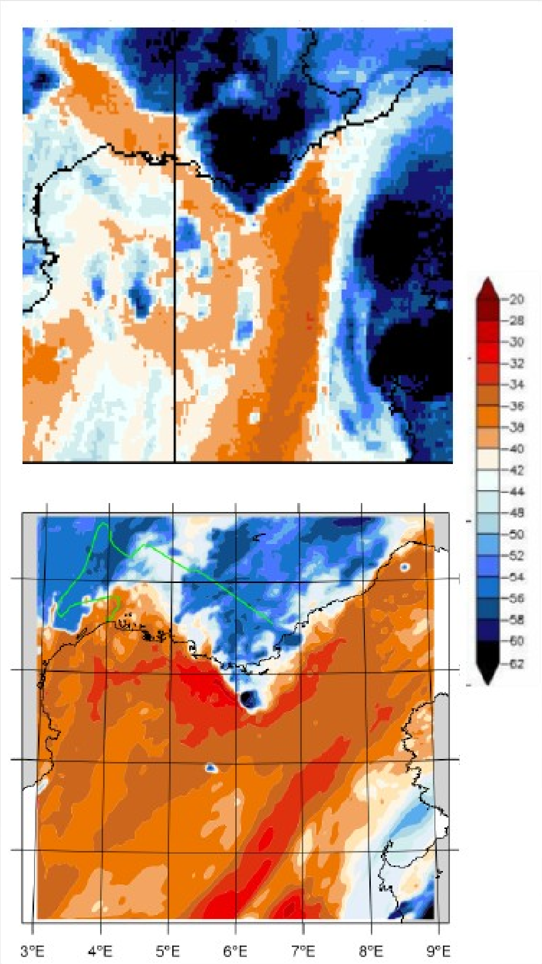


Zdr modèle (dB)

- Airborne obs.

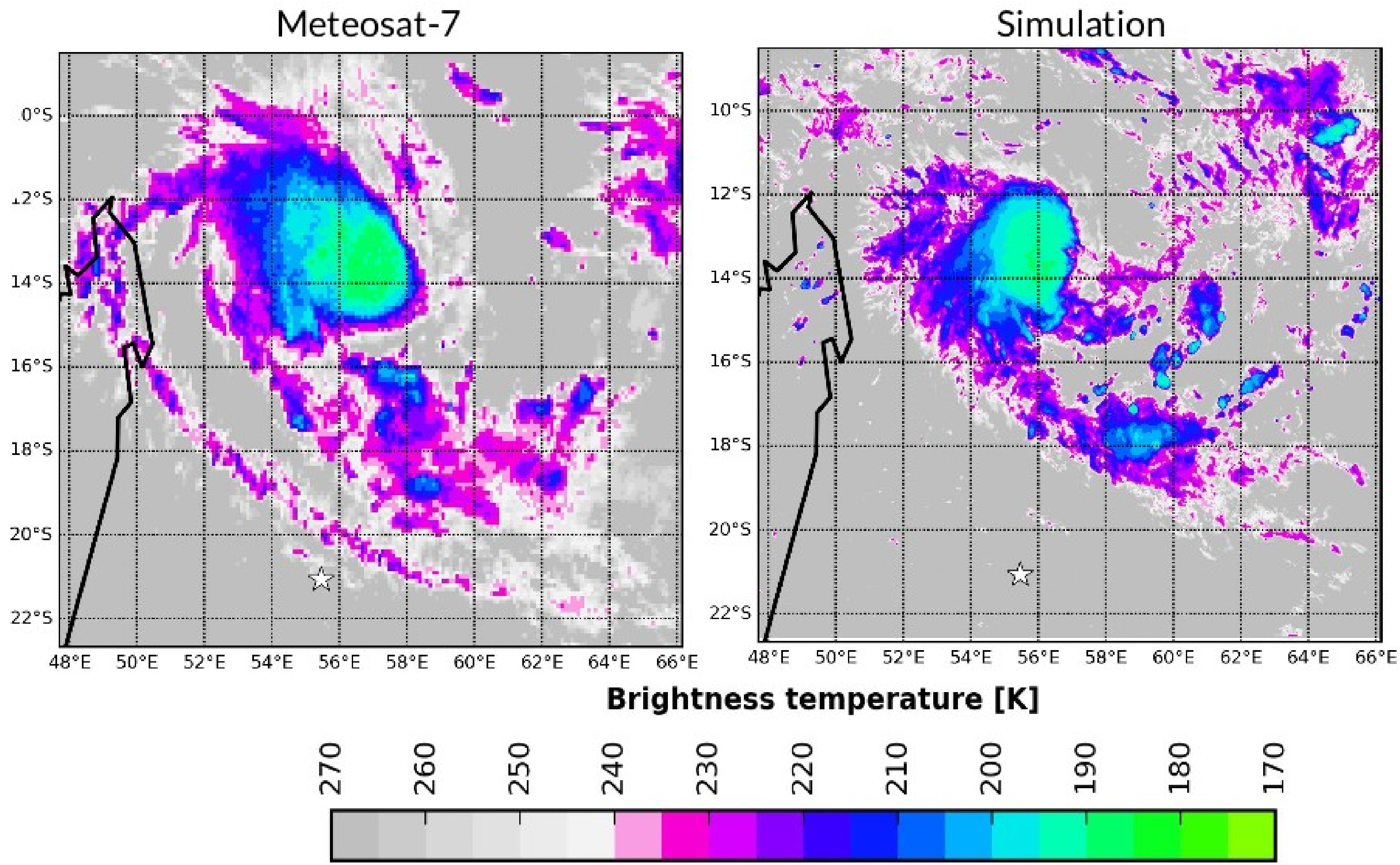


- Satellite



Observation simulators

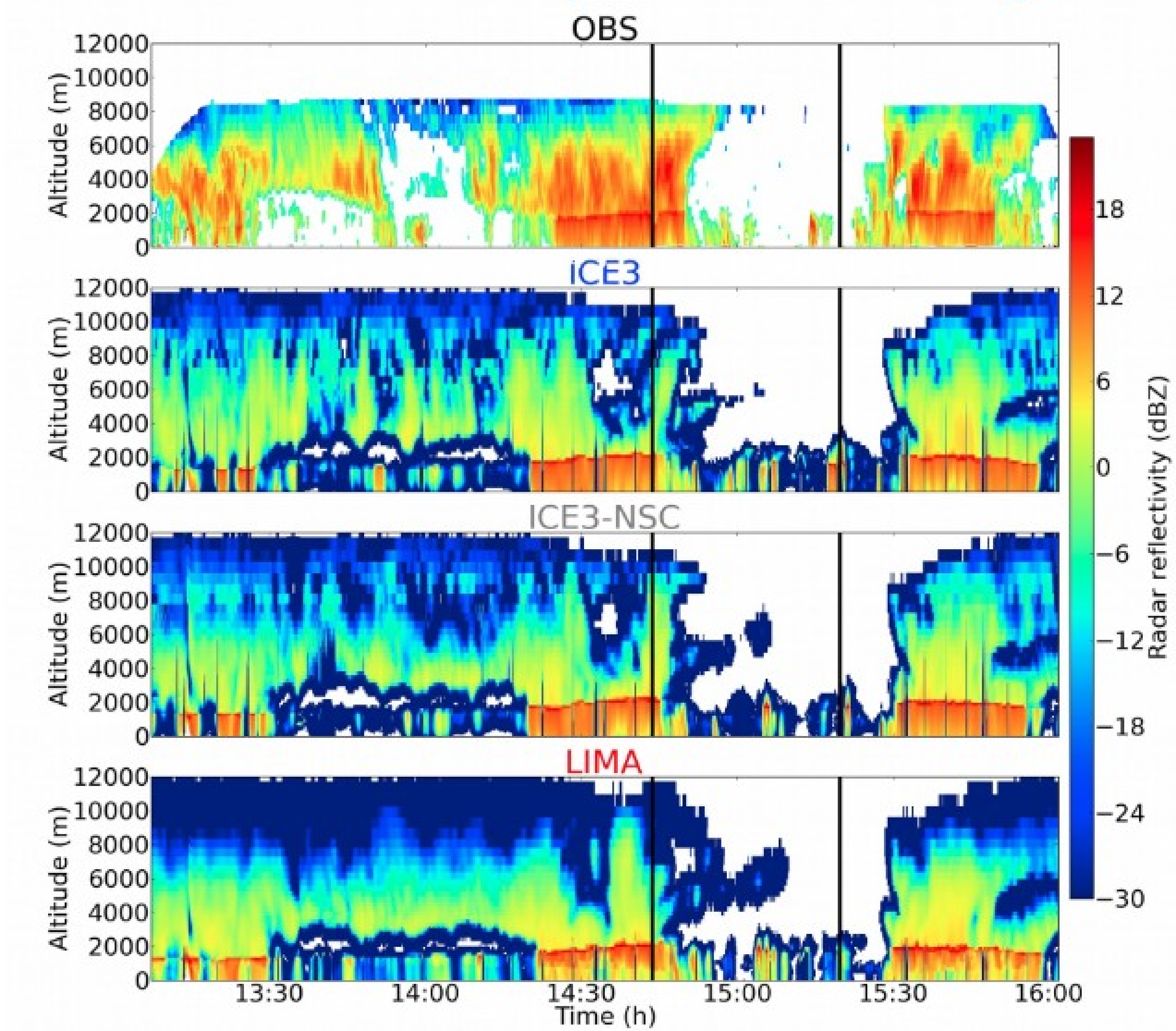
cyclone tropical ENAWO (2017)



Damien Héron, Doctorant au LACy (UMR 8105) pour les journées Meso-NH 2019.

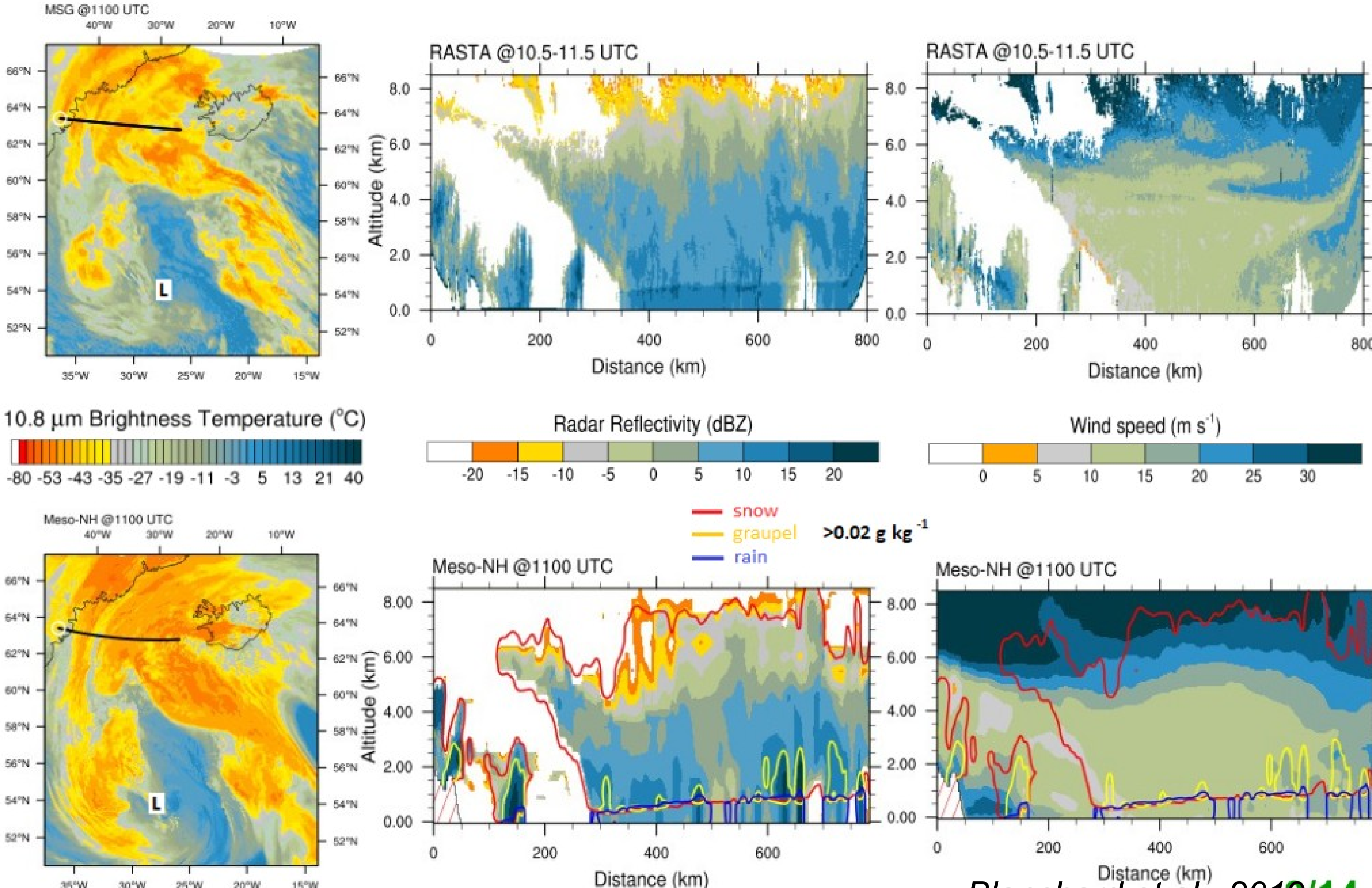
Observation simulators

Radar reflectivity in WCB during F7



Mazoyer et al., 2019

Observation simulators



Blanchard et al., 2019

Why do we need a high resolution research model like Meso-NH ?

- To improve parameterizations for Large Scale models : fine resolution simulations allow to resolve the main coherent patterns and inform on fine scale variability.
- To help the evaluation and the improvement of NWP models like AROME (High resolution capability, Grid Nesting)
- To better understand complex processes (e.g. cloud processes), to characterize local effects : meso-scale to large eddy simulations
- To carry out impact studies and use the model as a laboratory
- To develop Diagnostics : budgets, LES diagnostics ; observation simulators : satellite, radar, lidar, scintillometer, to validate the model and to develop new data assimilation
- **To develop new couplings (e.g. Electricity, Hydrology …) and applications (astronomy …). A tool for faisability studies**

What's new ?

Previous version : 5.6.0 (March 2023) with :

- **online forest fire module : Blaze**
- integration of surface developments for the next SURFEX v9
- **new versions of LIMA**
- **new version of aerosol, chemical codes** (consistent with microphysics, radiation codes)
- **PHYEX: common code for AROME/MesoNH physics**

Bugfix version 5.6.1 (September 2023) and version 5.6.2 (November 2023)

- small bug corrections (diagnostics for LES, for aircrafts and balloons...)
- add surface fields in outputs (stations, profilers,...)
- cleaning of aerosols climatology initialization ; possibility to use all three climatologies
- different names between variables from SURFEX and from Meso-NH for turbulence

New version: 5.7.0 (January 2024) + bugfix 5.7.1 (September 2024)

-**version 9 of SURFEX**, including more than 5 years of development, as well as multi-level coupling in the urban canyon (SURFEX/TEB) and the atmosphere,
- **a new wind turbine scheme**: the ADR, actuator disk with rotation,
- **a new lightning scheme ELE4** compatible with LIMA and ICE3 with time-splitting,
- **new forms of ice crystals in LIMA and their optical properties consistent with LIMA in ECRAD**,
- the **ability to call up radiation on an aggregated column** rather than on all columns to save computing time,
- internal reorganization and updating of PHYEX physics namelists.

Meso-NH
mesoscale non-hydrostatic model

Main characteristics

DYNAMICS

- ✗ A broad range of resolutions from synoptic scales (Δx~10km), meso-scale (Δx~1km) to Large Eddy Simulation (Δx~100m to 1m) up to DNS (Direct Numerical Simulation Δx~1mm)
- ✗ Non hydrostatic anelastic model
- ✗ Eulerian explicit grid-point model with 4th or 5th transport schemes
- ✗ Grid-nesting

PHYSICS

- ✗ Coupled with the externalized surface model SURFEX (vegetation, town, lake, sea)
- ✗ Turbulence 1D (meso-scale) or 3D → **Large Eddy Simulations (LES)**
- ✗ Microphysics 1-moment or 2-moment
- ✗ Shallow and deep convection schemes
- ✗ ECMWF radiation
- ✗ Chemistry, Aerosols and Dusts
- ✗ Electricity scheme

- ✗ The physics of AROME comes from Meso-NH (1D version)

General view

- ✗ **Real cases** (from ECMWF, ARPEGE, AROME, GFS analyses or forecasts)
- ✗ **Ideal cases** ≠ unrealistic cases
  - Academic cases (validation of the dynamics)
  - Basic studies (Diurnal cycle …): Cloud Resolving Model (CRM)
  - To reproduce an observed reality (via forcings) (intercomparison : GCSS, EUROCS …)
- ✗ Simulations **3D, 2D, 1D** – Real cases only in 3D

- ✗ From a simple to a sophisticated physics
- ✗ Different numerical schemes : from accurate and expensive to cheaper
- ✗ A set of **diagnostics** (budgets, profilers, trajectories …)
- ✗ Parallelized and vectorized
- ✗ A broad range of hardware system for the research community : CRAY, IBM, BULL, cluster of PC … towards GPU
- ✗ Adapted to **large grids**
- ✗ No operational objective.

Scalability

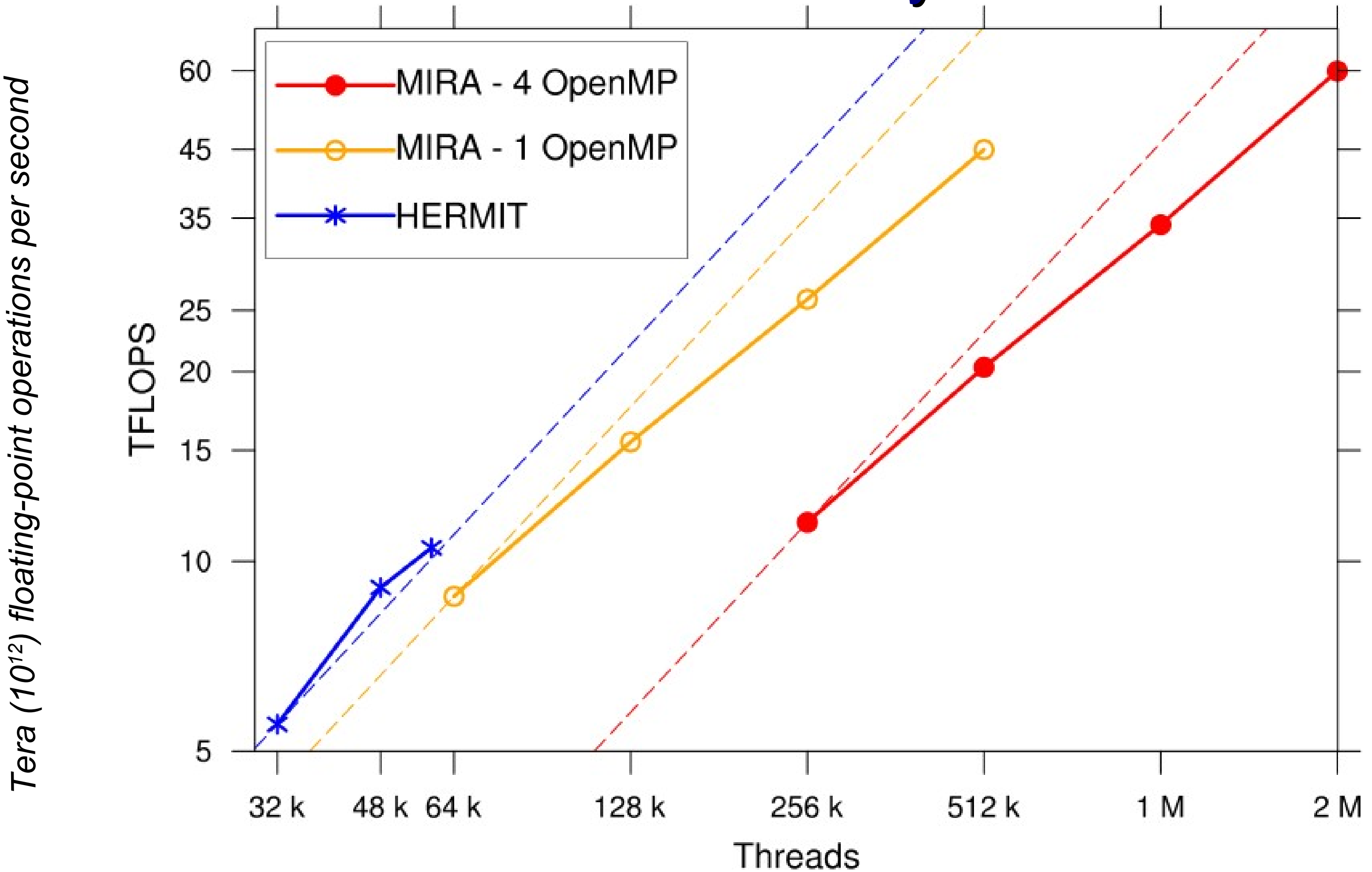


Figure 1. Performance of Meso-NH in scalability. Average sustained power (expressed in TFLOPS) depending on the number of threads obtained by Meso-NH for a grid of $4096 \times 4096 \times 1024$ points (17 billion points) on two machines (HERMIT, a Cray XE6 in Germany and MIRA, a IBM Blue Gene/Q in the USA using either one or four OpenMP tasks per core). The dashed lines show the optimal speedup.

TFLOPS gradually increases with the number of threads while remaining close to the optimal speedup

2. Dynamics

Part of the model to describe the evolution of a laminar fluid (no turbulence), without heat exchange (adiabatic).

Depends on :
- **Hypothesis** : Non-hydrostatism ; anelastic
- **Horizontal Geometry** : Coupling, Embedded models
- **Vertical coordinates** : Upper boundary limit
- **Orography characteristics** (average and envelop orography)
- **Numerical methods** : Grid points; Explicit ; Eulerian
- **Model variables**;
- **Dynamical sources** : Coriolis, gravity …

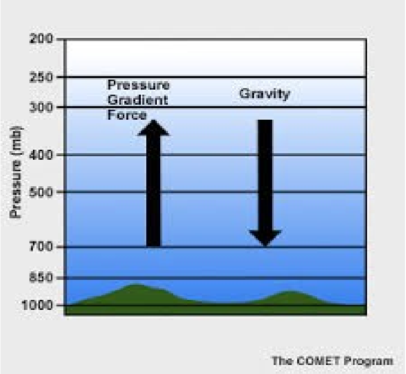
Non-hydrostatism / Anelastic

Meso-NH
mesoscale non-hydrostatic model

What is the hydrostatism ?

Non hydrostatic equation of the vertical motion

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$



If H << L we can neglect the vertical acceleration compared to the vertical component of the pressure force = **hydrostatic approximation**

- Pressure at a point is represented by the mass of the above air column
- W is not equal to 0 or constant, but it is diagnosed
- The hydrostatism filters acoustic waves

To represent correctly the processes at convective scale, it is necessary to keep the complete equation of the vertical motion **= non hydrostatism**

Perturbations from a reference state

In practice, we often write the non hydrostatic equations by decomposing the variables as the sum of a **reference rest state (hydrostatic)** and the difference with this reference state (noted ~ here)

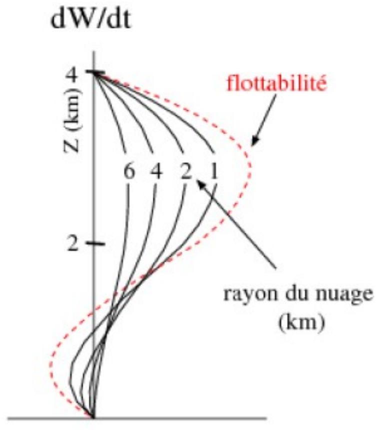
$$
\begin{aligned}
u &= 0 + \tilde{u} \\
v &= 0 + \tilde{v} \\
w &= 0 + \tilde{w} \\
T &= T_{ref} + \tilde{T} \\
p &= p_{ref} + \tilde{p} \\
\rho &= \rho_{ref} + \tilde{\rho}
\end{aligned}
$$

- The reference rest state has no meteorological interest
- Perturbations to this state represent meteorological phenomena

At the first order, the equation of the vertical motion becomes :

$$
\frac{Dw}{Dt} = \underbrace{-\frac{1}{\rho_{ref}}\frac{\partial \tilde{p}}{\partial z}}_{\text{Pressure term}} \underbrace{-\frac{g}{\rho_{ref}}\tilde{\rho}}_{\text{Buoyancy}}
$$

Validity of the non hydrostatism



Exemple analytique de Yau, 79

The non hydrostatic effects become important for horizontal scales less than 10 km → **Convection, gravity waves**

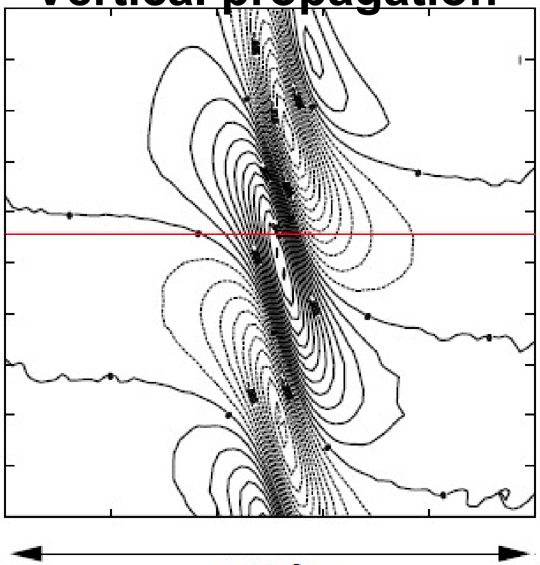
Orographic waves, H and NH waves

$N = 0,01 s^{-1}$
$U = 10\ m.s^{-1}$
H=hauteur montagne=10 m

→ $(NH)/U << 1$: cas linéaire

L = Width of the mountain
H = Height of the mountain

Vertical propagation

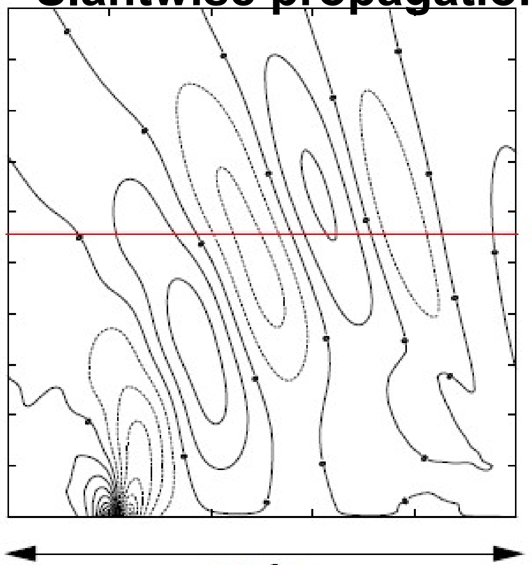


150 km

L>> H

L=largeur montagne=10 km
$(NL)/U >> 1$: hydrostatique

Slantwise propagation



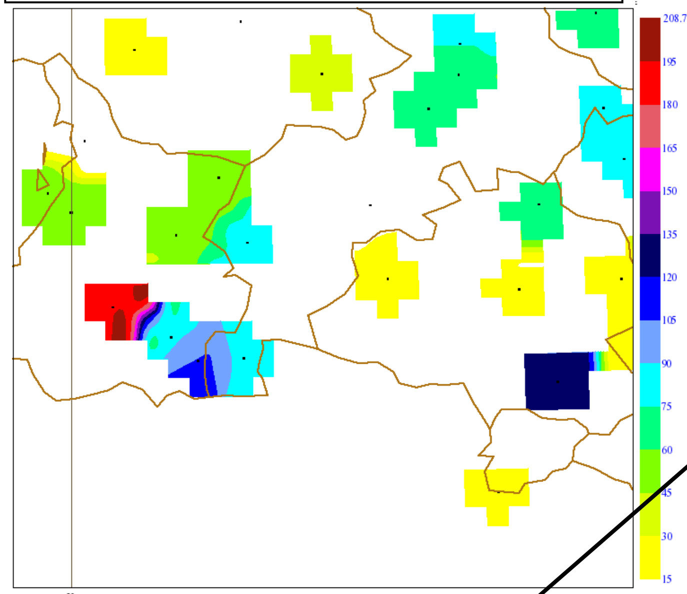
25 km

L~H

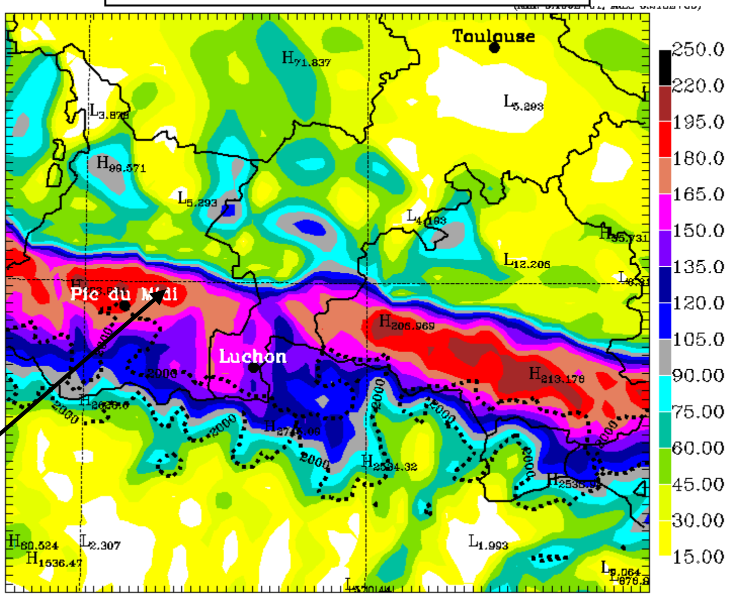
L=largeur montagne=665 m
$(NL)/U << 1$: non hydrostatique

Fine-scale simulations of Xynthia winds

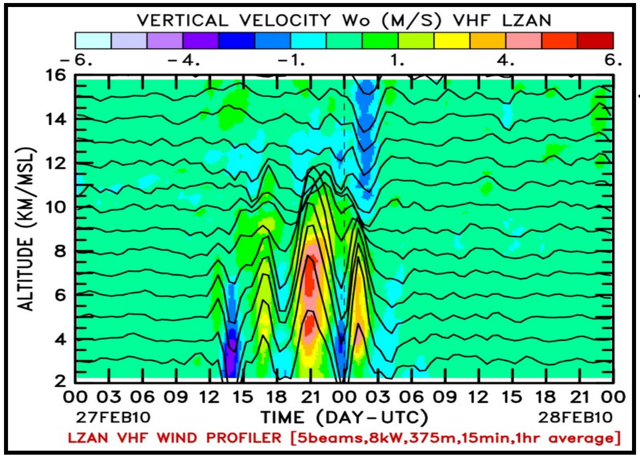
OBSERVATION Max=209km/h



AROME Max=213km/h



10m gust wind (km/h) 28 Feb. 2010 at 21 UTC

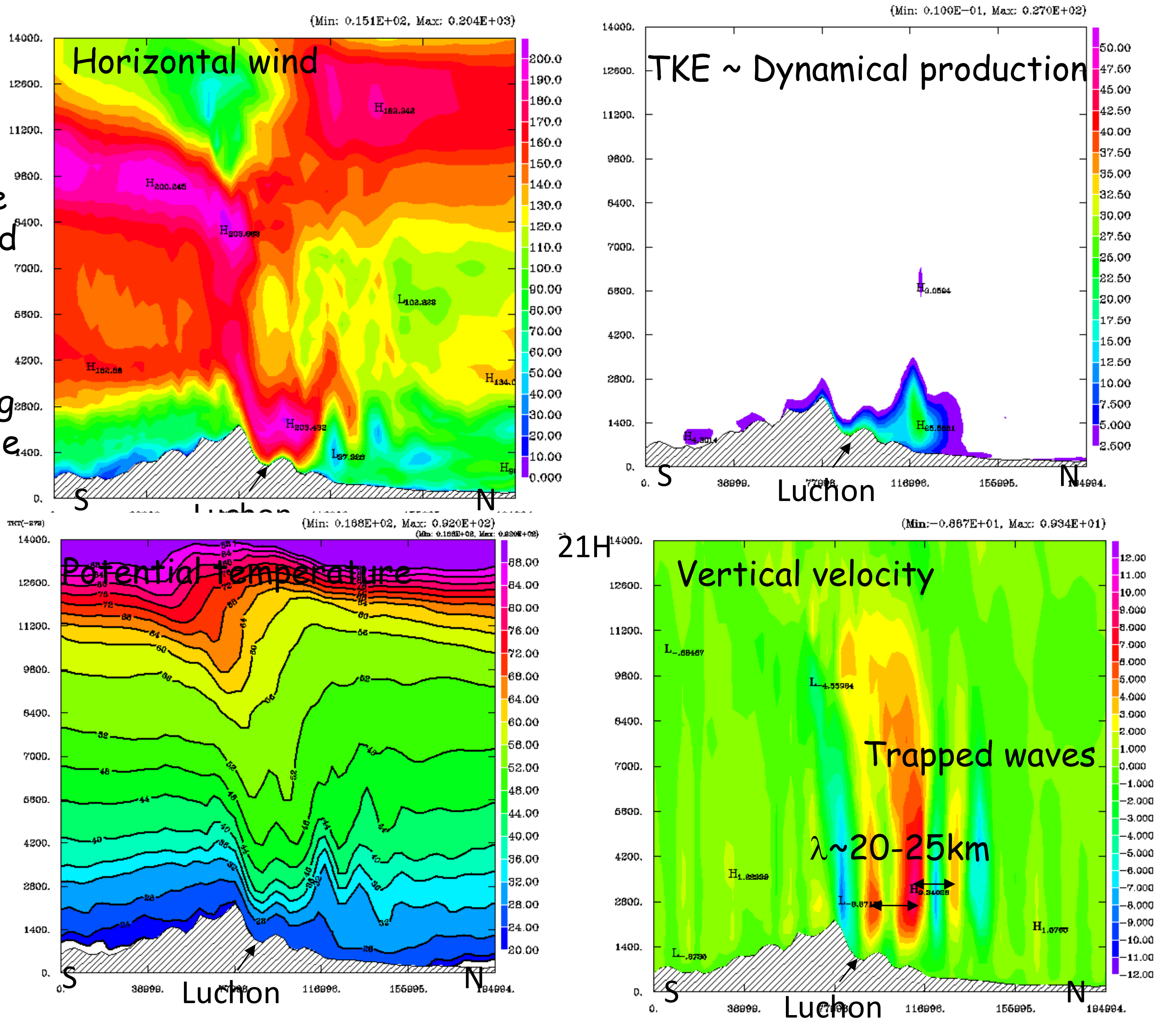


Lannemezan wind profiler shows a structure of trapped gravity waves

Good forecast on the Pyrenees with AROME, with a band of strong winds on the north of the Pyrenees in the South wind

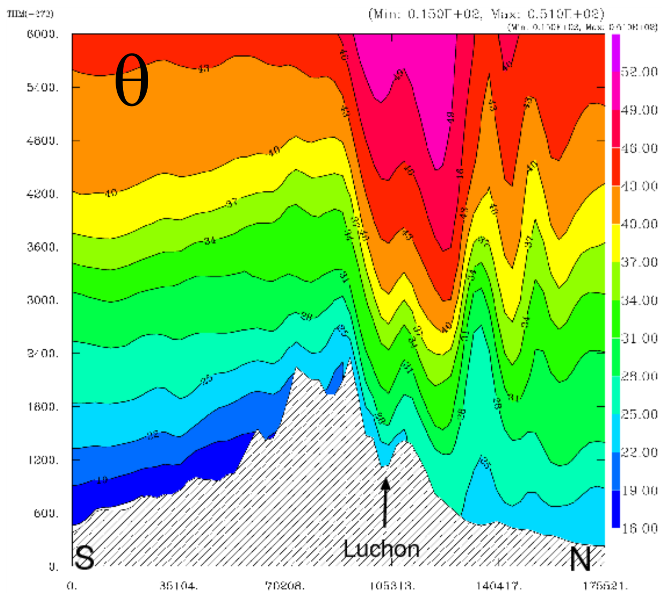
Meso-NH : same forecast than AROME

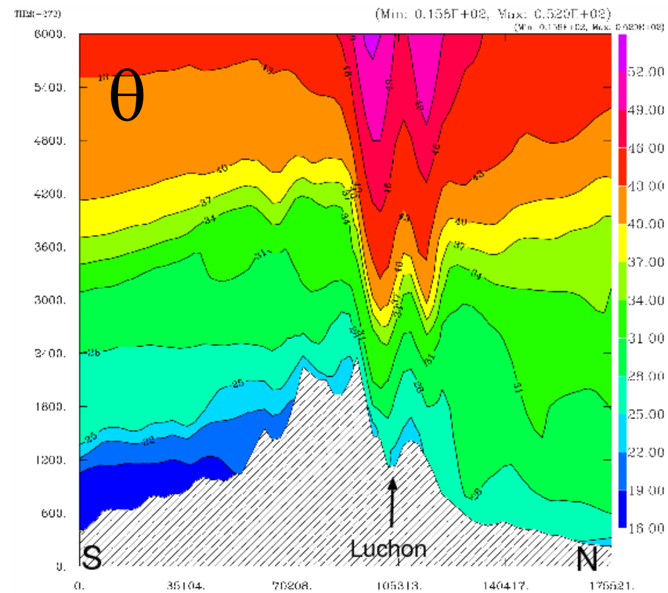
AROME : Structure of trapped gravity waves inducing the strong wind in the North valleys

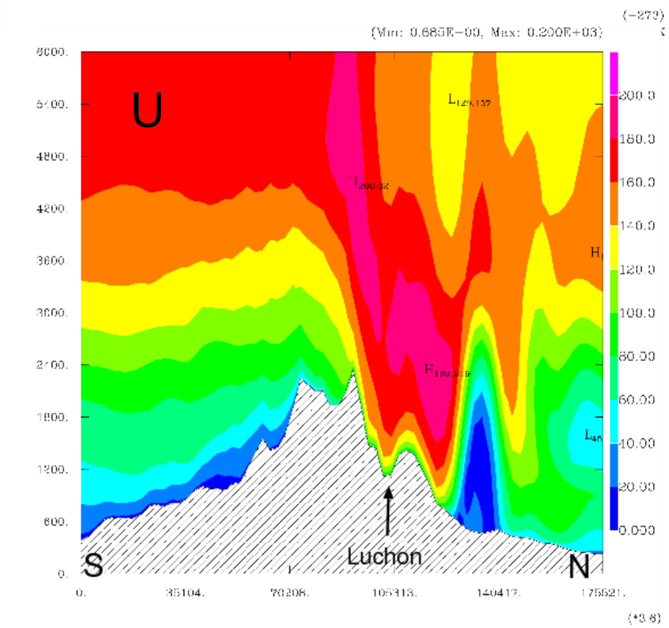


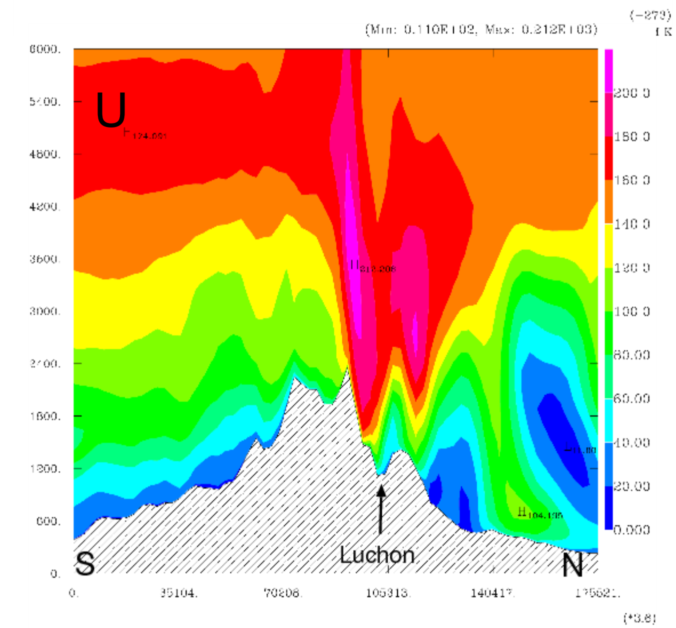
Non-Hydrostatic

Hydrostatic





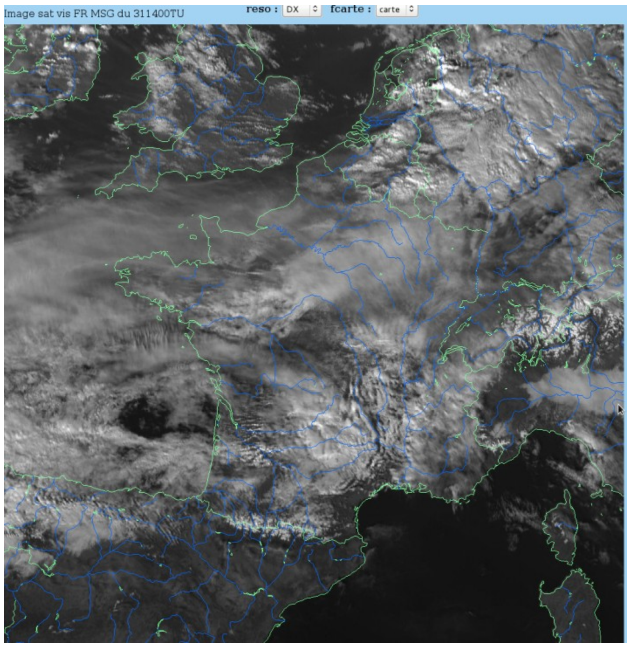




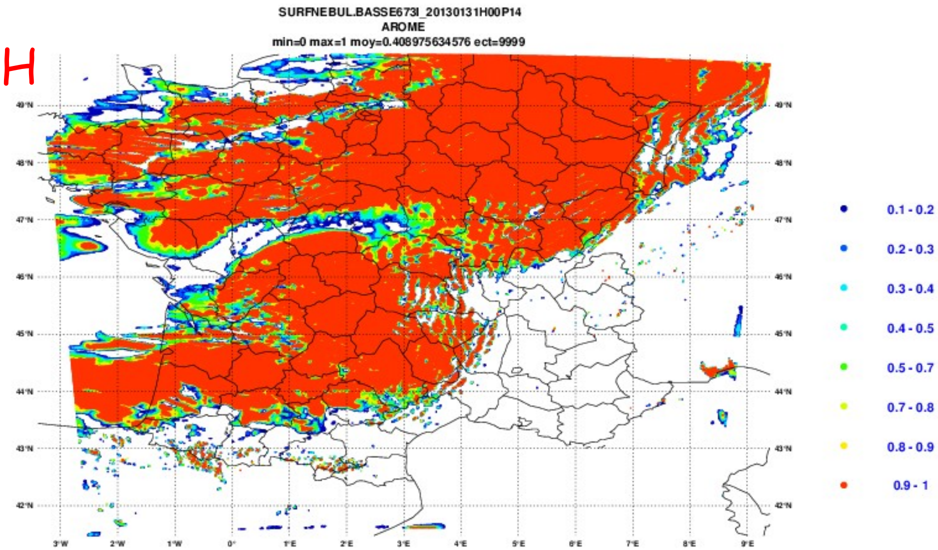
Hydrostatic : Trapping and low level winds are weakened

Non-Hydrostatic vs. Hydrostatic

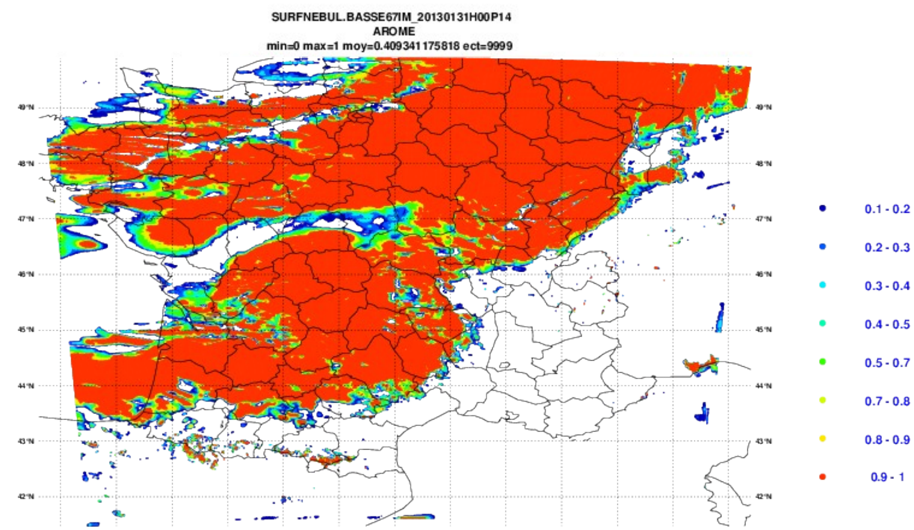
31 Janv. 2013



AROME
1.3km NH



AROME
1.3km H



Elastic processes

We know that air is compressible

Elastic processes correspond to a rapid response of the volume taken by an air mass submitted to pressure perturbations. Elasticity explains sound propagation in the atmosphere : Sound waves : very little energy and meteorologically unimportant. But severe limitation on Δt as $\Delta t <= \Delta x/Cs$ (CFL)

Volumic mass equation

The equation of the volume taken by an air mass is given by the Navier-Stokes system : **Continuity equation**

$$\frac{D\rho}{Dt} = -\frac{\rho}{V}\frac{DV}{Dt} = -\rho \mathrm{div}(\vec{u})$$

Filtering of elastic processes

Anelastic : $$\mathrm{div}(\rho_{ref}\,\vec{u}) = 0$$

$\rho = \rho_{ref}(z)$

$\tilde{p}$ becomes a diagnostic variable

By modifying the continuity equation, we can get out the volumic mass evolution associated to the air elasticity : it is not described in the continuity equation anymore : we **filter the acoustic waves**

Compressible + anélastique = pseudo-compressible

Summary

Modèle non hydrostatique

w est une variable pronostique (Méso-NH, Aladin-NH/Arome)

Modèle hydrostatique

w est une variable diagnostique (Arpège/IFS, Aladin)

Modèle « fully compressible »

$\tilde{p}$ est également pronostique (Aladin-NH/Arome)

Numerical methods to control acoustic waves

Modèle anélastique

$\tilde{p}$ est diagnostique (Méso-NH)

In idealized cases with Meso-NH :
possibility to use ***Boussinesq approximation*** : density variations are neglected (ρ_{ref}~cste) except for the buoyancy term : *incompressibility* : adapted to boundary layer studies (ρ varies less than 10%), but not in most of the cases

Anelastic – Pressure solver

- 3 different versions of the equation system : Anelastic modified, Lipps et Hemler, **Durran**

- Anelastic constraint + Momentum conservation equation = **Pressure problem resolution**

An elliptic equation is solved by the **pressure solver**, allowing to diagnose the pressure perturbation.

The solver cost increases linearly with the points number on the horizontal and on the vertical : Between 25% and 50% of the total numerical cost.

Steeper the slopes, higher the iteration number. No convergence for very strong slopes (> 60%) → For LES with steep slopes, orography needs to be smoothed.

Anorther constraint associated to the elliptic equation : we need to know the solution on the whole domain : implies **communication between processors**, that impacts the scalability

Prognostic variables

Prognostic variables

- Prognostic = Memory of the previous time step :

Wind (u,v,w), Potential temperature θ, mixing ratio of hydrometeors (r_v,r_c,r_r,r_i,r_g,r_s), Turbulent Kinetic Energy, tracers :

- **θ :** The potential temperature of a parcel of fluid at pressure P is the temperature that the parcel would acquire if adiabatically brought to a standard reference pressure P0, usually 1000hPa.

$$\theta = T\left(\frac{P_0}{P}\right)^{R_a/C_p}$$

where T is the current absolute temperature (in K) of the parcel, Ra is the gas constant of dry air, and Cp is the specific heat capacity at a constant pressure of dry air. This equation is often known as Poisson's equation.

T=$\pi.\theta$ where π is the Exner function

θ conserved during an adiabatic transform in a dry atmosphere (vertical motions are often associated to adiabatic transforms) : Vertical variations of θ, on the contrary to T, don't take into account P variations:

$$\frac{\partial T}{\partial z} = -9.8°/1000\,m \Leftrightarrow \frac{\partial \theta}{\partial z} = 0$$

θ evolution equation = Diabatic effects (radiation …) + Phase changes effects

Variables

Mixing ratio of a specie is expressed as a ratio of specie mass, per kilogram of dry air, in any given parcel of air : $r_j = m_j/m_d = \rho_j/\rho_d$

$$r_j(kg/kg) = \frac{q_j}{1-q_t}$$

q_j is the specific humidity (in kg/kg), per kilogram of total air
q_t is the total specific humidity : $q_t = q_v + q_c + q_r + q_i + q_s + q_g$

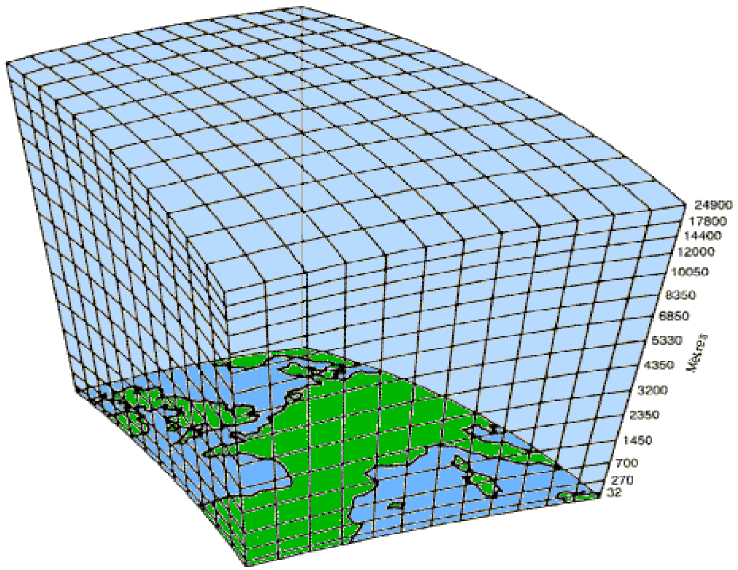
As there is conservation of dry air mass :
=> Conservation of a mass of a given species = conservation of its mixing ratio

Turbulent kinetic energy is the mean kinetic energy per unit mass associated with eddies in turbulent flow. Physically, the turbulence kinetic energy is characterised by measured root-mean-square (RMS) velocity fluctuations

$$TKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

Tracers : passive or chemical concentrations, or others

Coordinates system



Meso-NH
mesoscale non-hydrostatic model

Vertical coordinates

- **Following terrain** Vertical coordinate of **Gal-Chen et Sommerville** :

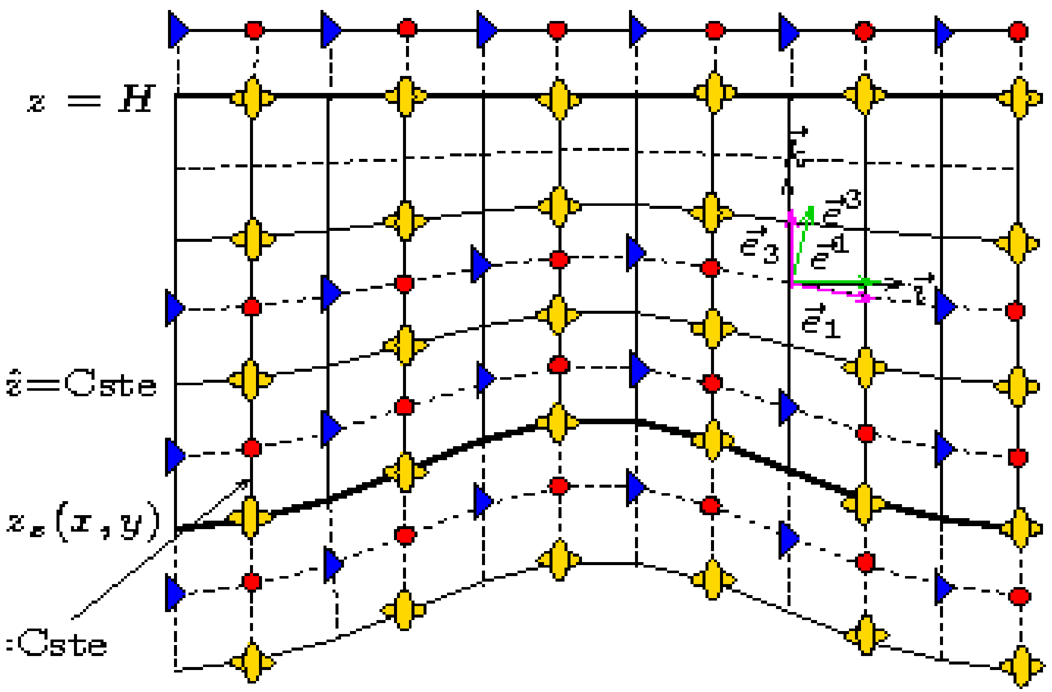
$$\hat{z}(k) = \frac{z(i,j,k) - z_s(i,j)}{H - z_s(i,j)} H$$

z = height of the model level, z_s = Orography

$$z = z_s \longrightarrow \hat{z} = 0, \quad z = H \longrightarrow \hat{z} = H$$

$$z(i,j,k) = \hat{z}(k) \frac{\left(H - ZS(i,j)\right)}{H} + ZS(i,j)$$

Linear decrease of the orography



$$z(i,j,k) = XZZ : flux\ \ pt$$
$$\hat{z}(k) = XZHAT : flux\ \ pt$$

Vertical coordinates

-Sleve coordinate: in the presence of steep orography, the small scale features decrease rapidly with height limiting steep slopes to the lowermost few kilometers

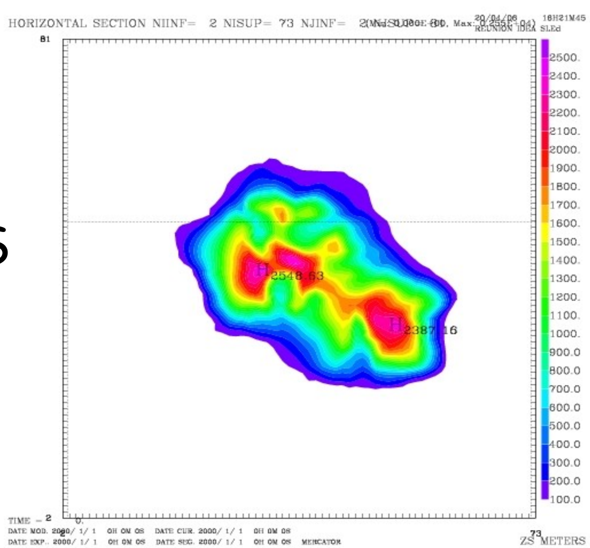
$$z(i,j,k)=\hat{z}+z_{S1}\times\frac{\sinh\left[\left(H-\hat{z}(k)\right)/s_1\right]}{\sinh\left[H/s_1\right]}+z_{S2}\times\frac{\sinh\left[\left(H-\hat{z}(k)\right)/s_2\right]}{\sinh\left[H/s_2\right]}$$

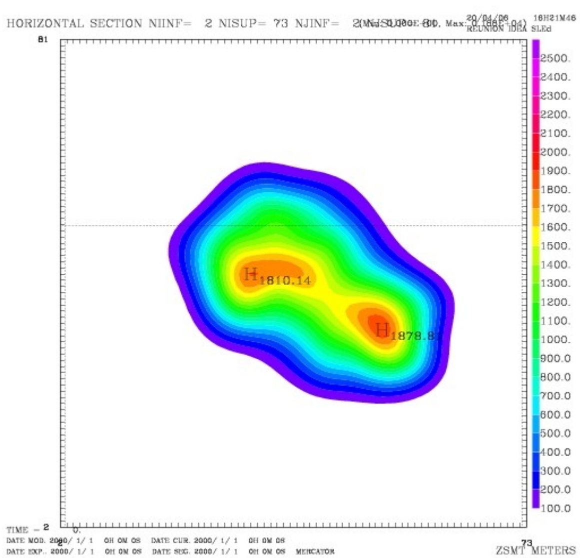
Large scale contribution of the smooth orography　　Small scale contribution

ZS=ZS1 +ZS2 = ZSMT + (ZS-ZSMT)

Reunion test case

ZS





ZS1

(average on 9 points)

Horizontal coordinates

- 3 types of **conformal projection** to take into account the Earth roundness : Polar stereographic, Lambert or Mercator (always for **real cases**)

Projection defined by :

- Conicity parameter *K* (noted XRPK) : K=0 Mercator, K=1 Stereo, 0<K<1 Lambert
- the earth radius *a*
- reference longitude λ_0 and latitude ϕ_0 : *recommended* XRPK=sin(ϕ_0)
- angle of rotation β,
- coordinates of the pole in projection $\widehat{x}_0, \widehat{y}_0$

$\rightarrow$Map scale factor **m**= Ratio of distances on the projection surface to distances on the sphere

$$m = \left(\frac{\cos\varphi_0}{\cos\varphi}\right)^{1-K} \left(\frac{1+\sin\varphi_0}{1+\sin\varphi}\right)^{K}$$

$\rightarrow$ Possibility to degenerate to **cartesian coordinates** when the Earth roundness can be neglected : m=1 (only for **ideal** cases) (~ tangent plan approximation)

Coordinates system

-Physical space : x, y, z – Transformed space $\hat{x}, \hat{y}, \hat{z}$

- Metric coefficients

$$
\begin{aligned}
\widehat{d}_{xx} &= \frac{\partial x}{\partial \widehat{x}} = \frac{r}{am} \\
\widehat{d}_{yy} &= \frac{\partial y}{\partial \widehat{y}} = \frac{r}{am} \\
\widehat{d}_{zz} &= \frac{\partial z}{\partial \widehat{z}} = 1 - \frac{z_s}{H} \\
\widehat{d}_{zx} &= \frac{\partial z}{\partial \widehat{x}} = \frac{\partial z_s}{\partial \widehat{x}}(1 - \frac{\widehat{z}}{H}) \\
\widehat{d}_{zy} &= \frac{\partial z}{\partial \widehat{y}} = \frac{\partial z_s}{\partial \widehat{y}}(1 - \frac{\widehat{z}}{H})
\end{aligned}
$$

r=distance to the earth center
a=earth radius

- Jacobian = ratio of the volumes in the transformed and physical spaces

$$\hat{J} = \hat{d}_{xx}\hat{d}_{yy}\hat{d}_{zz} = (\frac{r}{am})^2(1 - \frac{z_S}{H})$$

- Prognostic variables are multiplied by $\hat{\rho} = \hat{J}\rho_{ref}$ (RHODJ)
and are $\widehat{\rho}u, \widehat{\rho}v, \widehat{\rho}w, \widehat{\rho}\theta, \widehat{\rho}r_*,$ and $\widehat{\rho}s_*$

ρ_{ref} = dry density of the reference state

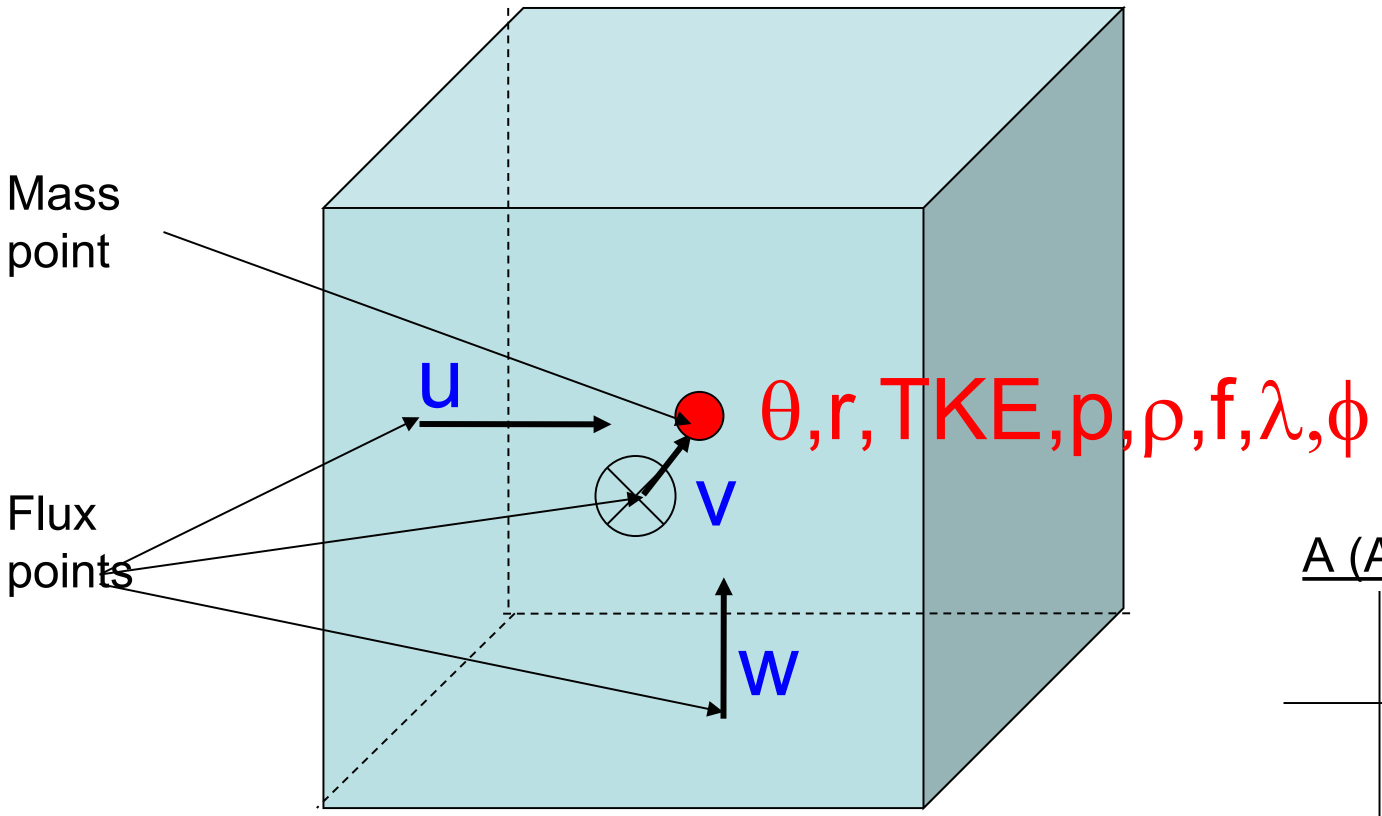
If z<< a is considered, **thin shell** hypothesis (possibility for ideal cases)

Spatial discretization

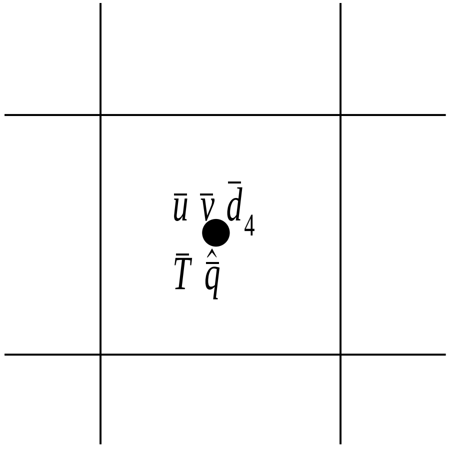
Meso-NH
mesoscale non-hydrostatic model

Spatial discretization

- Localization on the C grid of Arakawa (filtering of 2Δx waves)

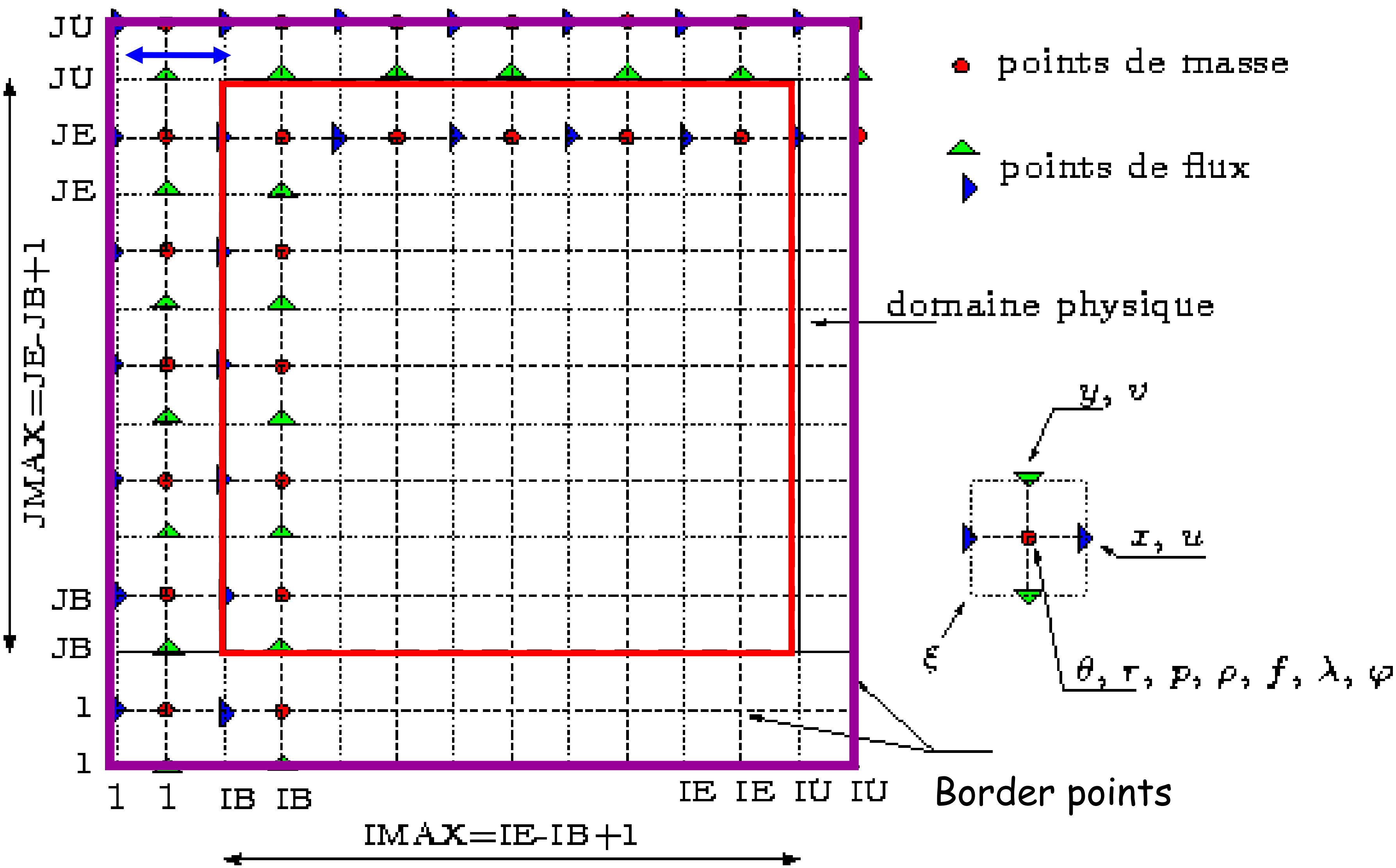


A (Arome example)



Horizontal discretization

JPHEXT (=1 or 3 if 5th order advection scheme)



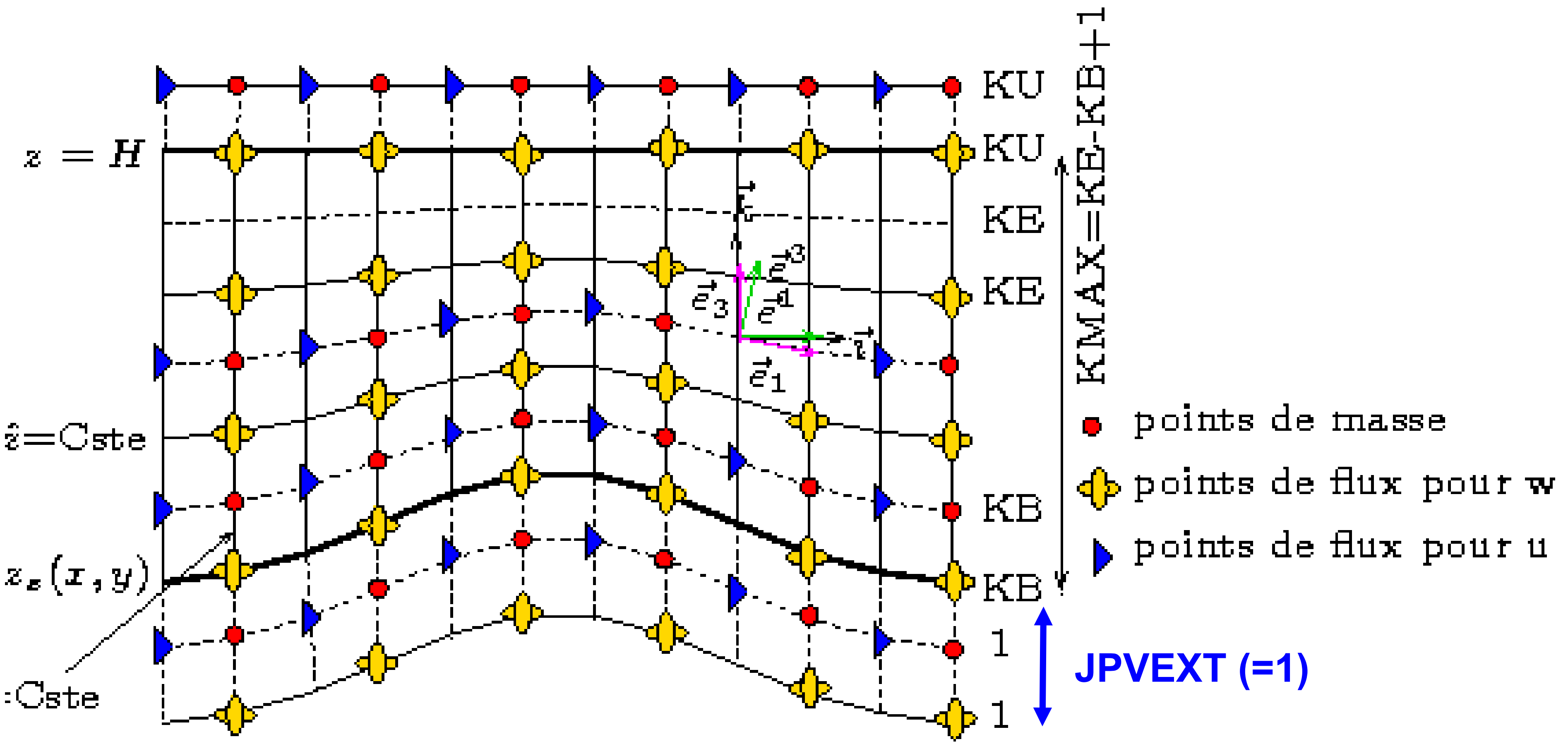
IB = 1+HEXT   IE = IB+IMAX -1   IU = IE+HEXT = IMAX + 2 HEXT

JB = 1+HEXT   JE = JB+JMAX -1   JU = JE+HEXT = JMAX + 2 HEXT

Vertical discretization

Gal Chen et Sommerville vertical coordinate

$$\hat{z} = \frac{z - z_s}{H - z_s} H$$



Numerical schemes

Transport schemes (resolved transport)

Eulerian scheme, explicit, vertical coordinate following the terrain, flux formulation for the advection equation

$$\frac{\partial}{\partial t}(\rho\phi) = -\frac{\partial}{\partial x}(\rho U\phi) - \frac{\partial}{\partial y}(\rho V\phi) - \frac{\partial}{\partial z}(\rho W\phi)$$

Temporal discretization FIT : $(\rho\phi)_i^{t+\Delta t} = (\rho\phi)_i^t - \mathcal{F}_{x,i}(\phi^t)$

- C grid : → 2 transport schemes :
  - For meteorological and scalar variables
  - For wind components

Scalar variables transport (θ,r,tracers) :

PPM scheme (3rd order, Colella and Woodward, 1984) (CMET_ADV_SCHEME and CSV_ADV_SCHEME = PPM_00 or PPM_01)

$$\mathcal{F}_{x,i}(\phi^t) = \frac{\Delta t}{\Delta x_i}\left[(\rho U)_{i+1/2} f(\phi^t)_{i+1/2} - (\rho U)_{i-1/2} f(\phi^t)_{i-1/2}\right]$$

Finite volume method

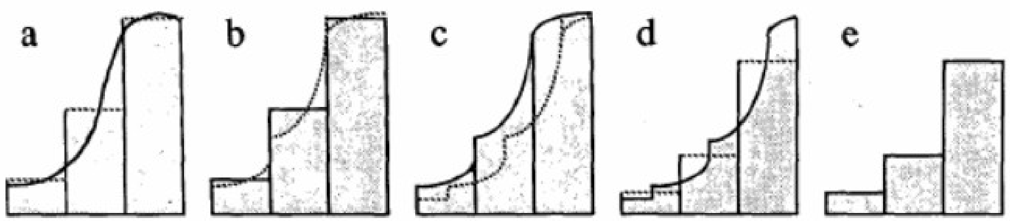


FIG. 5. Schematic illustration of the piecewise parabolic advection procedure. (a) From the initial distribution (solid curve), zone averages (dotted lines) are computed analytically. (This step is performed only at the beginning of the computations.) (b) Using the zone averages (solid lines), a parabola (dotted) is constructed within each zone. (c) The piecewise parabolic distribution is shown before (solid) and after (dotted) advection toward the right at a Courant number of approximately 0.5. (d) After advection, each parabola is integrated analytically to determine the new zone average (dotted). (e) The new zone averages are shown at the end of the time step (the beginning of the next time step). Adapted from van Leer (1977).

PPM conservative by construction, stable for Cr<1 +

monotonicity properties (so positive definite) with PPM_01

Time splitting introduced to follow CFL <1

evolving during the run as a function of CFL (LSPLIT_CFL=T)

Transport of the wind by itself (CUVW_ADV_SCHEME) associated to the temporal scheme for wind advection (CTEMP_ADV_SCHEME)

$$\frac{\partial}{\partial t}(\tilde{\rho}u) = -\frac{\partial}{\partial \overline{x}}(\tilde{\rho}U^c\, u) - \frac{\partial}{\partial \overline{y}}(\tilde{\rho}V^c\, u) - \frac{\partial}{\partial \overline{z}}(\tilde{\rho}W^c\, u)$$

(U^c,V^c,W^c) : advector field = contravariant = wind orthogonal to the coordinate lines

1. **4th order centred scheme (CEN4TH)** :

- with Leap-Frog and a come-back to FIT (CTEMP_ADV_SCHEME='LEFR')

Numerical diffusion necessary + Asselin temporal filter $u_{n+1}=u_{n-1}+2\Delta t\ f(u_n)$

Accurate but not efficient (small time steps)

- with Runge-Kutta RKC4 (CTEMP_ADV_SCHEME='RKC4')

Accurate and more efficient

$$\begin{aligned} u_n^{(1)} &= u_n \\ u_n^{(k)} &= u_n + \Delta t \sum_{i=1}^{k-1} a_{k,i}\ f\left(t_n + c_i \Delta t, u_n^{(i)}\right) \\ u_{n+1} &= u_n + \Delta t \sum_{k=1}^{s} b_k\ f\left(t_n + c_k \Delta t, u_n^{(k)}\right) \end{aligned}$$

Transport of the wind by itself (CUVW_ADV_SCHEME) associated to the temporal scheme for wind advection (CTEMP_ADV_SCHEME)

$$\frac{\partial}{\partial t}(\tilde{\rho}u) = -\frac{\partial}{\partial x}(\tilde{\rho}U^c u) - \frac{\partial}{\partial y}(\tilde{\rho}V^c u) - \frac{\partial}{\partial z}(\tilde{\rho}W^c u)$$

(U^c,V^c,W^c) : advector field = contravariant = wind orthogonal to the coordinate lines

1. **4th order centred scheme (CEN4TH)** :

- with Leap-Frog and a come-back to FIT (CTEMP_ADV_SCHEME='LEFR')

Numerical diffusion necessary + Asselin temporal filter $u_{n+1}=u_{n-1}+2\Delta t\, f(u_n)$

Accurate but not efficient (small time steps)

- with Runge-Kutta RKC4

(CTEMP_ADV_SCHEME='RKC4')

Accurate and more efficient

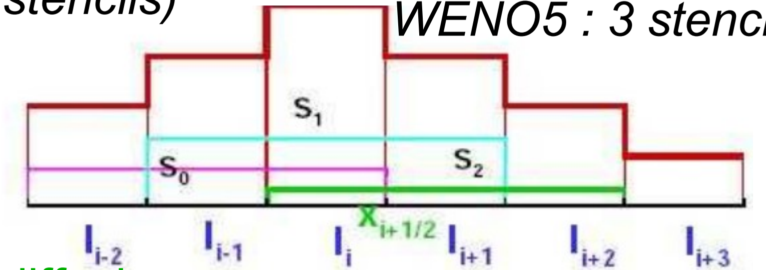
$$\begin{aligned} u_n^{(1)} &= u_n \\ u_n^{(k)} &= u_n + \Delta t \sum_{i=1}^{k-1} a_{k,i}\, f\left(t_n + c_i \Delta t, u_n^{(i)}\right) \\ u_{n+1} &= u_n + \Delta t \sum_{k=1}^{s} b_k\, f\left(t_n + c_k \Delta t, u_n^{(k)}\right) \end{aligned}$$

2. **WENO schemes** (Weighted Essentially Non Oscillating, Liu et al.(1994)) : WENO3 and WENO5 associated to RK53

Linear combination of polynomial curves using stencils of r width (nb of meshes in a stencil) (WENO3 : 2 stencils)

WENO5

WENO5 : 3 stencils

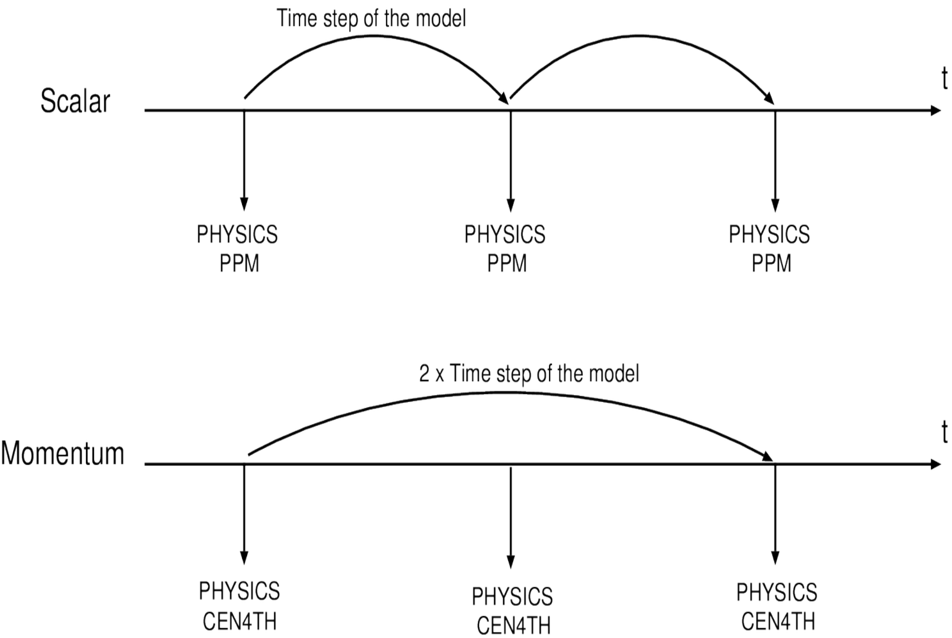


Conservative and non-oscillatory

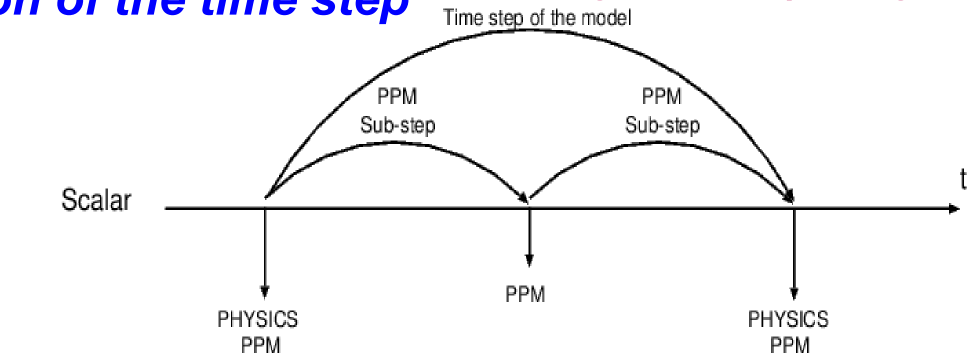
Efficient (long time steps). WENO3 very diffusive

Optimization of the time step

CEN4TH / LF

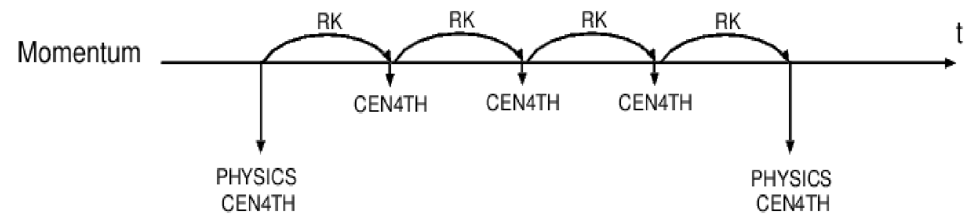


CEN4TH / RKC4

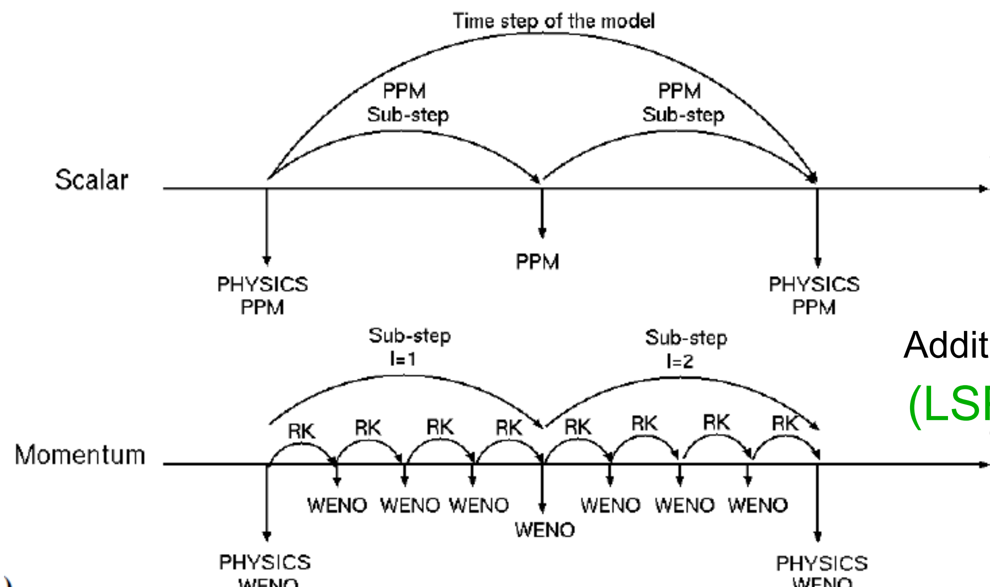


Δt of the model has increased

(LSPLIT_CFL=T)



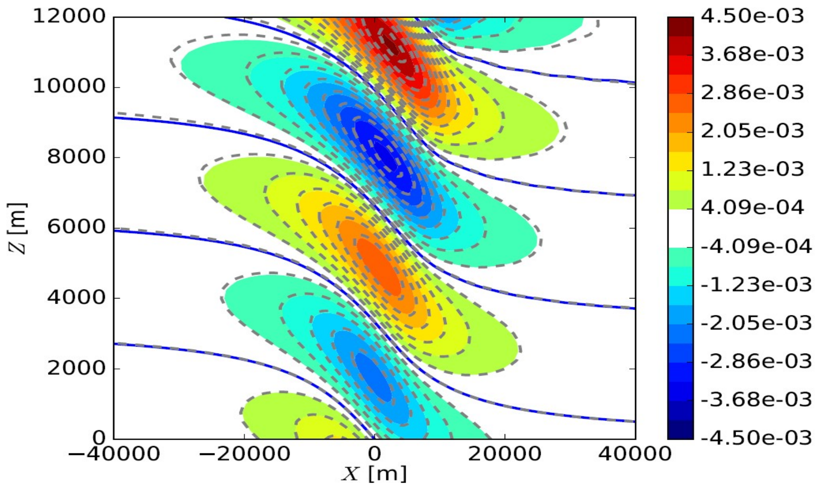
WENO5 / RKC4



Additional time-splitting

(LSPLIT_CFL=T)

Hydrostatic orographic wave

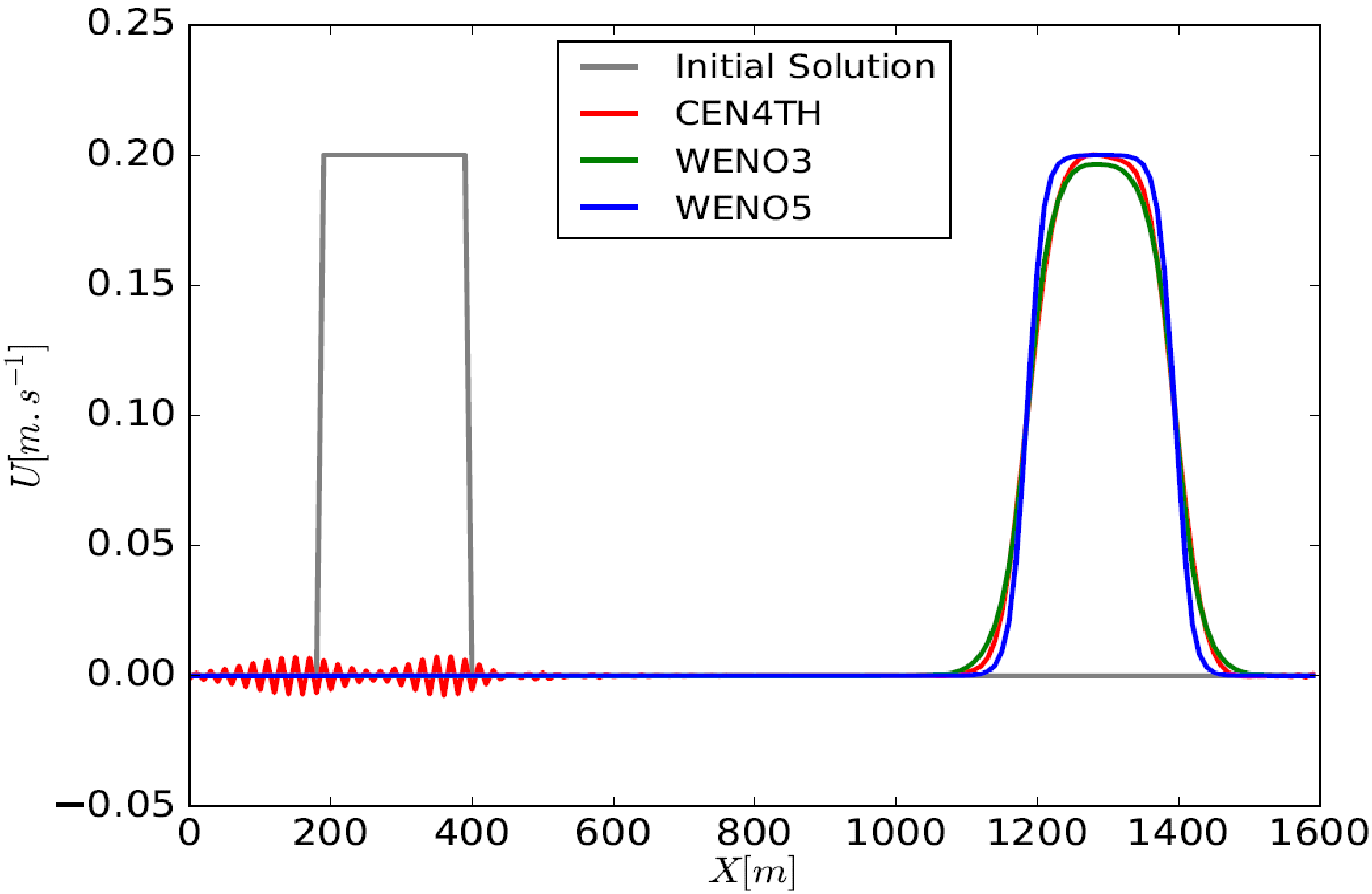


CFL max :

	LF	RK53	RKC4
CEN4TH	0.4		1.7
WENO5 splitting=1		1.4	1.4
WENO5 splitting=2		1.8	1.8
WENO3 splitting=1		1.3	1.3
WENO3 splitting=2		2.5	2.4

Lunet et al., 2017

Linear advection after 1000 s



CEN4TH : Finite difference scheme : 2Δx spurious waves
→ Numerical diffusion necessary

Spectrum tool
Numerical diffusion

Numerical diffusion

Numerical damping to avoid energy accumulation for the shortest waves (around $2\Delta x$) :

- Numerical diffusion : 4th order operator applied to the fluctuations of the prognostic variables (departure from the LS variables) (XT4DIFF)

Needed for dissipation : unavoidable BUT to use with moderation : otherwise will affect the accuracy and the effective resolution

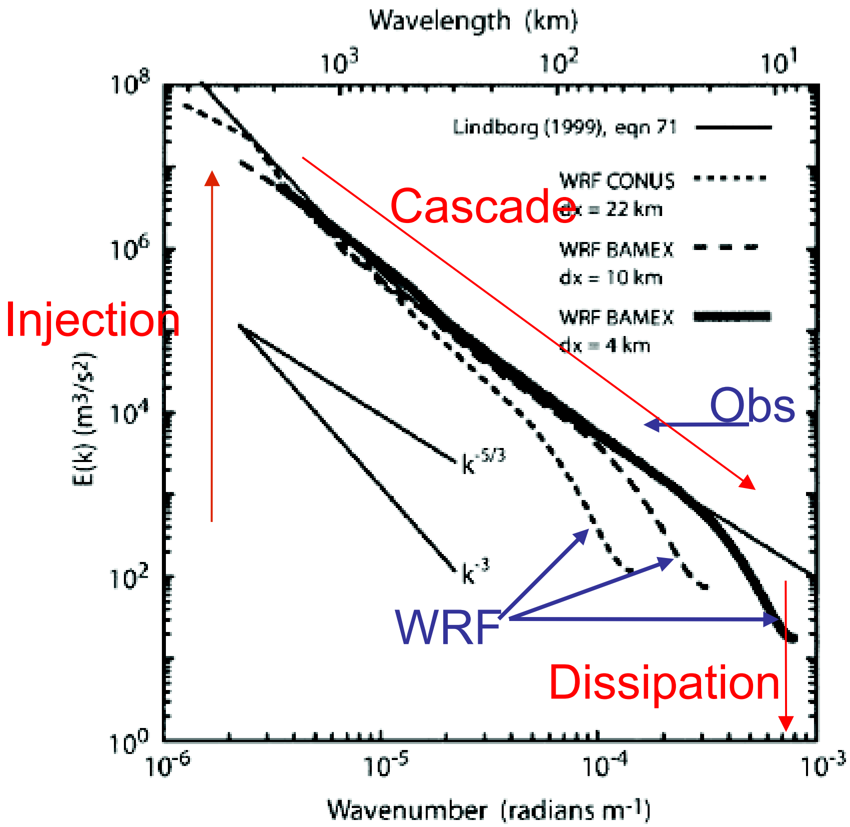
EXSEG1.nam : NAM_DYN LNUMDIFU
LNUMDIFTH

With CUVW_ADV_SCHEME= « CEN4TH » put LNUMDIFU=T
With CUVW_ADV_SCHEME= « WENO_K » put LNUMDIFU=F

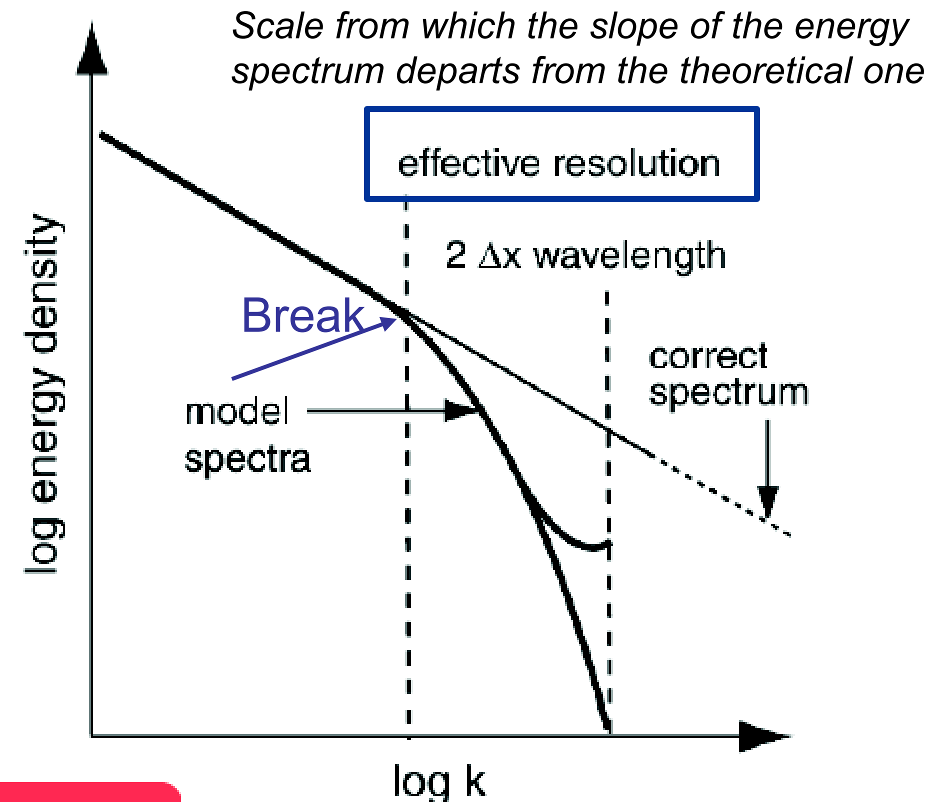
With CMET_ADV_SCHEME= « PPM_xx » LNUMDIFTH=F

Energy spectra

Program SPECTRE



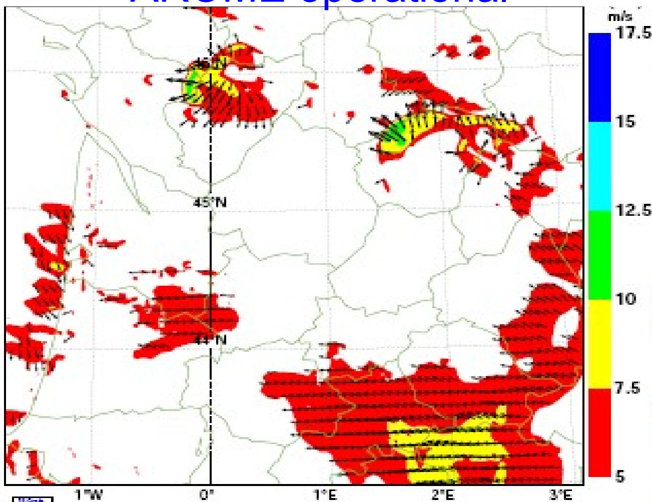
Spectre : prévisions avec le modèle WRF (Skamarock, 2004)



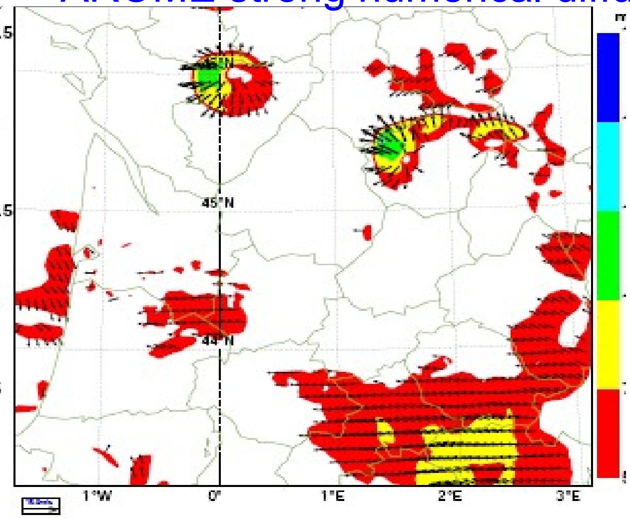
Example for WRF : effective resolution = 7Δx : e.g. 17km for Δx=2.5km

Isolated convective cells (11 april 2008) – Ricard et al., 2012, QJRMS

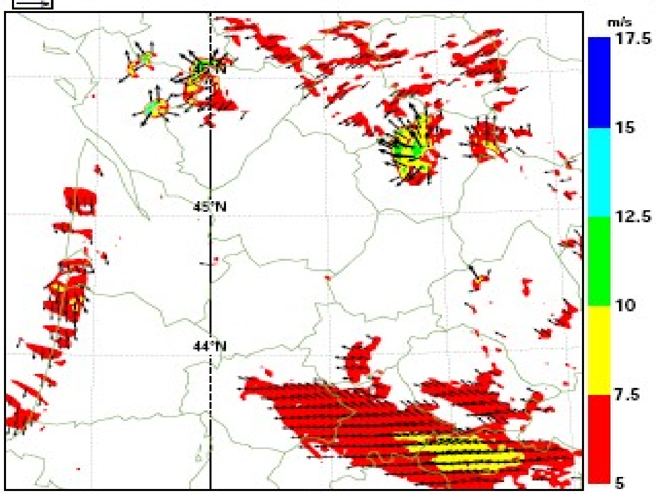
AROME operational



AROME strong numerical diffusion



Δx=2.5km



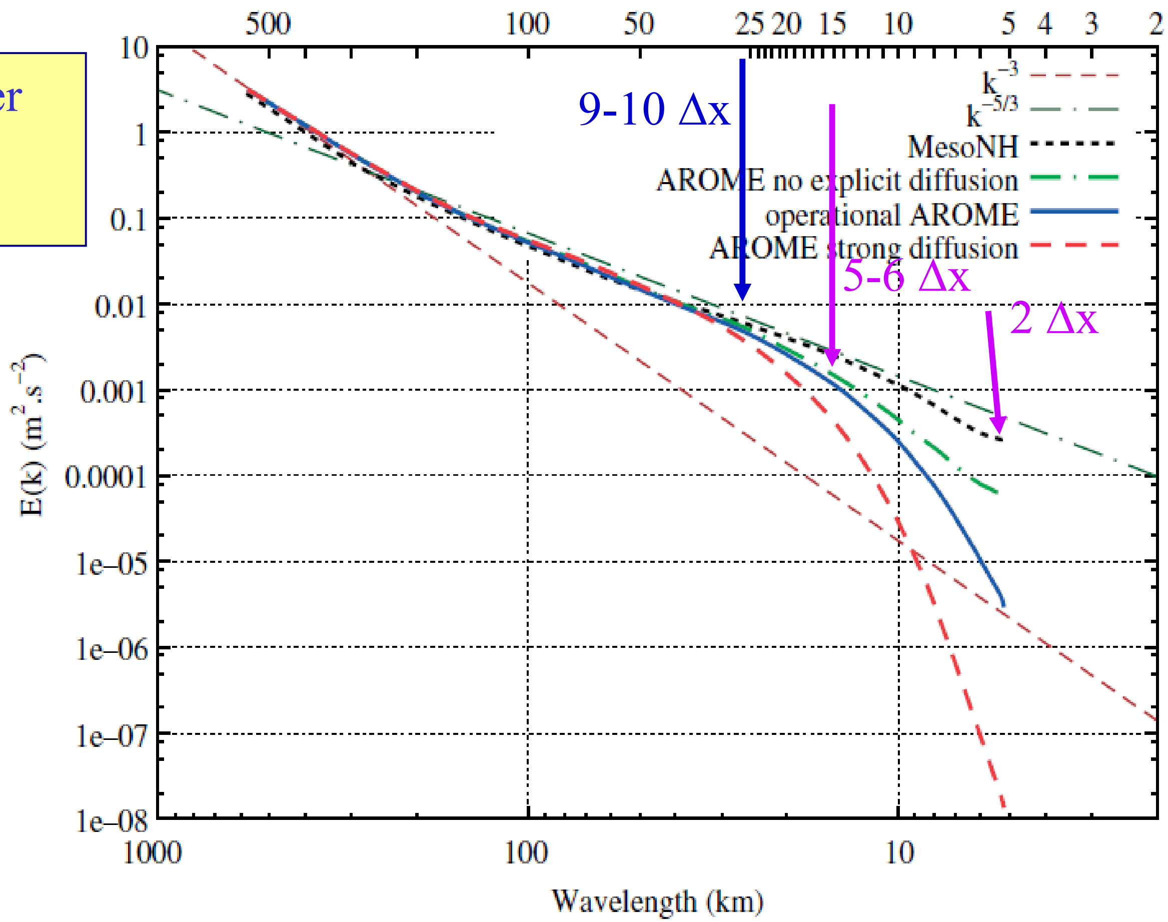
Méso-NH

The risk with an excess of numerical diffusion is too create too large scale patterns inducing too strong cooling and surface outflows

4 – KE spectra

Comparison between AROME and MesoNH (case: April 2007)

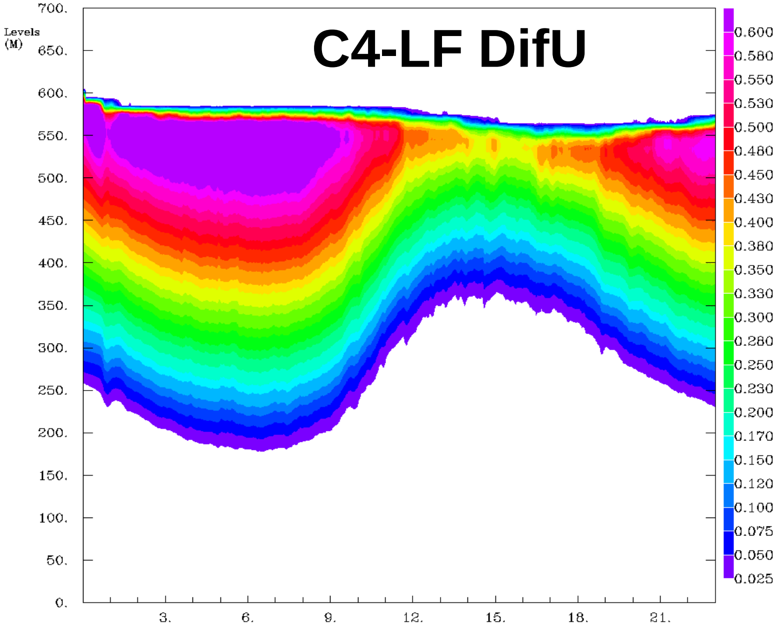
KE spectra (U,V) averaged over the free troposphere (3-9km) between 13 and 17 UTC

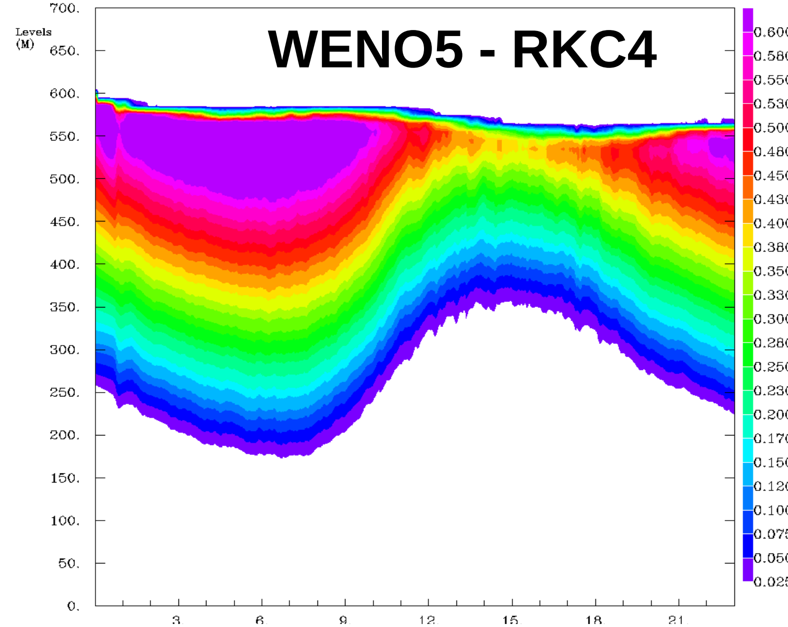


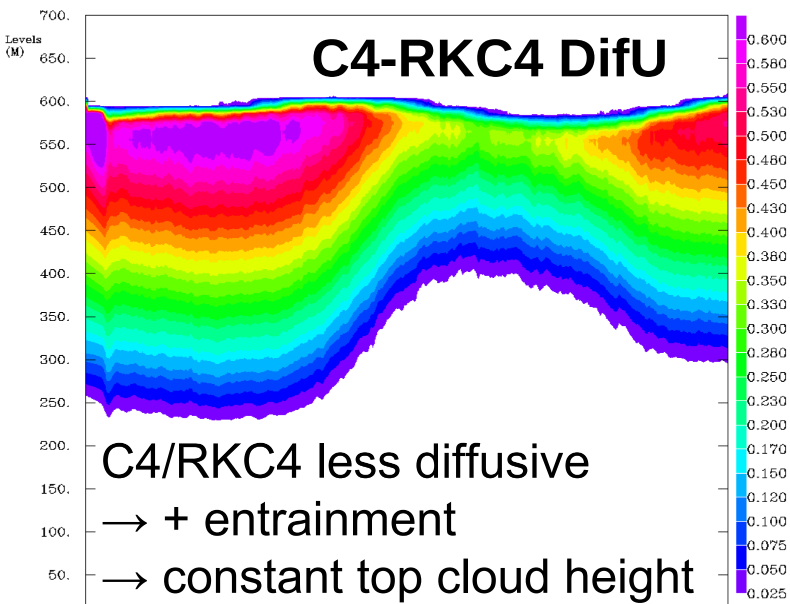
→ Effective resolution:

- MesoNH with CEN4TH : ~14 km ~ 5-6 Δx
- AROME: ~ 24 km ~9-10 Δx, variance loss more important

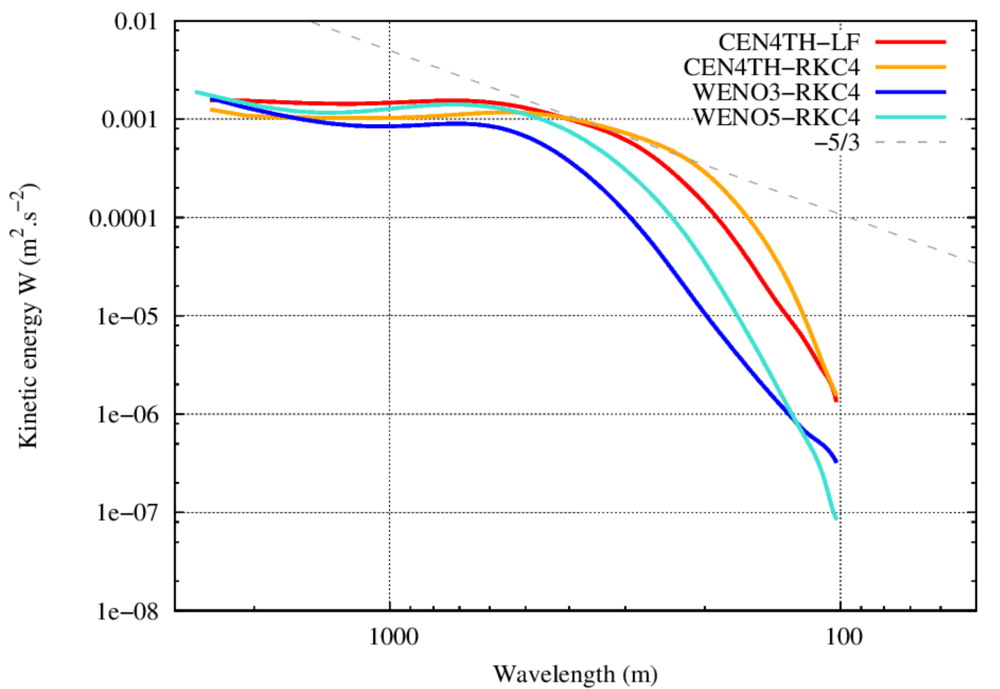
Cas FIRE : LES (Δx=50m)







C4/RKC4 less diffusive
→ + entrainment
→ constant top cloud height
→ - rc



Recommendations for the numerical schemes :

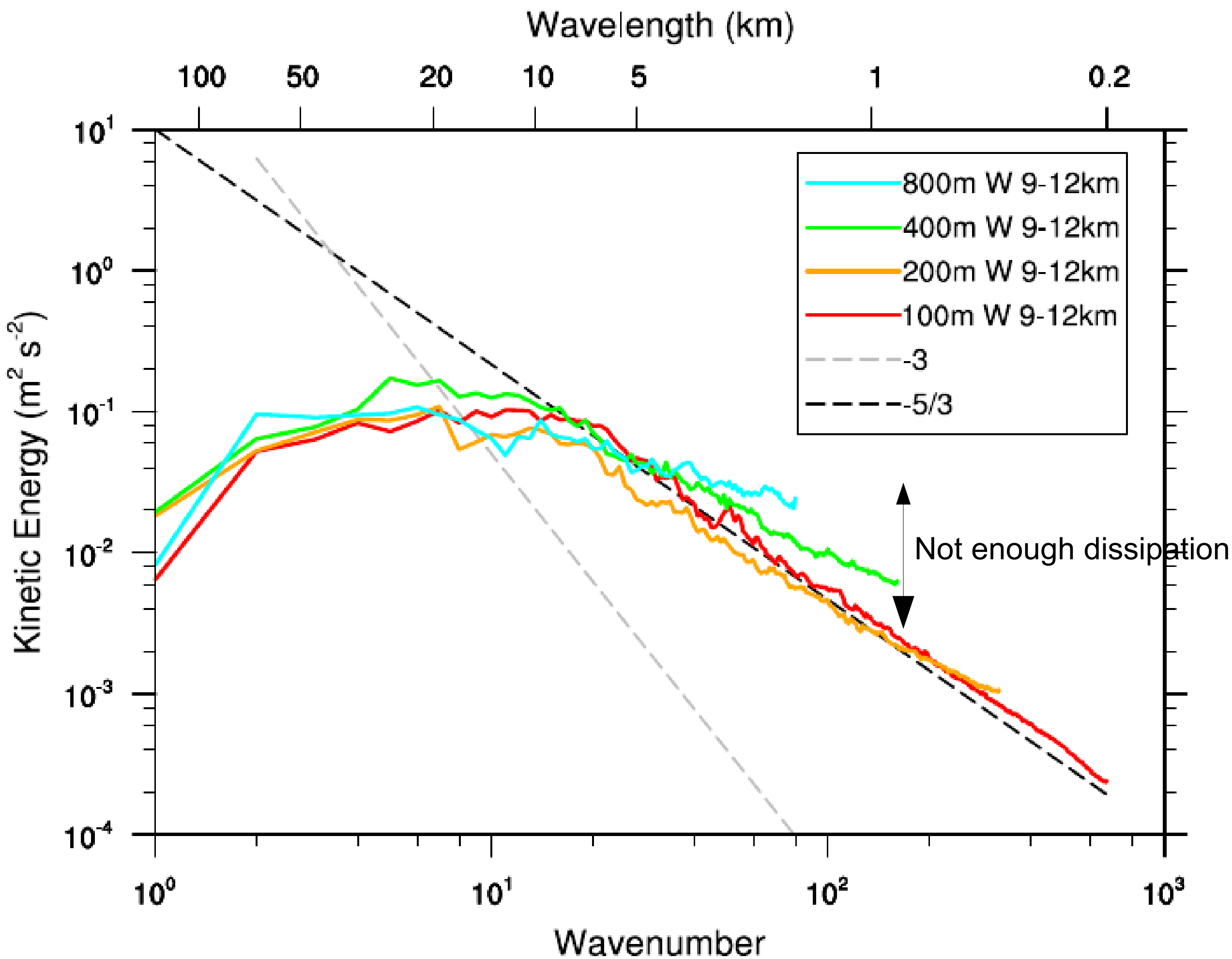
- For LES : CEN4TH/RKC4 recommended (best effective resolution) with added numerical diffusion

WENO3 prohibited

- For long « climate » simulations (convection and turbulence fully parametrized) : WENO3/RK21 the most appropriate due to the best wall-clock time to solution (without added numerical diffusion)

- WENO5/RK53 or RKC4 adapted to sharp gardients area . Ex : Immersed Boundary Method (without added numerical diffusion)

Hector the convector : Spectrum of vertical velocity

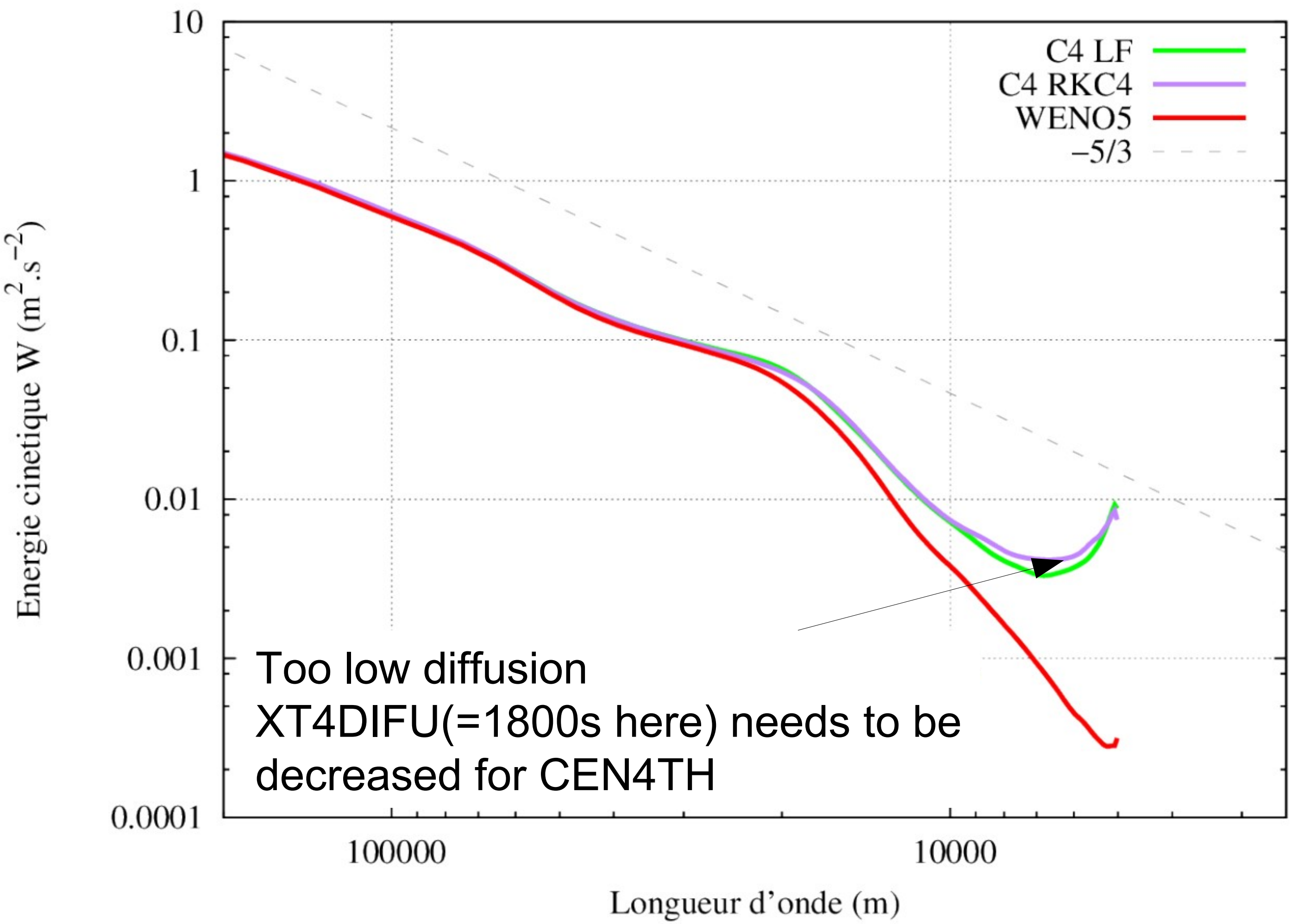


13:00

A grid spacing of Δx=200 m or 100 m is required to reproduce the -5/3 theorical slope and to converge : necessary resolution for a LES of convection

KE spectra

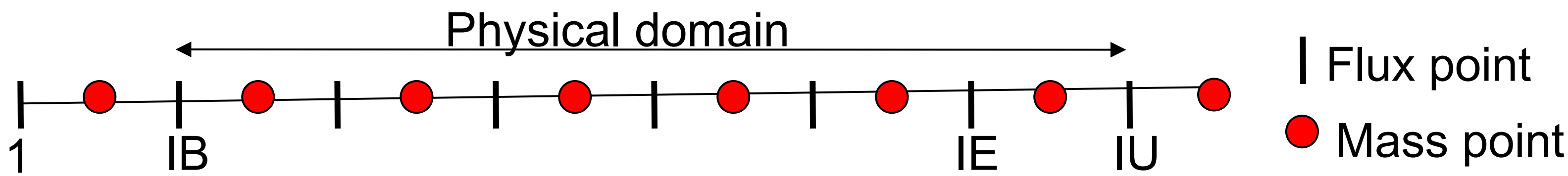
Also a good way to tune numerical diffusion



Lateral boundary conditions

Meso-NH
mesoscale non-hydrostatic model

Lateral boundary conditions (LBC)



There are 3 types of LBC :

- **CYCLIC (for both sides)** :

$$\varphi(IB)=\varphi(IU) \quad et \quad \varphi(1)=\varphi(IE)$$

- **RIGID WALL** : $\varphi(1)=\varphi(IB) \quad et \quad \varphi(IU)=\varphi(IE)$

$$u(IB)=u(IE)=0$$

Conservation of the mass (without sedimentation)

- **OPEN : wave-radiative** (systematic in real case) :
  - *Scalars and tangential velocity components* :
    - Outflow (given by the sign of Un): Extrapolation from the interior
    - Inflow : Interpolation between inside value and LS value
  - *Normal velocities (inflow and outflow):*

Non conservation of the mass

K=XCARPKMAX

$$\frac{\partial u_n}{\partial t} = \left(\frac{\partial u_n}{\partial t}\right)_{LB} - C^* \left(\frac{\partial u_n}{\partial x} - \left(\frac{\partial u_n}{\partial x}\right)_{LB}\right) - K\,(u_n - u_{nLB}), \qquad (5.4)$$

where the subscript LB stands for large-scale value of the field, C^* denotes the phase speed of the perturbation field $u_n - (u_n)_{LB}$, and K is the inverse of a damping time. The large scale gradient $(\partial u_n/\partial x)_{LB}$ and the time evolution $(\partial u_n/\partial t)_{LB}$ are specified by the coupling model. For idealized simulations including no larger-scale effects, they are of course set to zero.

Boundary conditions

- Lateral « sponge » : only for the father model, to slowly incorporate inward propagating LS waves (NAM_DYNn LHORELAX_xx, NRIMX, NRIMY, XRIMKMAX) (structure of « hippodrome ») : Rayleigh damping towards LS fields .

- Top and the bottom boundaries : slip conditions without friction (w=0)

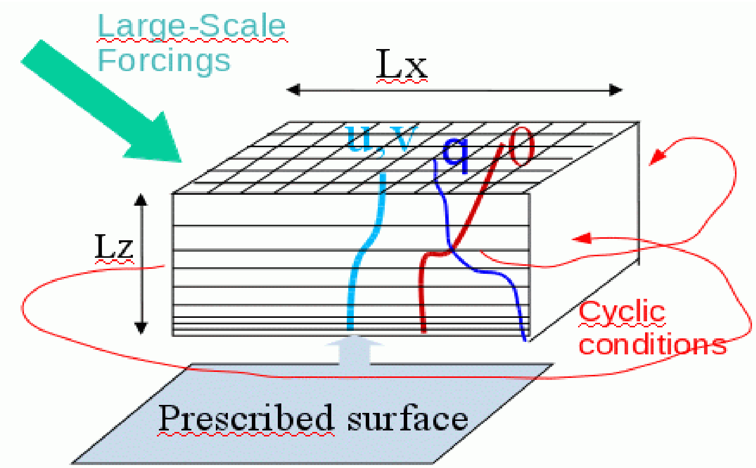
- Top absorbing layer (NAM_DYN et NAM_DYNn LVE_RELAX,XALKTOP, XALZBOT) to prevent spurious reflection : Rayleigh damping towards LS fields

→ **Most of the time necessary**

- In real cases : Initialization and coupling from the LS models : ARPEGE, ALADIN, IFS, AROME. GFS, ERA5.

Initial conditions

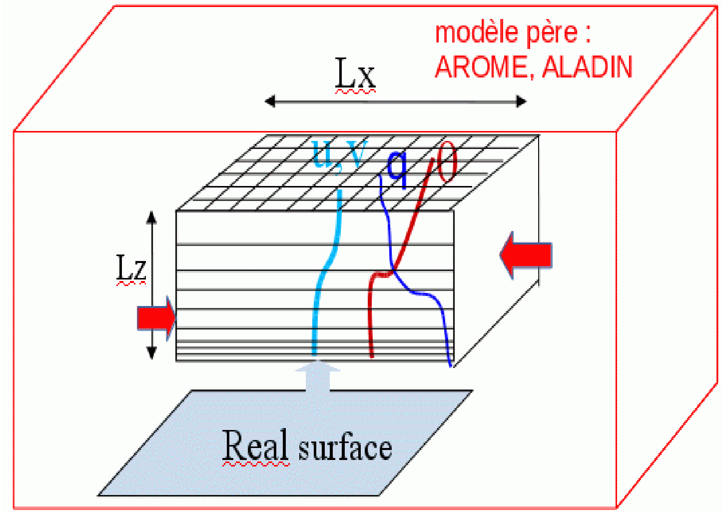
Idealized case



Input :
- U, V, T, HU initial profile
- Ug, Vg, T, HU forcing profile
- Prescribed surface

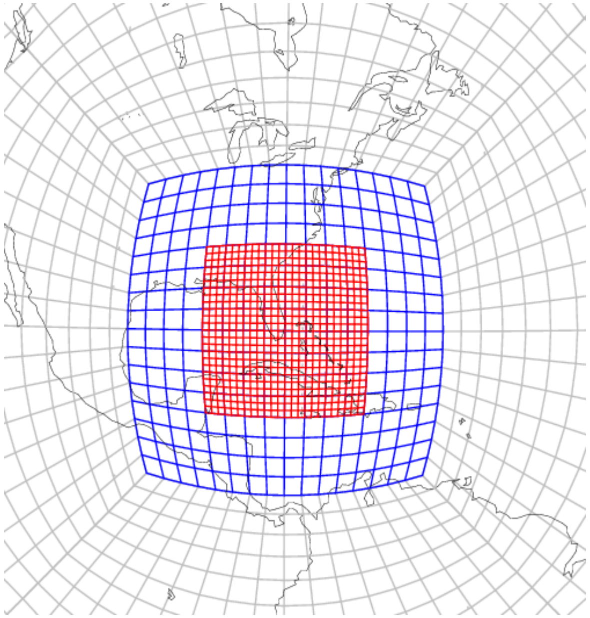
- Same initial and forcing conditions for all the points
- LBC : If CYCLIC : No orography

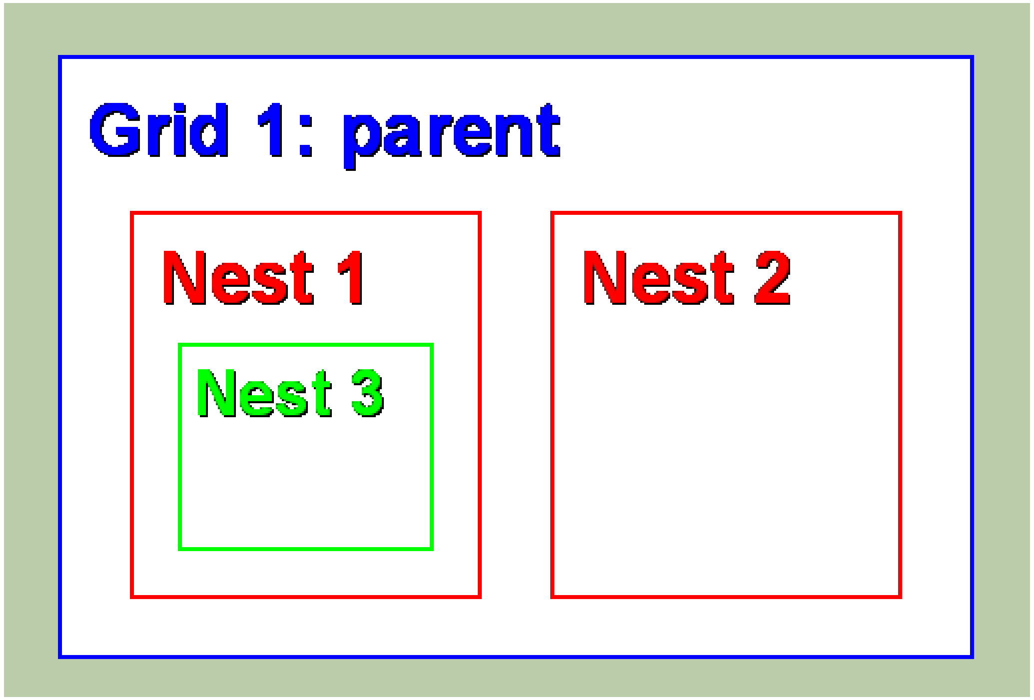
Real case



Input :
- Initial and coupling conditions on the whole domain from a LS model for the atmosphere and the surface -
Coupling conditions : interpolated in time between 2 coupling times

Grid nesting





Meso-NH
mesoscale non-hydrostatic model

Grid-nesting

Every time step of the father :

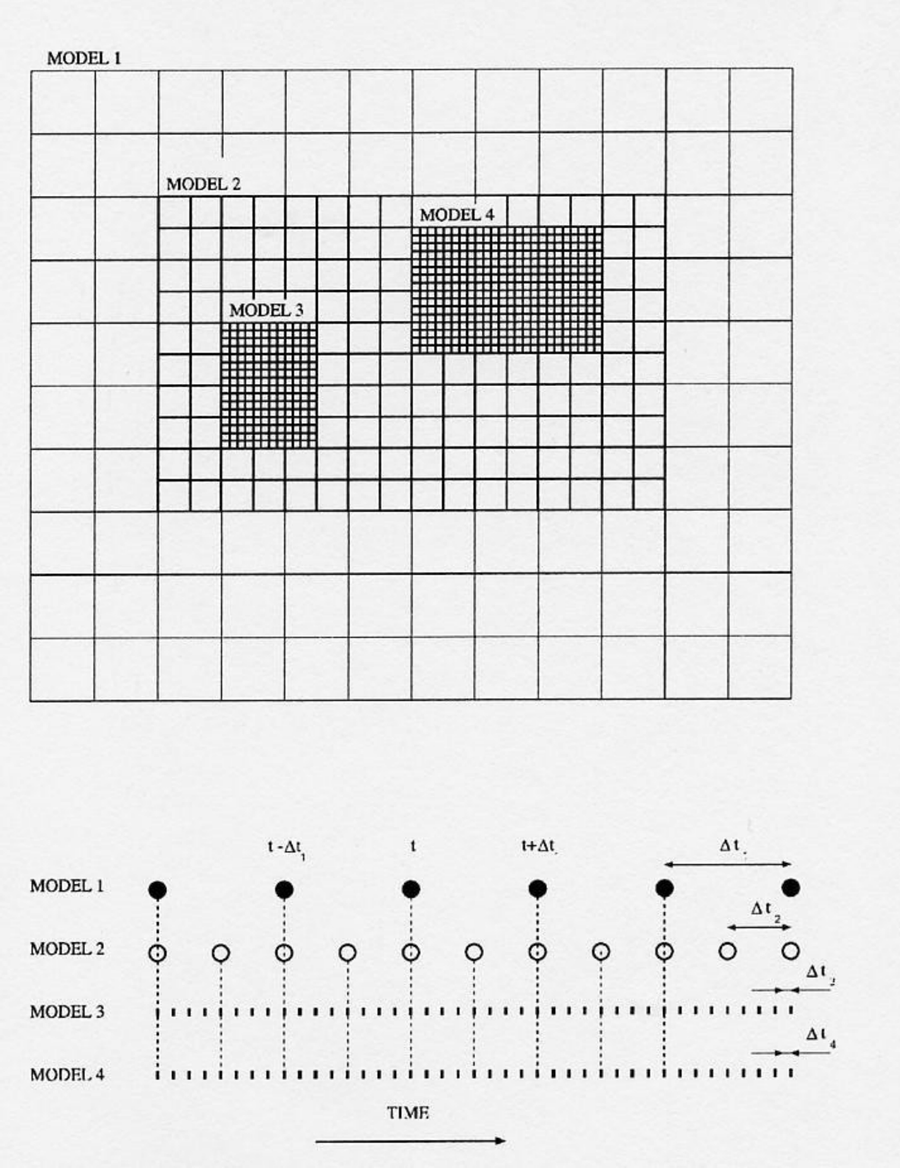
The father gives the LBC to the son by interpolation

One-way (XWAY=1) : The son doesn't influence the father : only father waves are allowed to enter and affect the son model

Two-way (XWAY=2) : Waves resolved by the son model can also affect the father model (all the 3D variables excepted TKE + 2D fields) on the common area : variables of the father are relaxed towards the son in the entire overlapping domain

Constraints :

- Integer Ratio between horizontal resolutions and between time steps
- The same vertical grid
- Only open BC for the son (no cyclic)

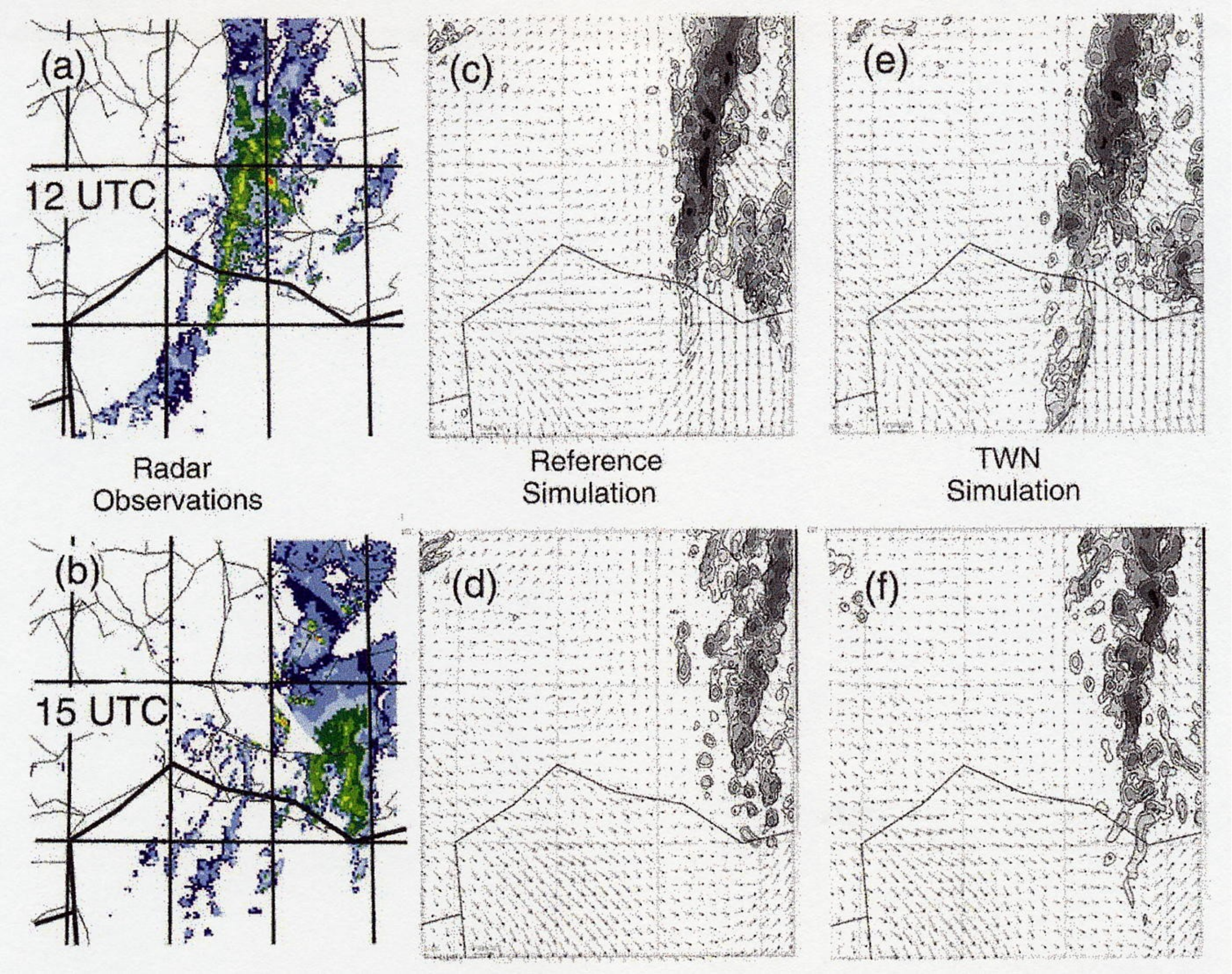


Vaison-la-Romaine : 22 september 1992

One-way Two-way

3 nested grids : 40/10/2.5km

Instantaneous precipitations 2.5km



Stein et al., 2000

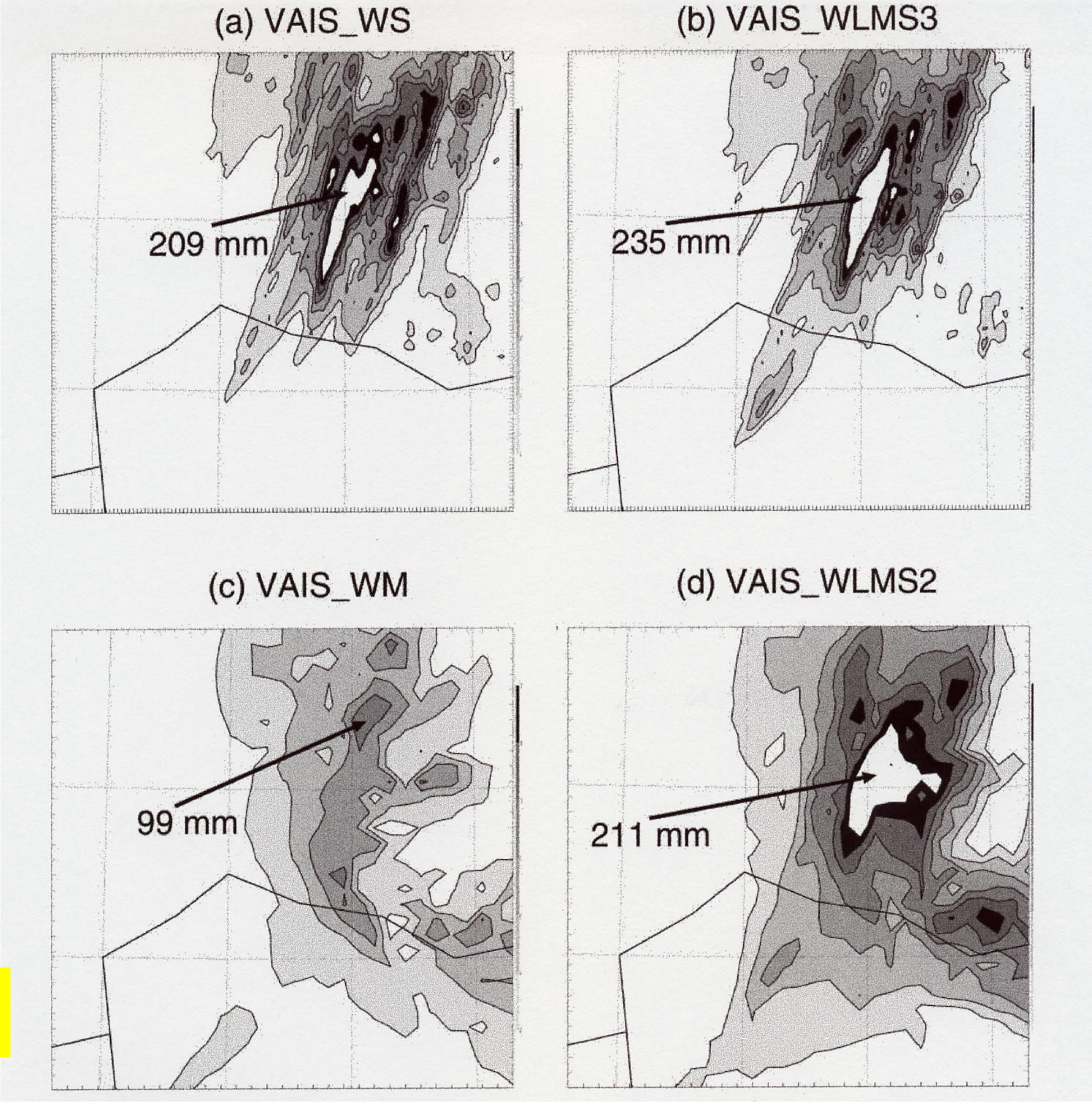
Vaison-la-Romaine : 22 september 1992

One-way Two-way

2.5 km

Cumulated precipitations for 9h (Obs=300mm in 6h)

10km

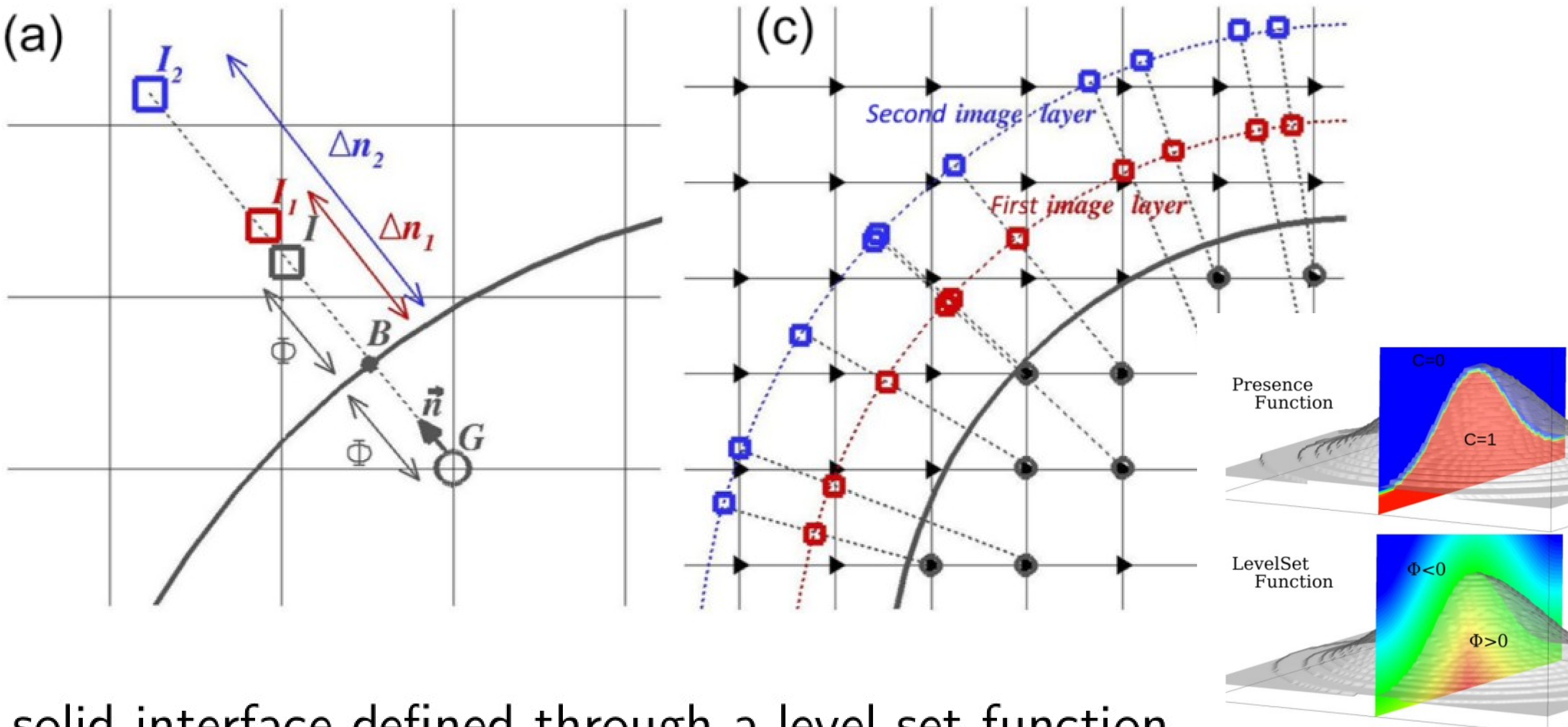


Stein et al., 2000

EXSEG1.nam : NAM_NESTING XWAY(2)= NDTRATIO(2)=

MesoNH-IBM (Immersed-Boundary Method)

Principle: modify boundary conditions to impose 0-wind approaching obstacles



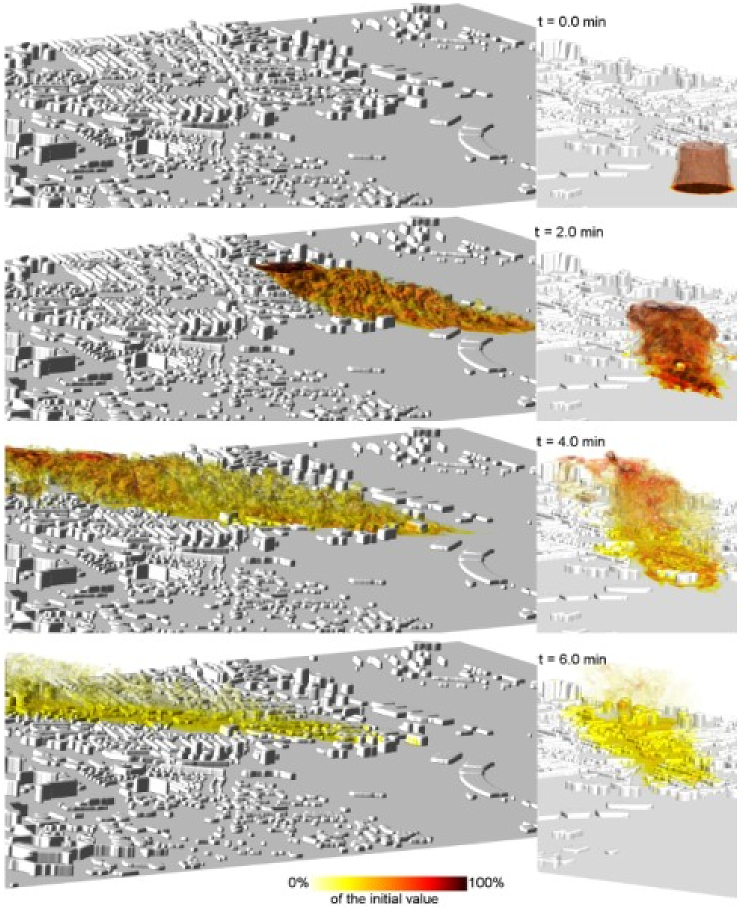
- Fluid-solid interface defined through a level-set function
- Ghost-cell technique: does not introduce source terms in the fluid conservation equations, BC are imposed at the fluid-solid interface.
- Cut-cell technique: allows to take into account the real shape of obstacles.

Auguste et al. [2019a], GMD

MesoNH-IBM

General purpose: explicitly model fluid-solid interaction in the surface boundary layer developed over grounds with complex topographies (cities)

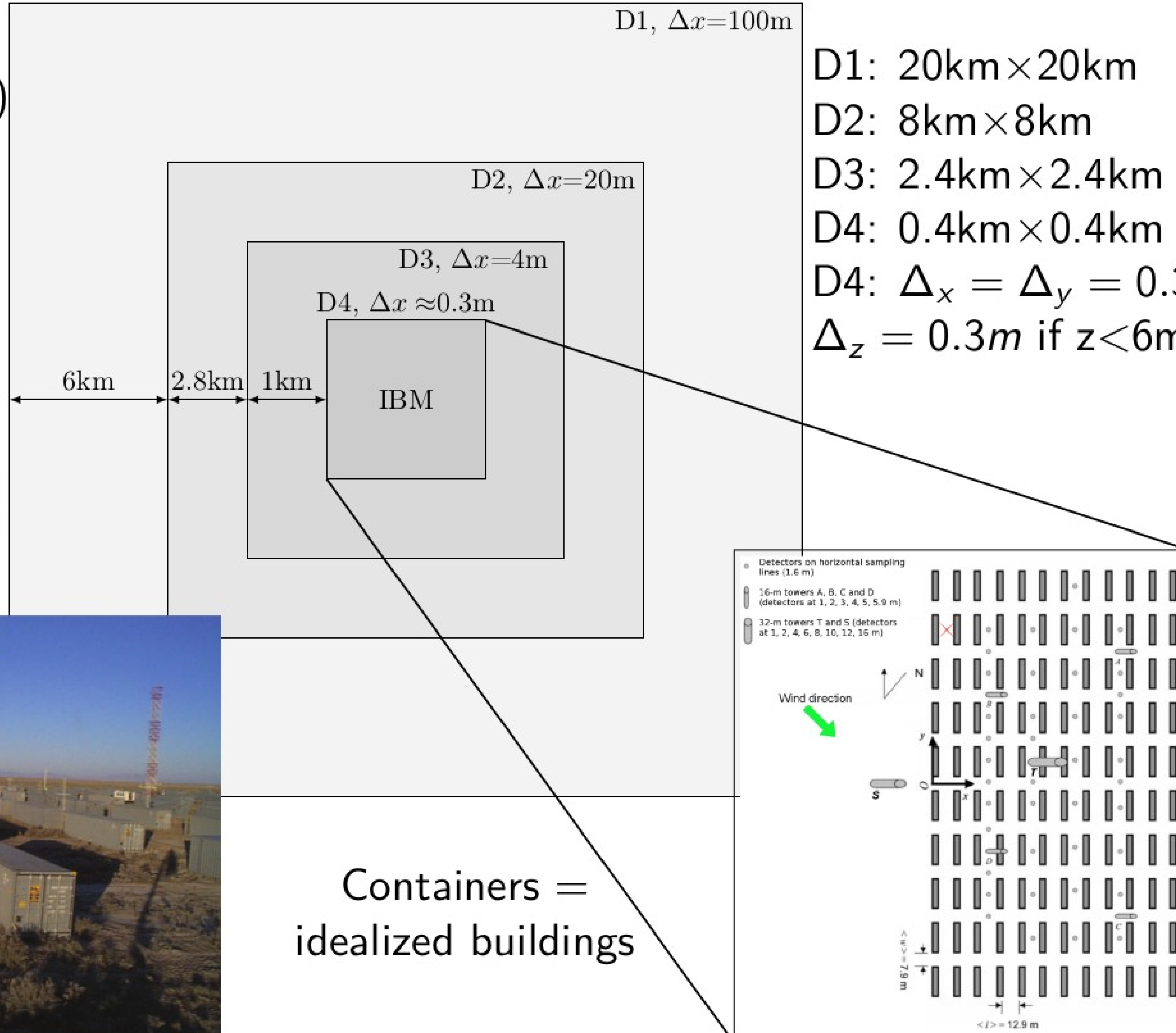
- Written for cartesian grid only.
- Used with succes on several complex cases:
  - Mock Urban Setting Test (MUST) ⇒ Auguste et al. [2019a], GMD.
  - AZF explosion (Toulouse, 2001) ⇒ Auguste et al. [2019b], AE.



Auguste et al. [2019b], AE.

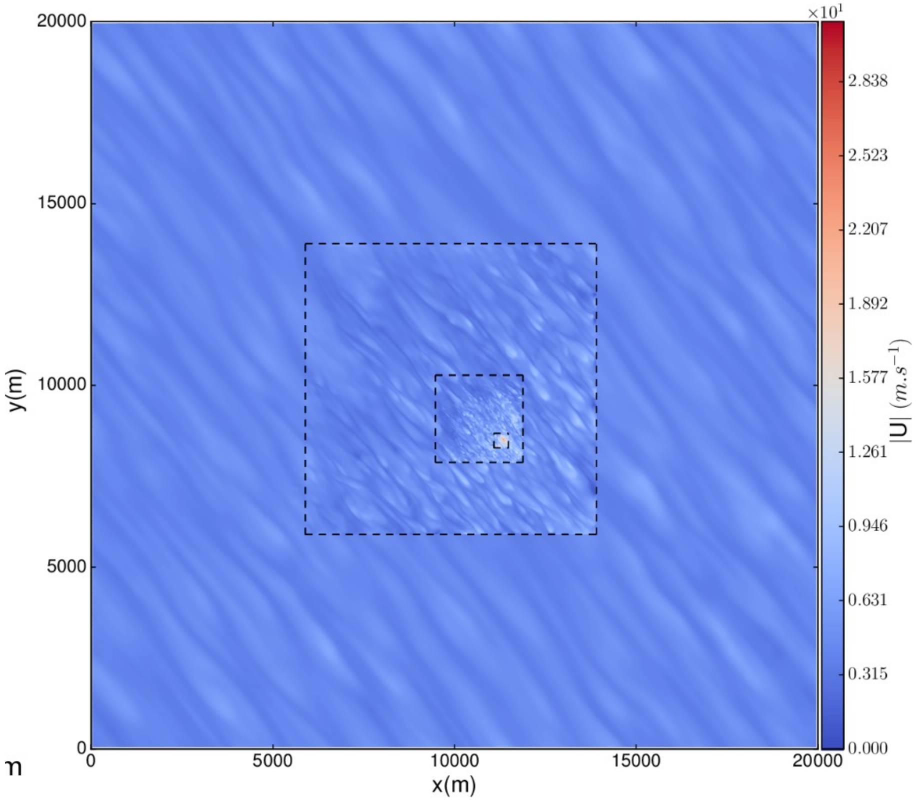
MesoNH-IBM : test on containers

- 120 Containers (2.4*12.2*2.5m)
- Flat ground
- Neutral case
- 4 nested grids
- IBM only in D4
- 3D LES in all 4 domains

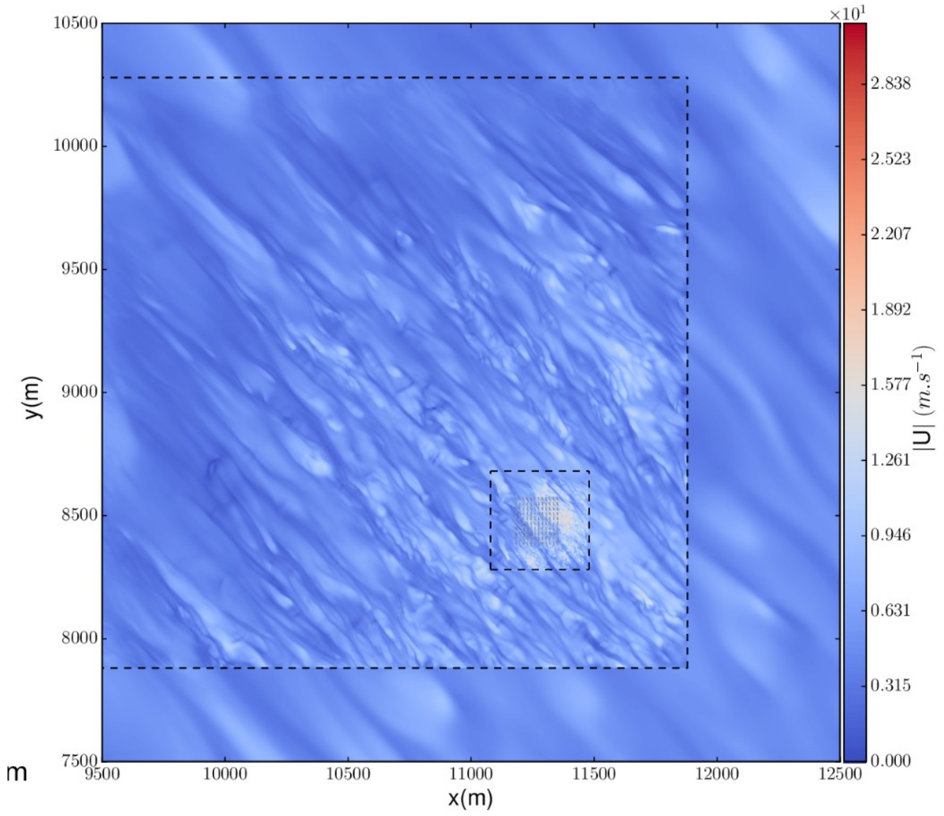


D1: 20km×20km
D2: 8km×8km
D3: 2.4km×2.4km
D4: 0.4km×0.4km
D4: $\Delta_x = \Delta_y = 0.3m$
$\Delta_z = 0.3m$ if z<6m

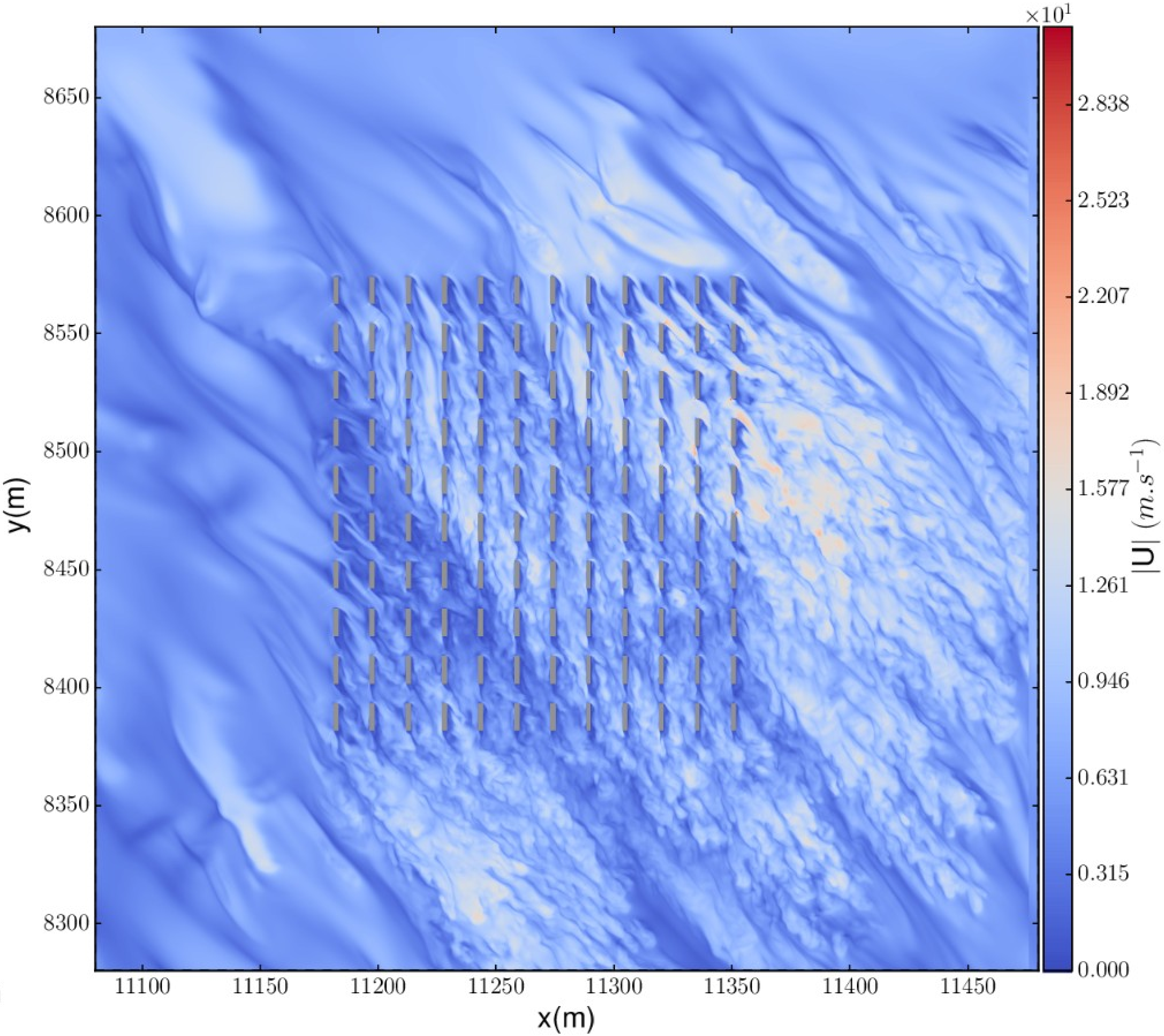
IBM



y(m)
x(m)
20000
15000
10000
5000
0
0
5000
10000
15000
20000
×10^1
2.838
2.523
2.207
1.892
1.577
1.261
0.946
0.631
0.315
0.000
|U| (m.s^-1)



y(m)
x(m)
10500
10000
9500
9000
8500
8000
7500
9500
10000
10500
11000
11500
12000
12500
×10^1
2.838
2.523
2.207
1.892
1.577
1.261
0.946
0.631
0.315
0.000
|U| (m.s^-1)



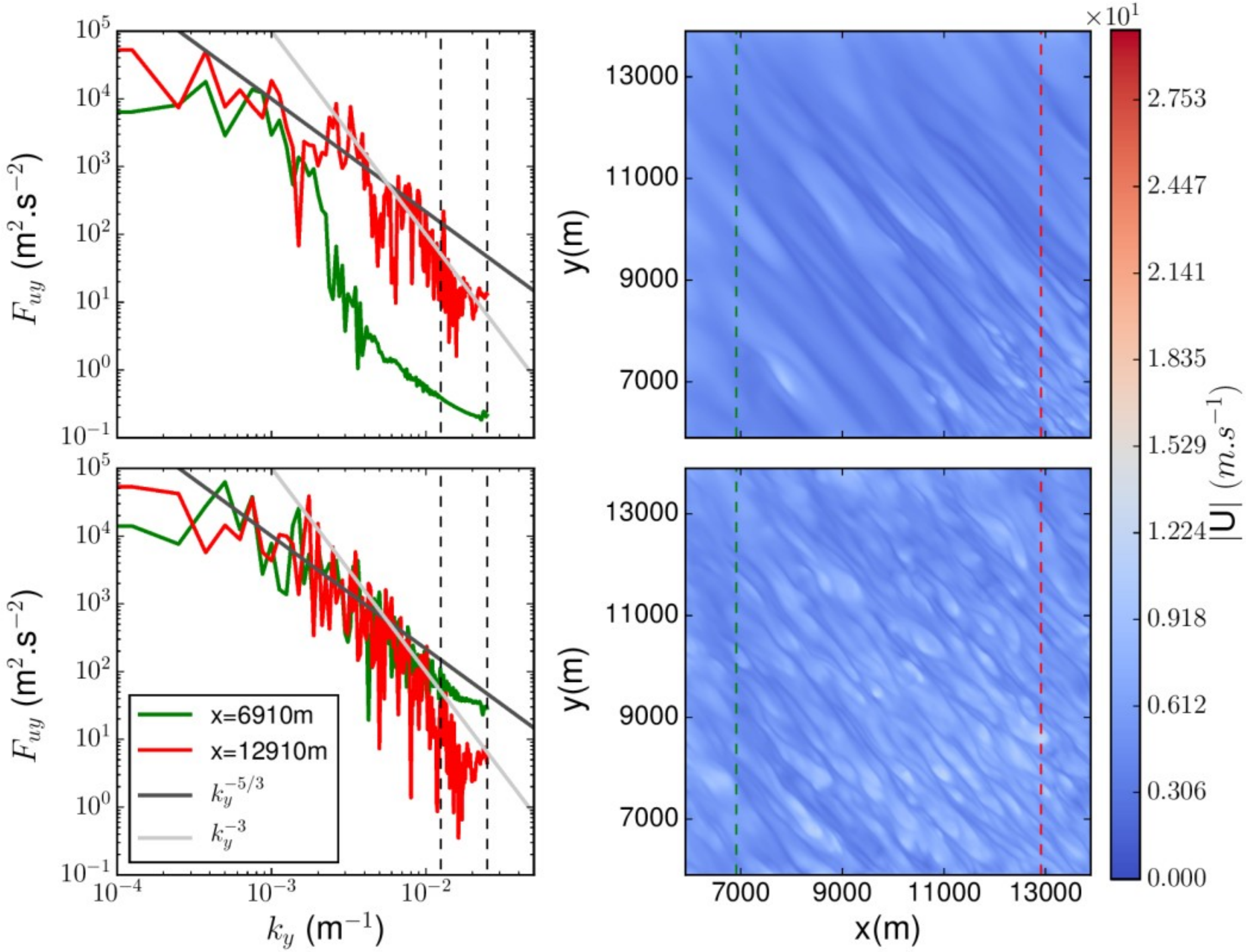
×10^1
2.838
2.523
2.207
1.892
1.577
1.261
0.946
0.631
0.315
0.000
|U| (m.s^-1)
8650
8600
8550
8500
8450
8400
8350
8300
y(m)
11100
11150
11200
11250
11300
11350
11400
11450
x(m)

z=1.5m

Turbulence recycling method

Without recycling

With recycling



Recycling the velocity fluctuations efficiently improves the turbulence scaling between nested grids.

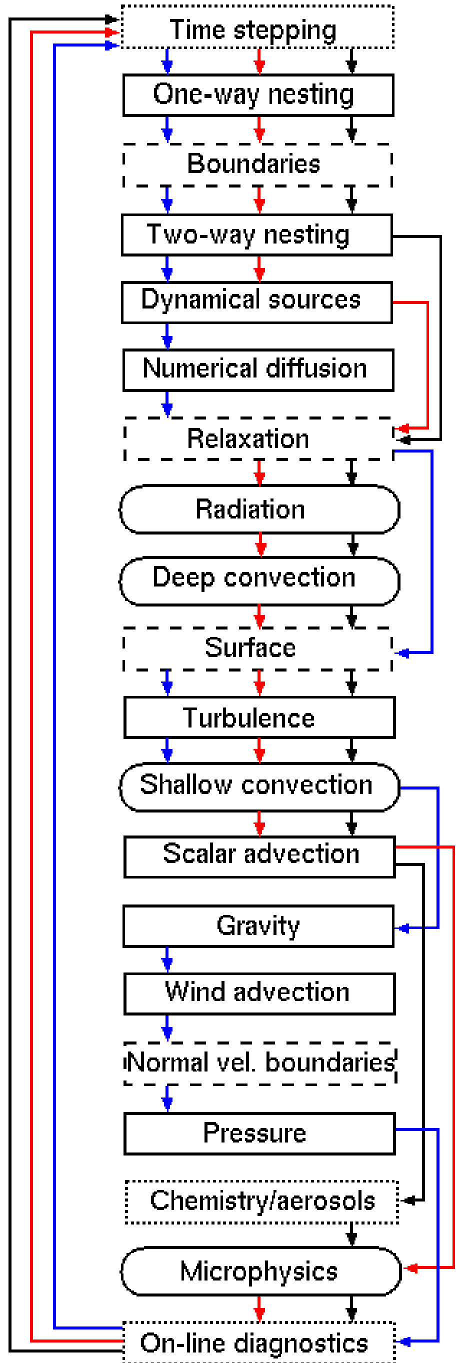
DYNAMICS

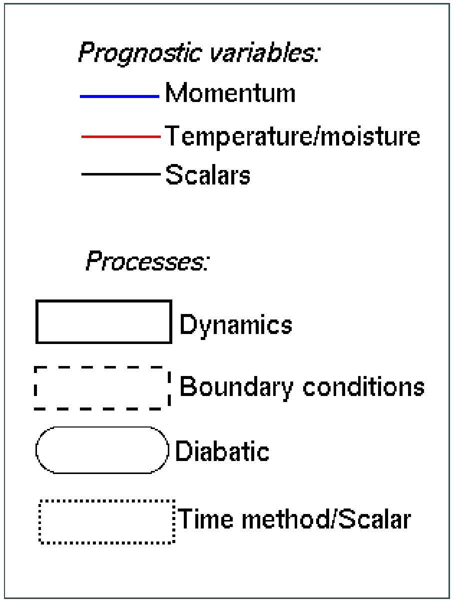
	1980's		1990's			2000's			
Models	**MM5 PSU/NCAR**	**RAMS**	**MC2 UQM**	**ARPS U.Okl.**	**Meso-NH MF/LA**	**WRF NCAR/MMM**	**LM COSMO**	**UM UKMO**	**AROME MF**
Higher Resolution	**LES**	**LES**	**2km**	**LES**	**LES**	**LES**	**LES**	**1km**	**2.5km Up to 1km**
Hypothesis	NH Anelas	NH Anelas	NH Full compres	NH Full compres	NH Anelas	NH Full compres	NH Full compres	NH Full compres	NH Full compres
Spectral/ grid point	Grid	Grid	Spectral	Grid	Grid	Grid	Grid	Spectral	Spectral
Grid (Arakawa)	C	C	C	C	C	C	C	C	A
Advection scheme	Euler.	Euler.	SL	Euler.	Euler.	Euler.	Euler.	SL	SL
Temporal scheme	Explicit LF	Explicit LF	SI	Explicit LF	Explicit LF	Explicit Split	Explicit Split	SI	SI
Time step	**For 2.5km 8s**	**For 2.5km 8s**	**For 2.5km 60s**	**For 2.5km 6-8s**	**For 2.5km**	**For 2.5km 15s**	**For 2.5km 15s**	**For 2.5km 60s**	**For 2.5km 60s**
Nesting	**2 way**	**2 way**	**1 way**	**2 way**	**2 way**	**2 way**	**2 way**	**1 way**	**1 way**

60s(15s):WENO
15s : CEN4th-RKC4
6s : CEN4TH-LF

Organization of the time step

Parallel splitting approach :
All process tendencies are computed from the same model state and then the sum of the tendencies is used to step forward

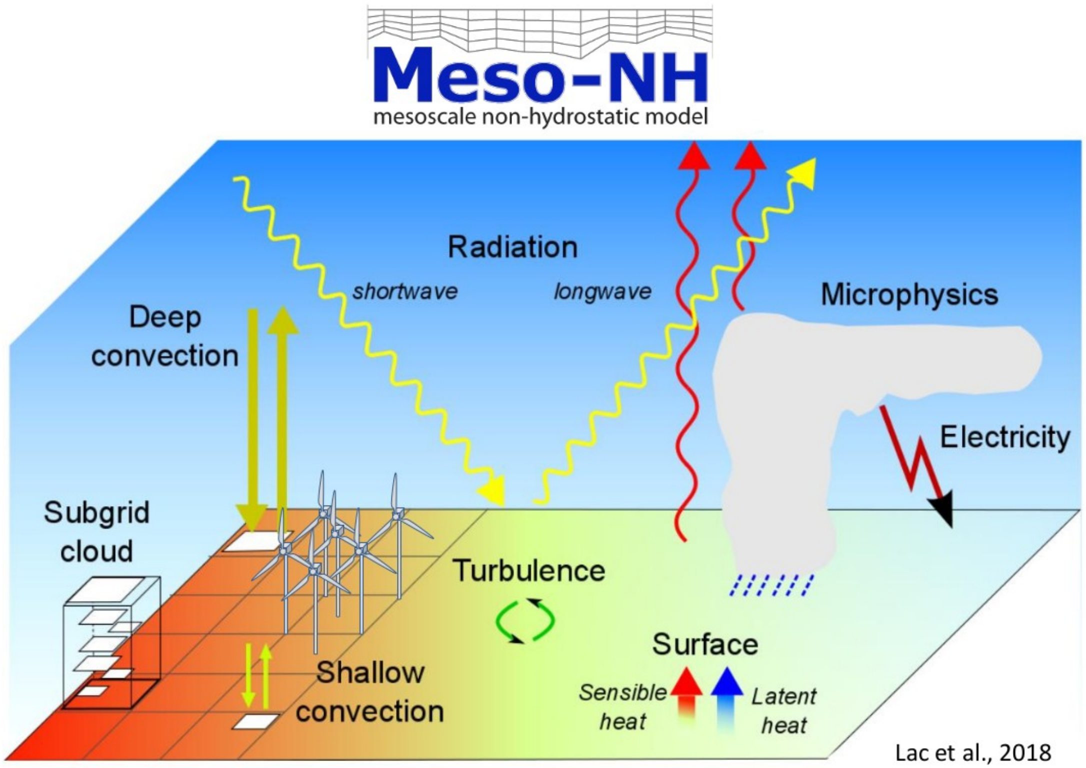




Physics

PHYSICS : Part of the model that deals with diabatic processes, water state changes, subgrid processes, surface interaction.

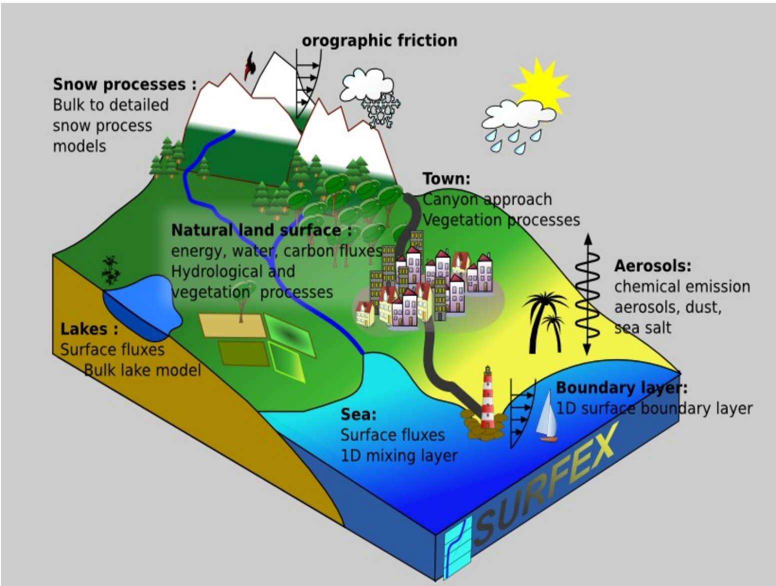
- SURFACE (externalized)
- TURBULENCE
- CONVECTION
- MICROPHYSICS
- RADIATION
- WIND TURBINE
- CHEMISTRY



Lac et al., 2018

SURFACE schemes

SURFEX, Masson et al.



Models

	**Seas and oceans:** Prescribed SST, Charnock formulation ECUME (multi-campaign parameterization), 1D Ocean Mixed Layer model
	**Lakes :** Prescribed LST, Charnock formulation FLake lake model
	**Soil and vegetation:** ISBA Force restore or diffusion for heat and water transfers in the soil
	**Town:** TEB Canyon concept, detailed radiative scheme Vegetated buildings, impact of trees in canyon

At each Δt

ATMOSPHERE

SURFEX

interface

radiative properties:
- albedo
- emissivity
- surface radiative temperature

surface fluxes:
- momentum
- sensible heat
- latent heat
- CO2
- chemical species
- aerosols

atmospheric forcing:
- air temperature
- specific humidity
- wind components
- pressure
- rain rate
- snow rate
- CO2, chemical species, aerosols concentration

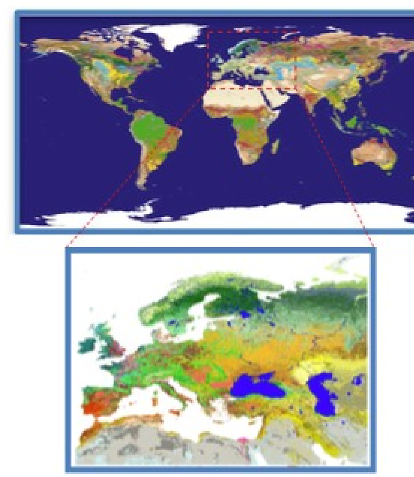
radiative forcing:
- solar radiation
- infrared radiation

surface

$$\mathcal{F} = f_n\mathcal{F}_n + f_l\mathcal{F}_l + f_t\mathcal{F}_t + f_s\mathcal{F}_s$$

$\mathcal{F}_n$	$\mathcal{F}_l$	$\mathcal{F}_t$	$\mathcal{F}_s$
nature	lake	town	sea
f_n	f_l	f_t	f_s

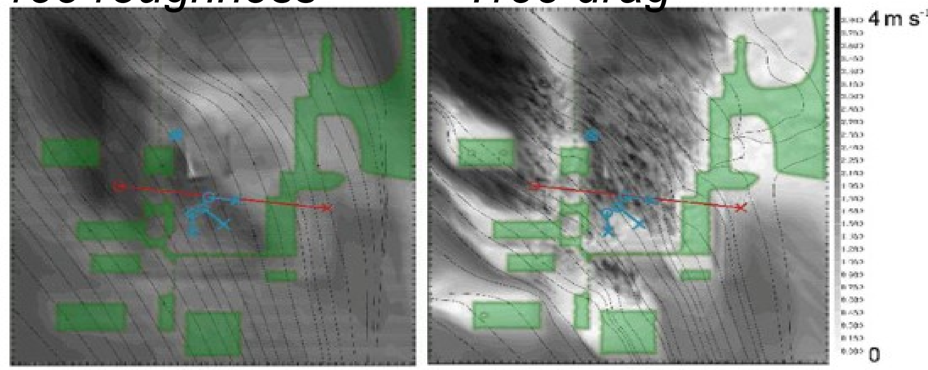
Land cover database



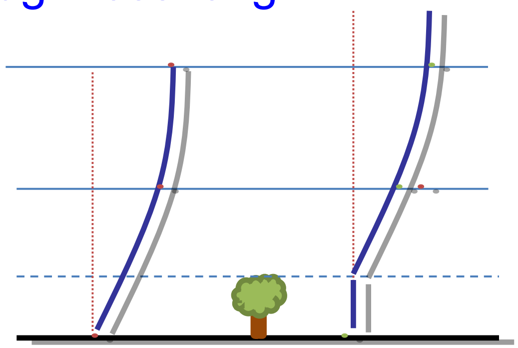
Surface heterogeneities with LES

Aumond et al., 2013

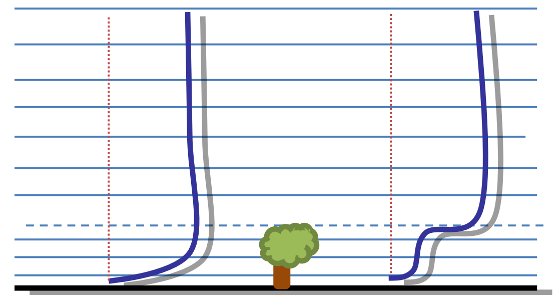
Tree roughness *Tree drag*



1. Roughness length with TEB/ISBA :



2. Drag force with presence of buildings/trees :



$$\frac{\partial U}{\partial t} = F_u - \underline{C_d A_f(z) U \left(U^2 + V^2\right)^{0,5}}$$

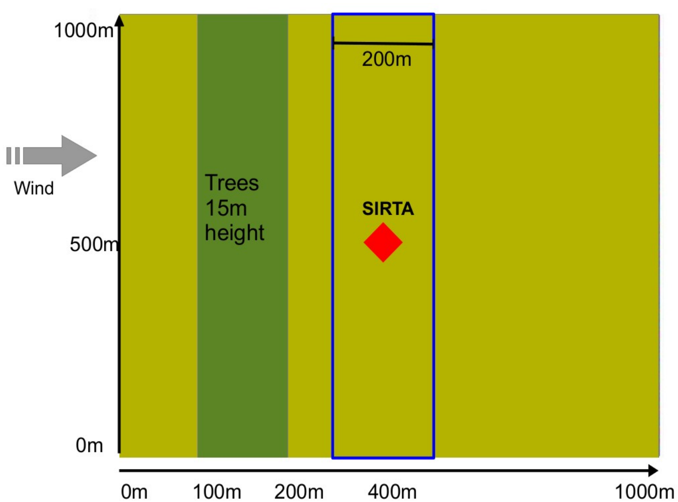
$$\frac{\partial e}{\partial t} = F_e - \underline{C_d A_f(z) e}$$

A_f= Canopy area density
Building not porous

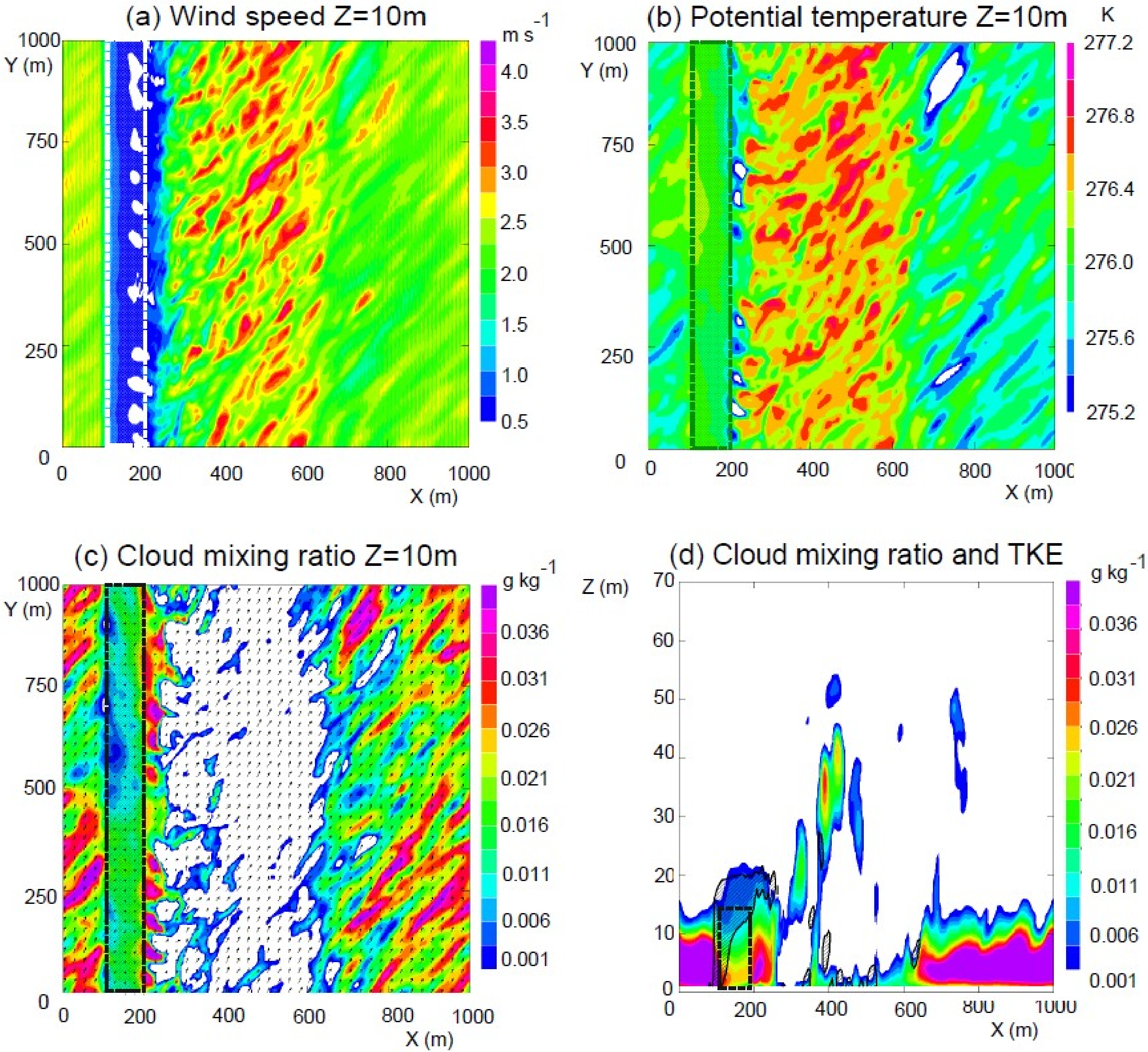
Becomes necessary at very fine vertical resolution

Fog at SIRTA : impact of trees (Mazoyer et al., 2017, ACP)

Wind direction ~ 80°



Fog at SIRTA : impact of trees (Mazoyer et al., 2017, ACP)



Subgrid transport

Prognostic variables represent a mean state on the mesh grid.

Resolution of a model -> subgrid processes are filtered
Parametrization to close the Reynolds system

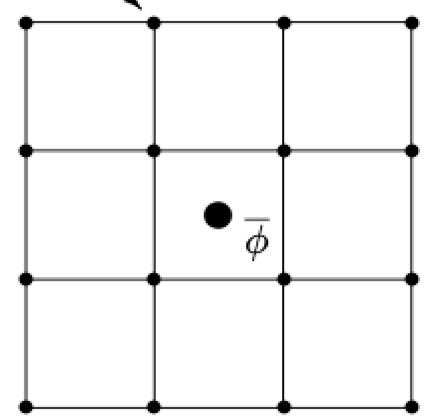
Subgrid transport

Prognostic variables represent a mean state on the mesh grid.

Reynolds formalism

$$\phi = \overline{\phi} + \phi'$$

$$\overline{\phi'} = 0$$



$$\left(\frac{\partial \phi}{\partial t}\right)_{adv} = -u_i \frac{\partial \phi}{\partial x_i}$$

Resolved

Subgrid

$$\left(\frac{\partial \overline{\phi}}{\partial t}\right) = -\overline{u_i}\frac{\partial \overline{\phi}}{\partial x_i} - \boxed{\frac{\partial \overline{u_i'\phi'}}{\partial x_i}}$$

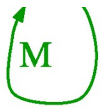
Resolution of a model -> subgrid processes are filtered

Parametrization to close the Reynolds system

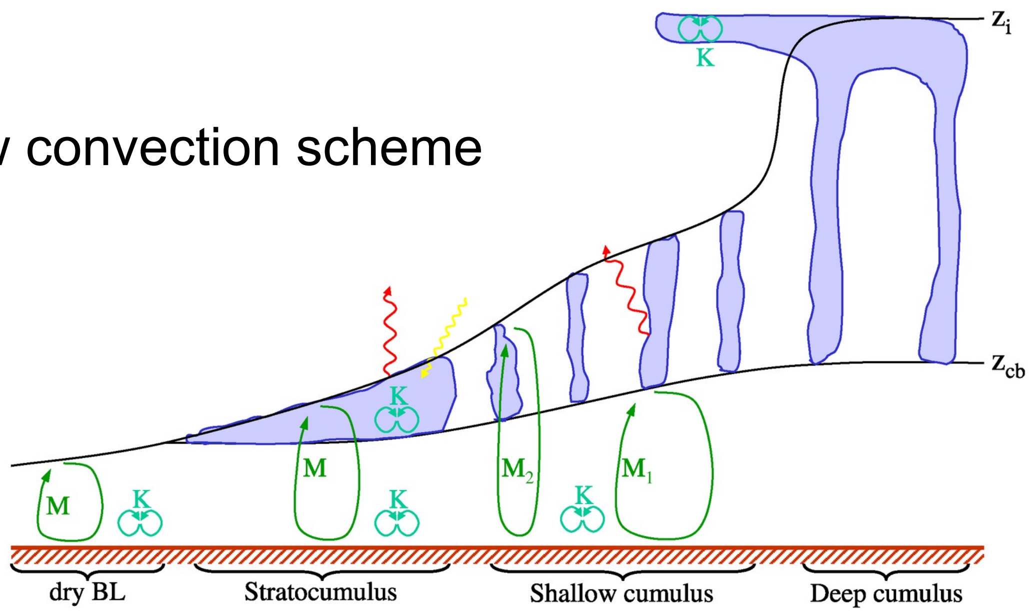
Transport of ϕ by subgrid fluctuations : Parametrization

SUBGRID TRANSPORT

Turbulence scheme



Shallow convection scheme



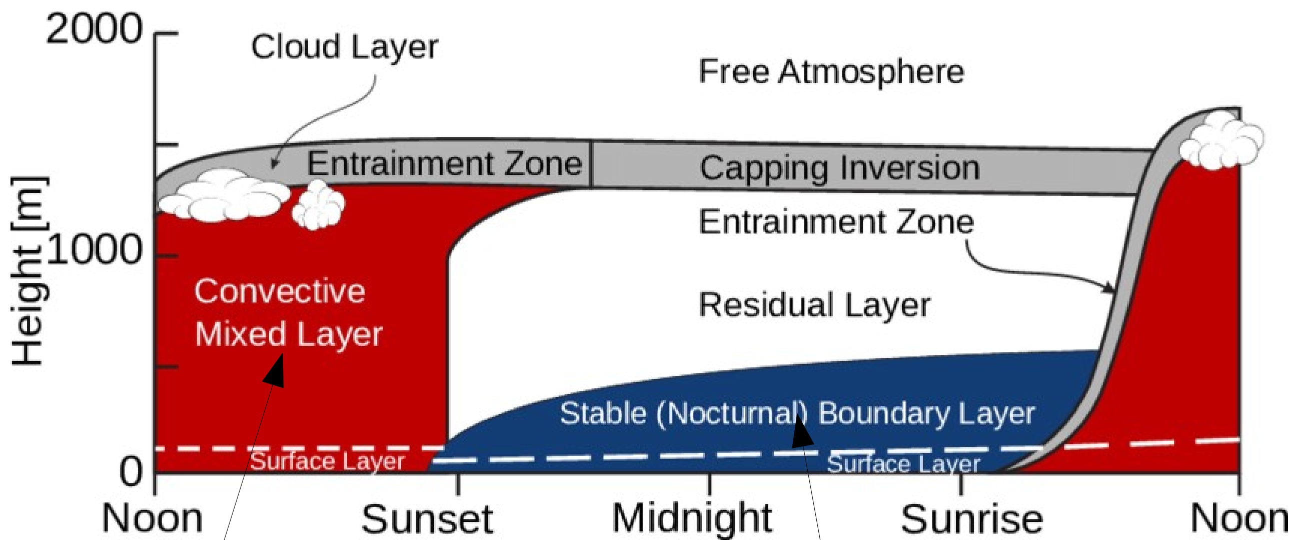
- Homogeneous small eddies → Turbulence
- Higher vertical extension, with or without cloud → Shallow convection
- Deep vertical extension of clouds, with precipitation → Deep convection

TURBULENCE

- TURBULENCE=SUBGRID TRANSPORT by small eddies

- TURBULENCE = Parametrization of the mean effect of the transport of momentum, sensible heat (enthalpy) and latent heat (no precipitating water) by small subgrid eddies considered as homogeneous and isotropic.

- Turbulence is mainly active in the Boundary Layer, but not only . At the surface, turbulent fluxes are computed in the surface model (SURFEX).



LES : Δx ~ 100m

LES : Δx ~ 1m

TURBULENCE

Same turbulence scheme for mesoscale and LES modes : Cuxart et al. (2000), Redelsperger and Sommeria (1981). Local scheme. Second-order moments are diagnosed (12) :

$$u'_i = u_i - \overline{u_i}$$

$$
\begin{aligned}
\overline{u'_i \theta'} &= -\frac{2}{3}\frac{L}{C_s} e^{\frac{1}{2}} \frac{\partial \overline{\theta}}{\partial x_i} \phi_i \\
\overline{u'_i r'_v} &= -\frac{2}{3}\frac{L}{C_h} e^{\frac{1}{2}} \frac{\partial \overline{r_v}}{\partial x_i} \psi_i, \\
\overline{u'_i u'_j} &= \frac{2}{3}\delta_{ij}\, e - \frac{4}{15}\frac{L}{C_m} e^{\frac{1}{2}} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_m}{\partial x_m}\right), \\
\overline{\theta' r'_v} &= C_2 L^2 \left(\frac{\partial \overline{\theta}}{\partial x_m}\frac{\partial \overline{r_v}}{\partial x_m}\right)(\phi_m + \psi_m), \\
\overline{\theta'^2} &= C_1 L^2 \left(\frac{\partial \overline{\theta}}{\partial x_m}\frac{\partial \overline{\theta}}{\partial x_m}\right)\phi_m, \\
\overline{r'^2_v} &= C_1 L^2 \left(\frac{\partial \overline{r_v}}{\partial x_m}\frac{\partial \overline{r_v}}{\partial x_m}\right)\psi_m.
\end{aligned}
$$

Stability functions (inverse turbulent Prandtl and Schmidt numbers)

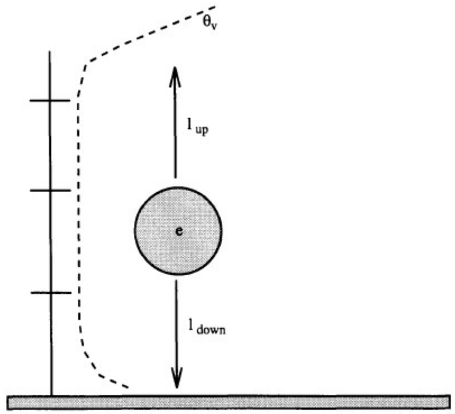
-> K method with

$$\overline{w'\theta'} = -K\frac{\partial \theta}{\partial z}$$

$K = c\, L\, e^{1/2}$

TURBULENCE

L is the **mixing length** that allows to close the system = Size of the most energetic eddies that feed the energy cascade towards the dissipation.



Different possibilities to parametrize L (**CTURBLEN**) :

• **meso-scale** : BL89 : The distance a parcel of air having the initial TKE of the level can travel upwards (l_{up}) and downwards (l_{down}) before being stopped by buoyancy effects : $L=f(l_{up},l_{down})$ (**CTURBLEN='BL89'**)

LES (inertial subrange) : $(\Delta x.\Delta y.\Delta z)1/3$ and Deardorff mixing length (**CTURBLEN='DEAR'** or CTURBLEN='DELT')

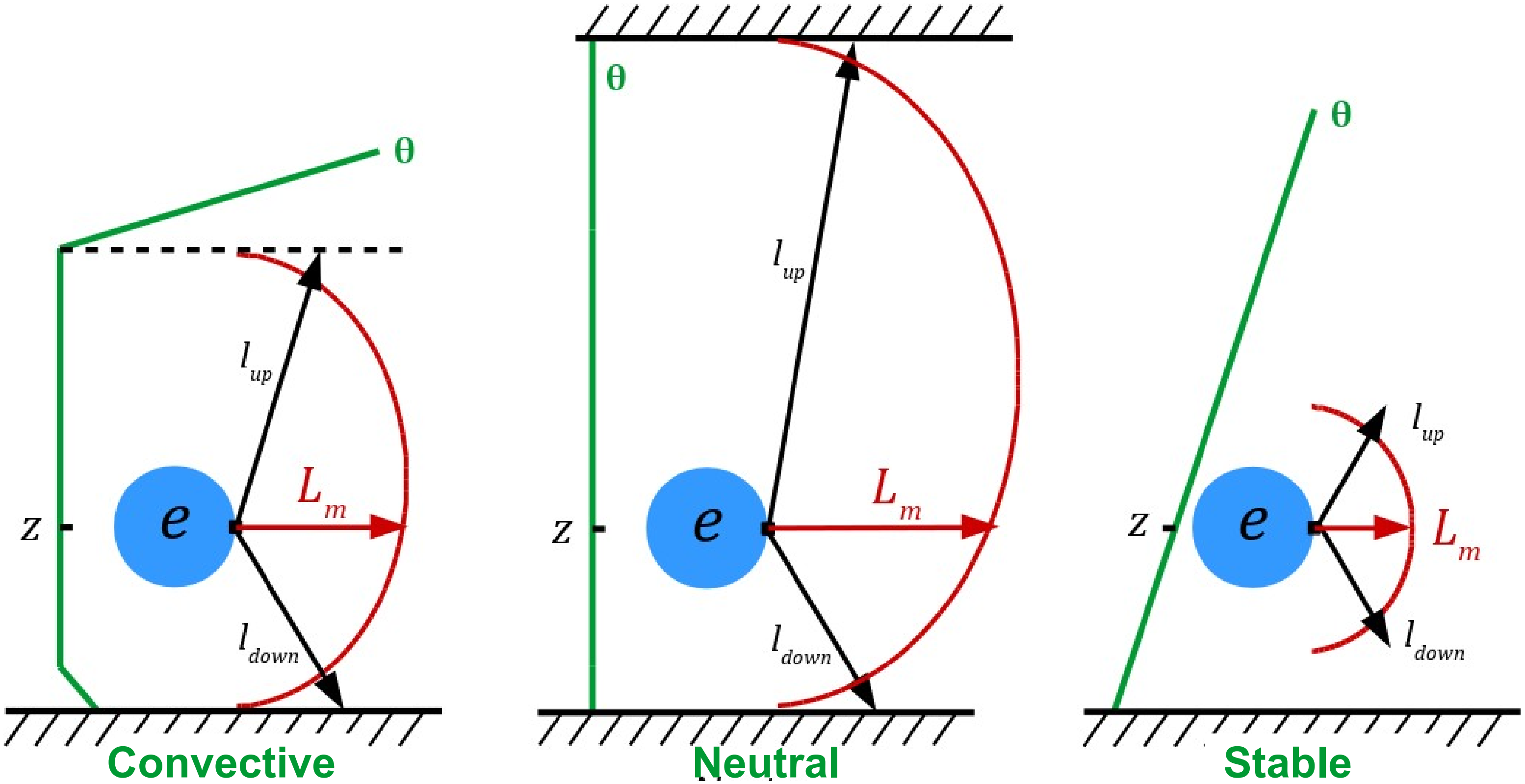
$$L_m = min\left((\Delta x \Delta y \Delta z)^{1/3}, 0.76\sqrt{\frac{e}{N^2}}\right)$$

Mixing length BL89

Bougeault and Lacarrere (1989)

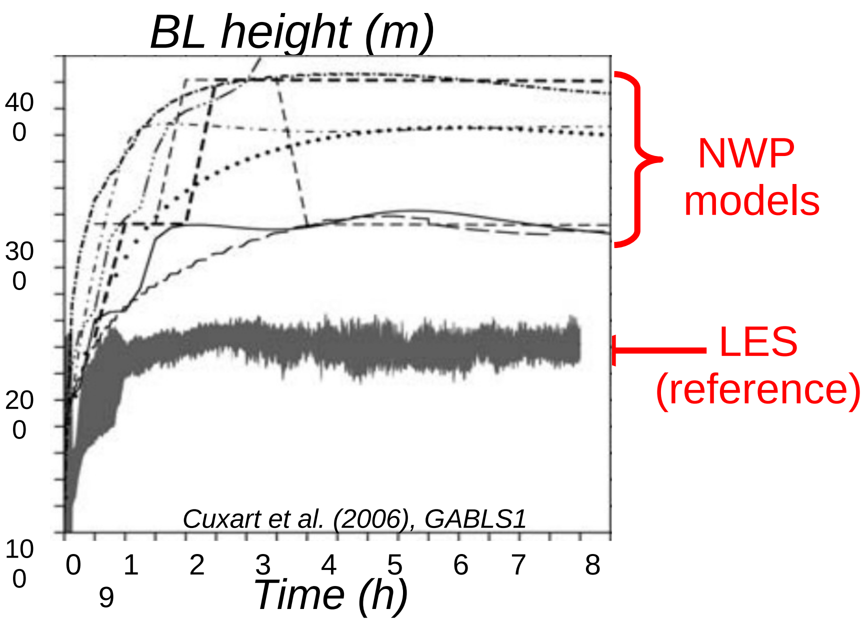
$$\int_{z}^{z+l_{up}} \beta\left[\theta(z') - \theta(z)\right] dz' = e(z)$$

$$\int_{z-l_{down}}^{z} \beta\left[\theta(z) - \theta(z')\right] dz' = e(z)$$

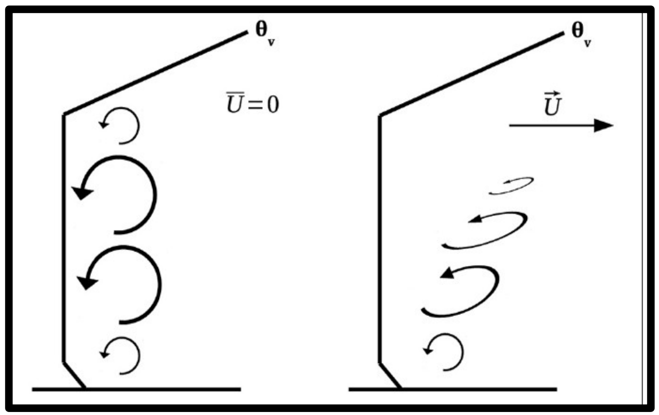


Problem : BL89 not physical in neutral condition, overestimated in stable condition

Turbulent scheme : weakly stable BL



- In weakly stable BL, overestimation of the mixing by most of the NWP models
- In neutral and stable conditions BL89 no longer valid
- Vertical wind shear is the only local positive source of TKE and influences eddies



BL89 + wind-shear : RM17

$$\int_{z}^{z+l_{up}} \left[\beta(\theta(z')-\theta(z)) + \boxed{C_0\sqrt{e}S(z')}\right] dz' = e(z) \qquad S=\sqrt{\left(\frac{\partial \overline{U}}{\partial z}\right)^2+\left(\frac{\partial \overline{V}}{\partial z}\right)^2}$$

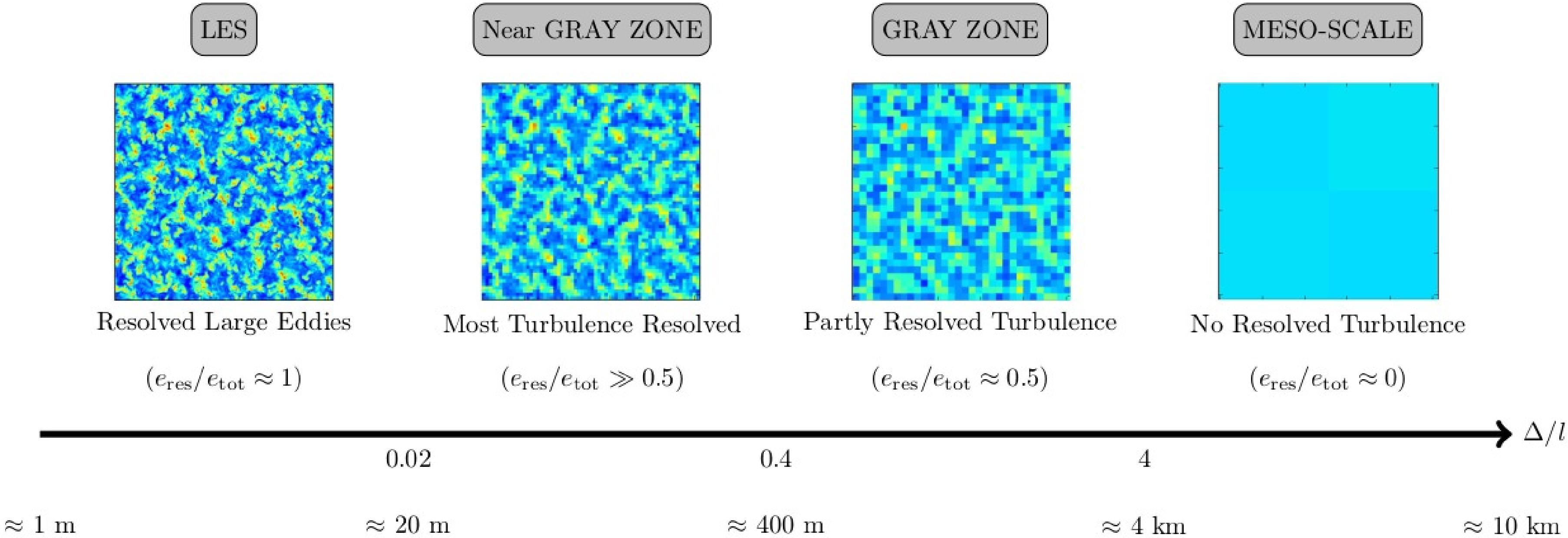
$$\int_{z-l_{down}}^{z} \left[\beta(\theta(z)-\theta(z')) + \boxed{C_0\sqrt{e}S(z')}\right] dz' = e(z)$$

Buoyancy Shear

METEO FRANCE

(Rodier et al., 2017, Frontiers)

Turbulence : adaptive mixing length



- For grey-zone resolution (~200-1000m)

Honnert et al. 2021

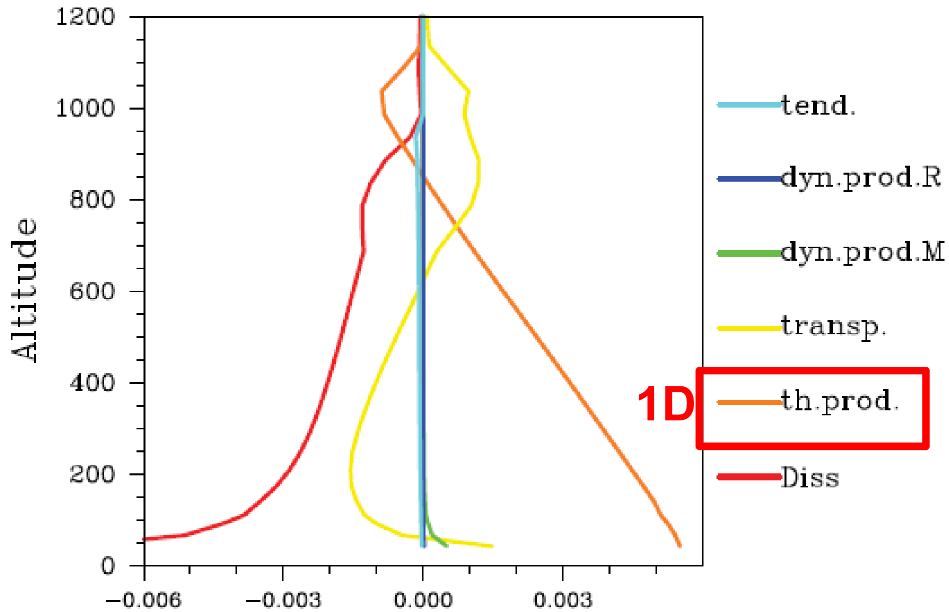
- CTURBLEN='ADAP'
- = min(RM17,0.5* √(ΔxΔy))

Prognostic TKE : $e = \frac{1}{2}\left(u'^2 + v'^2 + w'^2\right)$

$$\frac{\partial TKE}{\partial t} = advection + \underbrace{prod.dyn.\ \ (DP)}_{\overline{u'_i u'_j}\frac{\partial \overline{U}_i}{\partial x_j}}^{\textbf{3D}} + \underbrace{prod.therm.\ \ (TP)}_{\frac{g}{\theta_{vref}}\left(E_\theta \overline{w'\theta'_l} + E_r \overline{w' r'_{np}}\right)}^{\textbf{1D}} + transport + dissipation$$

$(r_{np} = r_c + r_i + r_v)$

BUDGET of TKE : case of IHOP (convective BL) (from Honnert, 2012)



Δx=8km

Prognostic TKE : $e = \frac{1}{2}\left(u'^2 + v'^2 + w'^2\right)$

$$\frac{\partial TKE}{\partial t} = advection + \underbrace{\overset{\textbf{3D}}{prod.dyn.\ (DP)}}_{\overline{u'_i u'_j}\frac{\partial \overline{U}_i}{\partial x_j}} + \underbrace{\overset{\textbf{1D}}{prod.therm.\ (TP)}}_{\frac{g}{\theta_{vref}}\left(E_\theta \overline{w'\theta'_l} + E_r \overline{w'r'_{np}}\right)} + transport + dissipation$$

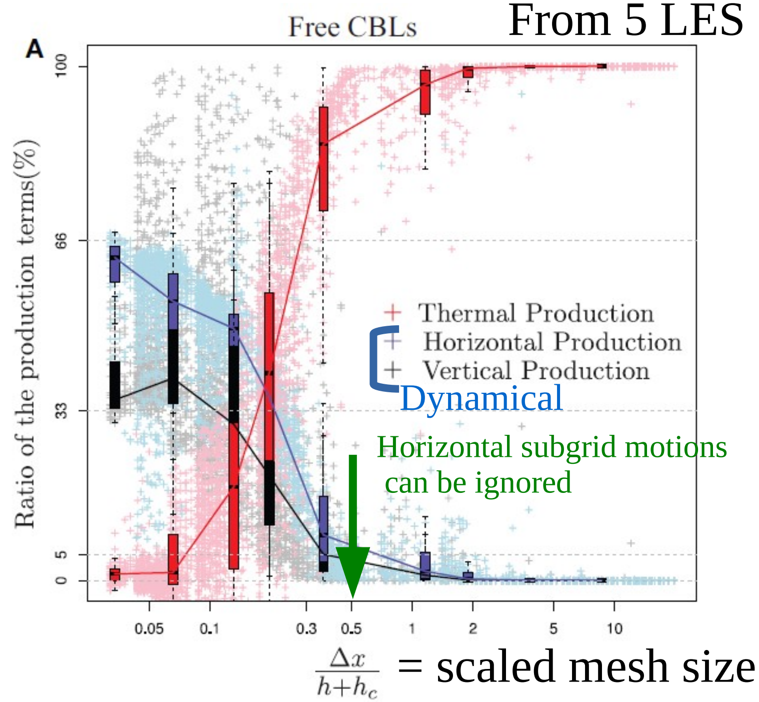
$(r_{np} = r_c + r_i + r_v)$

At mesoscale horizontal fluxes and gradients can be neglected except for the transport of TKE : T1D

AROME in T1D BL89

At finer resolution, entire equation system :T3D

From 5 LES



For CBL, T3D necessary for :

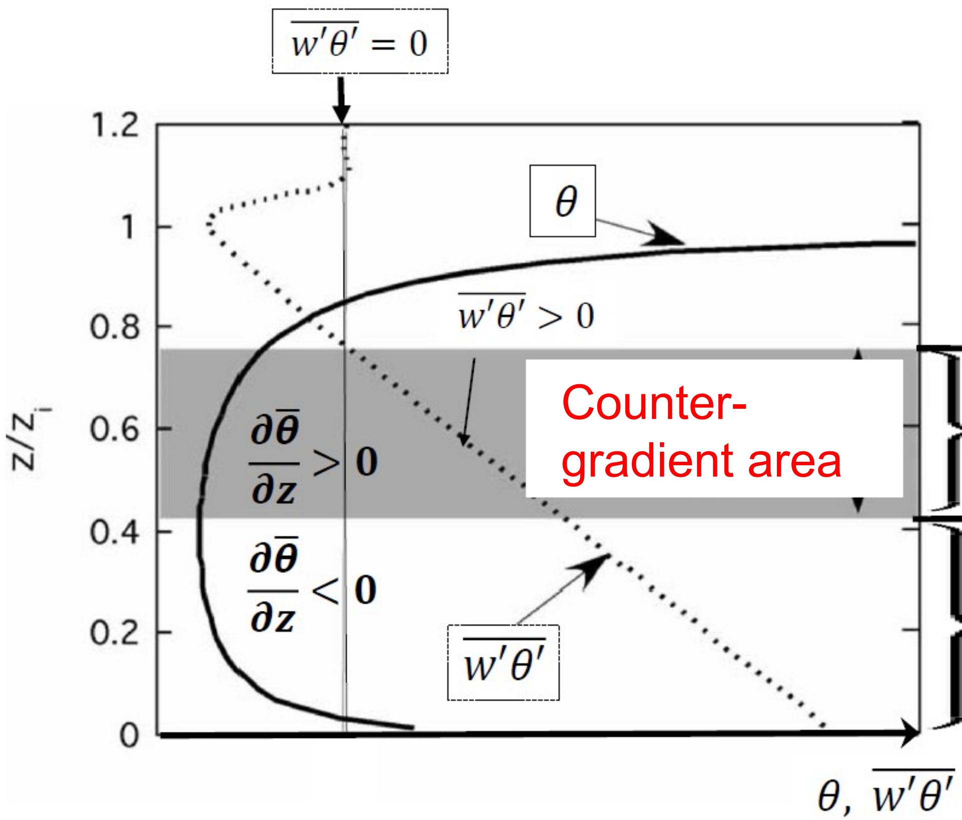
$$\frac{\Delta x}{h+h_c} = 0.5\ (\approx 500\ \text{m})$$

h_c :depth of the cloud layer, h : BL height

(Honnert and Masson, 2014)

Limit of the K method for a convective boundary layer

$$\overline{w'\theta'} = -K\frac{\partial \theta}{\partial z}$$



Observé	modèle	
$\frac{\partial\bar{\theta}}{\partial z}\overline{w'\theta'}_l > 0$	$\cancel{\overline{w'\theta'} = -K\frac{\partial\bar{\theta}}{\partial z}}$	
$\frac{\partial\bar{\theta}}{\partial z}\overline{w'\theta'}_l < 0$	$\overline{w'\theta'} = -K\frac{\partial\bar{\theta}}{\partial z}$	✓ O.K.

SHALLOW CONVECTION

- Historical approach : K-theory or eddy-diffusivity

: good small eddy closure but problem in the countergradient zone of the convective BL (Stull, 1988)

$$\boxed{\overline{w'\phi'} \cong -K \frac{\partial \overline{\phi}}{\partial z}}$$

- Counter gradient Term (Deardorff, 1972) :

  ν : effect of the non local transport

$$\overline{w'\theta'} = -K'\left(\frac{\partial \overline{\theta}}{\partial z} - \gamma c\right)$$

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

- Based on the EDMF scheme (Soares et al,2004) : Mass-flux approach

Turbulence
Small Eddies
Local Effect

Shallow convection
Thermals
(coherent structures)
Non local transport

EDKF scheme (PMMC09)

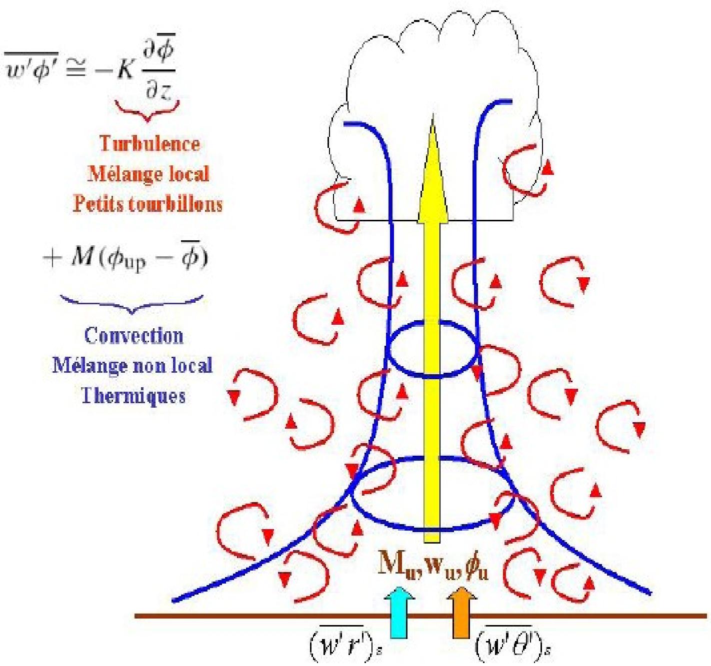
1. Pergaud J., Masson V., Malardel S. and Couvreux F. (2009) A parameterization of dry thermals and shallow cumuli for mesoscale numerical weather prediction. *Boun. Layer Meteor.* 132 :93-106.

- **Necessary until Δx ~1km – 500m**

EDKF : A parametrization for dry and cloudy convective boundary layers

PMMC09[1] (ou EDKF)

- The scheme is diagnostic (no memory of the convective activity from the previous Δt)
- Two equations (mass flux and vertical velocity) resolved from the bottom to the top
- Closure with the initialization of mass flux from the surface as a function of buoyancy



$$
\begin{cases}
w_u \frac{\partial w_u}{\partial z} = aB_u - b\epsilon w_u^2 \\
\frac{1}{M}\frac{\partial M}{\partial z} = (\epsilon - \delta) \\
M_0 = C_{M_0}\rho\left(\frac{g}{\theta_{vref}}\overline{w'\theta'_{vs}}L_{up}\right)^{\frac{1}{3}}
\end{cases}
$$

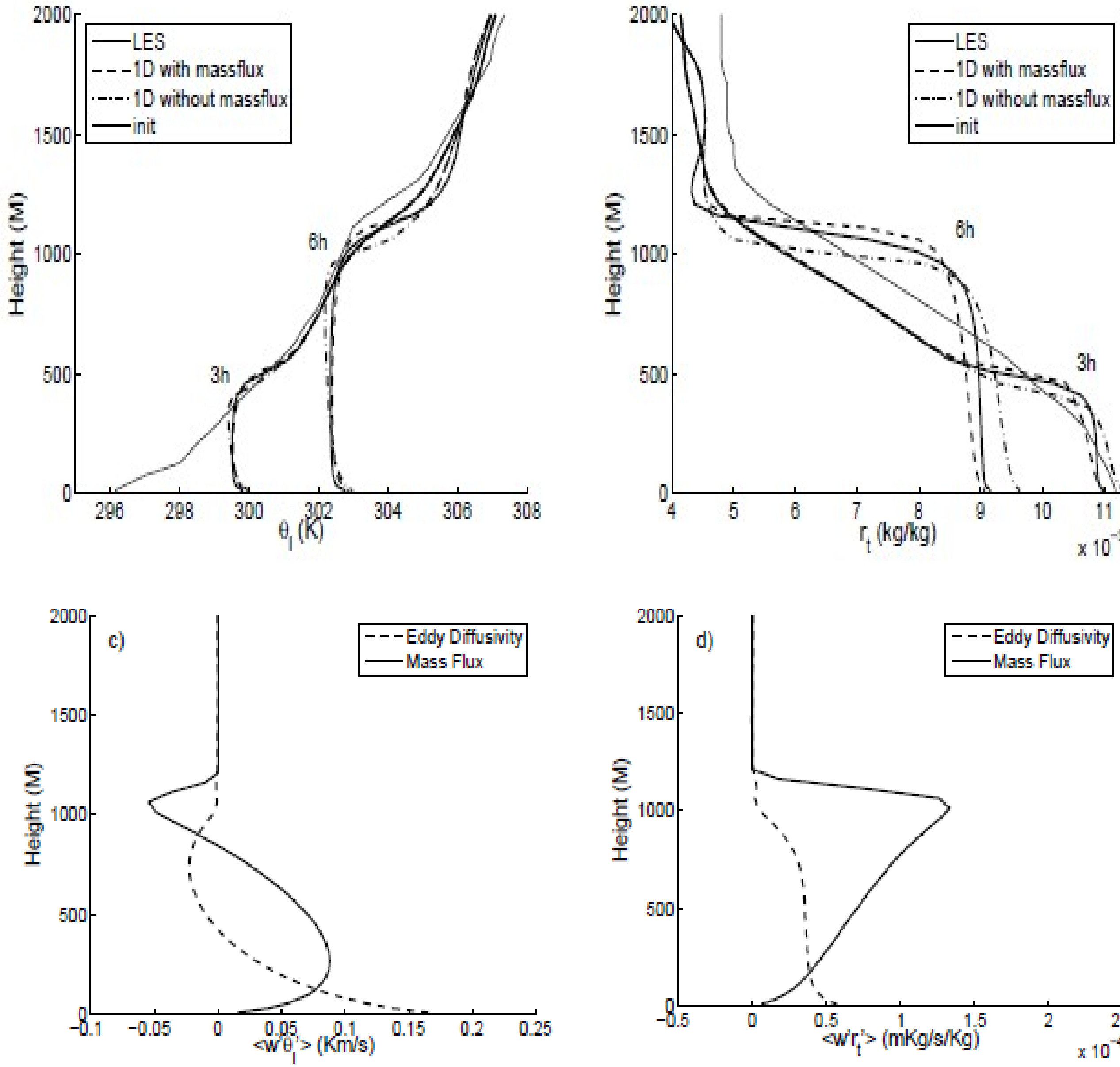
Dry convective boundary layer : IHOP (Pergaud et al., 2009)

Without mass-flux :

- Insufficient top-entrainment -> too low inversion
- BL too cold and too moist

Eddy-diffusivity in the low part of the BL (local)

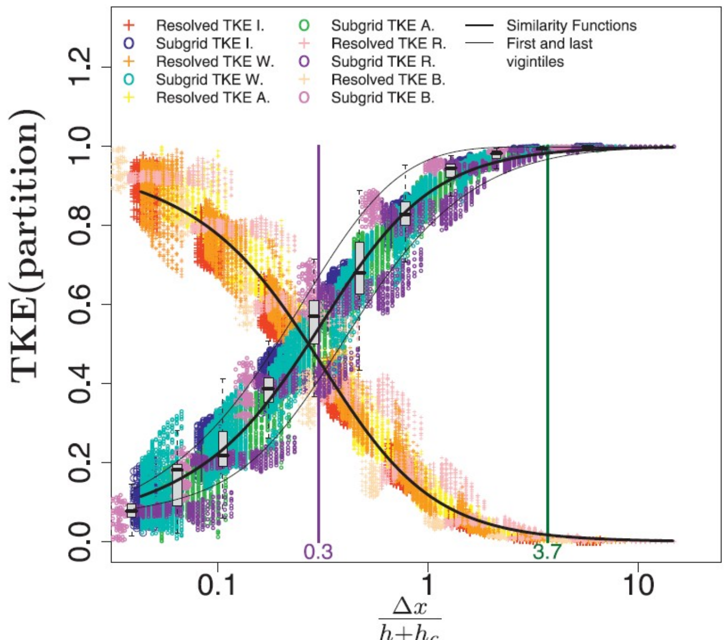
Mass-flux in the upper part (non local)



Grey zone of shallow convection

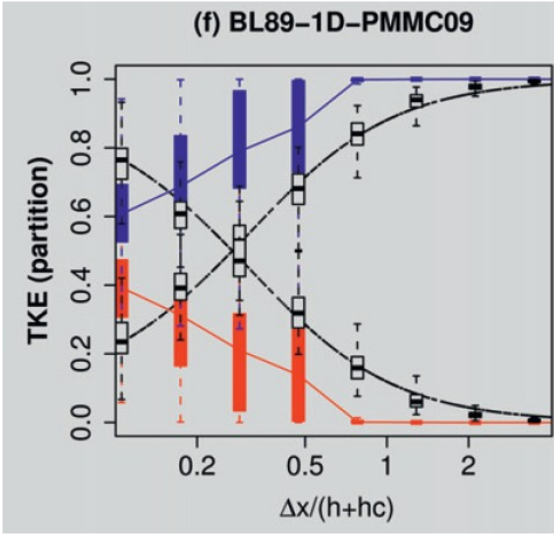
SBG TKE

RES TKE

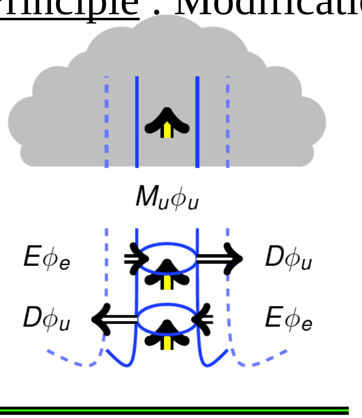


Δx=1km

With the EDMF scheme (like in AROME) :
Too much SBG



Principle : Modification of EDMF for the GZ



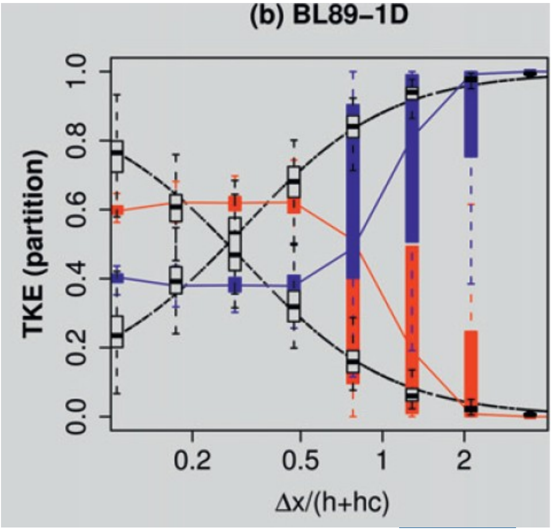
$$\frac{\partial M_u\phi_u}{\partial z} = \tilde{E}\phi_e - \tilde{D}\phi_u$$

Depend on Δx

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

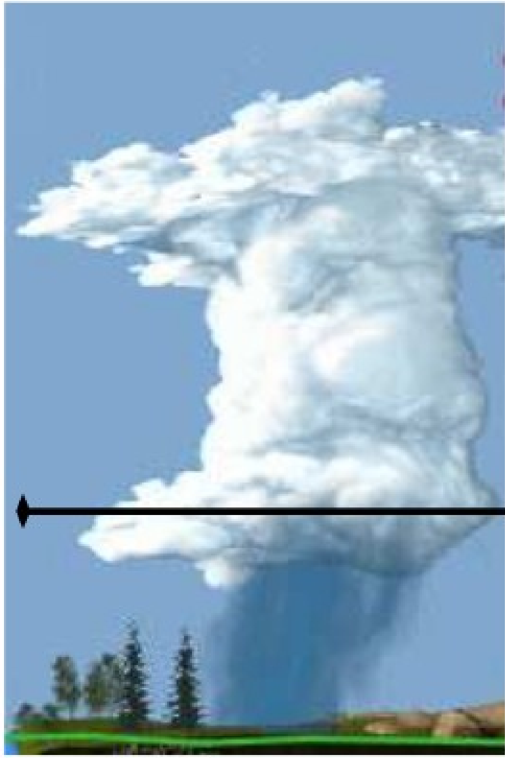
Not negligible

Without the EDMF scheme :
Too much RESOLVED



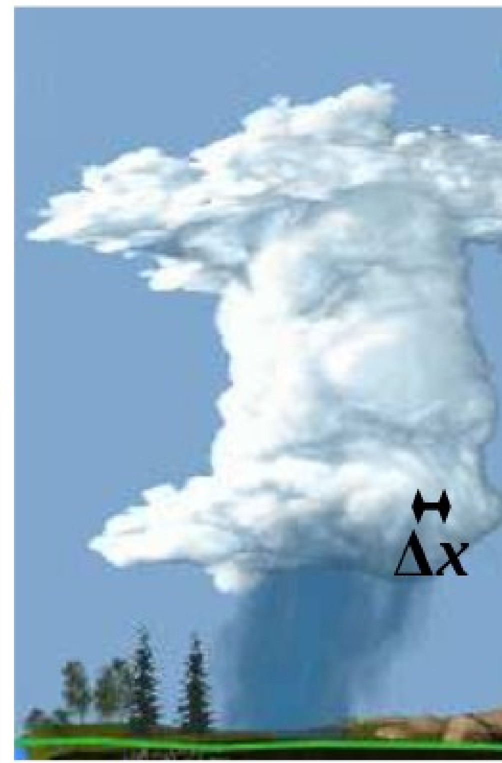
(Honnert et al., 2011)

Deep convection



Deep convection is not resolved, parameterization is needed

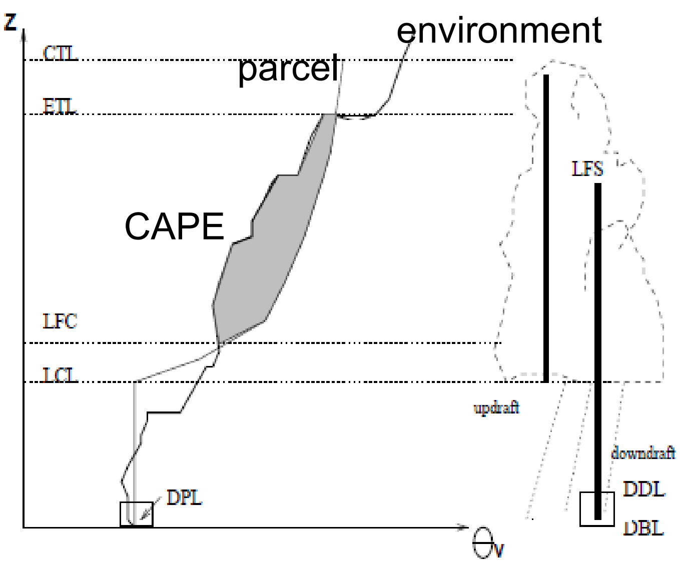
Deep convection is resolved, parameterization is not needed. Updrafts and downdrafts are resolved, formation of precipitation is simulated by cloud microphysics.



Deep convection

Necessary for Δx > 5km. But not below where it is explicitly resolved.

Mass flux scheme : Kain-Fritsch-Bechtold (KFB) (Bechtold et al., 2005)



LCL = Lifting condensation level
DPL = Departure level
CTL = Cloud top level
LFC = Level of free convection (positive buoyancy)
ETL = Equilibrium temperature level (zero buoyancy)
LFS = Level of free sink
DBL = Downdraft base level

$$\left.\frac{\partial\overline{\Psi}}{\partial t}\right|_{\mathrm{conv}} = \frac{\partial(\overline{w'\Psi'})}{\partial z}$$

~ : environment

\- : mean horizontal

$$\approx \frac{1}{\overline{\rho}A}\frac{\partial}{\partial z}\left[M^u(\Psi^u-\overline{\Psi})+M^d(\Psi^d-\overline{\Psi})+\tilde{M}(\tilde{\Psi}-\overline{\Psi})\right]$$

$$\approx \frac{1}{\overline{\rho}A}\frac{\partial}{\partial z}\left[M^u\Psi^u+M^d\Psi^d-(M^u+M^d)\overline{\Psi}\right],$$

where Ψ is a conserved variable, $M=\overline{\rho}wA$ is the mass flux (kg s^{-1}), w the vertical velocity, and $A=A^u+A^d+\tilde{A}$ denotes the horizontal domain (grid size). O

$$\frac{\partial}{\partial z}(M^u\Psi^u)=\epsilon^u\overline{\Psi}-\delta^u\Psi^u; \qquad \frac{\partial}{\partial z}(M^d\Psi^d)=\epsilon^d\overline{\Psi}-\delta^d\Psi^d$$

entrainment ϵ and detrainment δ,

$$\left.\frac{\partial\overline{\Psi}}{\partial t}\right|_{\mathrm{conv}} = \frac{1}{\overline{\rho}A}\left[\frac{\partial}{\partial z}([M^u+M^d]\overline{\Psi})-[\epsilon^u+\epsilon^d]\overline{\Psi}+\delta^u\Psi^u+\delta^d\Psi^d\right]$$

Deep convection produces 2D convective precipitation at the ground (PRCONV,PACCONV) to add to the explicit precipitation (from the microphysics : INPRT, ACPRT)

Microphysics and cloud scheme

Microphysics and cloud scheme

Motivation : Cloud microphysical schemes have to describe the formation, growth and sedimentation of water particles (hydrometeors).
They provide the latent heating rates for the dynamics.

For NWP : important for quantitative precipitation forecasts
For climate : radiative impact and aerosol-cloud-radiation interactions

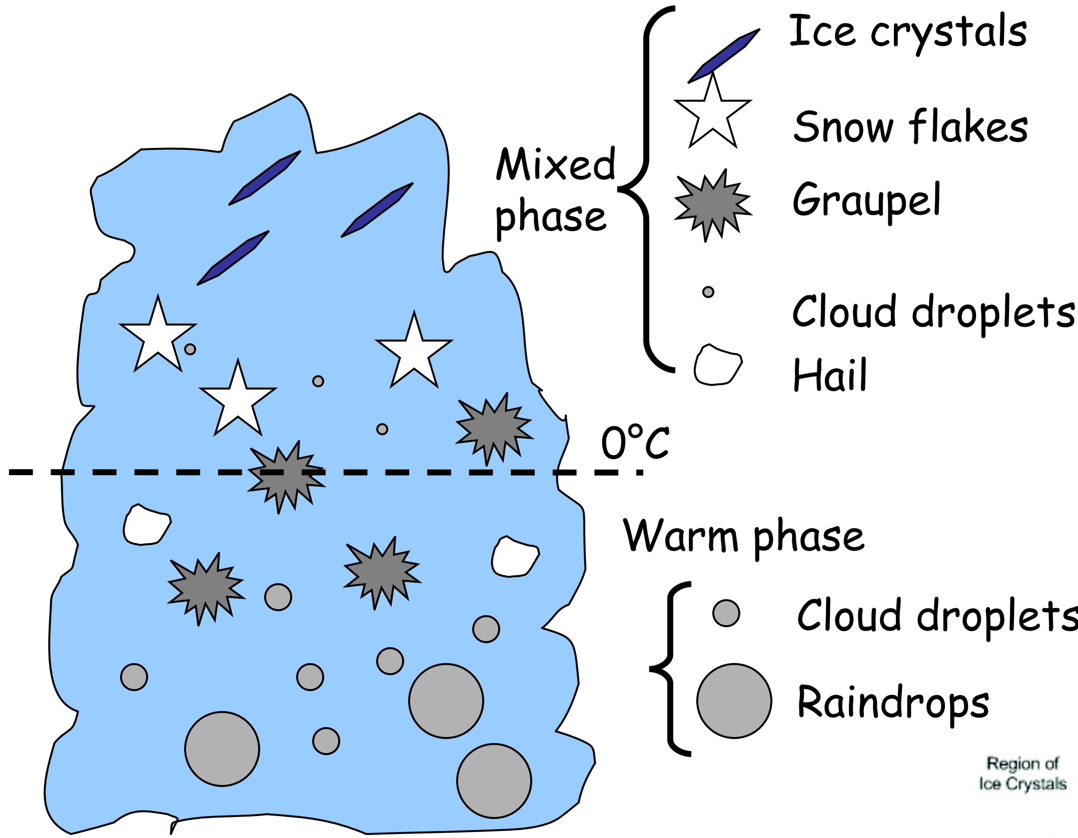
Basic assumptions :

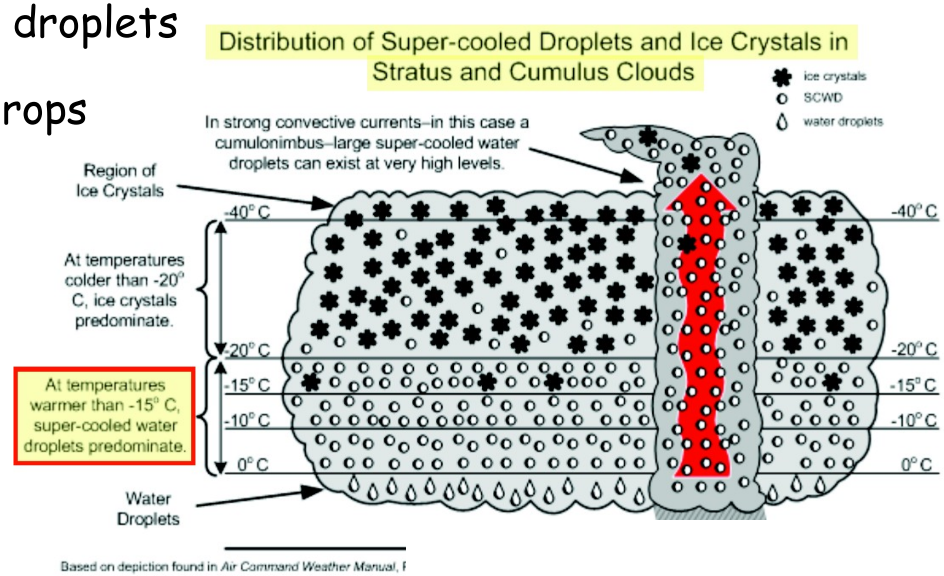
1. The various types of hydrometeors are simplified to a few categories, e.g., cloud droplets, raindrops, cloud ice, snow, graupel, hail : BULK ↔BIN

2. We assume thermodynamic equilibrium between cloud droplets and water vapor. Therefore the condensation/evaporation of cloud droplets can be treated diagnostically, i.e., by the so-called saturation adjustment.

Meso-NH
mesoscale non-hydrostatic model

MICROPHYSICS

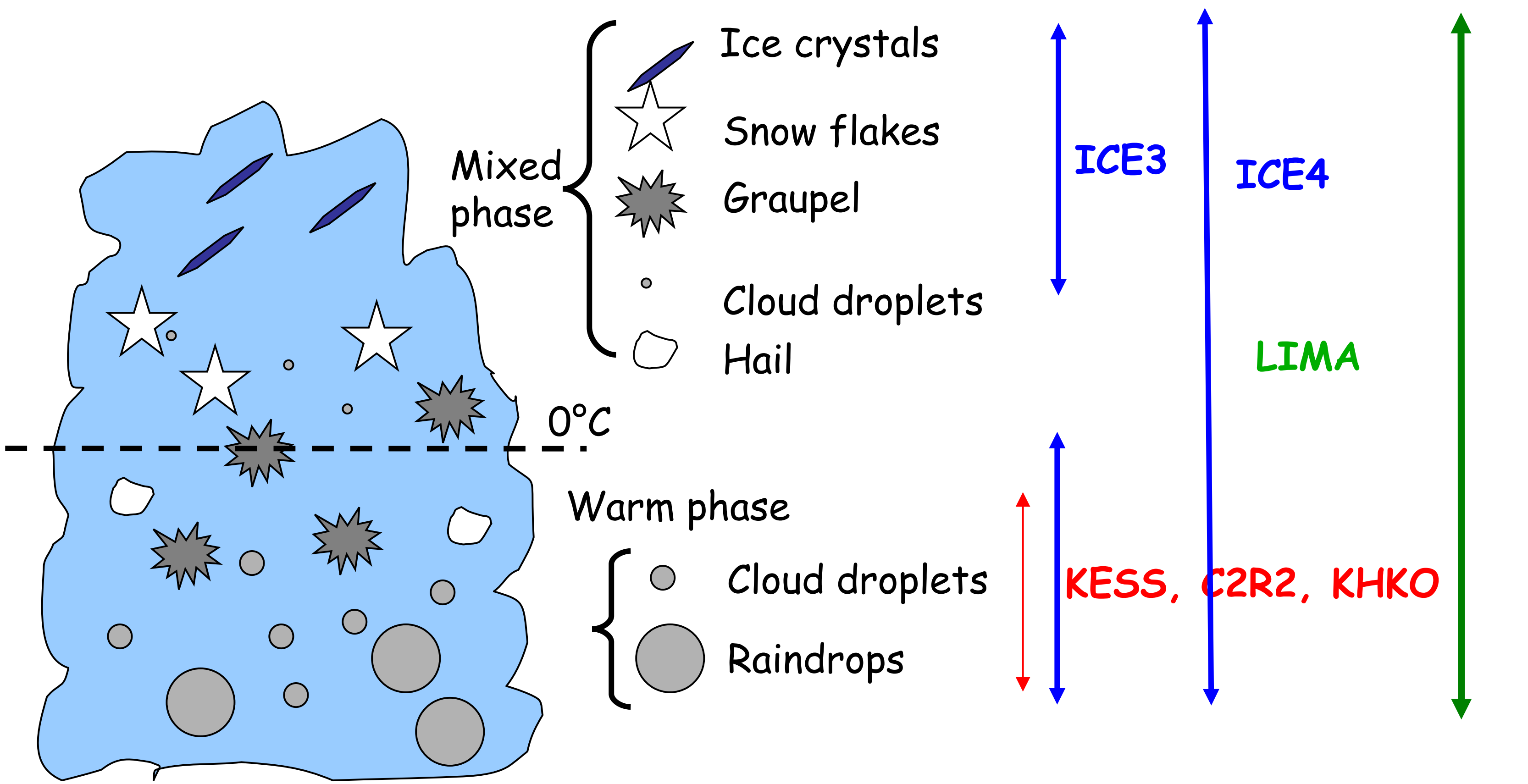




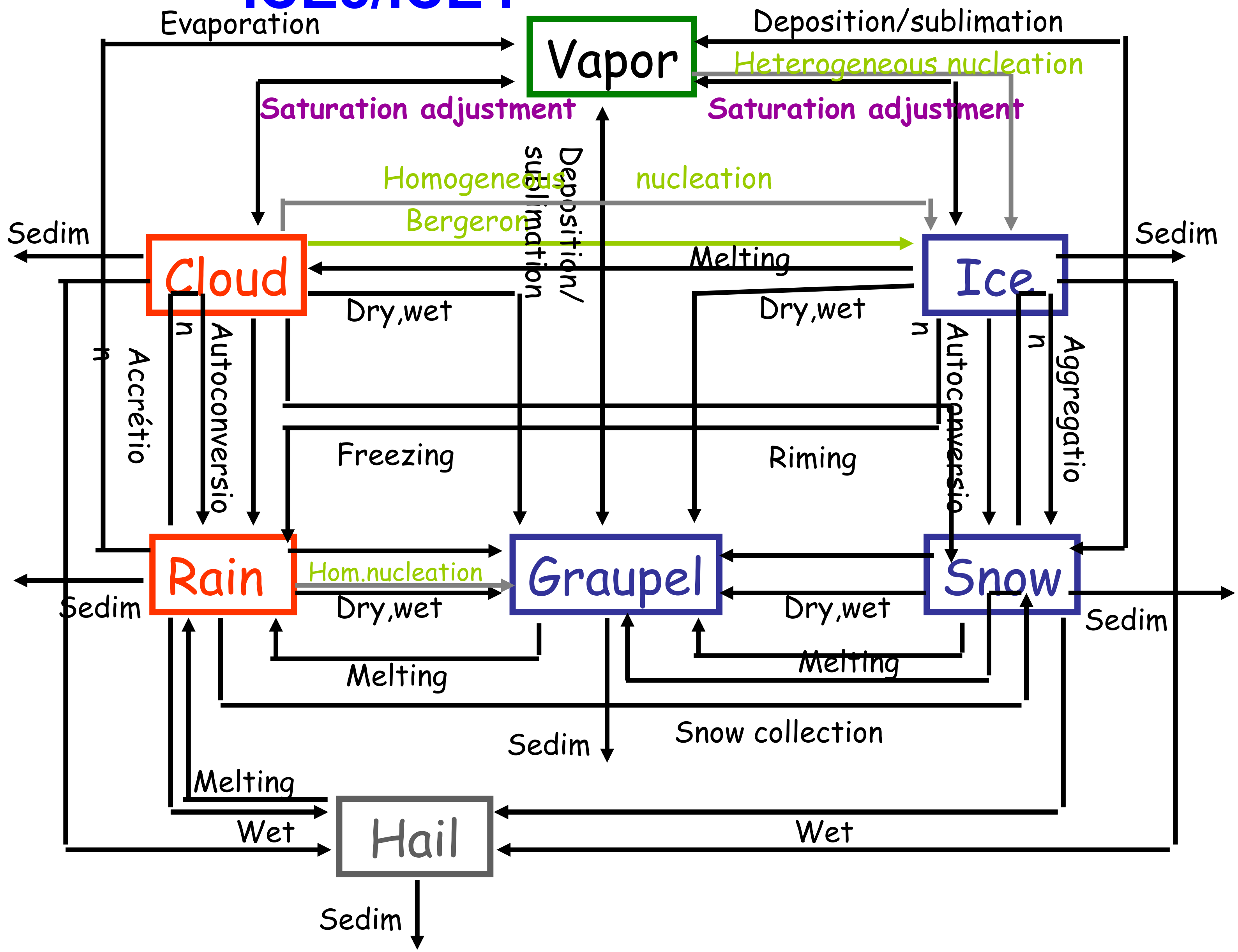
MICROPHYSICS

Concentrations : * 1-moment scheme $N_i = C\lambda_i^x, i=\{r,s,g,h\}$ KESS ICE3, ICE4

* 2-moment scheme : Integration of $\partial N_i / \partial t$ C2R2, KHKO, LIMA



ICE3/ICE4



Caniaux, 1993 – Pinty and Jabouille, 1998

Particle size distributions

- Size distribution (n(D)): Generalized Gamma law

$$n(D)\,\mathrm{dD} = Ng(D)\,\mathrm{dD} = N\frac{\alpha}{\Gamma(\nu)}\lambda^{\alpha\nu}D^{\alpha\nu-1}\exp\left(-(\lambda D)^{\alpha}\right)\mathrm{dD}$$

N is the total concentration

Precipitating species : $N = C\lambda^{x}$

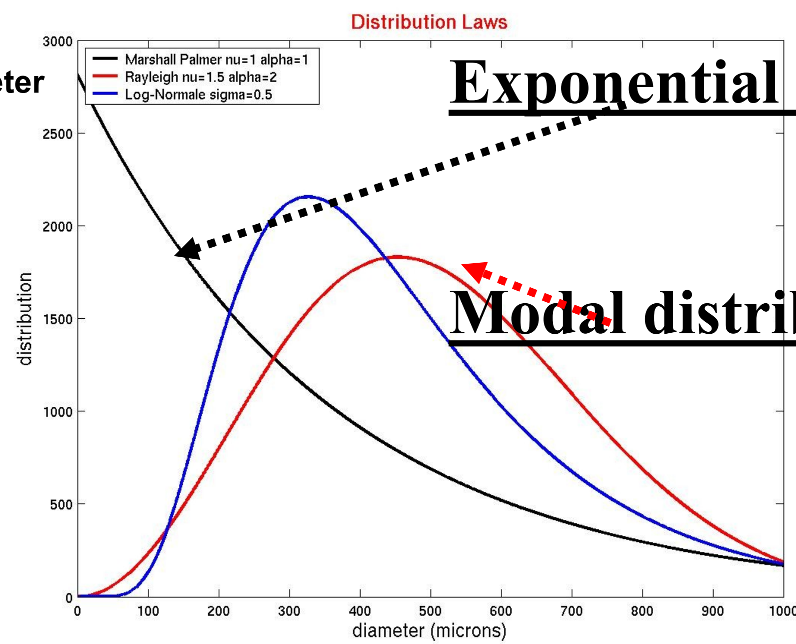
For clouds, N imposed (Nc=300/cm3 on land, 100/cm3 on sea)

λ is the slope parameter deduced from the mixing ratio

1-moment scheme

(α, ν) are free shape parameters (Marshall-Palmer law: α=ν=1)

Intercept parameter



Exponential decay : rain, snow, graupel

Modal distribution : droplets, cloud ice

Microphysical characteristics

Very useful p-moment formula

$$M(p)=\int_0^{\infty} D^p n(D)\,\mathrm{dD}=\frac{\Gamma(\nu+p/\alpha)}{\Gamma(\nu)}\frac{1}{\lambda^p}=NG(p)\frac{1}{\lambda^p}$$

M(0)=Concentration
M(1)=Mean diameter
M(3)=Mean volume

The content of any specy : $\rho_d r=\int_0^{\infty} m(D)n(D)dD=aNM(b)$

The slope parameter depends on the content : $\lambda=\left(\frac{\rho_d r}{aCG(b)}\right)^{\frac{1}{x-b}}$

Microphysical characteristics

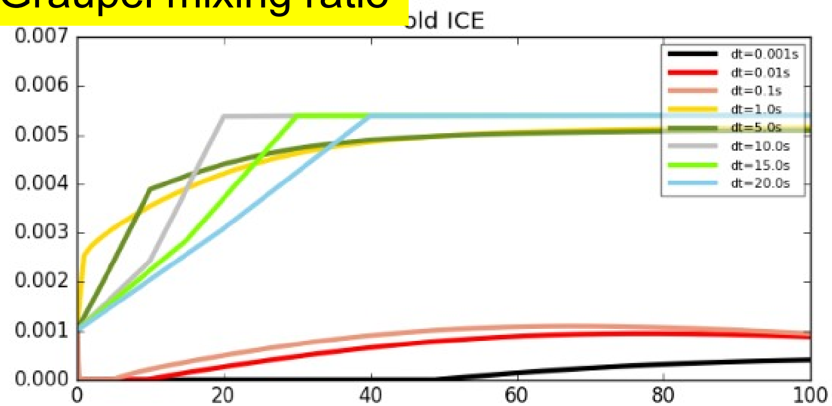
- **Mass-Size relationship: $m=aD^b$**
- **Fall speed-Size relationship: $v=cD^d \cdot (\rho_{00}/\rho_a)^{0.4}$**

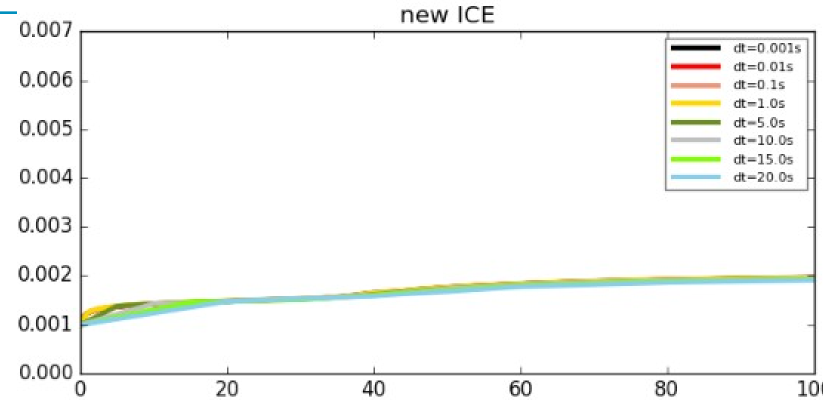
Category → Parameters		Cloud water	Rain water	Cloud ice	Snowflake Aggregate	Graupel	Hail
mass	a	524	524	0.82	0.02	19.6	470
	b	3	3	2.5	1.9	2.8	3.0
speed	c	3.2e7	842	800	5.1	124	207
	d	2	0.8	1.00	0.27	0.66	0.64

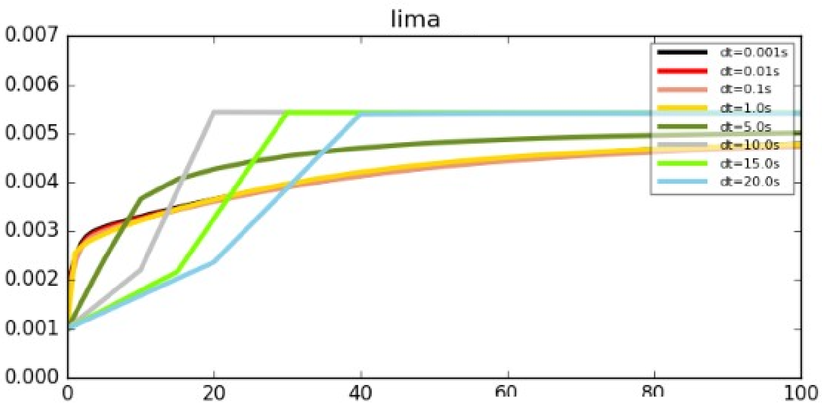
The **a, b, c** and **d** coefficients (MKS units) are adjusted from ground or *in situ* measurements

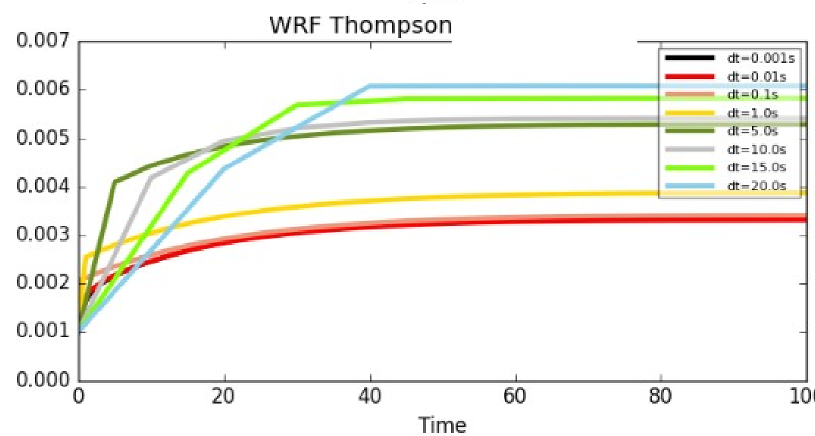
0D tool: comparison between different microphysics

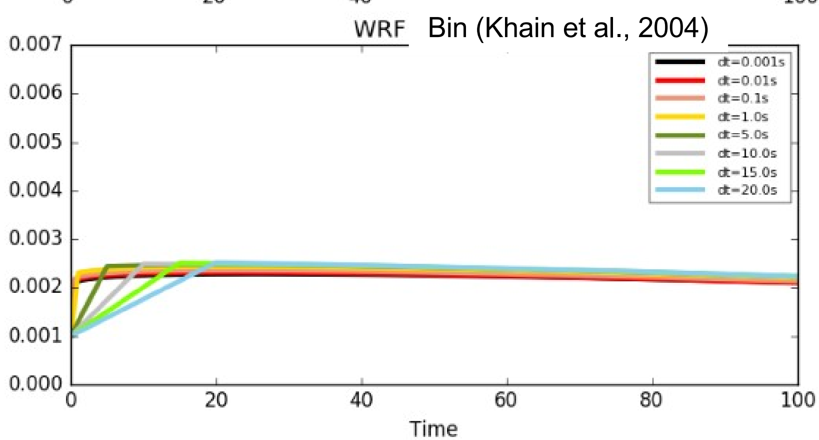
Graupel mixing ratio











Strong sensitivity to Δt for some schemes and absence of convergence

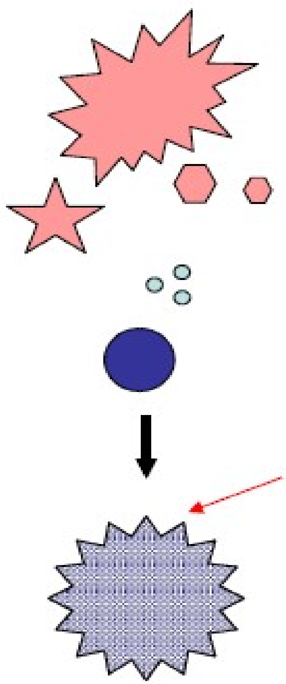
LRED=T

Riette (2020)

METEO FRANCE

Hail formation

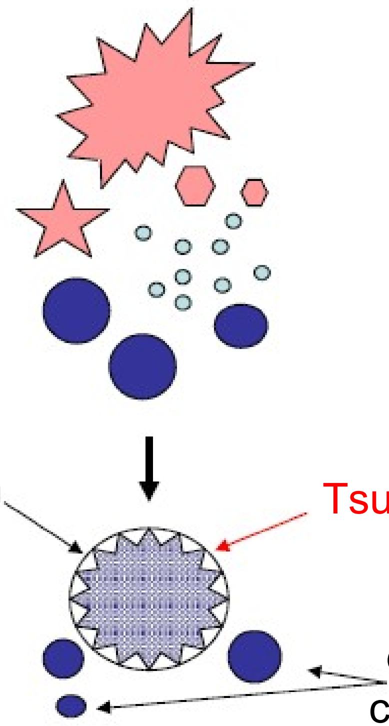
<u>DRY GROWTH</u>



=> GRAUPEL

Growth mainly by supercooled droplet collection.
With collection, latent heat release increases Tsurf, sometimes up to Tsurf=0°C

<u>WET GROWTH</u>



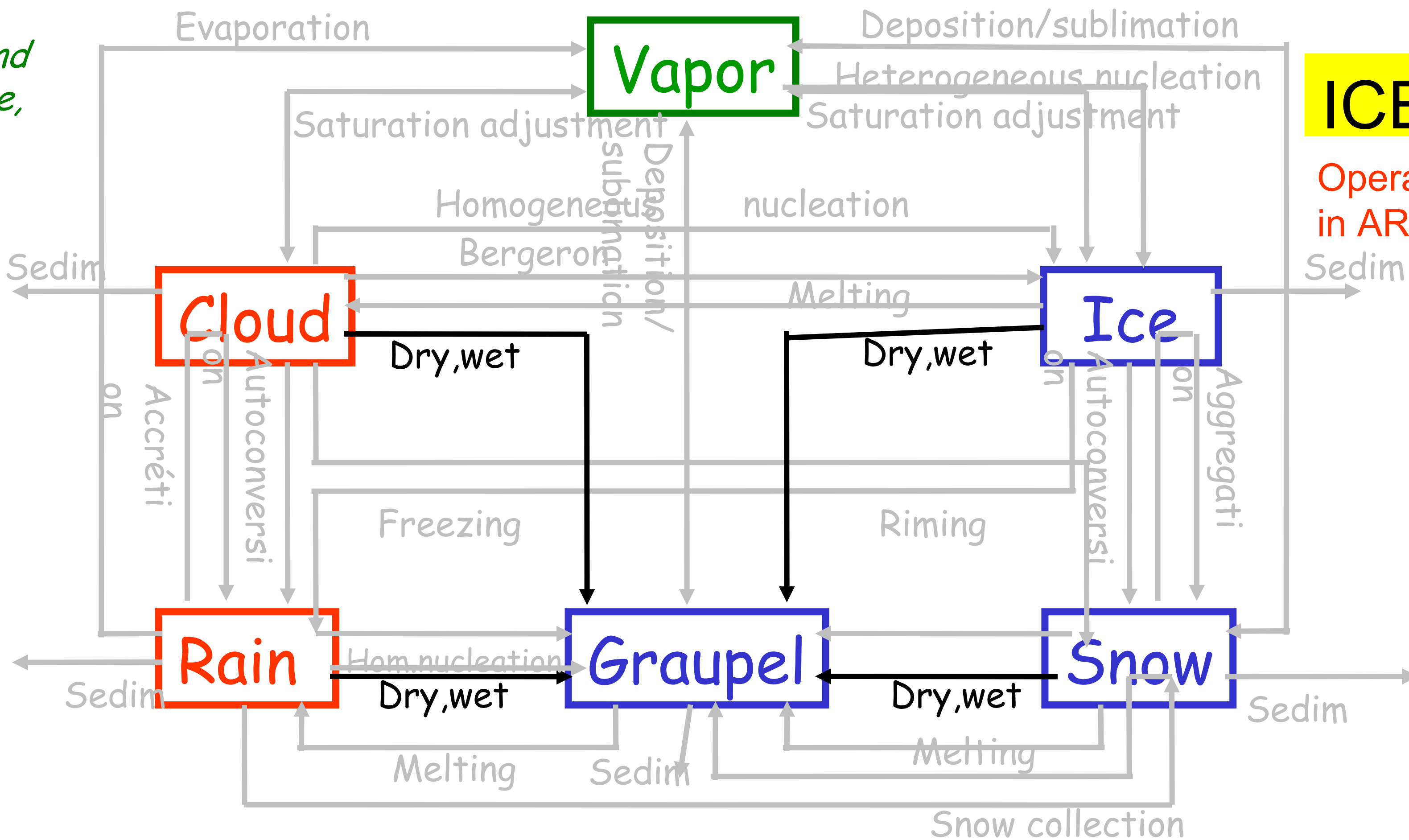
=> HAIL

ICE3 : Dry and wet growth lead to graupel
ICE4 : Wet growth leads to hail

Shedding important source of new raindrops (Wisner et al., 1972).
New raindrops may serve as new hailstone embryos (Rasmussen and Heymsfield, 1987).

Méso-NH and AROME : ICE3 1-moment scheme

(Pinty and Jabouille, 1998)

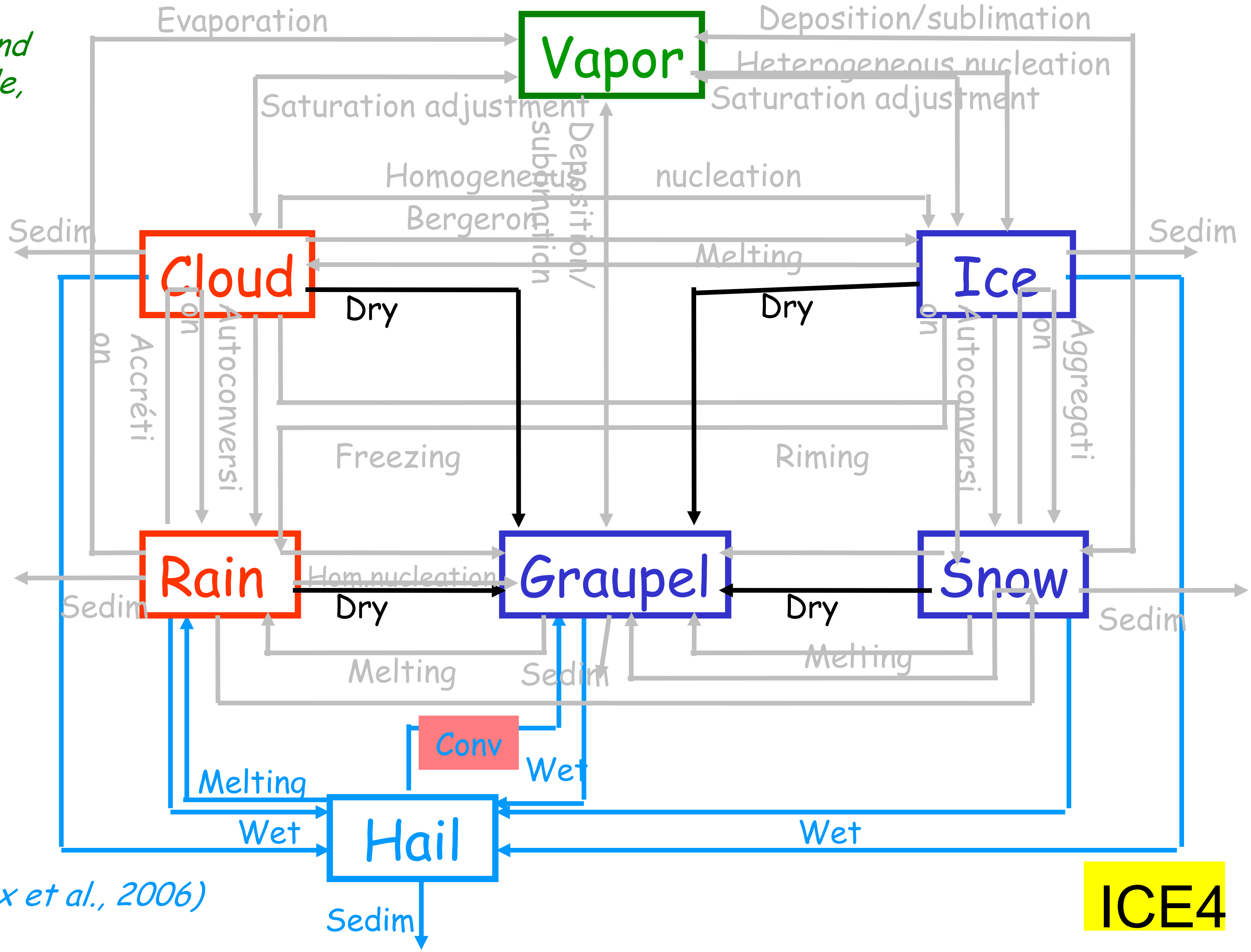


ICE3

Operational in AROME

Méso-NH and AROME : ICE4 1-moment scheme

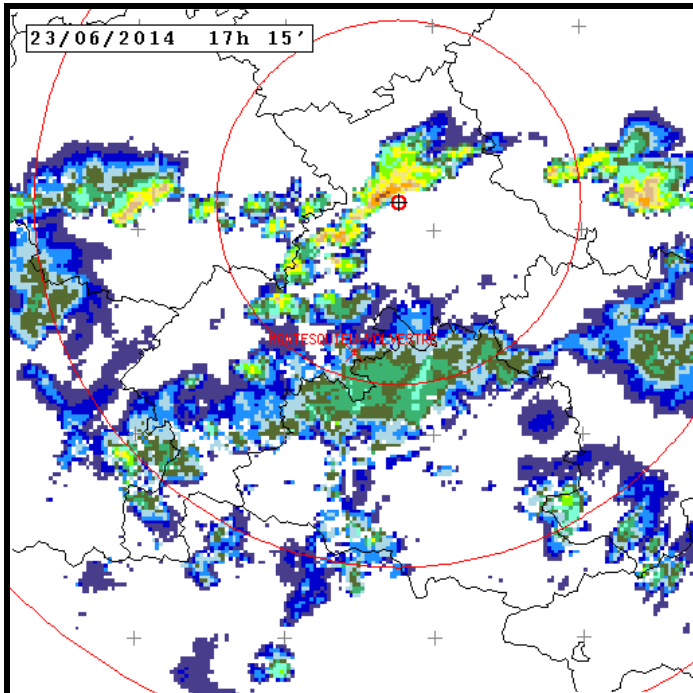
(Pinty and Jabouille, 1998)



(Lascaux et al., 2006)

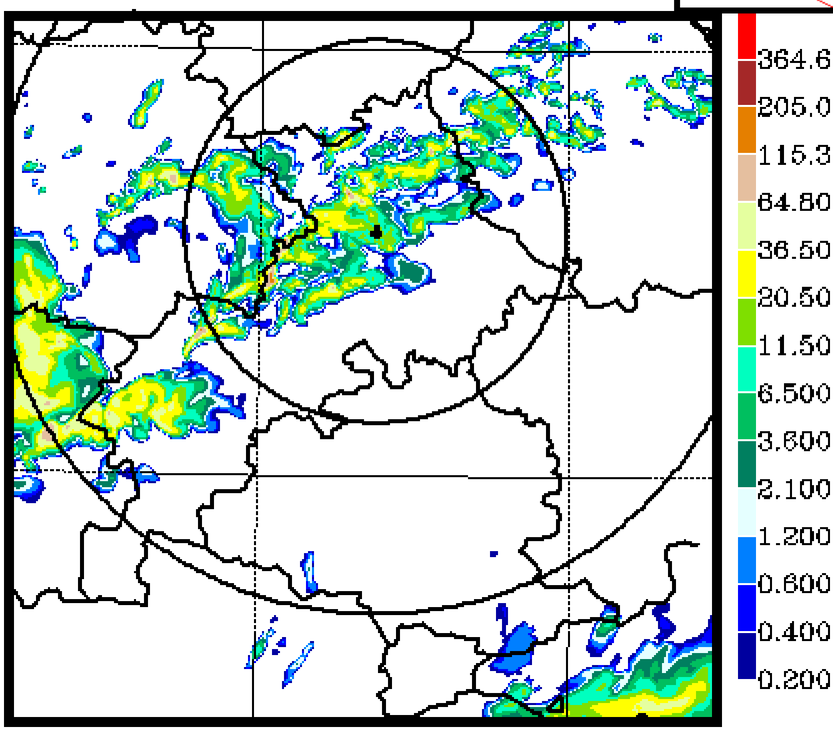
ICE4

Instantaneous
Precipitation rate (mm/h)
Toulouse radar
17h15 TU



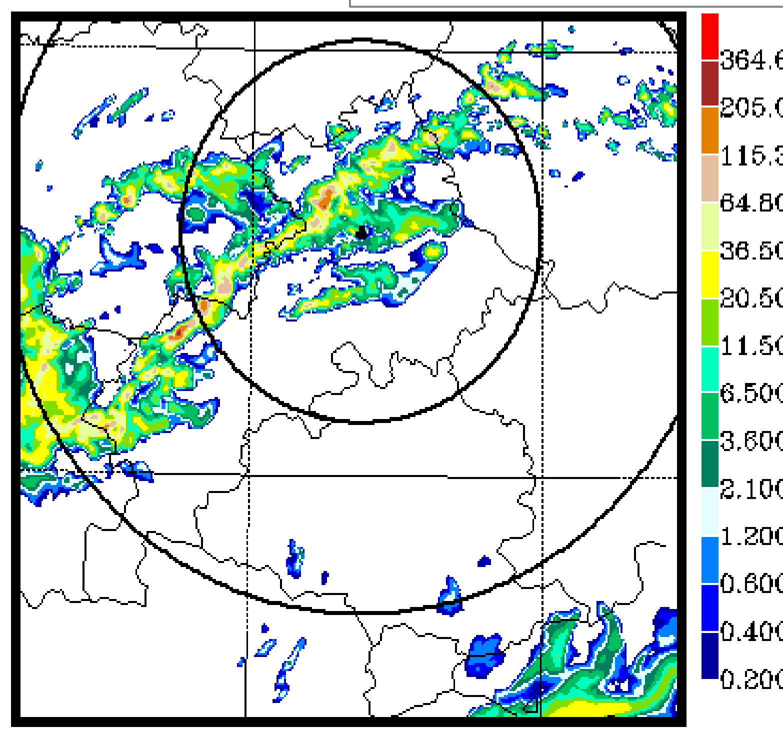
ICE3

Δx=500m

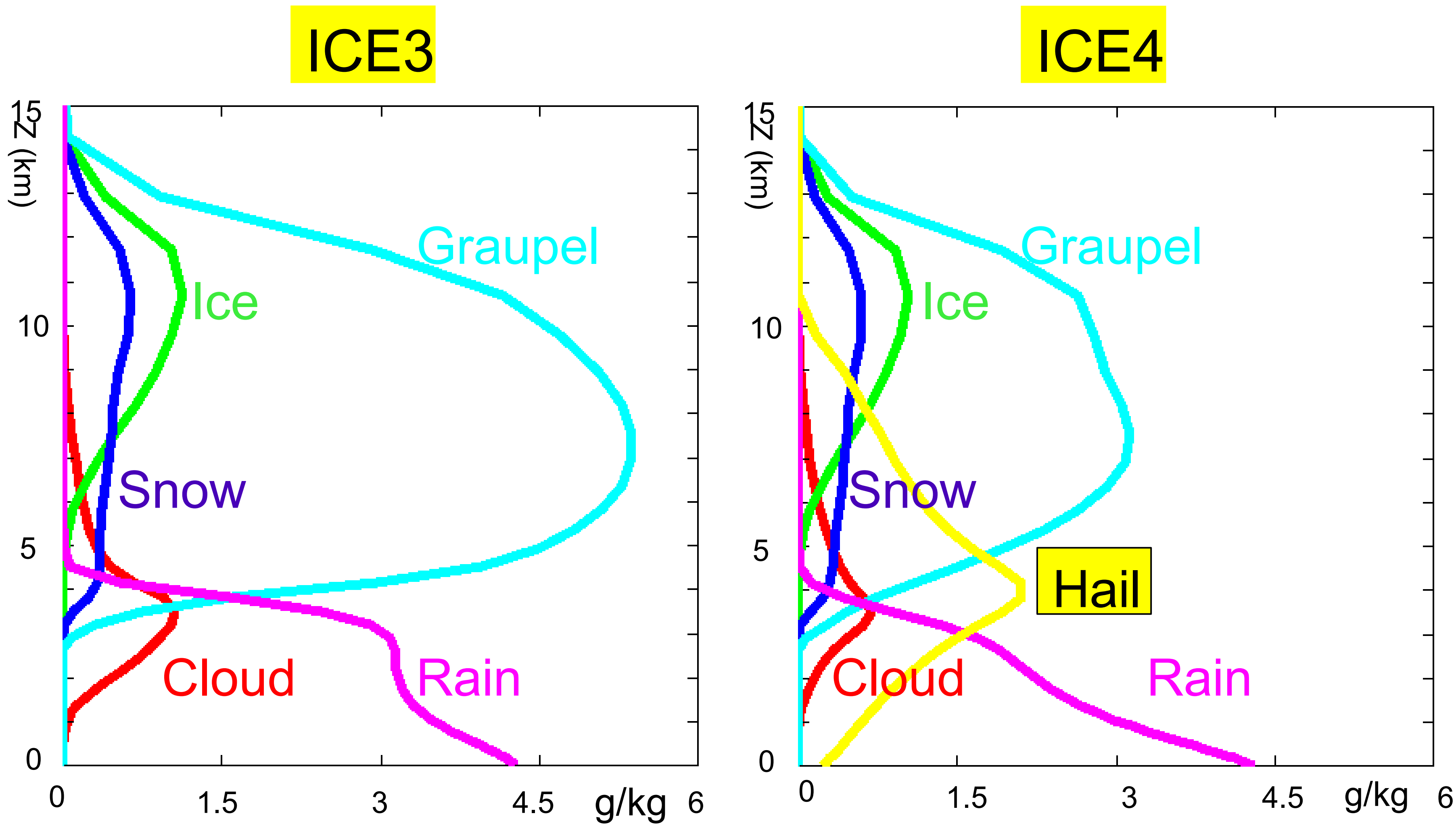


ICE4

Stronger precipitation

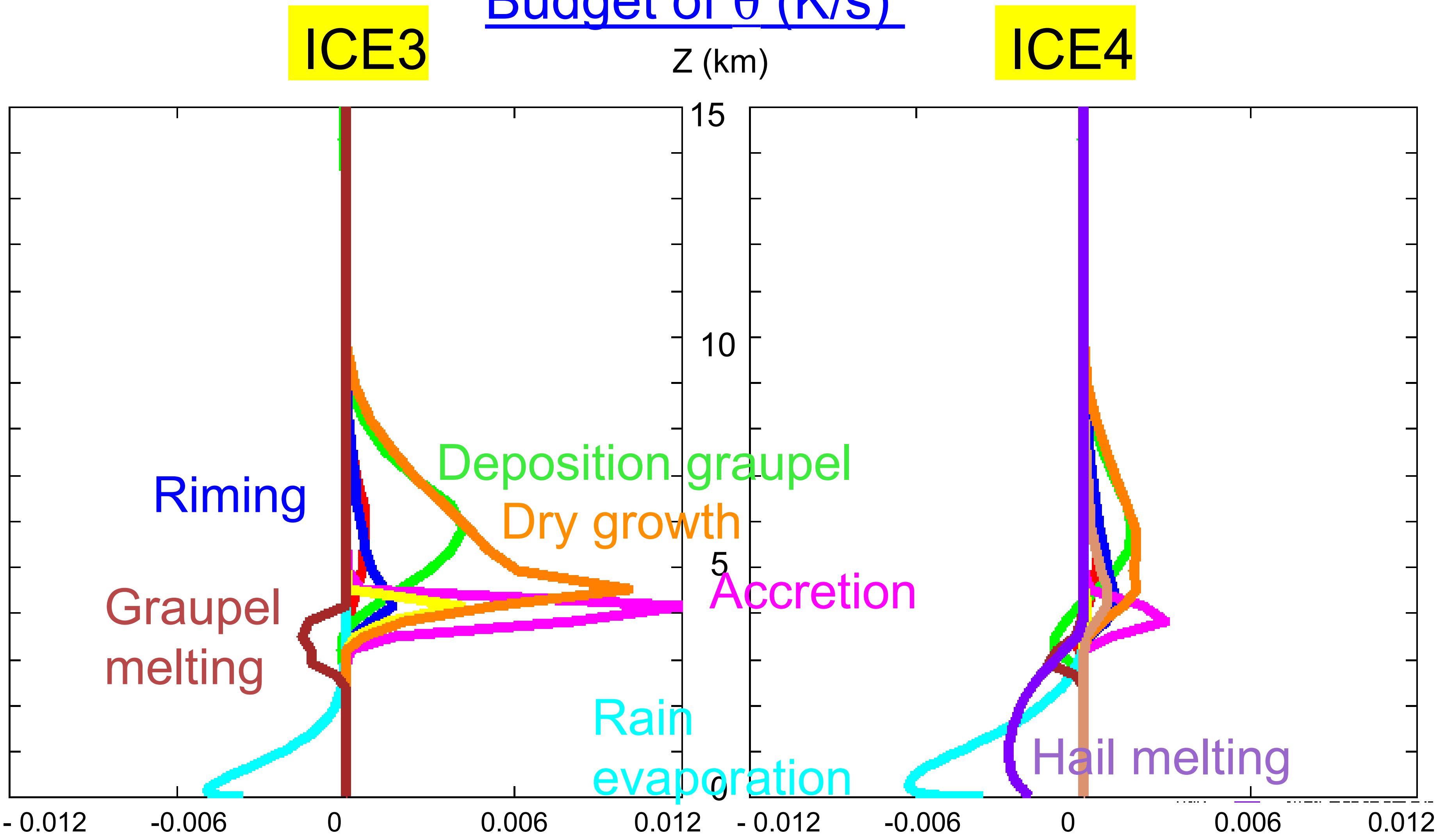


Hydrometeor budget



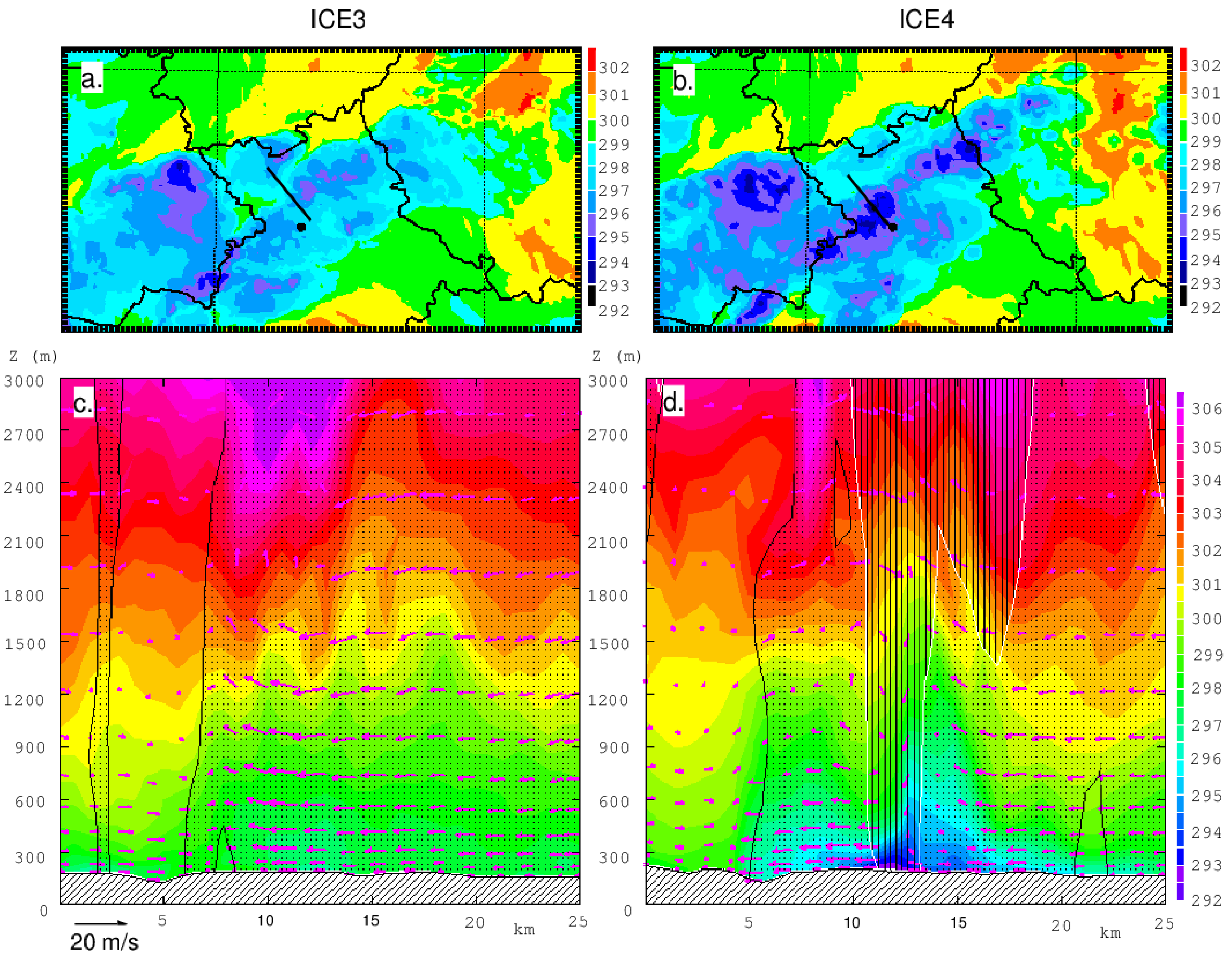
1-hour mean mixing ratios over area where ground precipitation rate > 100 mm/h

Budget of θ (K/s)



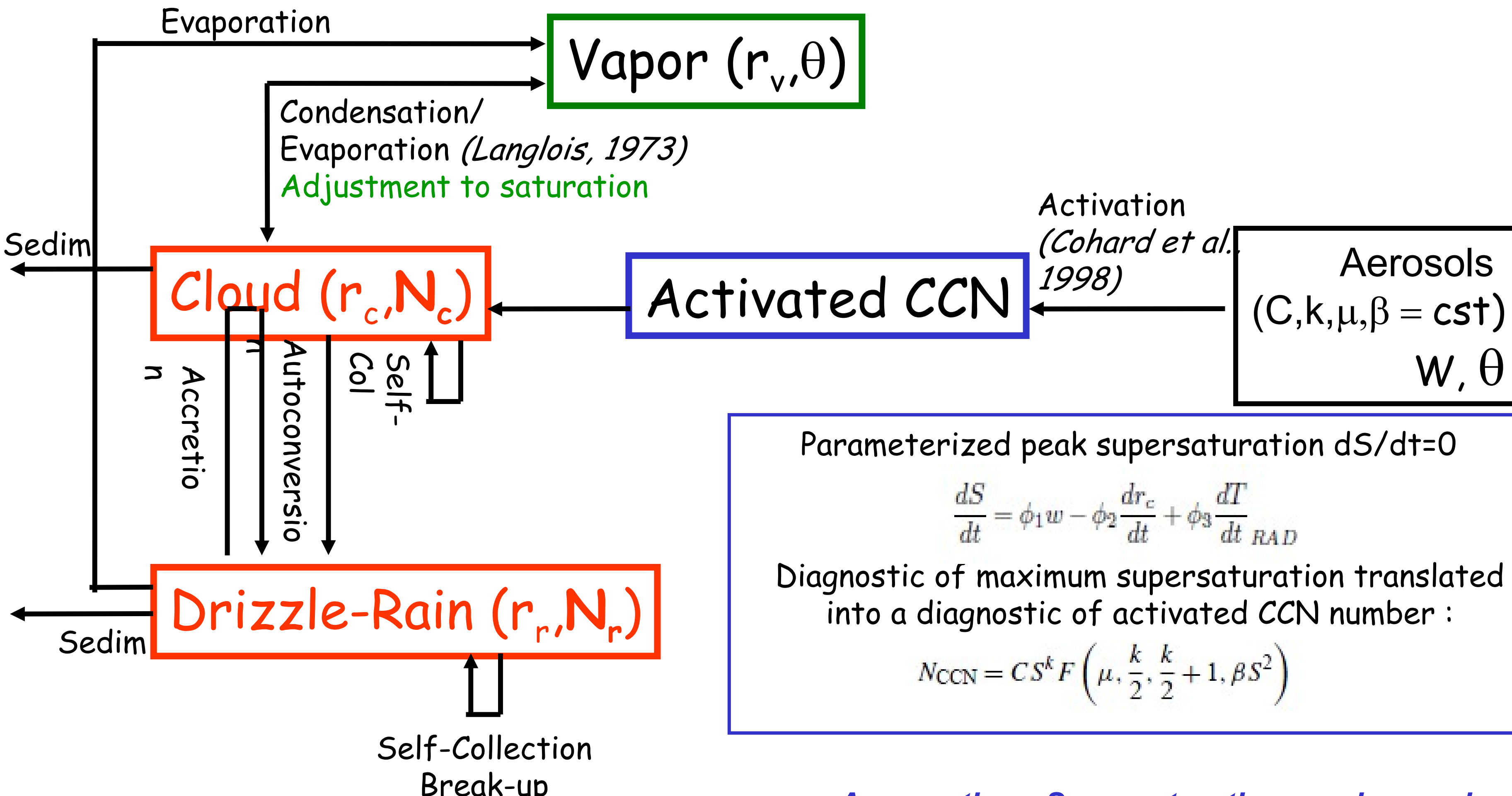
ICE3 : Heating in the mid-troposphere due to dry growth and deposition on graupel and accretion on droplets

ICE4 : Cold pool stronger and deeper due to hail melting and stronger evaporation rate.
Low level convective dynamics reinforced.


ICE3
ICE4
a.
b.
c.
d.
302
301
300
299
298
297
296
295
294
293
292
Z (m)
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
5
10
15
20
25
km
20 m/s
306
305
304
303
302
301
300
299
298
297
296
295
294
293
292

Meso-NH : Warm 2-moment microphysical schemes

Cohard and Pinty, 1998 for Cu ; Geoffroy et al., 2008 for Sc-St



Parameterized peak supersaturation dS/dt=0

$$\frac{dS}{dt} = \phi_1 w - \phi_2 \frac{dr_c}{dt} + \phi_3 \frac{dT}{dt}_{RAD}$$

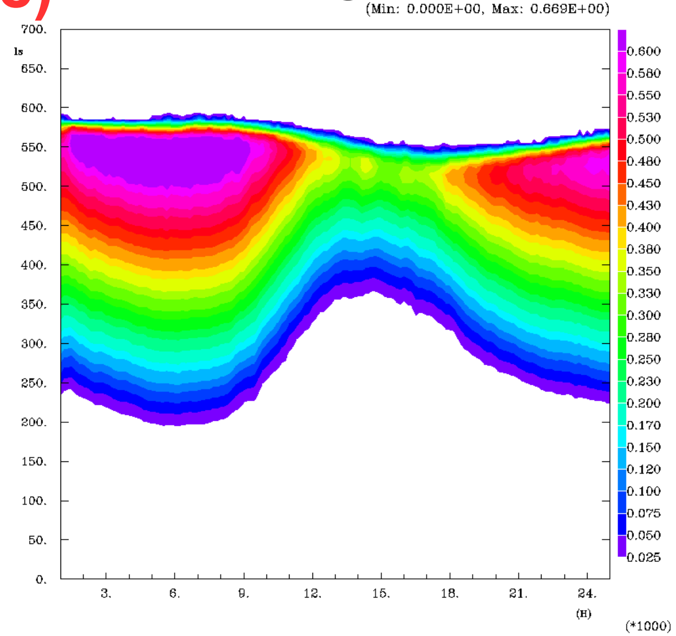
Diagnostic of maximum supersaturation translated into a diagnostic of activated CCN number :

$$N_{CCN} = C S^k F\left(\mu, \frac{k}{2}, \frac{k}{2}+1, \beta S^2\right)$$

Assumption : Supersaturation reaches and passes its maximum within a time step

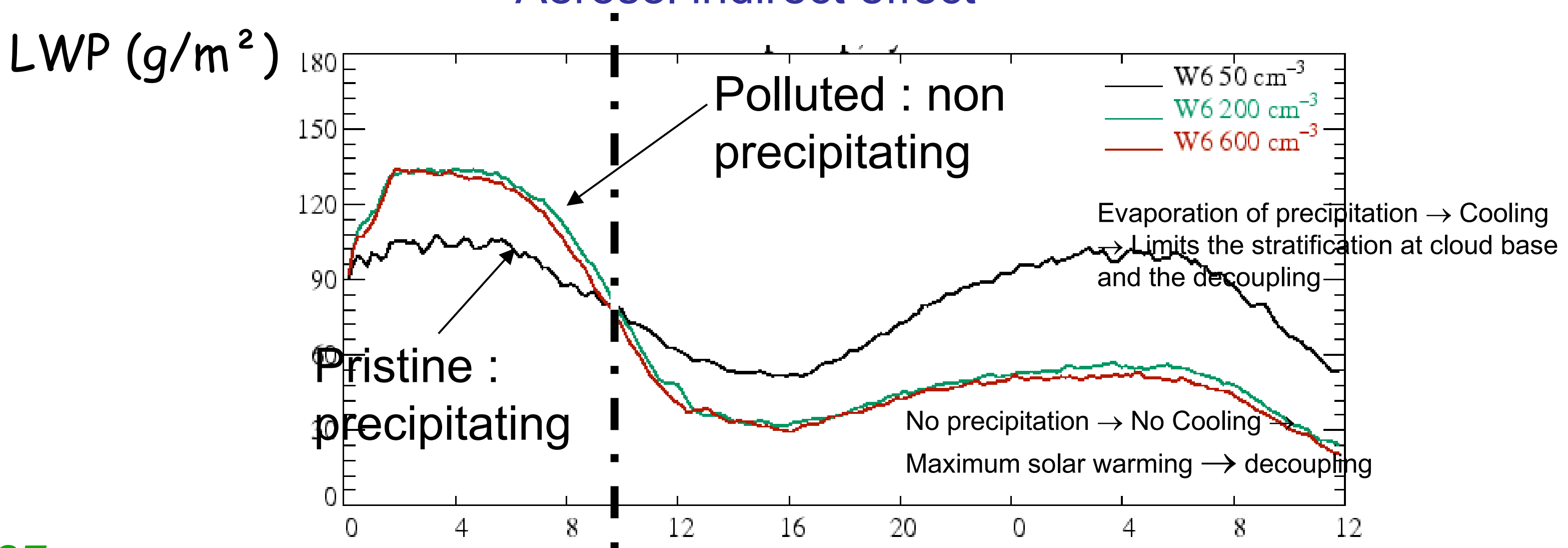
FIRE (Sc)

LES



$\Delta x = \Delta y = 50m$, $\Delta z = 10m$
T=36h

LES study : Impact of the pollution on the stratocumulus diurnal cycle = Aerosol indirect effect



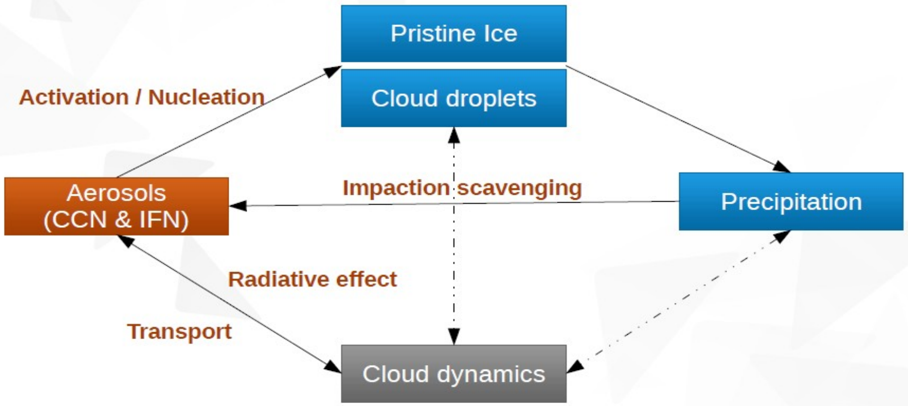
Sandu, I., 2007

The 2-moment microphysical scheme LIMA

LIMA : Liquid Ice Multiple Aerosols

Complex aerosols – clouds – precipitations interactions

Vié et al., 2015



- 2-moment, mixed-phase microphysical scheme in Meso-NH

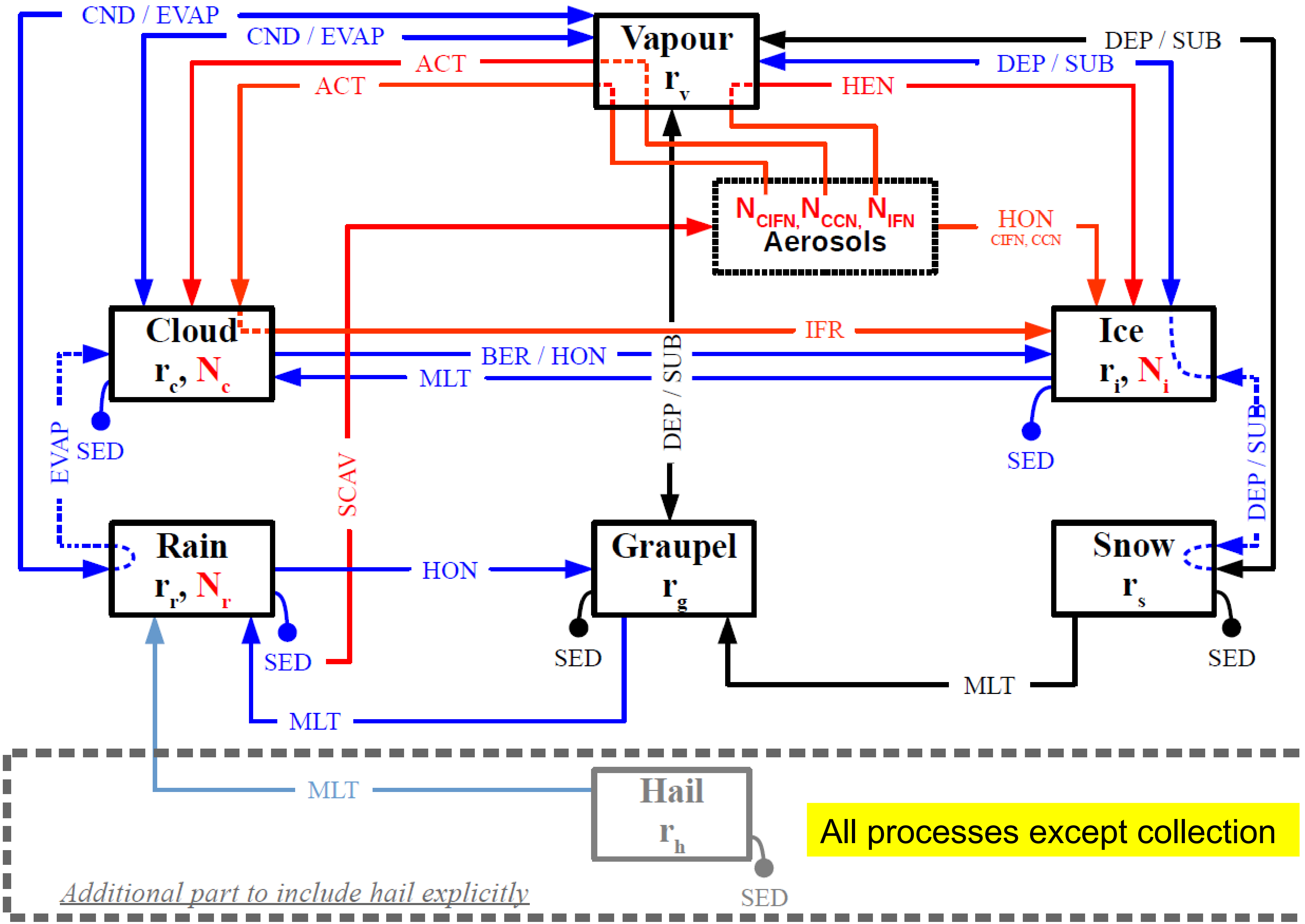
Free aerosols – Activated

N_{free} N_{act}

Droplets	Drops	Ice	Snow	Graupel	Hail
r_c N_c	r_r N_r	r_i N_i	r_s	r_g	r_h

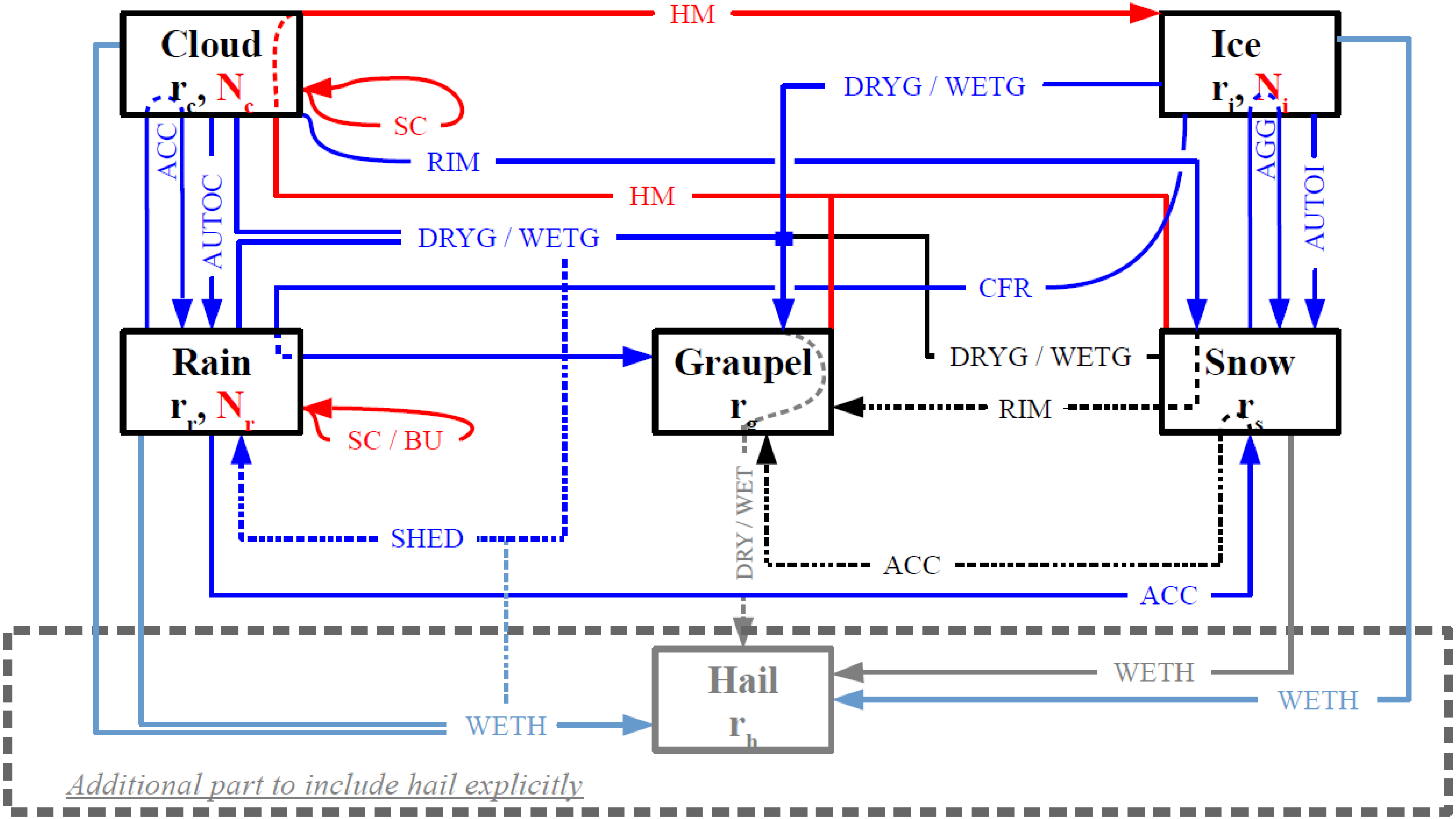
r: mass mixing ratio ($kg.kg^{-1}$) N: number conc. ($\#.kg^{-1}$)

- Prognostic evolution of a realistic aerosol population
  - Multimodal (lognormal psd), 3D externally mixed aerosols
  - Distinction between several types of CCN / IN / coated IN
  - MACC analyses provide realistic aerosol populations



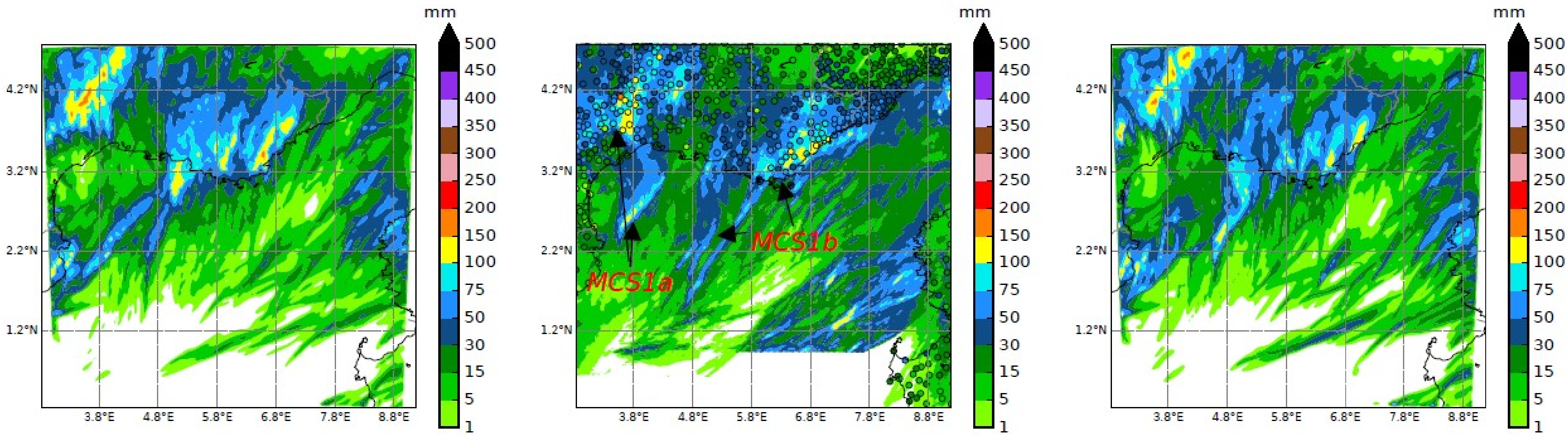
Vapour
r_v
Aerosols
N_{CIFN}, N_{CCN}, N_{IFN}
Cloud
r_c, N_c
Ice
r_i, N_i
Rain
r_r, N_r
Graupel
r_g
Snow
r_s
Hail
r_h
CND / EVAP
CND / EVAP
ACT
ACT
DEP / SUB
DEP / SUB
HEN
HON
CIFN, CCN
IFR
BER / HON
MLT
DEP / SUB
EVAP
SED
SED
SCAV
HON
SED
SED
SED
MLT
MLT
DEP / SUB
MLT
SED
All processes except collection
Additional part to include hail explicitly

Collection processes

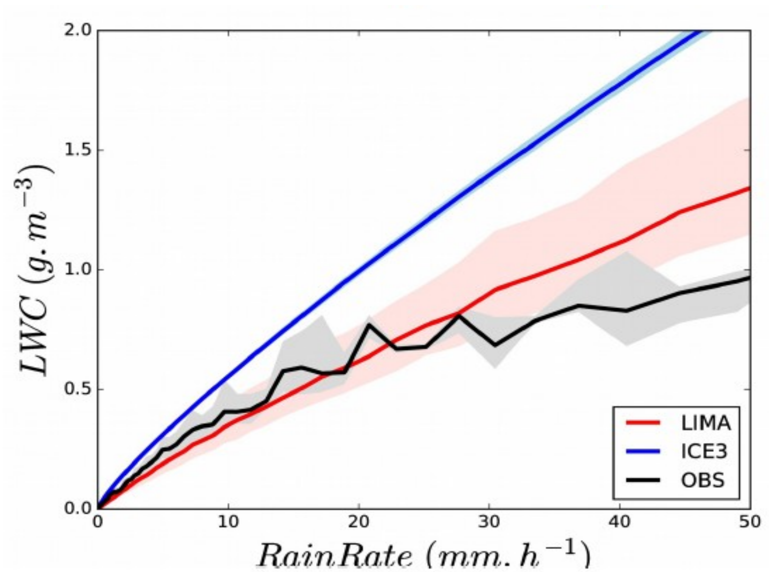


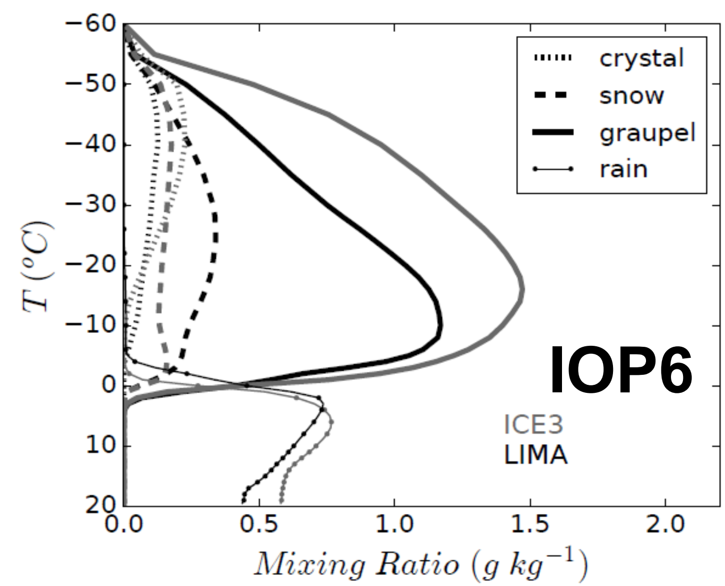
Application to HYMEX : IOP16

Taufour et al., 2018



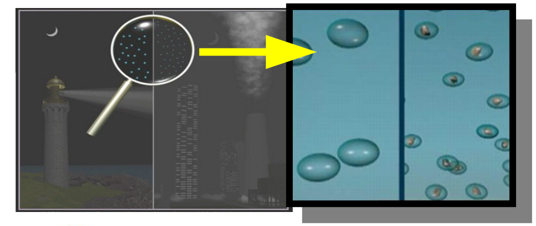
(a) ICE3 (b) Observations (c) LIMA

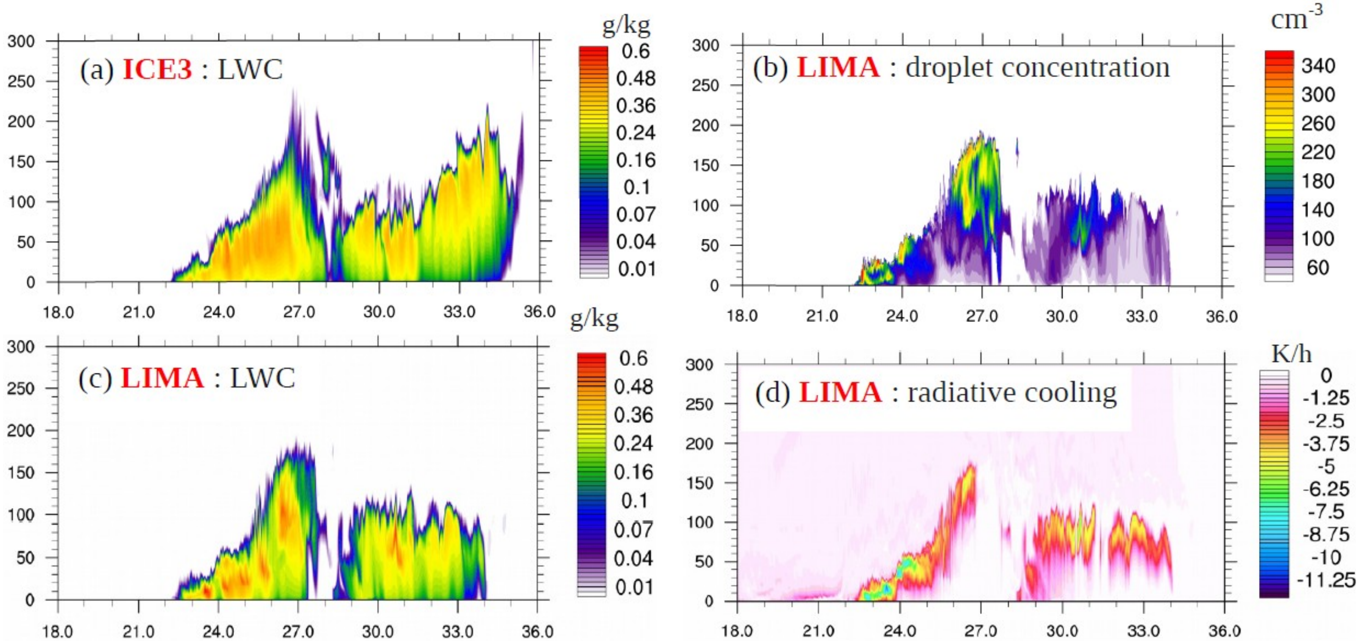




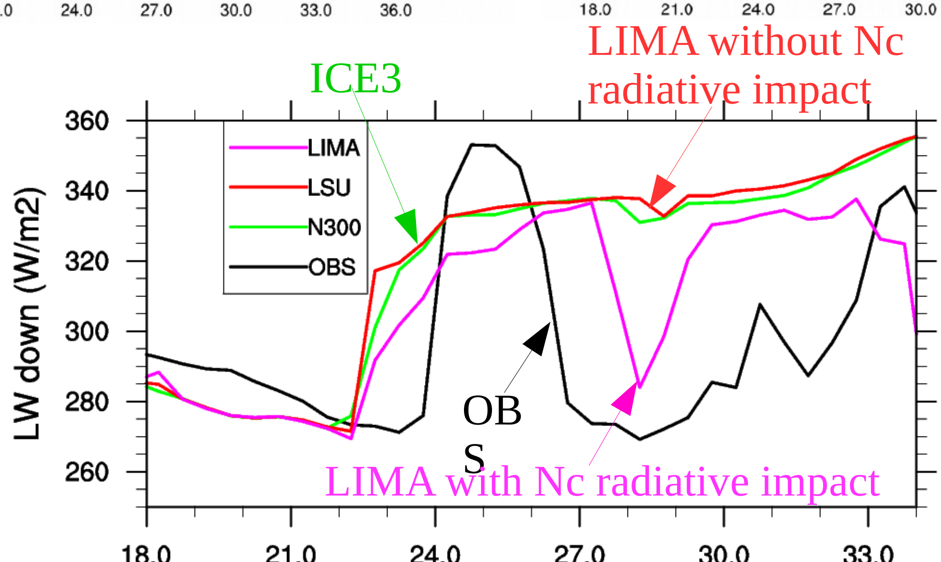
Impact on Fog (Léo Ducongé PhD)

For the same water amount, a fog can be optically thin (few big droplets) or thick (a lot of small droplets) → impact the development of the fog layer : Importance of a 2-moment scheme (Nc prognostic)





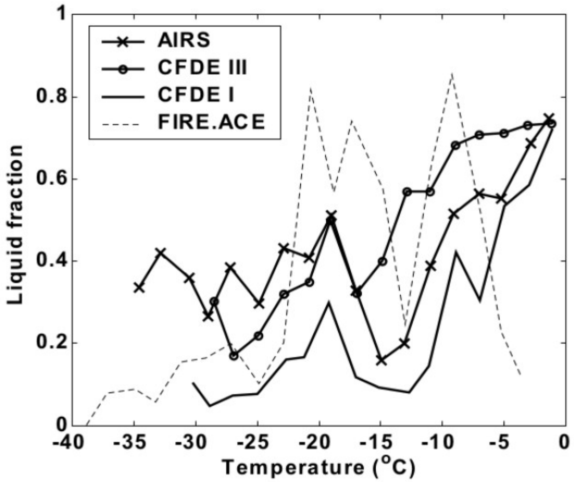
LIMA : realistic vertical variability



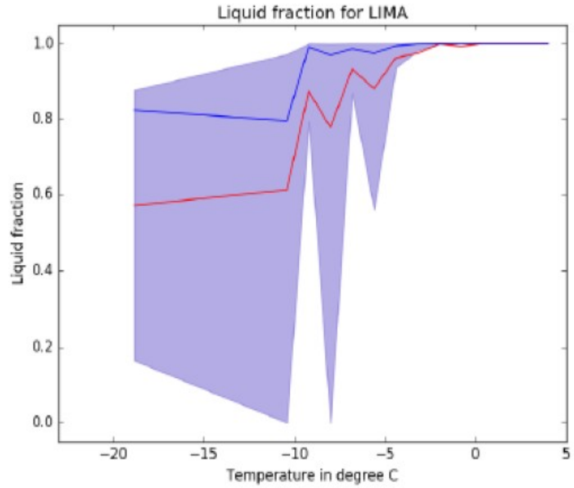
LIMA : impact on fog if cloud optical properties take into account Nc (Re,τ,g,SSA)

Partition liquid/ice water

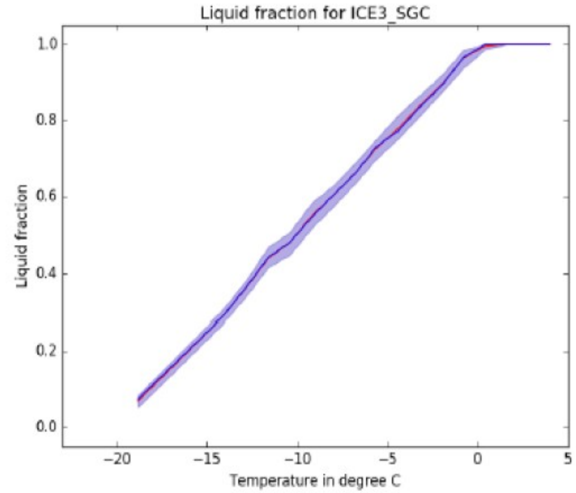
- Different studies have shown underestimation of supercooled water in AROME/Meso-NH (but not only) → impact for aircraft icing



LIMA



ICE3



Observations from different campaigns on Sc. Boudala et al. (2004)

Simulation of 25 flights during an aircraft icing campaign. From M. Cassas

- Necessity to improve and validate the partition for different mixed cloud types

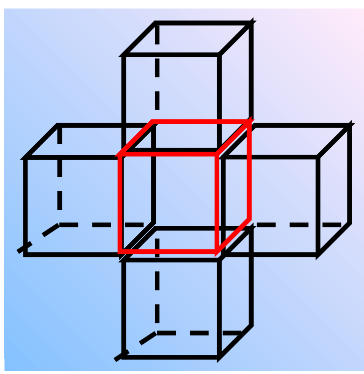
FAST MICROPHYSICS : Adjustment to saturation

At the end of the Δt, the guesses of r_v, r_c, r_i et θ à $t+\Delta t$ are adjusted consistently to satisfy strict saturation criterium : any deficit or excess of vapor is compensated or absorbed by cloud species : Essential as it produces the cloud and ice amounts and defines the temperature

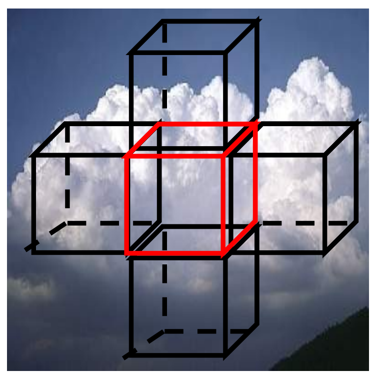
$\rightarrow$ 2 possibilities :

- « All or nothing » adjustment :

Cloud fraction = 0 or 1



OR



a/ *No saturated case*

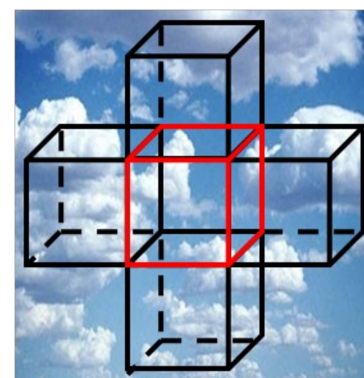
$\Rightarrow$ **Clear sky** $\overline{r}_c = 0$

b/ *Fully saturated*

$\Rightarrow$ **Fully cloudy** $\overline{r}_c = \overline{r}_t - r_{sat}(\overline{T})$

Correct only for resolved clouds

- Subgrid adjustment : Cloud fraction (between 0 and 1) computed from the subgrid variability given by the turbulence or/and the shallow convection, through a PDF

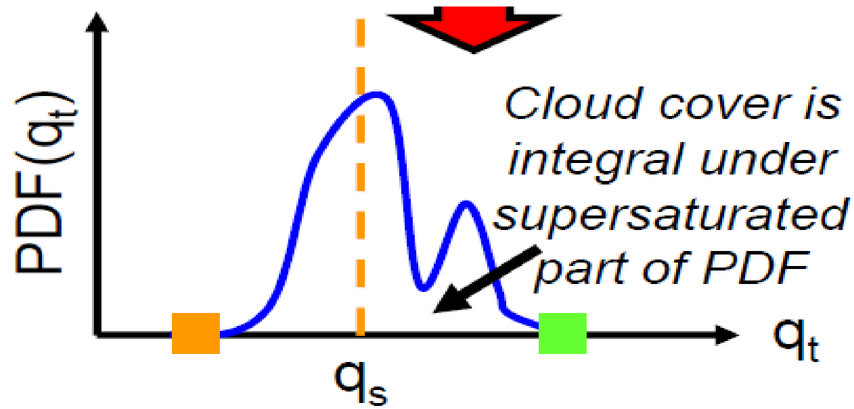


Correct for all cloud types (resolved and subgrid)

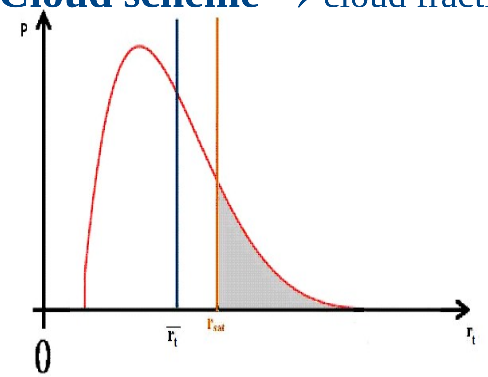
Subgrid cloud schemes

$$C = \int_{q_s}^{\infty} PDF\,(q_t)\,dq_t$$

$$q_c = \int_{q_s}^{\infty} (q_t - q_s)\,PDF(q_t)\,dq_t$$



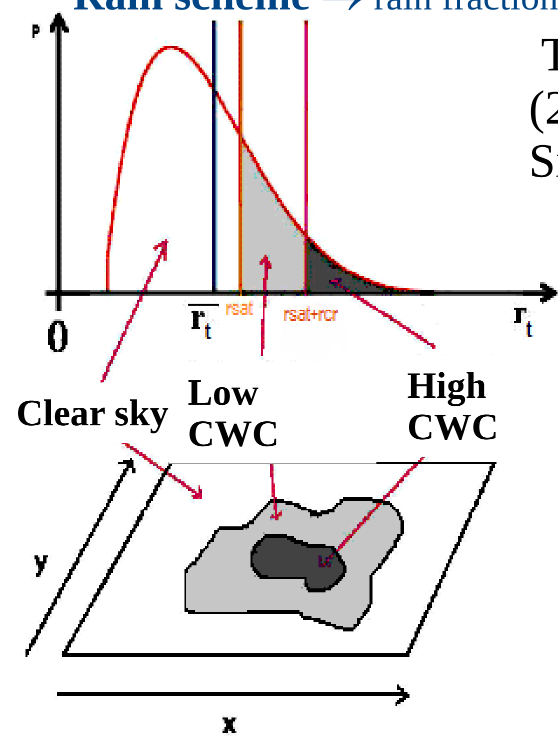
Cloud scheme → cloud fraction



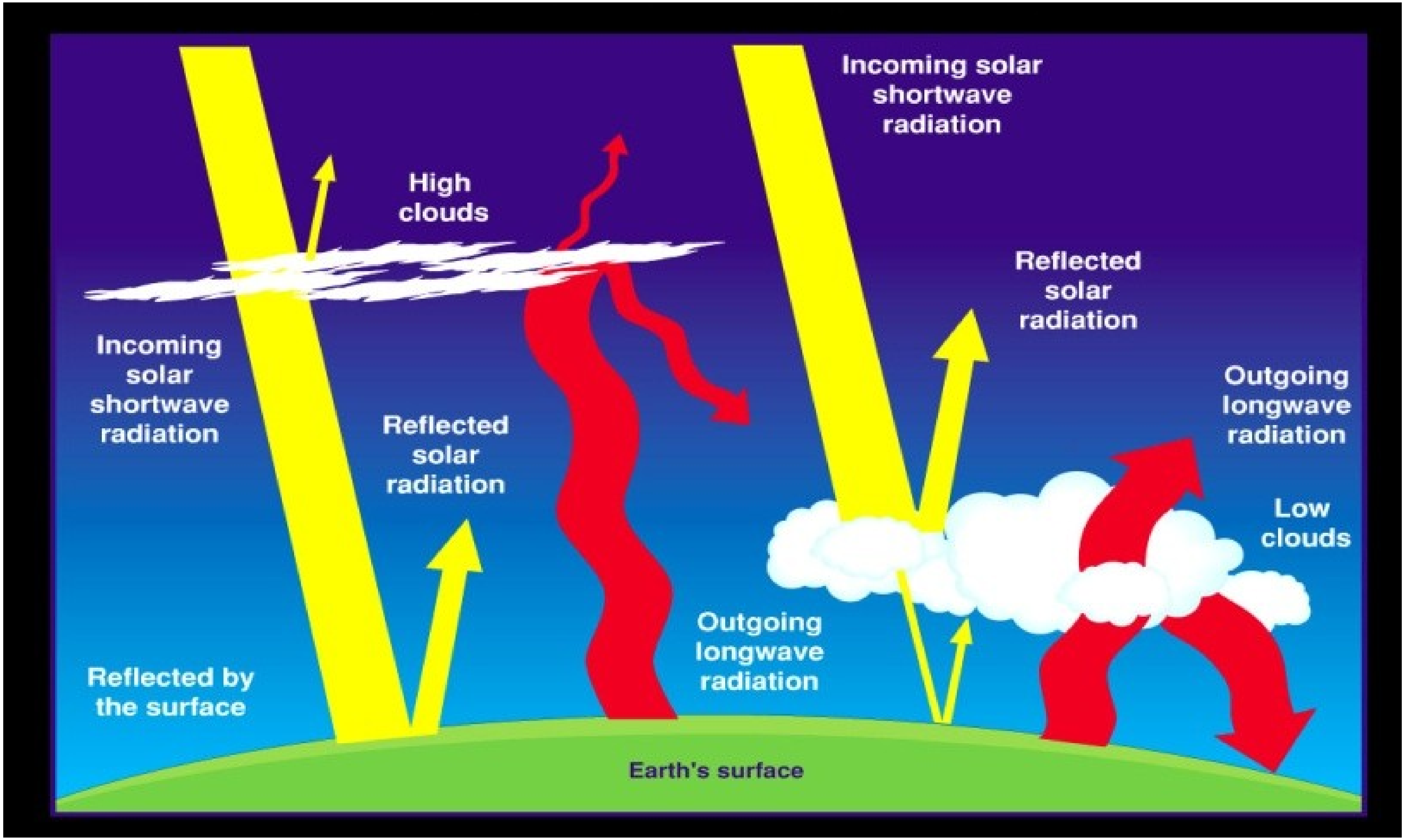
Operational : Combination of Gaussian and skewed exponential PDFs (Chaboureau and Bechtold, 2002) from turbulence + CF from EDMF scheme

Rain scheme → rain fraction

Turner et al. (2012) Simple PDFs



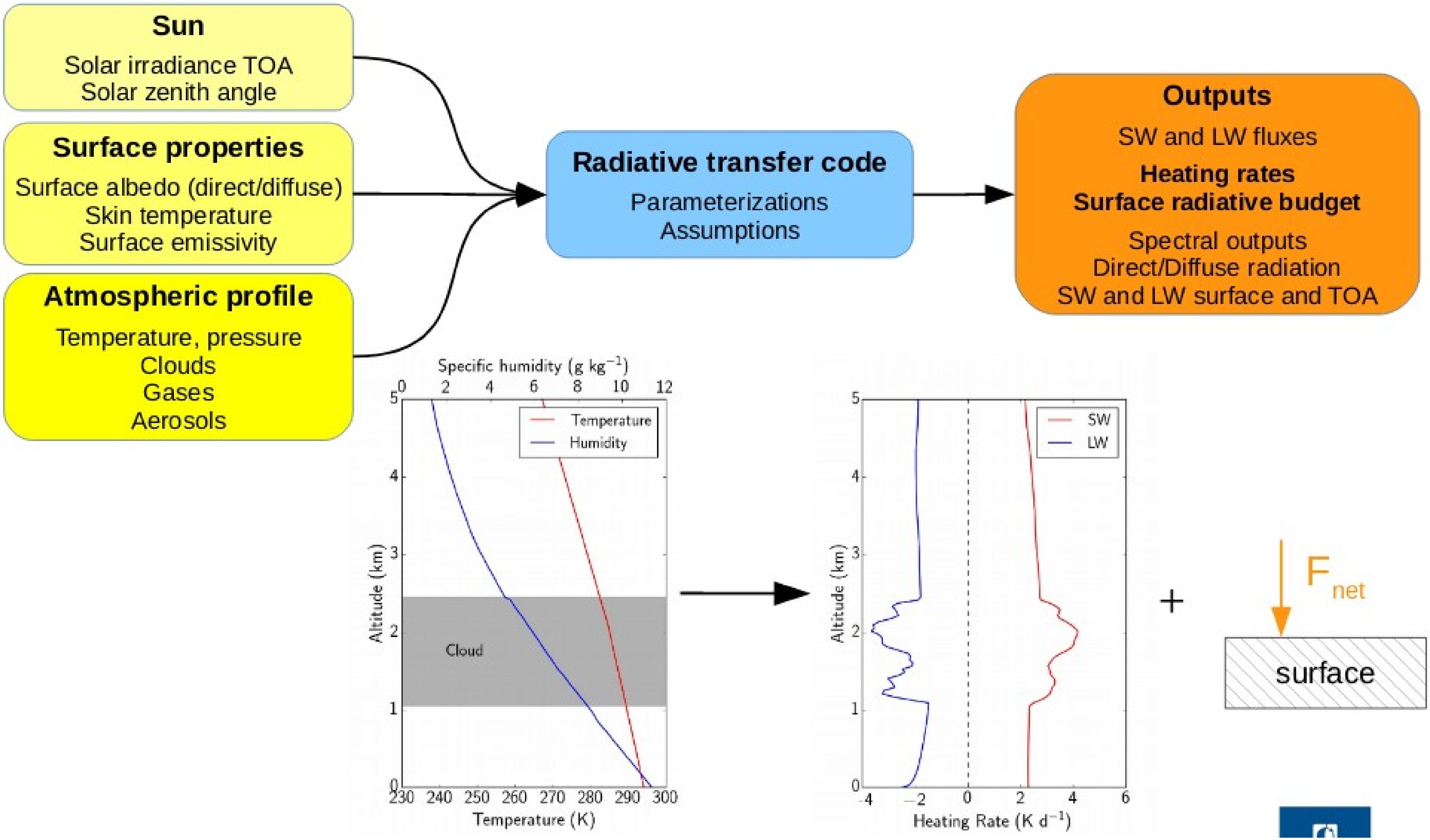
Radiation



SWnet=SW ↓– SW↑

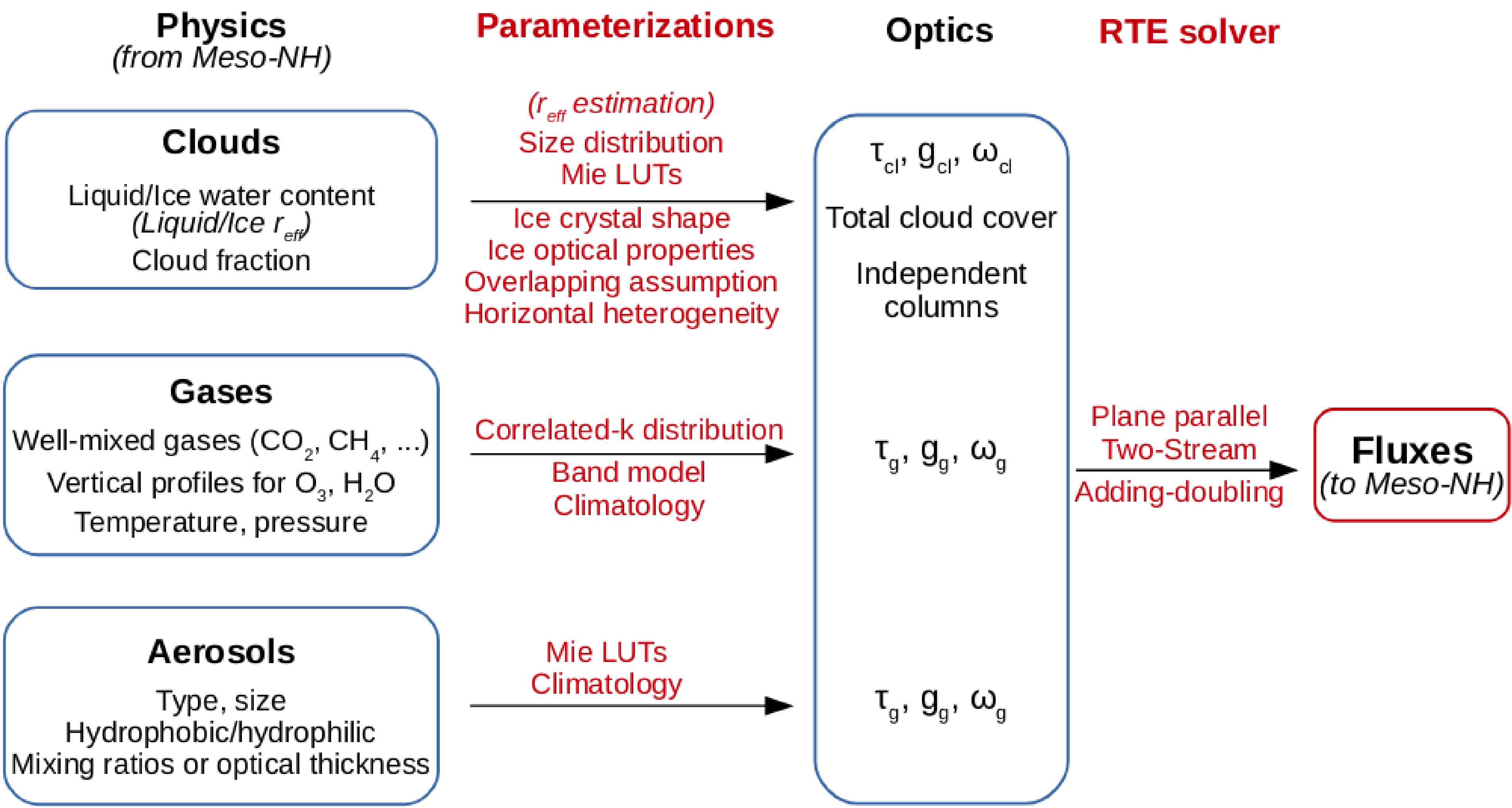
LWnet=LW ↓– LW↑

Reminder - What does an atmospheric radiative transfer code do ?



Q. Libois (2019)

Reminder - What is parameterized ?



Q. Libois (2019)

Radiation schemes :

2 radiation codes : **ECMW** or **ecRad** (Hogan and Bozzo, 2016)

- 1D scheme : parallel plan assumption. But with ecRad, possibility of 3D parametrization with SPARTACUS
- Expensive cost -> called at a lower frequency than Δt.

- LW: Emission and absorption of telluric and atmospheric radiation :
  - LW scheme: 9 spectral bands
  - RRTM scheme : 16 spectral bands
- SW : Reflexion, diffusion and absorption of solar radiation :
  - SW scheme: 1 single : 6 spectral bands
  - SRTM (ecRad) : 14 bands

METEO FRANCE

Q. Libois (2019)

Reminder - What is ecRad ?

- Operational radiative code of ECMWF
  (Hogan and Bozzo, 2018 + technical note)
- **Highly modular**, making it easy to
  - perform sensitivity tests
  - implement new parameterizations, change climatologies, databases, LUTs etc.
- **More physics**
  - 14 vs 6 bands in SW (RRTM-SW)
  - Cloud horizontal heterogeneity
    (McICA, TripleClouds, FSD)
  - More cloud overlap assumptions options
    (Max-Ran, Exp-Ran, Exp-Exp)
  - LW scattering
  - Updated water vapor spectroscopy
  - Reduced solar constant (1366 → 1361 W m^{-2})
  - 12 vs 6 aerosol species
    (hydrophilic/hydrophobic, mixing ratios)
  - Refined climatologies (CAMS)
  - 3-D radiative effects (SPARTACUS)
    (effective cloud size, clustering)

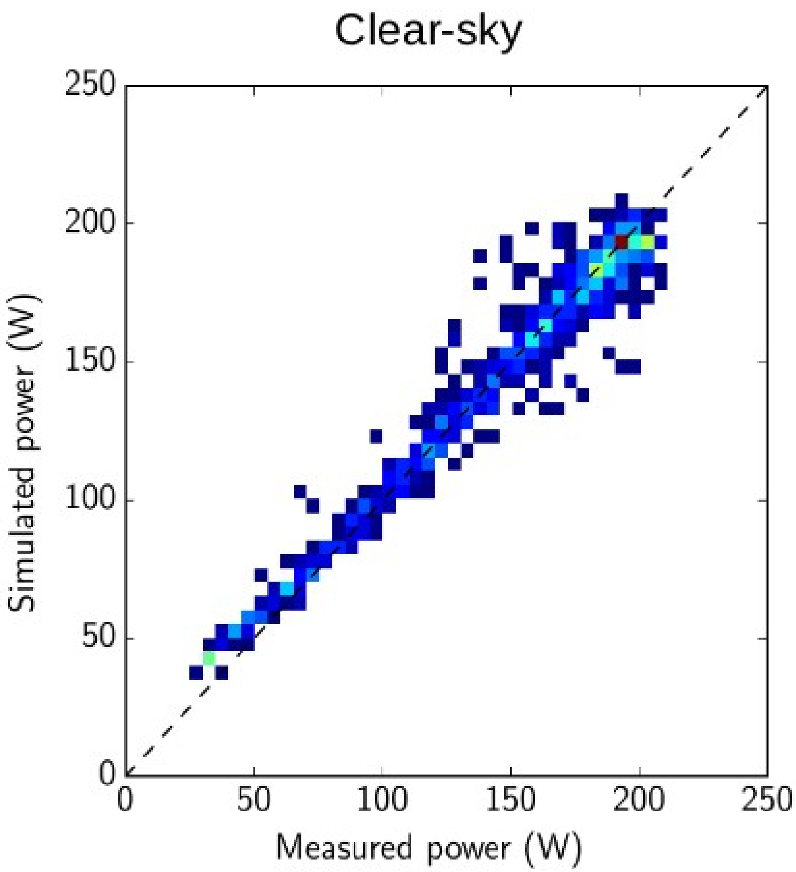
- **Two-stream code**
  → no communication between model columns
- δ-Eddington approximation
  → Direct SW fluxes contain scattered radiation
- **Novelties mostly useful for subgrid clouds**
- **Offline version available**
  → practical for new developments
- Available since MNH V. 5.4
- **Using ecRad in MNH**
  - Export MNH_ECRAD = 1
  - Create a directory *data* and link it to
    src/LIB/RAD/ecrad-1.0.1/data
  - compilation
  - CRAD = "ECRA"
- **Simulations with ecRad take more time** :
  → +10% with McICA
  → +20% with TripleClouds Solver
  → +100% with SPARTACUS

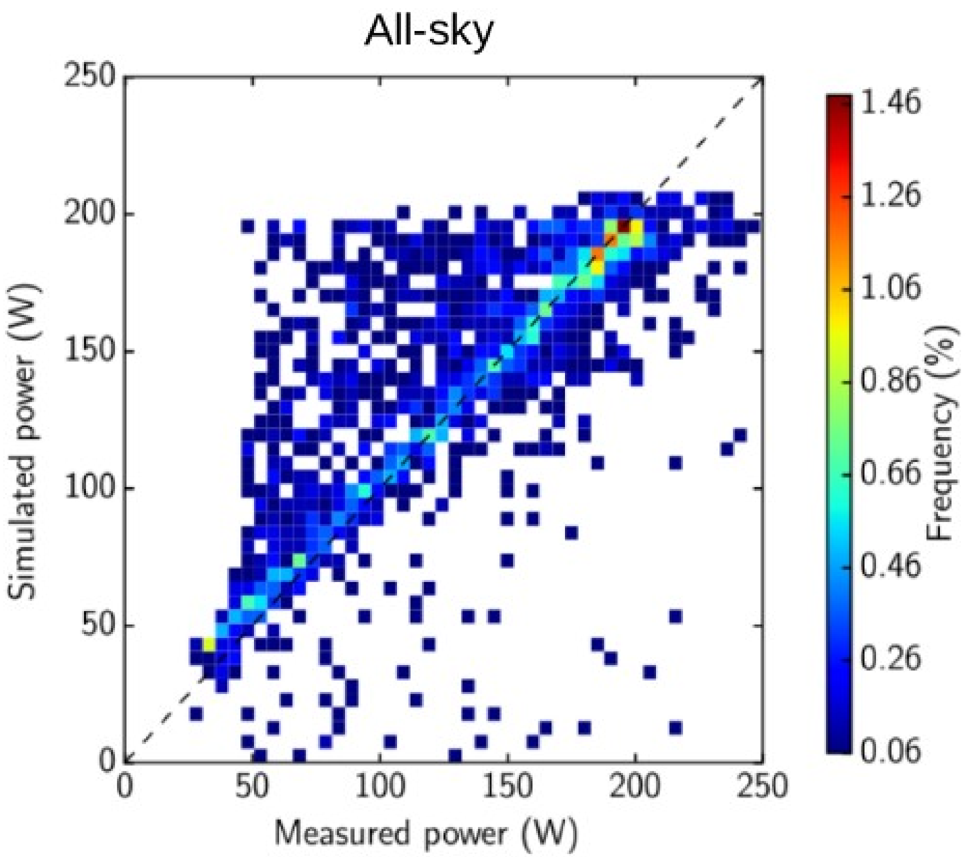
METEO FRANCE

Q. Libois (2019)

Application to solar energy

- PV code to convert Meso-NH outputs into PV power (Lindsay et al.)
- Case study on SIRTA (June 2017)

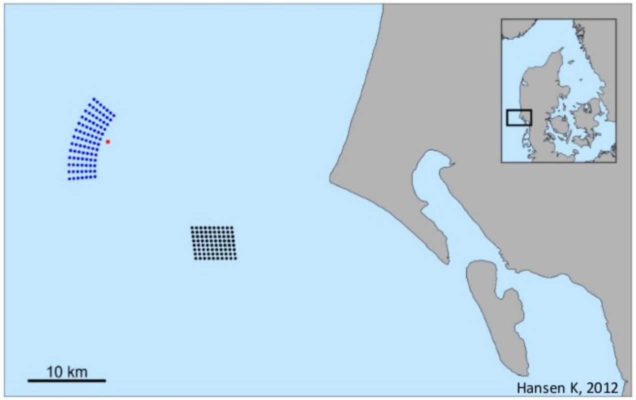




Lindsay and Libois (2020)

Wind Turbine

1. The Horns Rev 1 photo Case



Joulin, 2019

Photography

Simulation

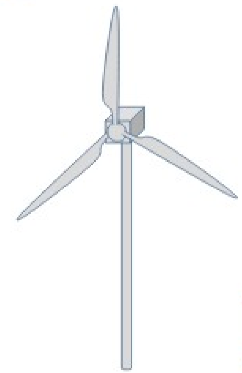
$\Delta x = 5m$

+ vidéos

Coupling with a wind farm

Joulin et al., 2020

Wind field around the wind turbine



METEO FRANCE

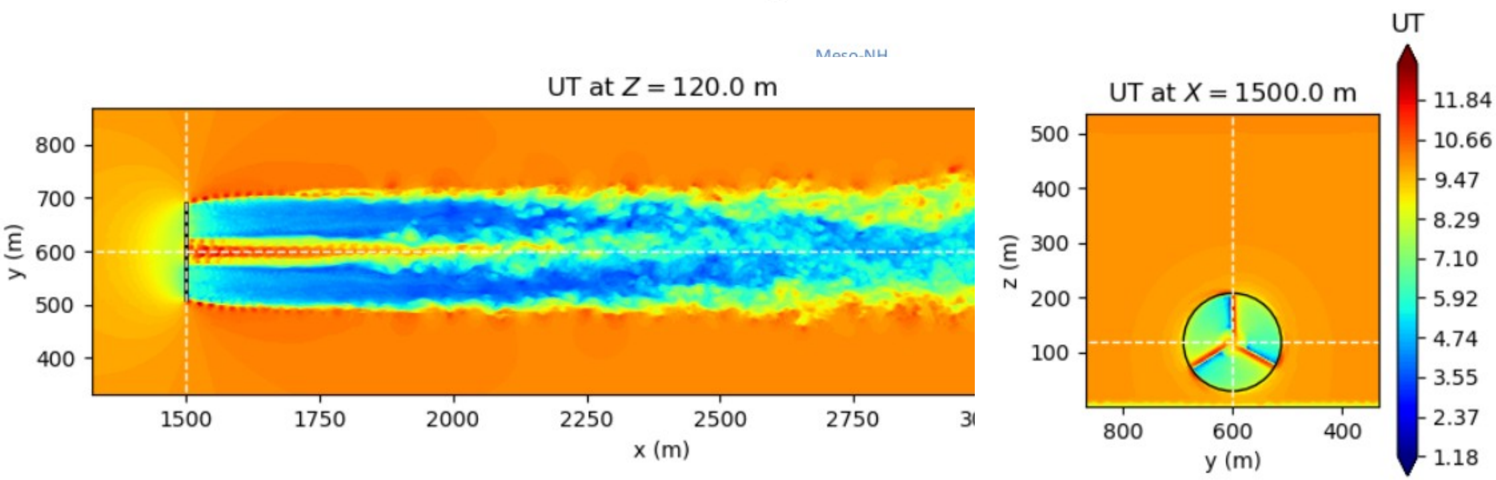
Meso-NH
mesoscale non-hydrostatic model

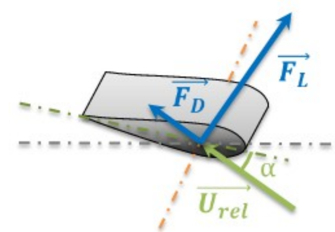
- Modelling the ABL
- LES Framework
- Resolution ~ 10m x 10m x 10m

IFP Energies nouvelles

- Actuator Disc without Rotation
- Actuator Disc with Rotation
- Actuator Line

Forces exerted by the wind turbines on the wind





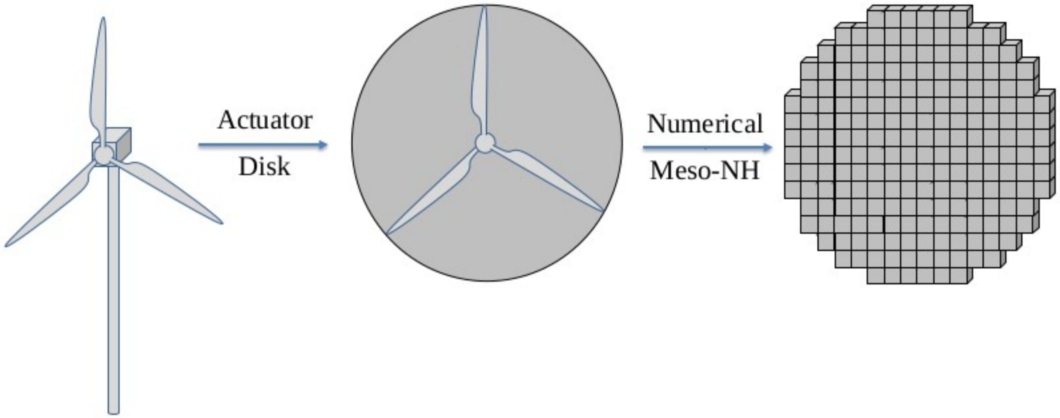
Aerodynamic forces :

$$F_D = \frac{1}{2}\rho\, S\, C_D\, U_{rel}^2$$

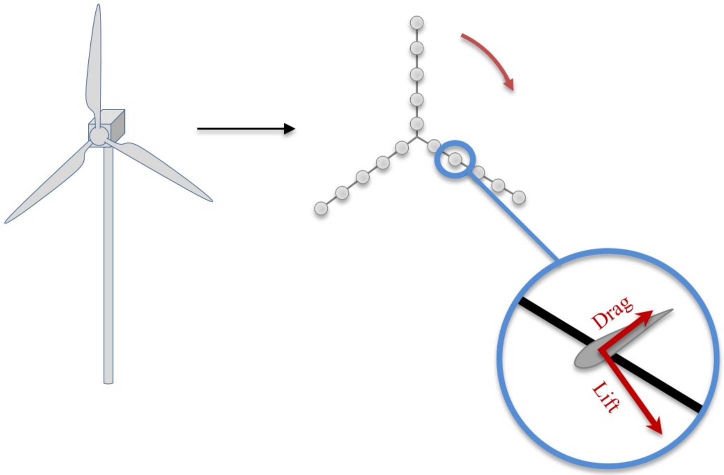
$$F_L = \frac{1}{2}\rho\, S\, C_L\, U_{rel}^2$$

Wind turbine

- 2 models (with LES)
  - Actuator Disk Non-Rotating (ADNR)



  - Actuator Line Method (ALM)



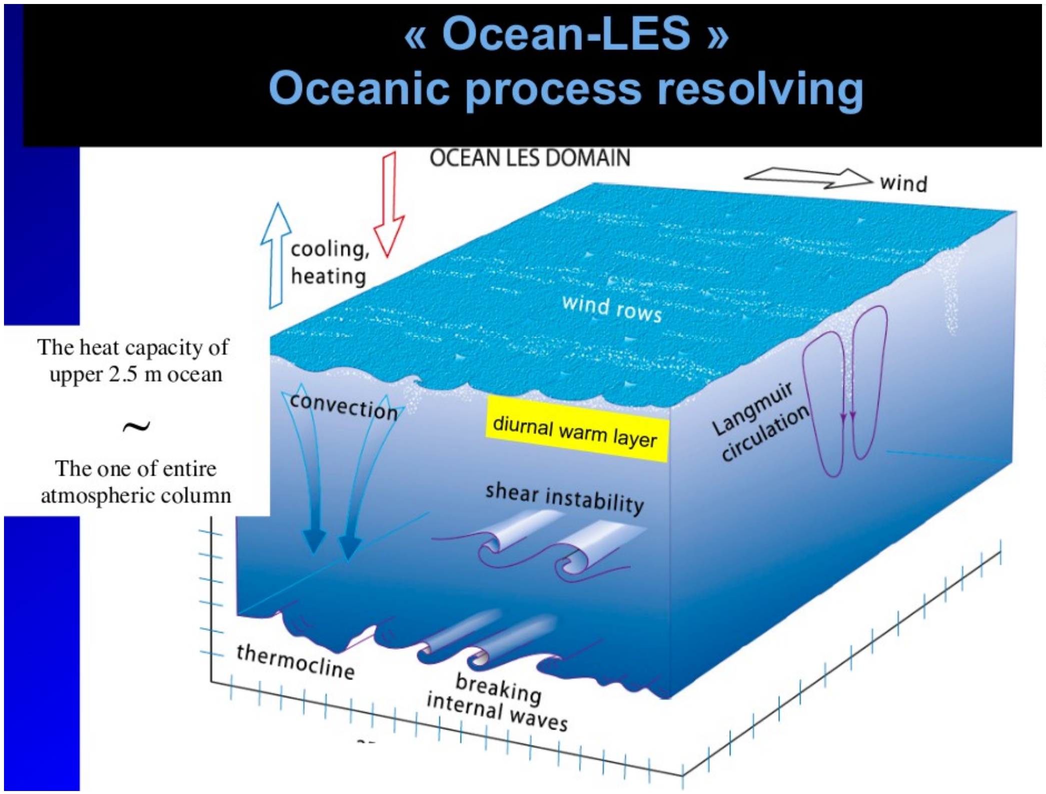
Outline

1. Introduction (a few illustrations)
2. Dynamics
3. Physics (without SURFEX)
4. A few words about on-line couplings : electricity, fire, chemistry/aerosols ...

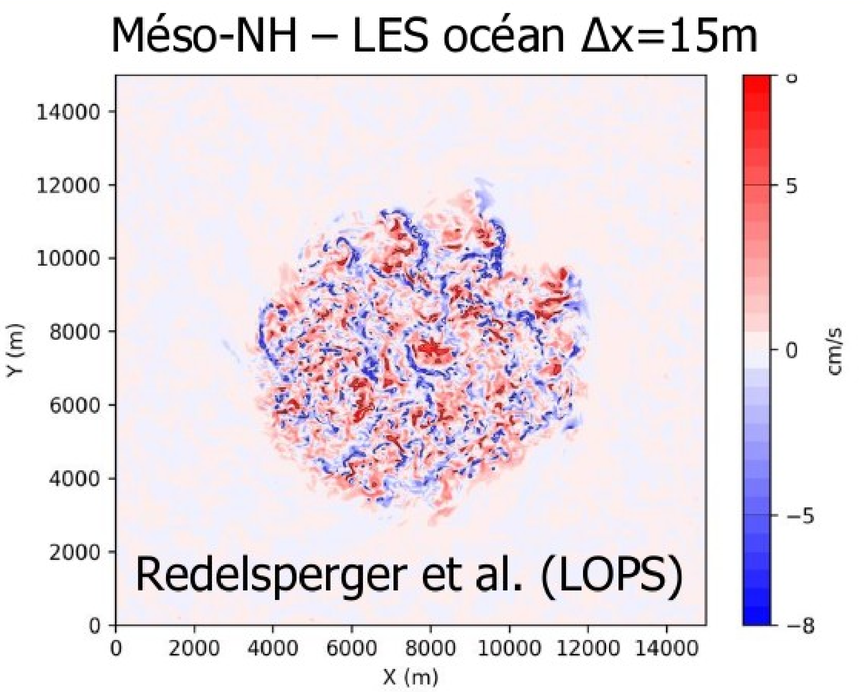
Meso-NH
mesoscale non-hydrostatic model

LES Ocean

Idealized NH simulation of ocean deep convection



Adapted from Hoecker-Martinez et al , JPO 2016



In current dev. : ocean-atmosphere online coupling (domain 1 = atm ; domain 2 = ocean)

Electrical scheme of MesoNH

3 CRM (Mansell et al., 2002; Barthe et Pinty, 2007; Fierro et al., 2013) with a complete explicit 3D electrical scheme.

- Prognostic equation for the charge density of each hydrometeor.

Source terms : turbulence, charging mechanism rates, sedimentation, charge neutralization by lightning flashes

- Charge separation mainly driven by non inductive charging mechanism

- Then charges can be exchanged between the different hydrometeor species during the microphysical processes

- Also equations for positive and negative ion concentrations

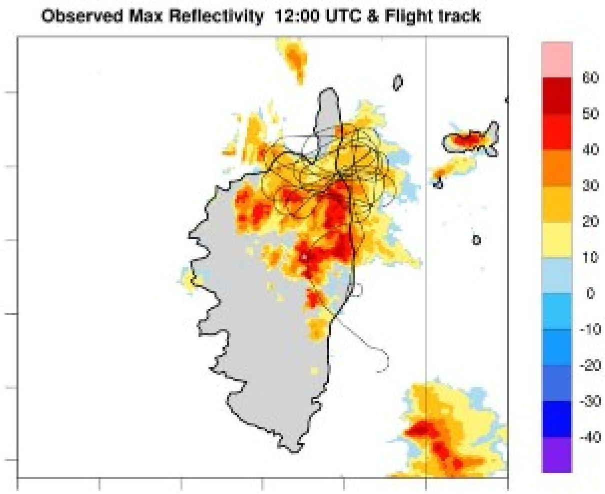
- Electric field computation

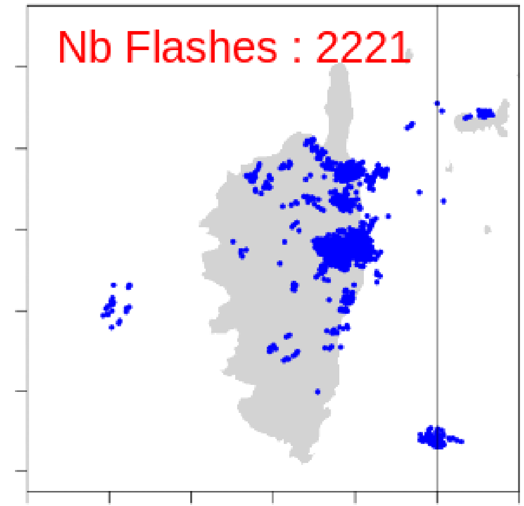
- Ligthning flashes and neutralization of charges

Explicit electrical scheme in Meso-NH

Pinty and Barthe

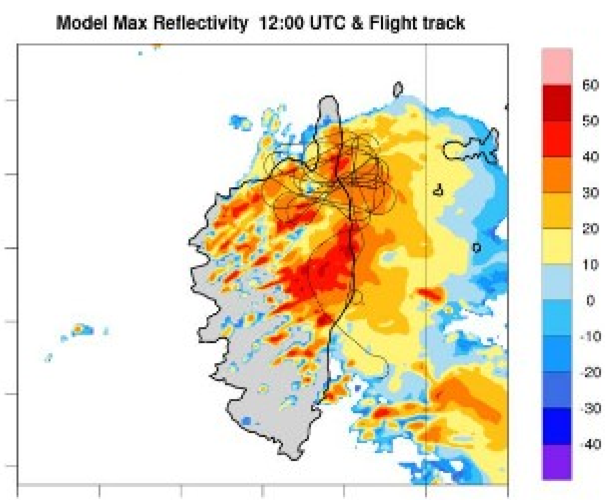
Observation



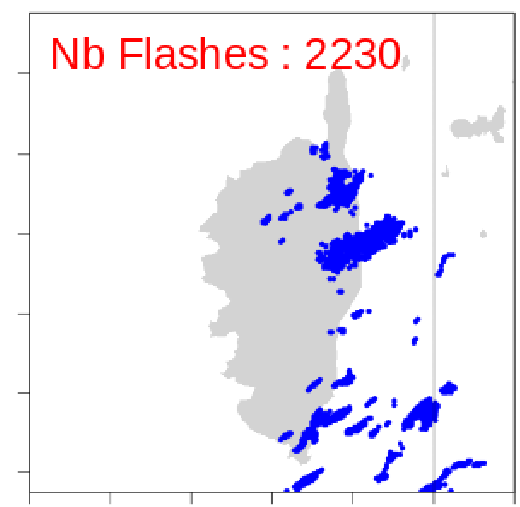


LMA Observations (Chong's algo)

Simulation

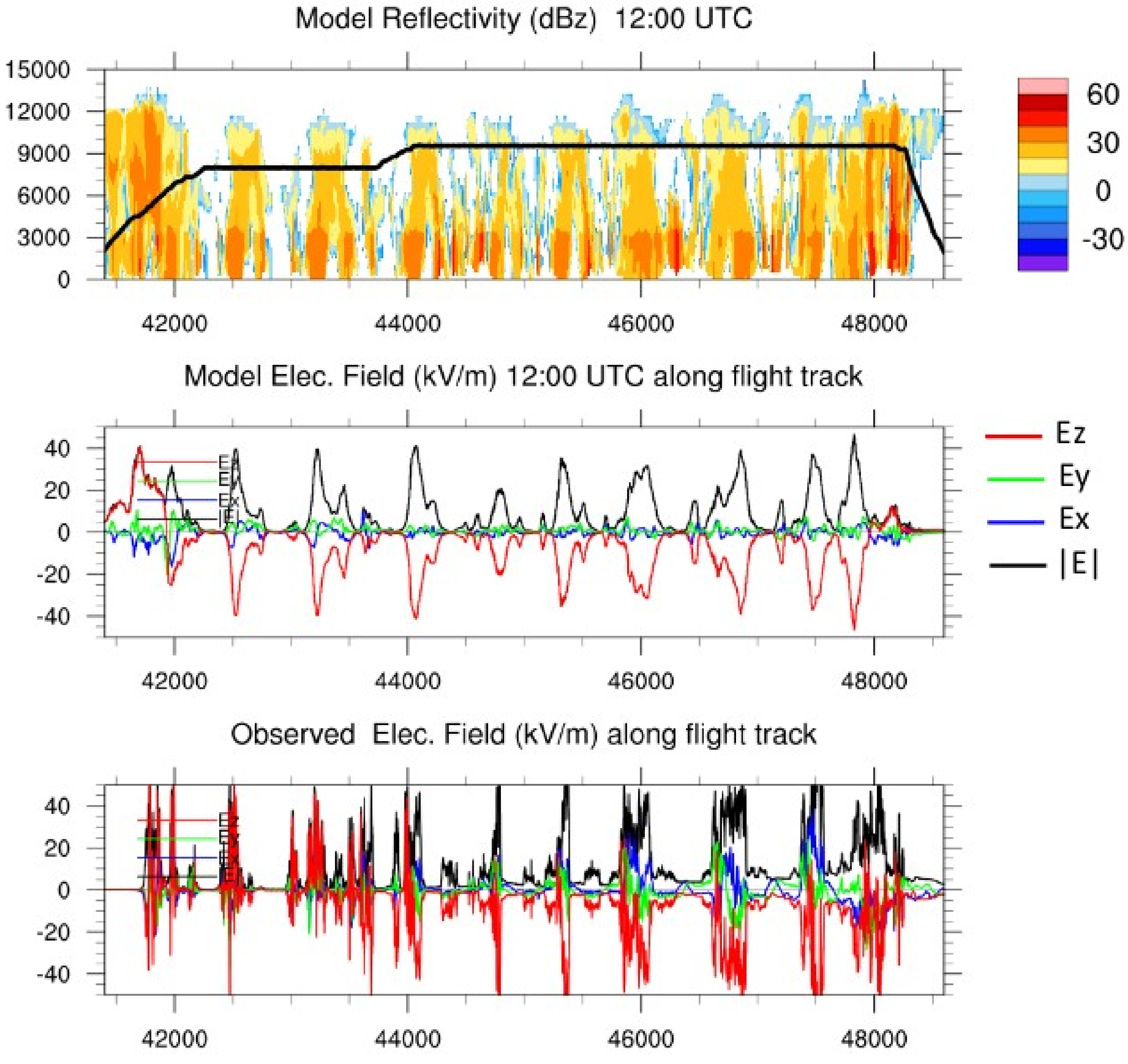


12 UTC



Simulation (flash_geom)

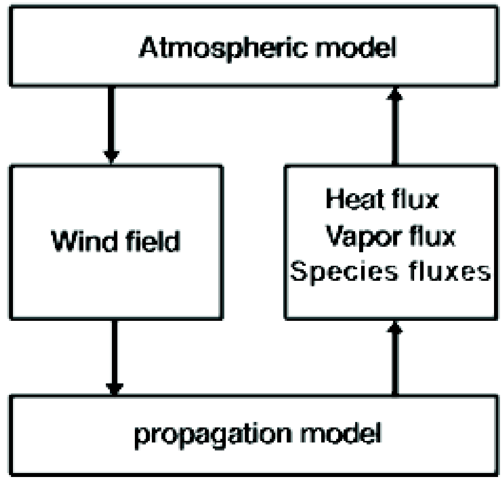
Evaluation during the EXAEDRE campaign (Lee KO et al.)



- Despite some lack of variability, sign and amplitude of the three components of the electric field are consistent with the AMPERA observations.

(Lee KO et al.)

Coupling with a fire propagation model ForeFIRE



+ vidéos

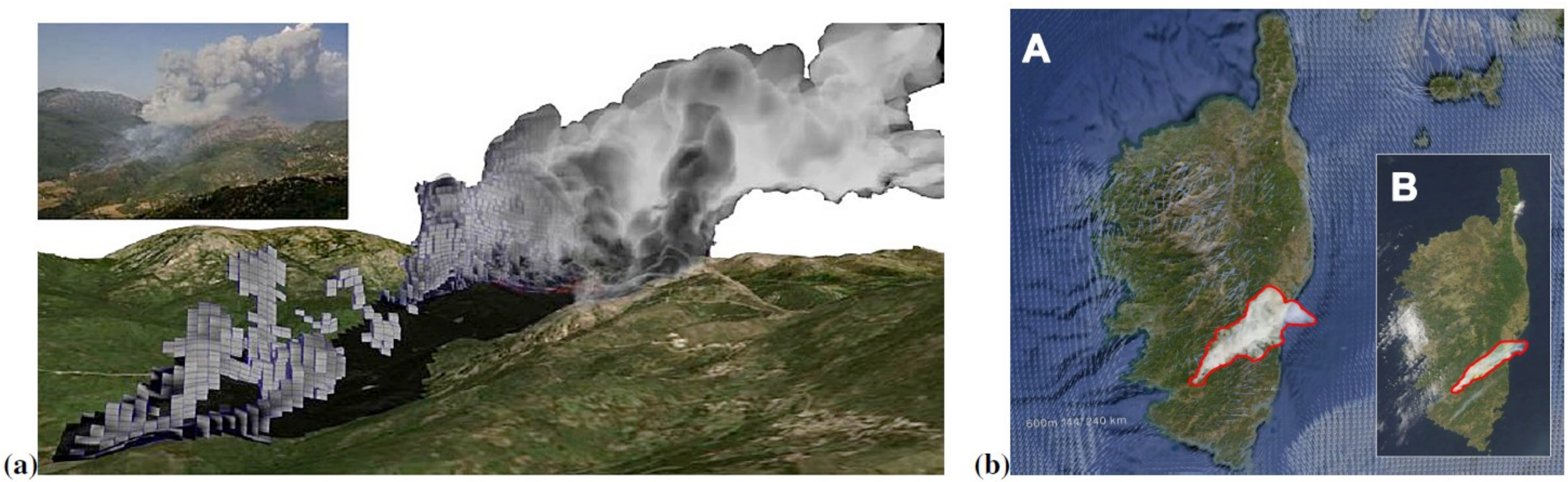
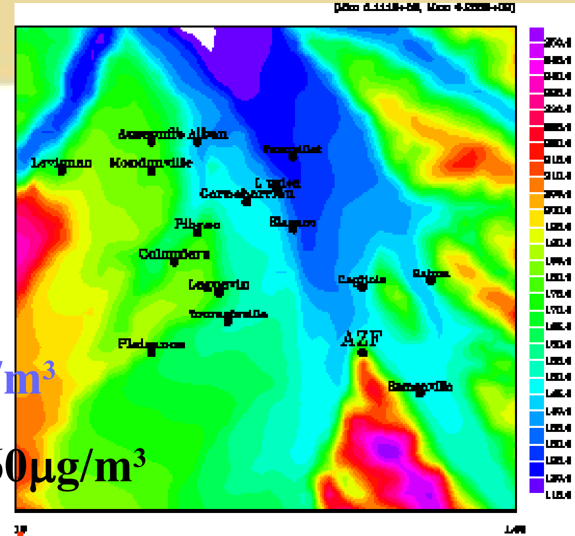


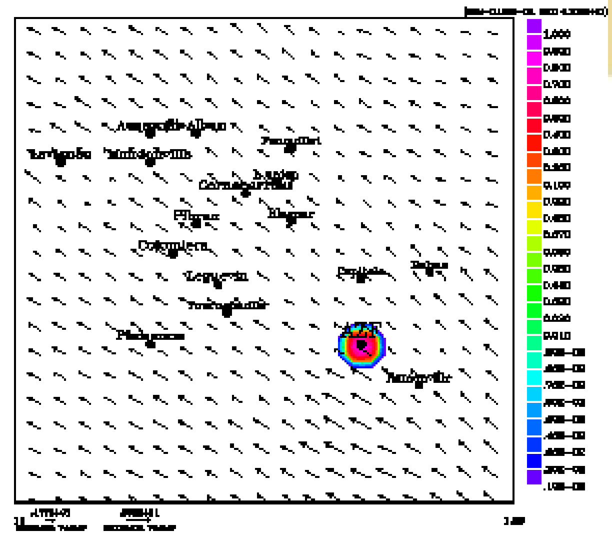
Figure 12. Simulated smoke tracer on 23 July 2009 (a) in the 50 m resolution domain compared to the plume's photograph (at the top left) and (b) in the 600 m resolution domain highlighted in red (A) at 15:00 UTC compared to the MODIS image (B) of Corsica at 14:50 UTC.

On-line Chemistry & Aerosols

- Passive tracers
- Gazeous chemistry
- Aerosols
- Dusts
- Sea salts
- Aqueous chemistry

PASSIVE SCALARS : Industrial accidental release : AZF





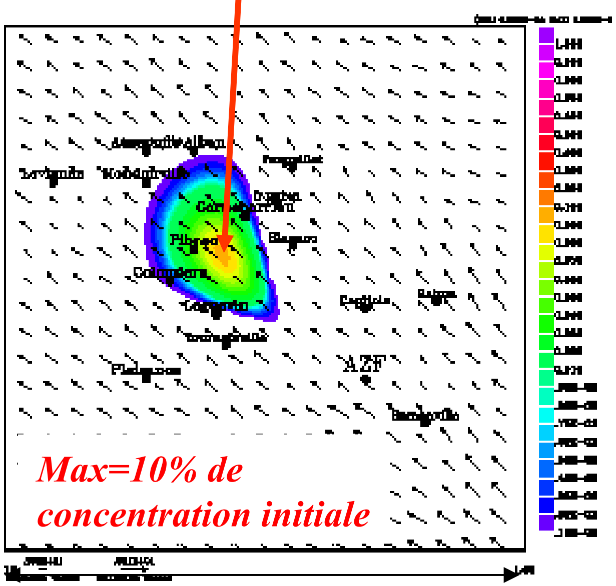
10%=97µg/m^3

Max_obs=60µg/m^3

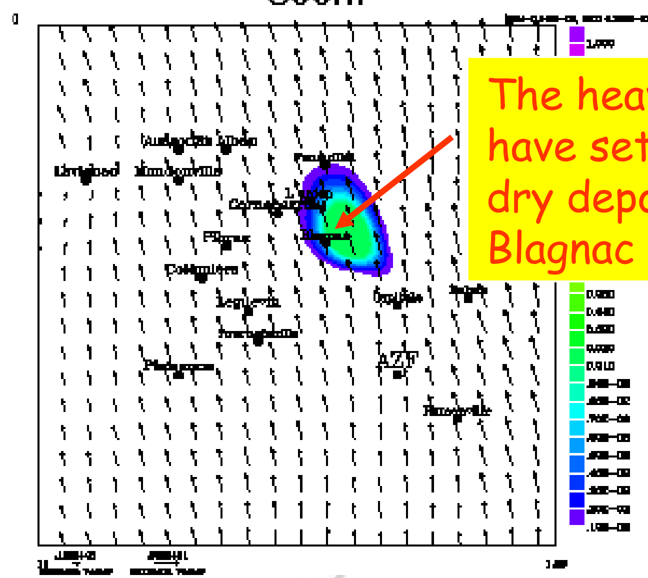
30km, Δx=500m

Sol *Couche de mélange : flux de SE*

800m *Couche résiduelle : flux de S*



Max=10% de concentration initiale



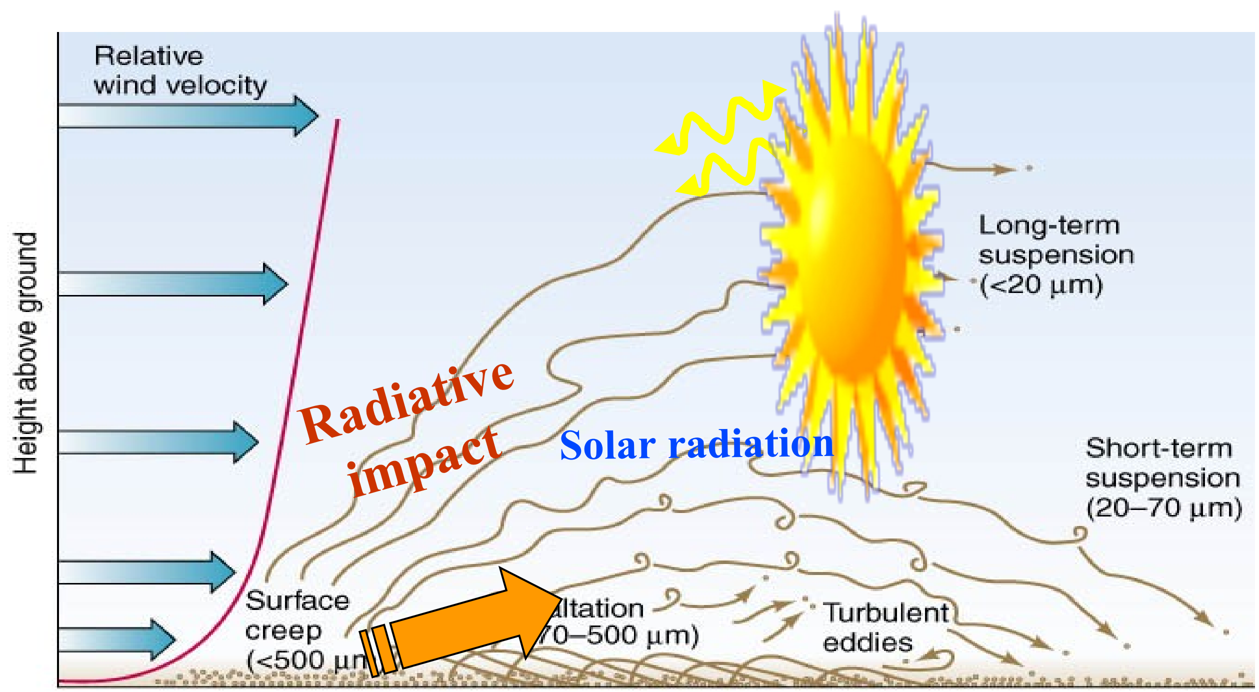
The heaviest particles have settled : strong dry deposition on Blagnac

30km, Δx=500m

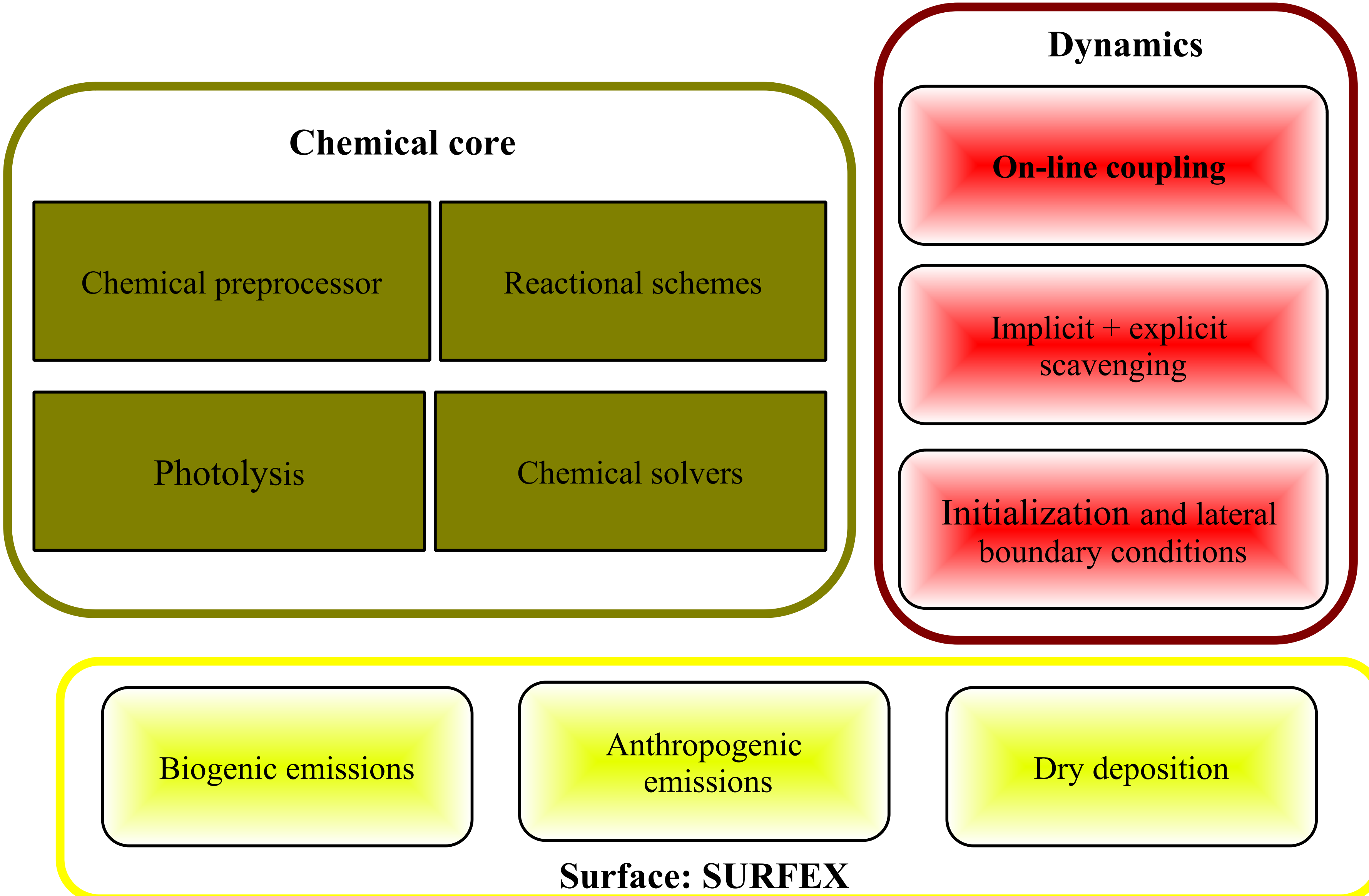
Dust parametrization in MesoNH/SURFEX
(Grini et al, 2006, Tulet et al, 2005)

Only 3 additive prognostic variables

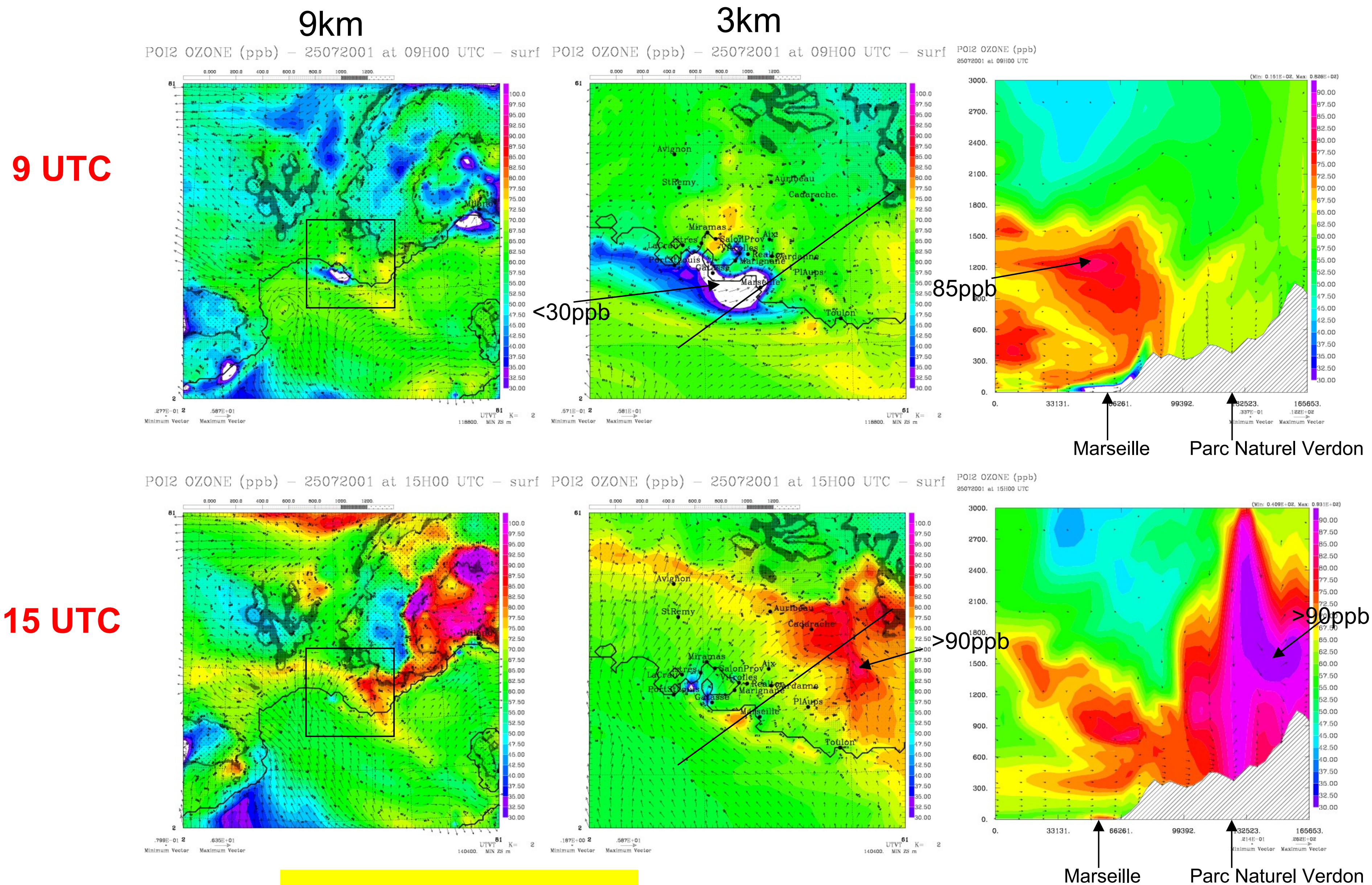
No chemistry



Gazeous chemistry



OZONE le 25 Juin 2001



Cousin et Tulet, 2004

Aerosol chemistry

Scheme = ORILAM

Coeur aérosol: MesoNH / AROME

Coagulation
/ nucléation
(V. Crassier)

Schéma réactionnels
précurseurs SOA
(P. Tulet)

Équilibres
thermodynamiques
(V. Crassier, P. Tulet)

Solveurs
SOA
(P. Tulet, A. Grini)

Emissions
aérosols
désertiques, sels
(A. Grini, M. Mohktari
P. Tulet)

Dépôt sec
(P. Tulet)

Surface: SURFEX

Atmosphère: MesoNH,
AROME, ALADIN

Sédimentation
(P. Tulet)

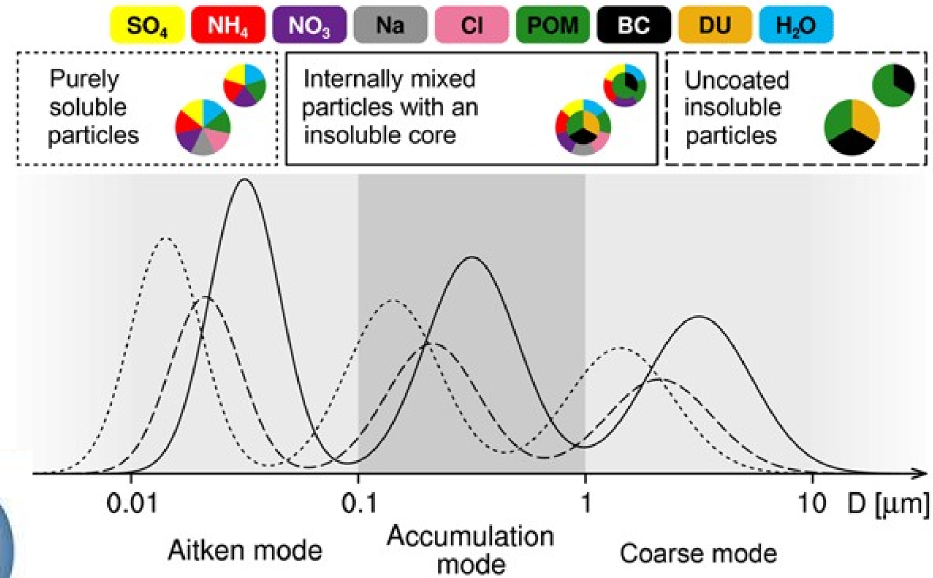
Lessivage aérosol
implicite/explicite
(P. Tulet, N. Begue)

Activation CCN
(J. Rangonio,P. Tulet,
M. Leriche)

Propriétés optiques et
Couplage radiatif
(B. Aouizerats, A. Grini)

Aérosols

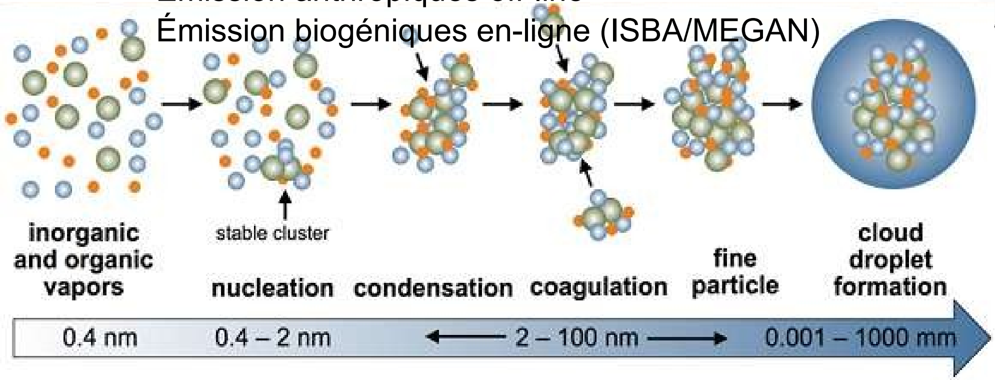
ORILAM – trois modèles d'aérosols



Mélange interne – distributions log-normales

ORILAM

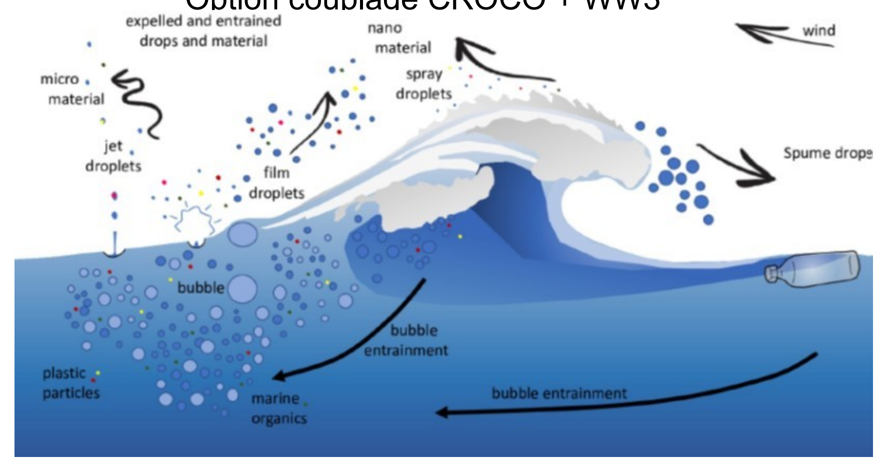
2 modes ~ 40 variables 3D + module de chimie gazeuse
Couplage chimie gazeuse
Émission anthropiques off-line
Émission biogéniques en-ligne (ISBA/MEGAN)



Mélange externe

ORILAM-SALT

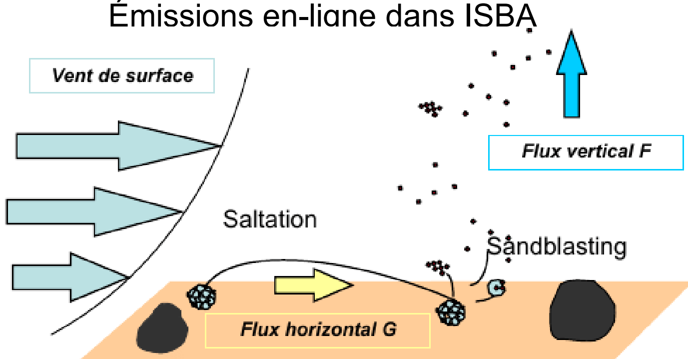
5 modes (aérosols) + 3 modes (embruns)
~ 5 à 40 variables 3D
Émission en-ligne dans SEA-FLUX
Option couplage CROCO + WW3



Mélange externe

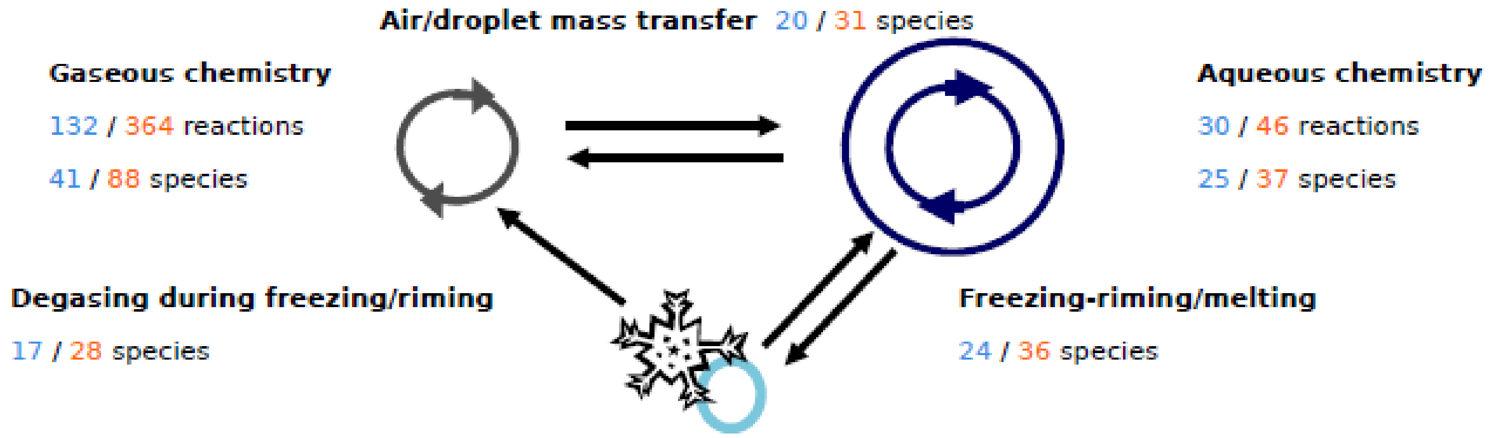
ORILAM-DUST

3 modes ~ entre 3 et 12 variables 3D
Émissions en-ligne dans ISBA



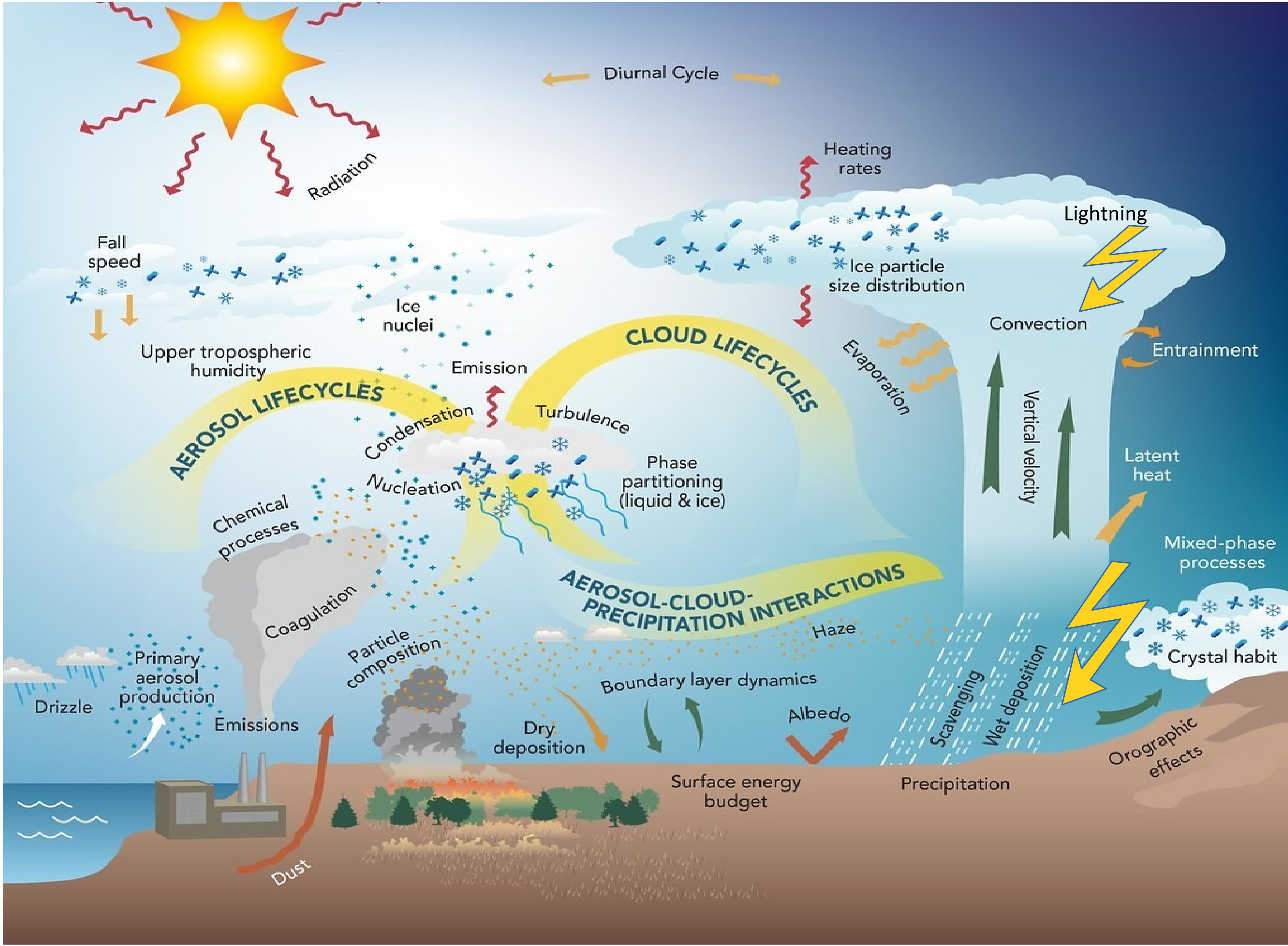
Cloud chemistry module

- ReLACS-AQ or ReLACS2-AQ mechanism
- Air/droplet mass transfer for cloud and rain
- Cloud microphysical mass transfer of chemical species for mixed phase cloud (collision/coalescence, freezing and riming, melting, hydrometeors sedimentation)
- Computing pH as a diagnostic by solving the electro-neutrality equation
- Solving the chemical system using the Rosenbrock family solver



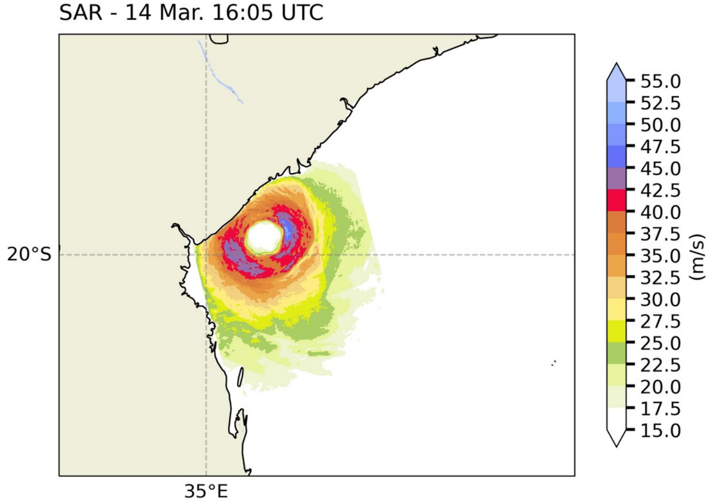
Total species 91 (115 if ice) / 162 (198 if ice) – **Total reactions** 272 / 580

Aérosols - nuages - rayonnement - électricité

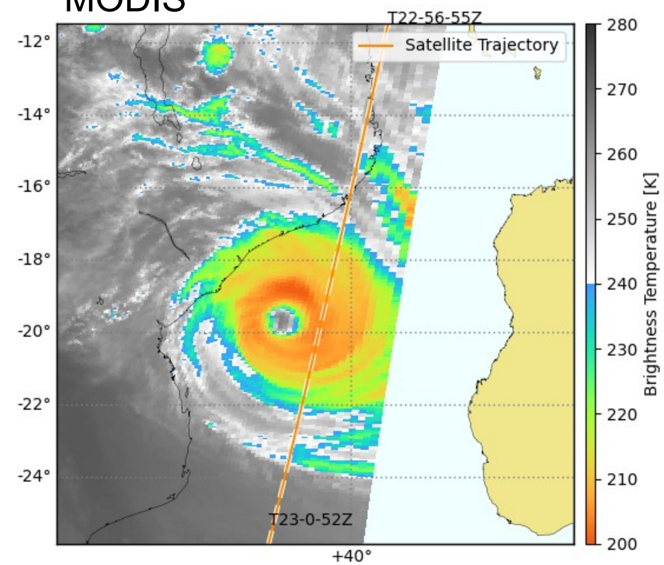


Exemple intégré : cyclone tropical Idai (2019)

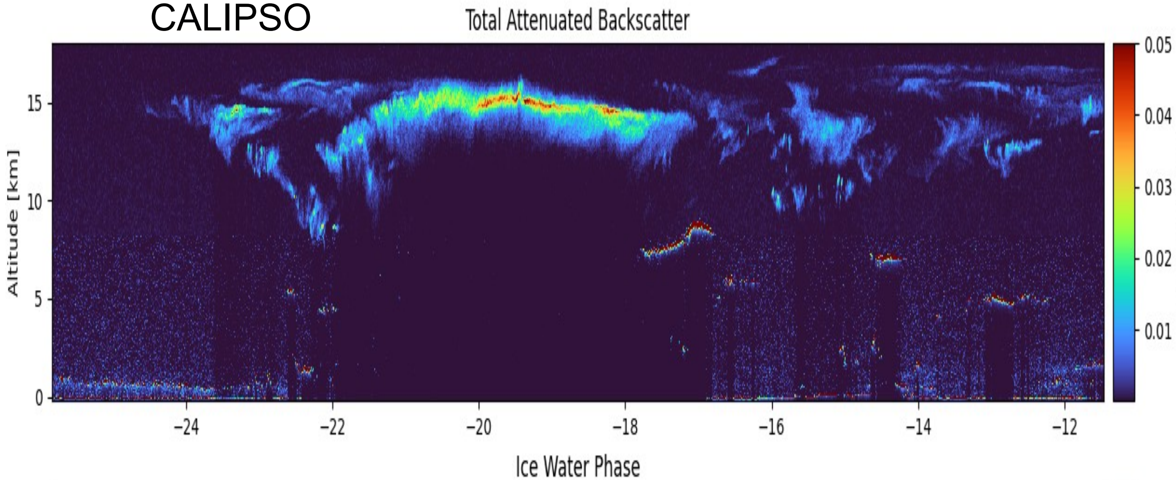
SENTINEL-1 (SAR)

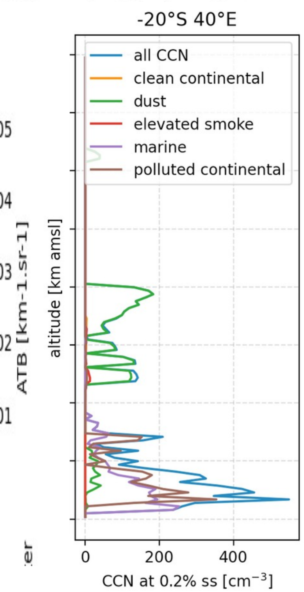


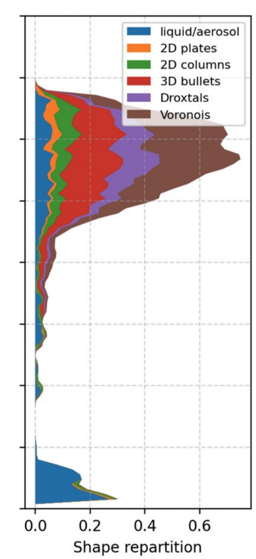
MODIS



CALIPSO







Choudhury and Tesche, 2023

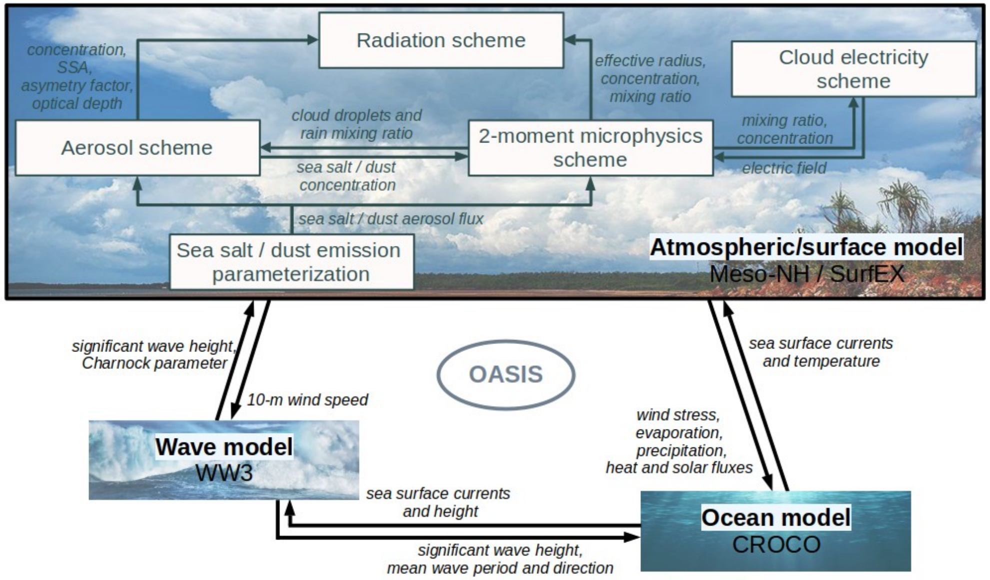
produit V. Noel

Exemple intégré : cyclone tropical Idai (2019)

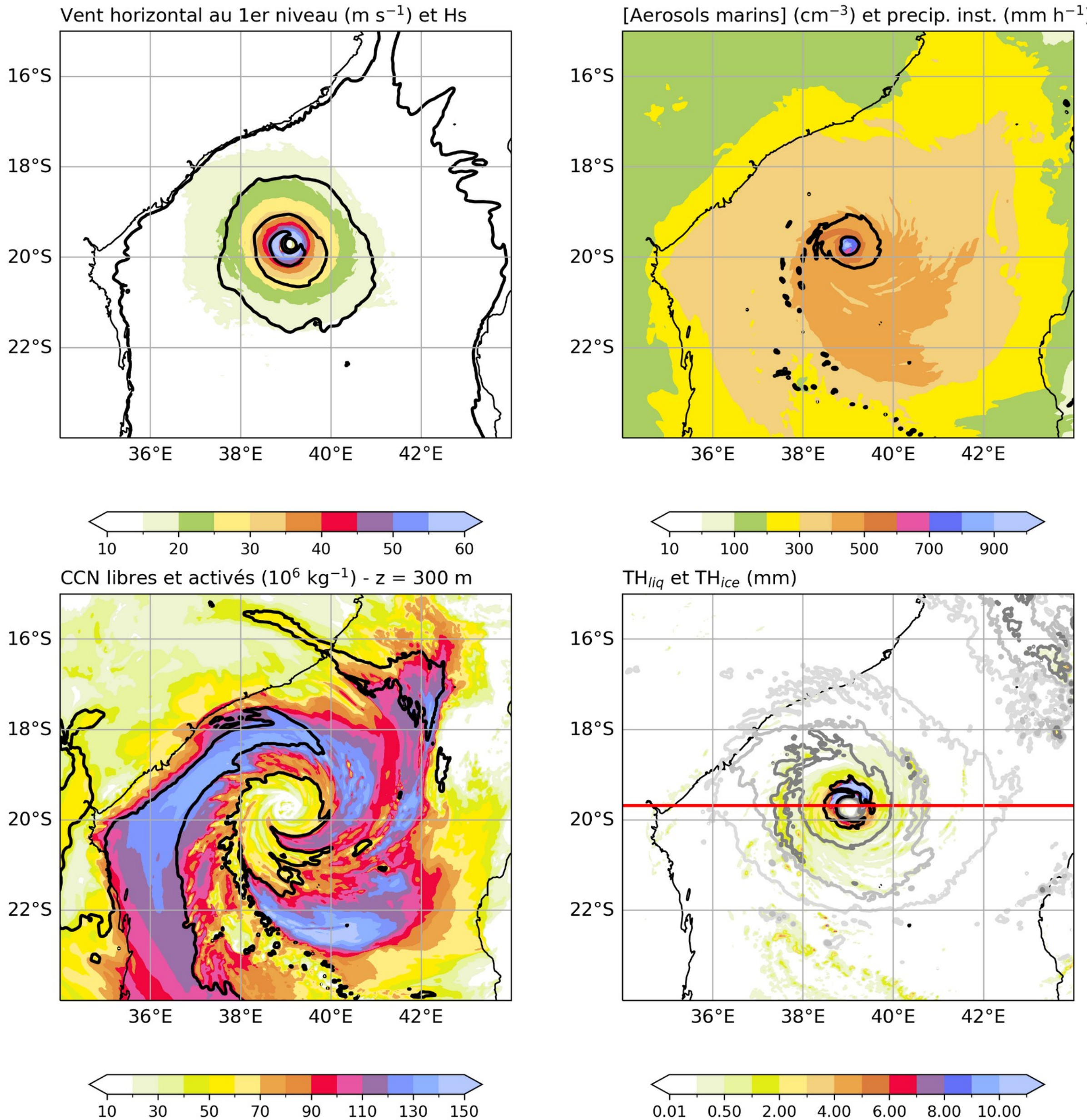
Configuration de la simulation

→ modélisation couplée océan (CROCO) - vagues (WW3) - atmosphère (Meso-NH)

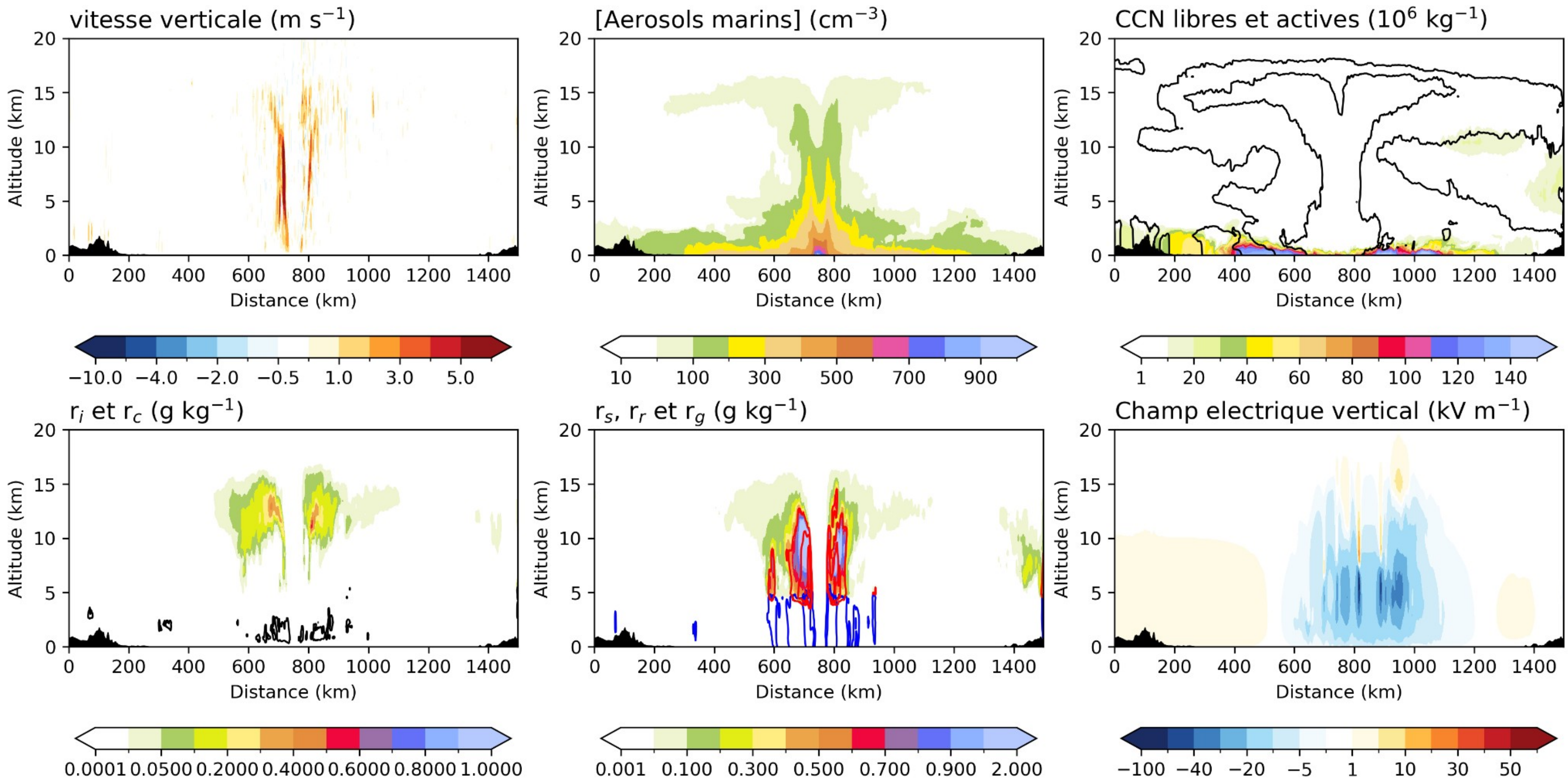
- domaine : 750 x 800 x 70 points, dx = dy = 2km, dz variable
- période : 11/03/2019 00 UTC → 15/03/2019 00 UTC
- initialisation : analyses ECMWF + CAMS (via ORILAM)
- physique
  - aérosols : ORILAM-SALT + ORILAM-DUST
  - émissions de sels marins : ‘OvB21b’
  - microphysique : ‘LIMA’, N_c, N_r et N_i pronostiques, LSPRO=T, LADJUST=F
  - électricité : ‘ELE4’,
    restart le 13/03/2019 à 00 UTC
  - rayonnement : ‘ECMW’
  - turbulence : ‘1DIM’, ‘BL89’
  - convection : ‘EDKF’
  - flux OA : ‘COARE3’



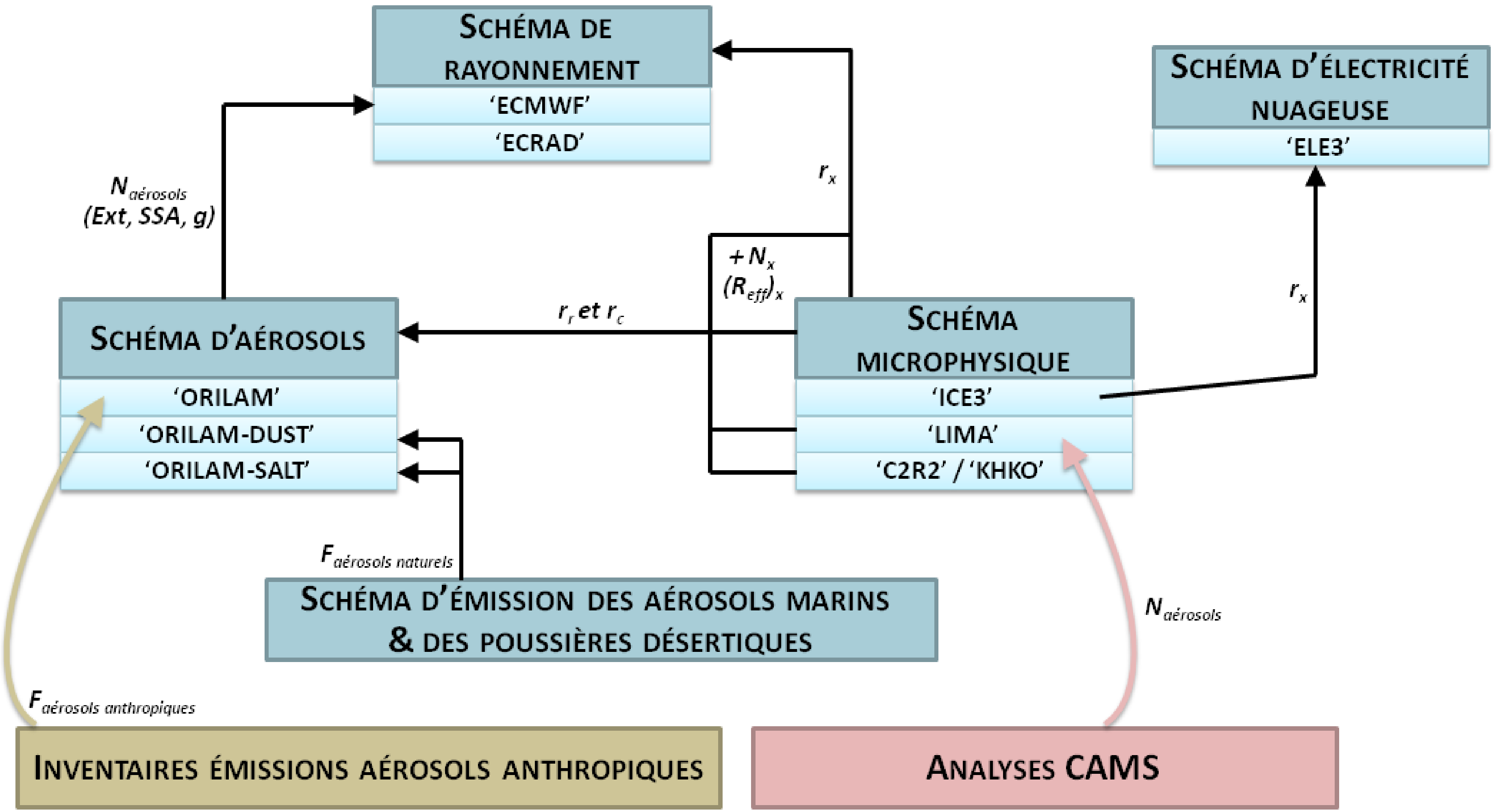
Exemple intégré : cyclone tropical Idai (2019)



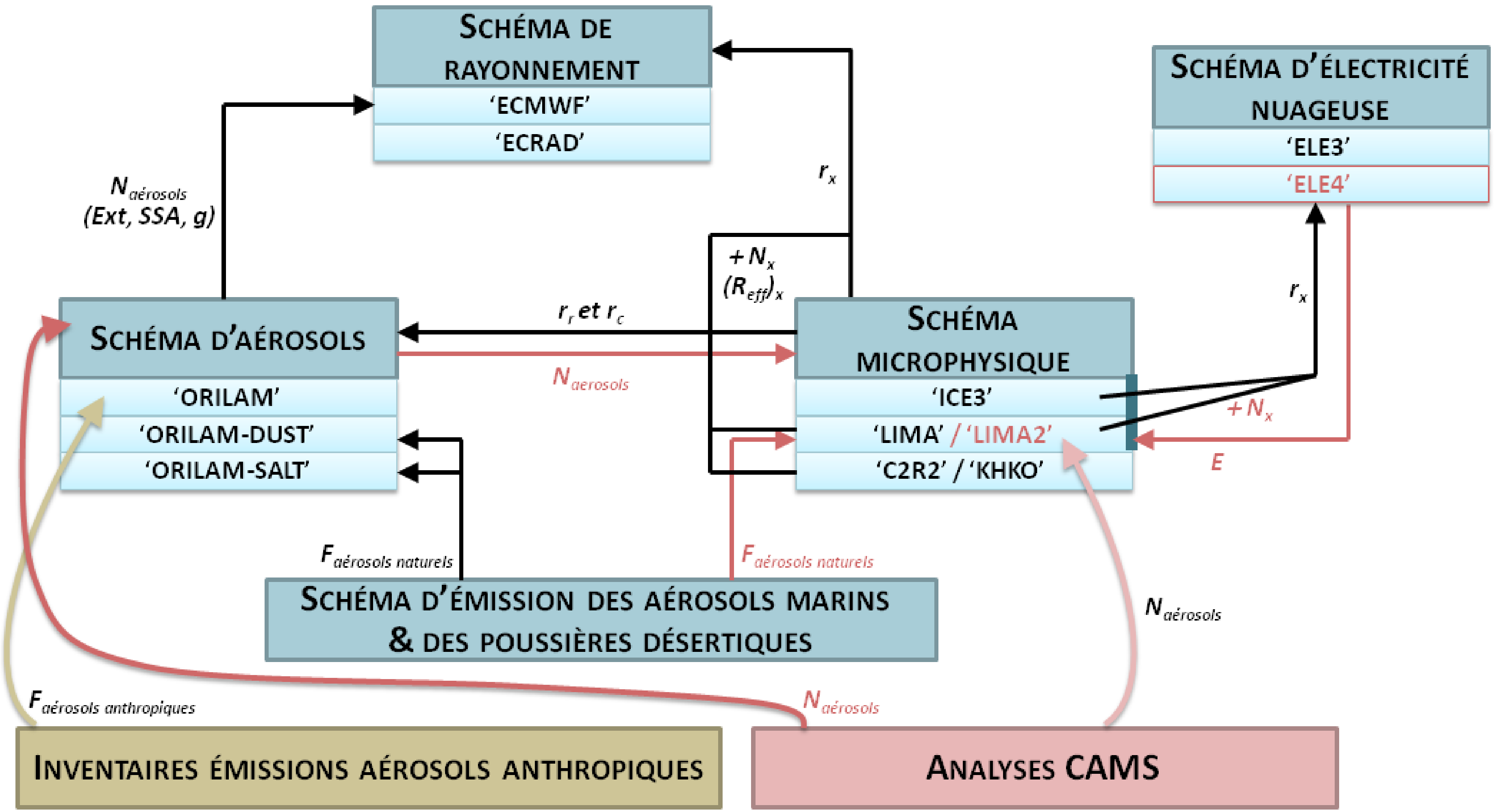
Exemple intégré : cyclone tropical Idai (2019)



Couplage des schémas physiques de Meso-NH en 2021



Couplage des schémas physiques de Meso-NH en 2023 (> MASDEV 5-6-0)



Conclusions

- Increased complexity in parameterizations
- Increased interactions between parameterizations
- **Consistent representation of aerosols, clouds, electricity and radiation**

➔ **Huge possibilities with various levels of complexity / precision**

➔ **Design your experiments with care or ask for help !**