General texts on the principles of climate modeling

https://www.lmd.jussieu.fr/~hourdin/PUBLIS/HourdinGuillemotUniversalis.pdf
Un article de présentation générale de la modélisation du climat (français)

https://web.lmd.jussieu.fr/~hourdin/PUBLIS/110329_LivreClimat_IV.6_10.pdf
Le principe des paramétrisations physiques

https://web.lmd.jussieu.fr/~hourdin/PUBLIS/110329_LivreClimat_IV.13_06.pdf
Stratégie d'évaluation des modèles

https://www.lmd.jussieu.fr/~hourdin/PUBLIS/bams-d-15-00135.1.pdf
The art and science of climate model tuning (english)

More technical and directly related to the course

http://www.lmd.jussieu.fr/~hourdin/HDR/habil.pdf (in french ...)
Reynolds decomposition (Section 2.2.2)
Advection schemes (Section 2.3)
Turbulent diffusion (Section 3.1)
Boundary layer convection (Section 3.3)

http://hmf.enseeiht.fr/coursenligne/estivalezes/notes_tmms.pdf
COURS ENSEEIHT : Reynolds, TKE equation

Parameterizations and use of models

I. Convective parameterisations

II. Parametrizations and calibration/tuning

Parameterizations : principles




• Compute the **average effect of unresolved processes on the global model state variables** ($\underline{U}$, θ, q)

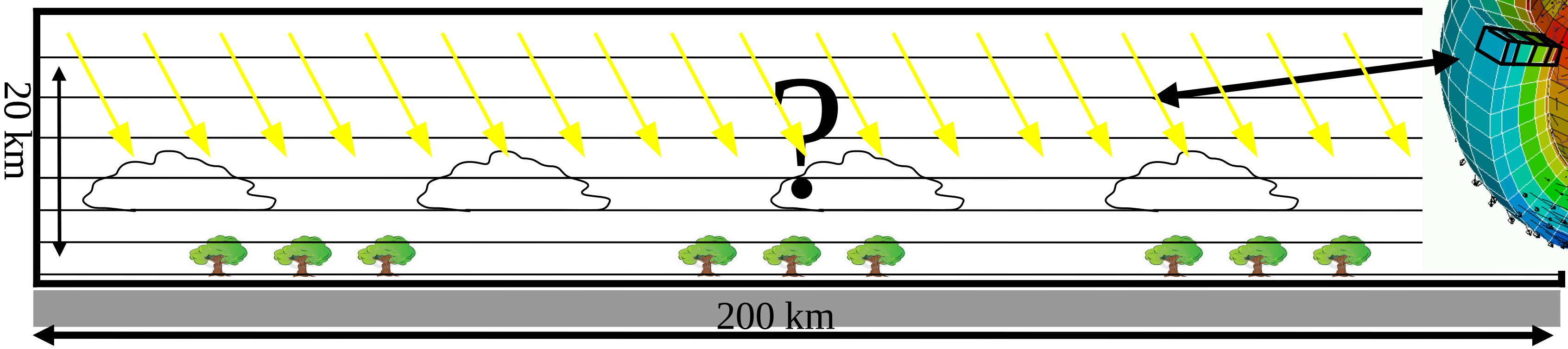
• **Based on a description of the approximate collective behavior** of processes

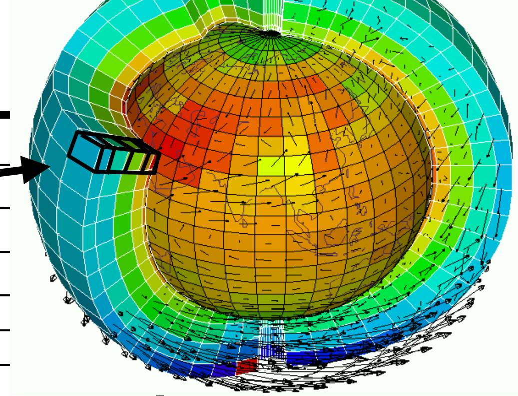
• Involve additional **parameterization internal variables** (cloud characteristics, standard deviation of the sub-grid scale distribution of a variable, …)

• Derive **equations** relating internal variables to the state variables
$\underline{U}$, θ, q at time t → **internal variables** → $\underline{F}$, Q, Sq → $\underline{U}$, θ, q at t+δt

• **Homogeneity hypothesis** (statistical) on the horizontal of the targeted processes (like in the plane-parallel approximation of radiative transfer)
→ 1-dimensional equations in z (vertical exchanges only)
→ Independent atmospheric column

Inside an « atmospheric column » ...

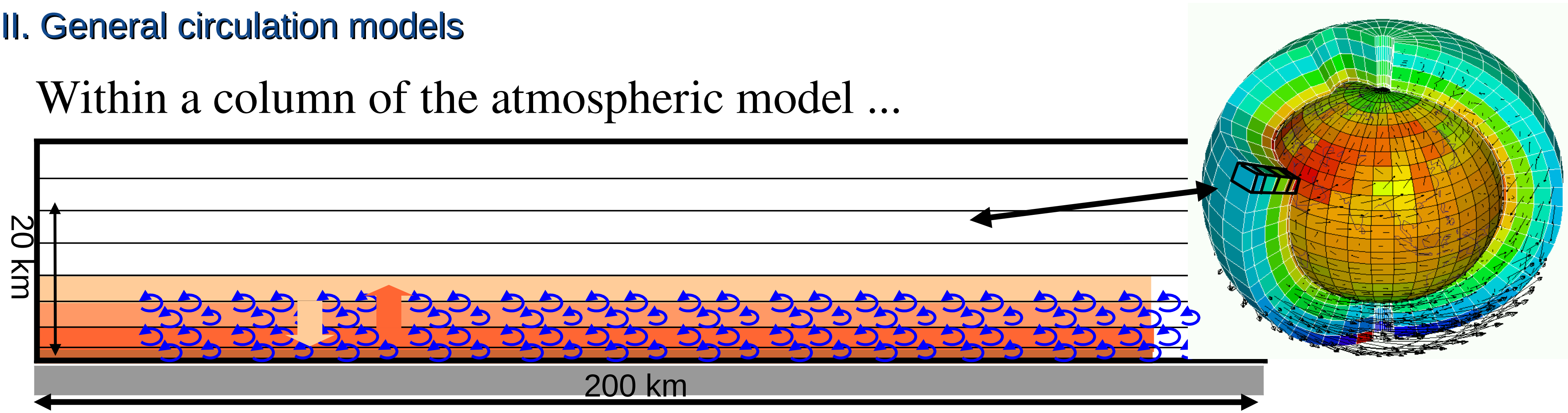





Current approaches for parameterizations of convection and clouds

II. General circulation models

Within a column of the atmospheric model ...



Turbulence parameterization

→ **« turbulent mixing»** or turbulent diffusion
Transport by small random motions.
Analogous to molecular diffusion

$Dq/Dt = Sq$ with $Sq = \frac{\partial}{\partial z}\left(K_z \frac{\partial q}{\partial z} \right)$

→ Prandtl mixing length : $K_z = l|w|$
l : Caracteristic mixing length
w : Caracterisitc velocity

→ Turbulent kinetic energy : $K_z = l\sqrt{e}$

$De/Dt = f\,(dU/dz,\ d\theta/dz, e, ...)$

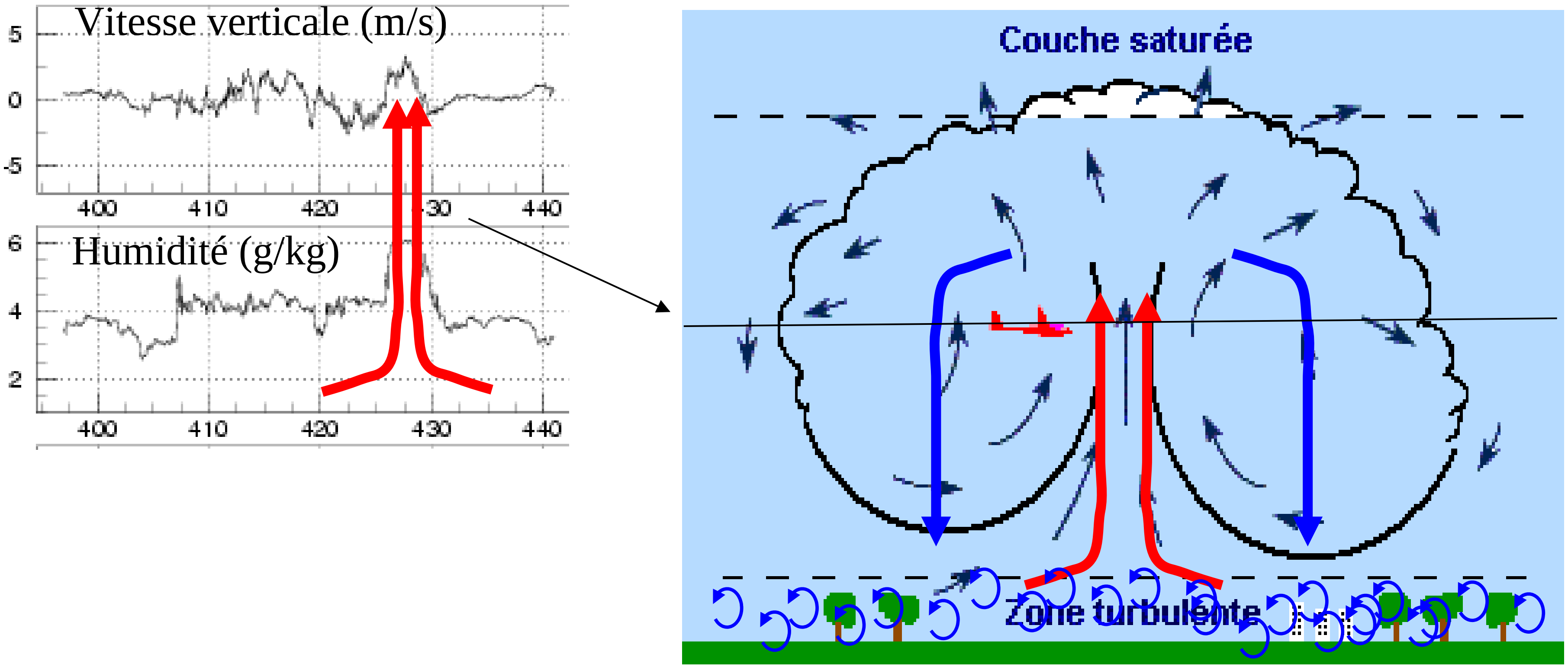
$Dl/dt = ...$

A world by itself

Same models are used in ingineering sciences
Similarity → Tests à des échelles différentes en laboratoire

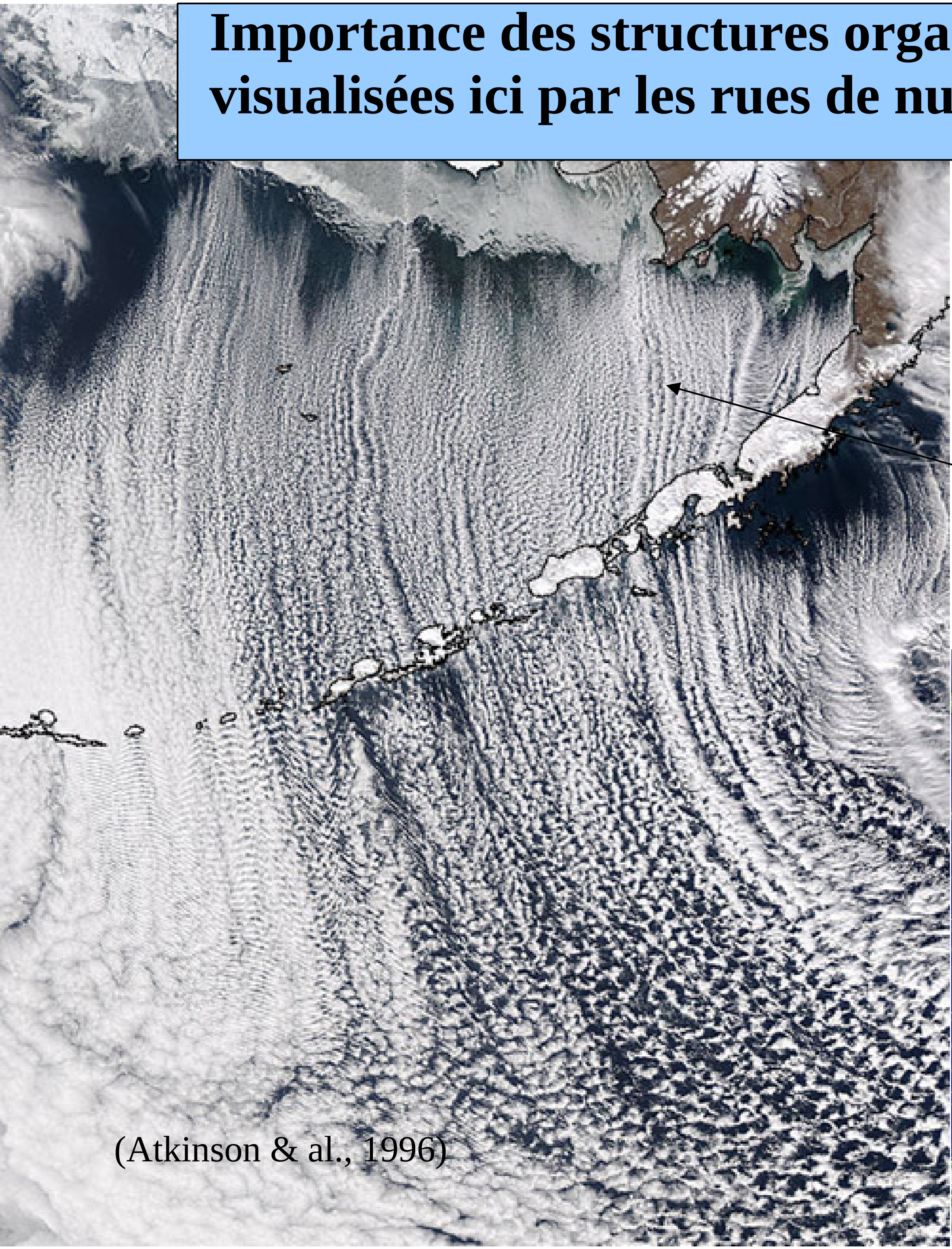
Turbulence isotrope de petite échelle -> mélange turbulent
Turbulence atmosphérique : “méso-échelle”, organisée et anistrope

Exemples de mesures avion
(région parisienne, conditions estivales, cumulus)

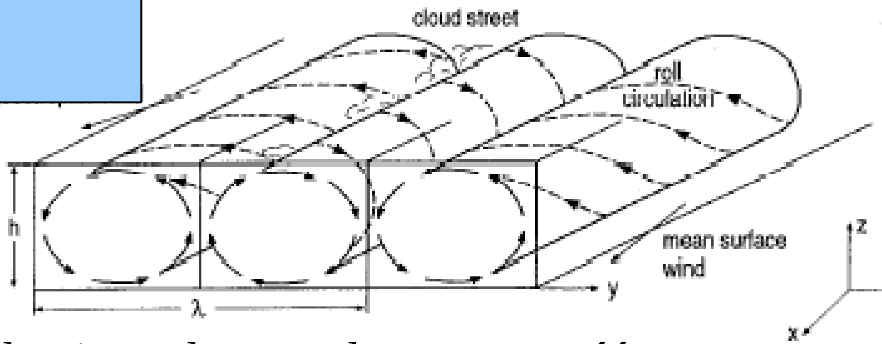


- L'air chaud (léger) et humide monte de la surface sous l'effet des forces d'Archimède.
- En montant cet air ce refroidit (détente adiabatique) et ne peut plus contenir autant de vapeur d'eau.
- En cas de saturation : apparition de cumulus en haut du panache chaud.

Importance des structures organisées visualisées ici par les rues de nuages

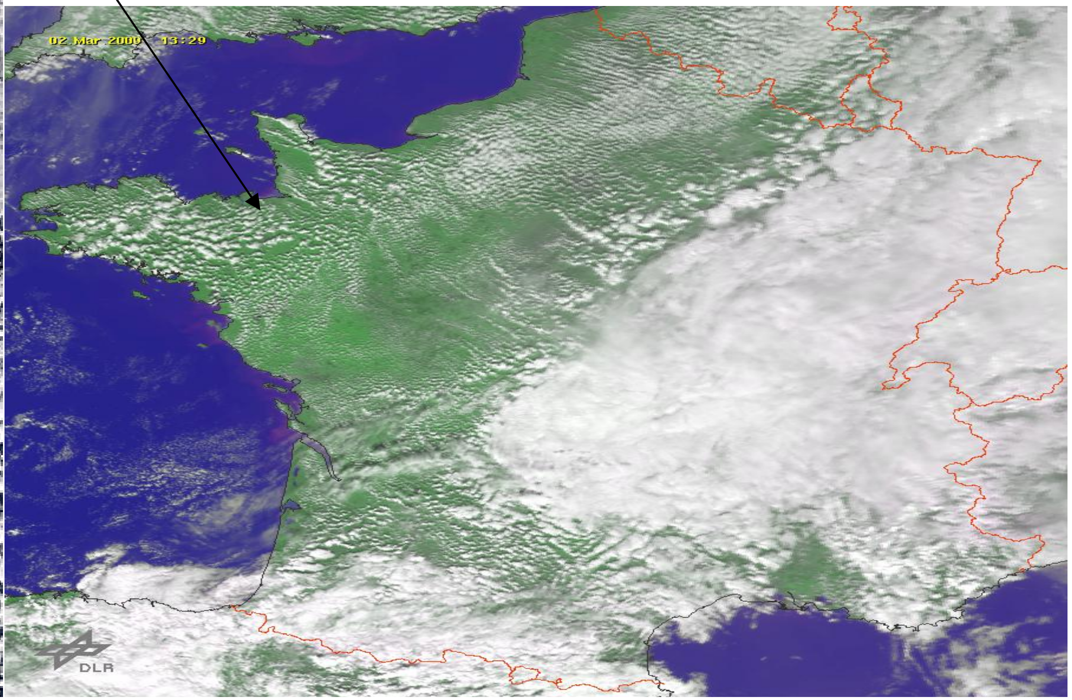


(Atkinson & al., 1996)



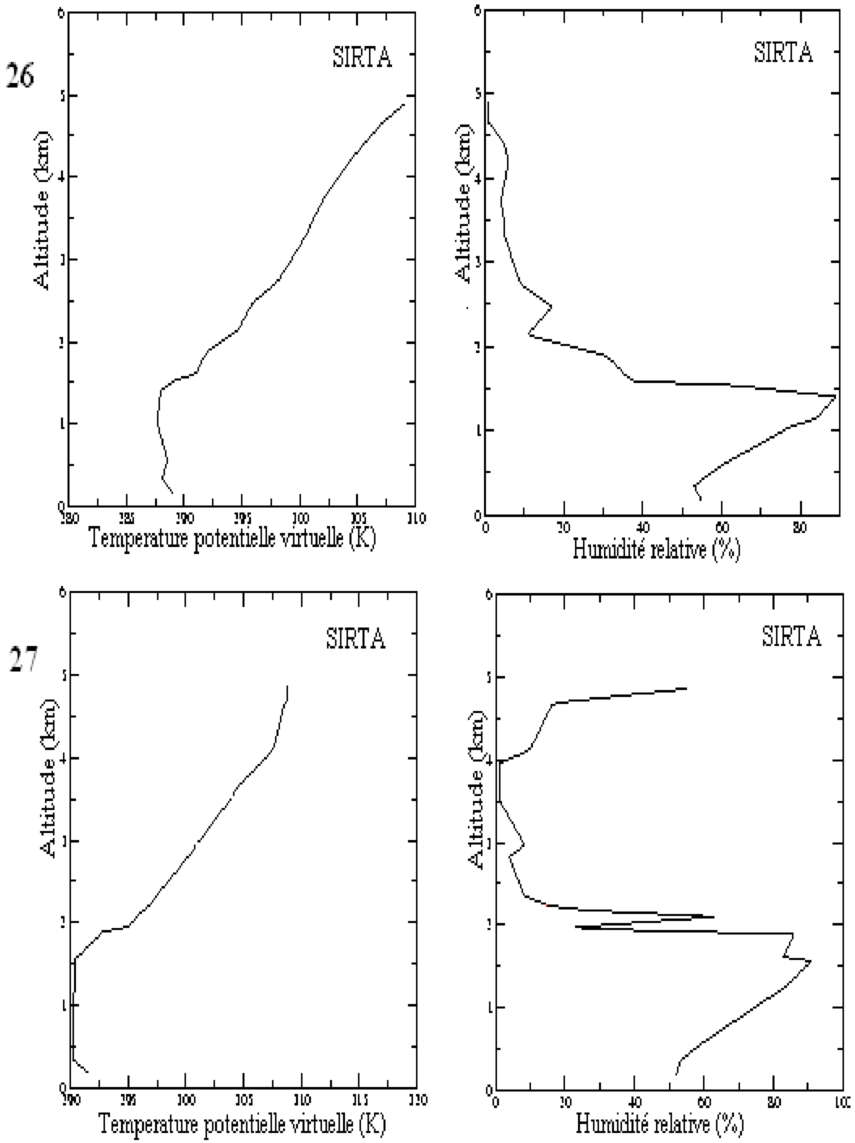
Exemple classique de rues de nuages créées au sommets de rouleaux convectifs :

- arrivé d'air polaire froid sur des masses océaniques plus chaudes
- entrée d'air marin doux sur un continent plus chaud

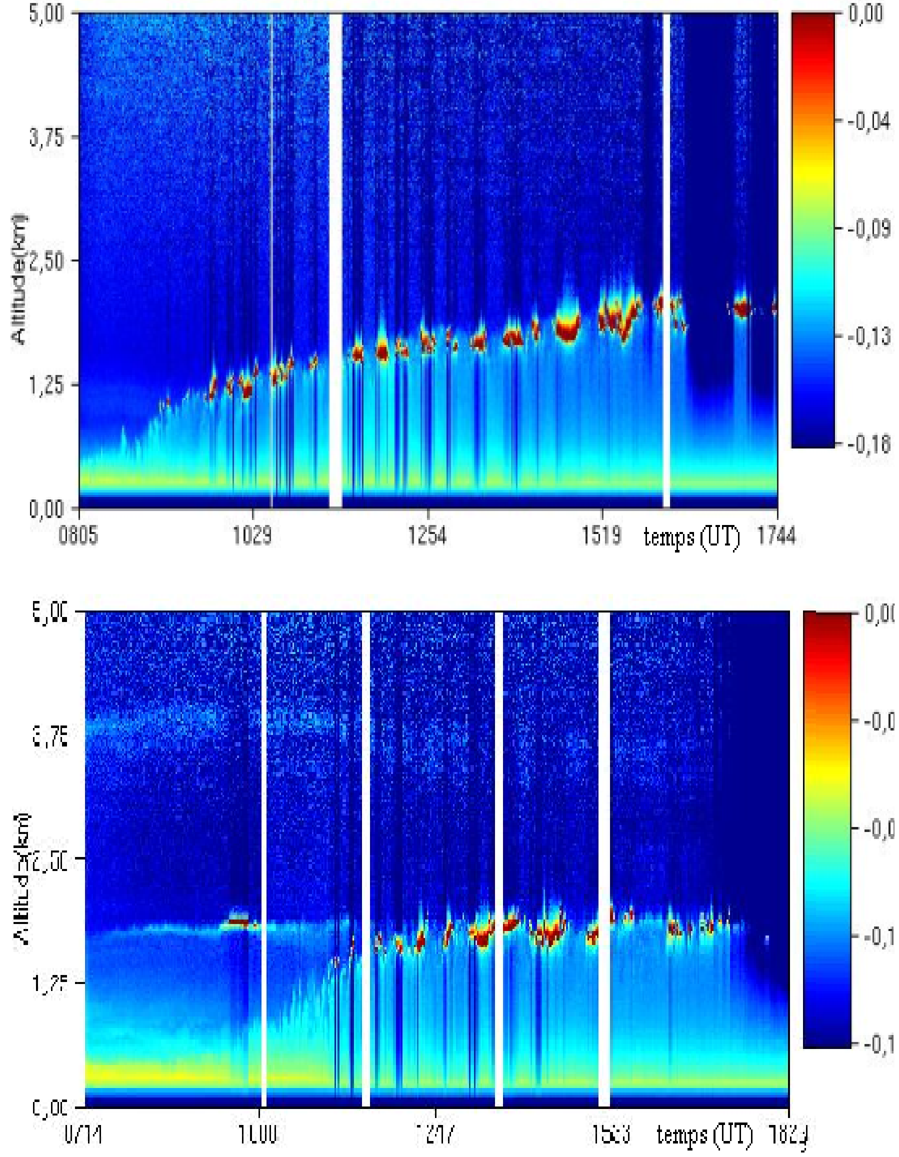


Exemple d'observations de la couche limite en région parisienne

Sondages de Trappes (Paris)



Observations Lidar



Exemple d'observations de la couche limite en région parisienne

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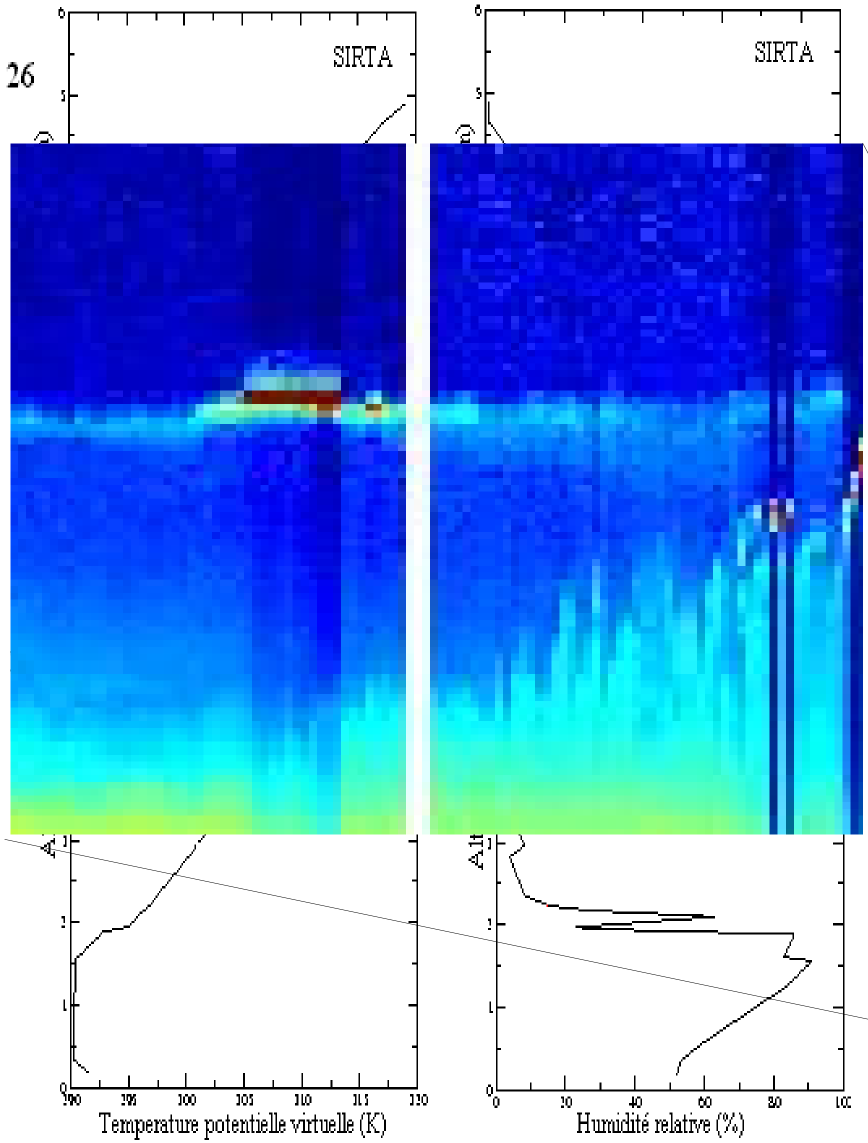
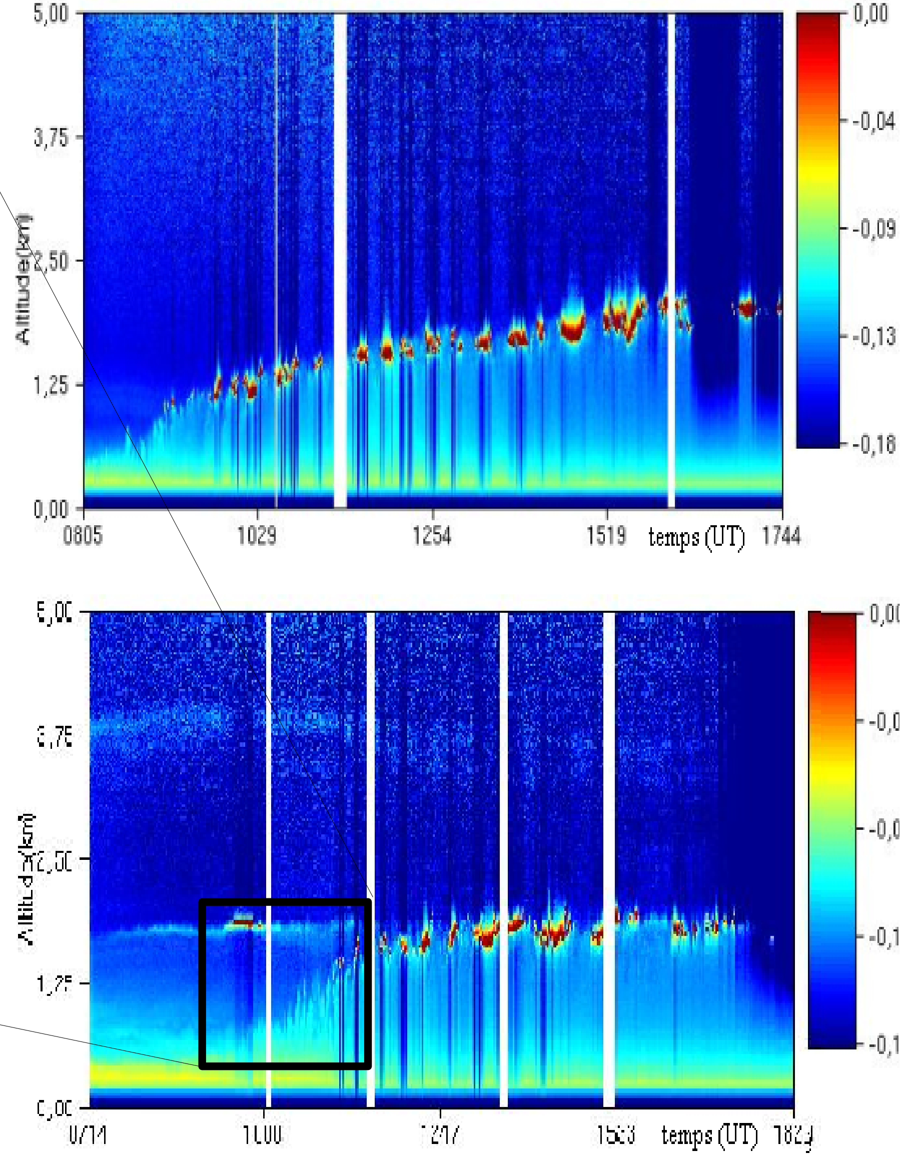


Observations Lidar



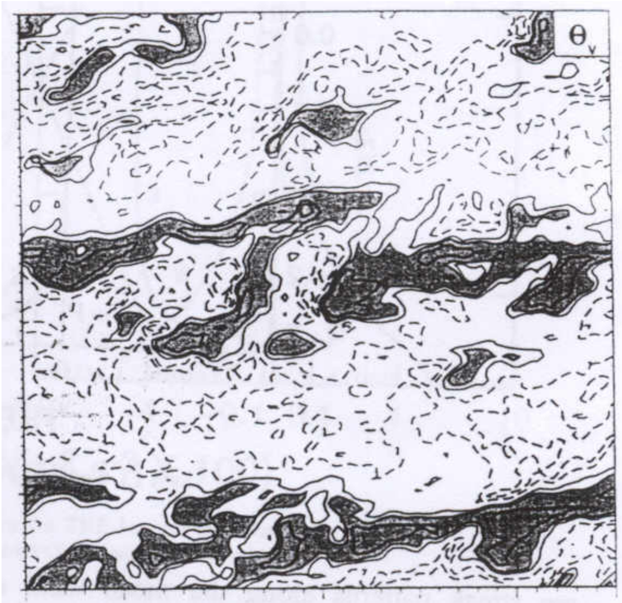
2. Couche limite convective

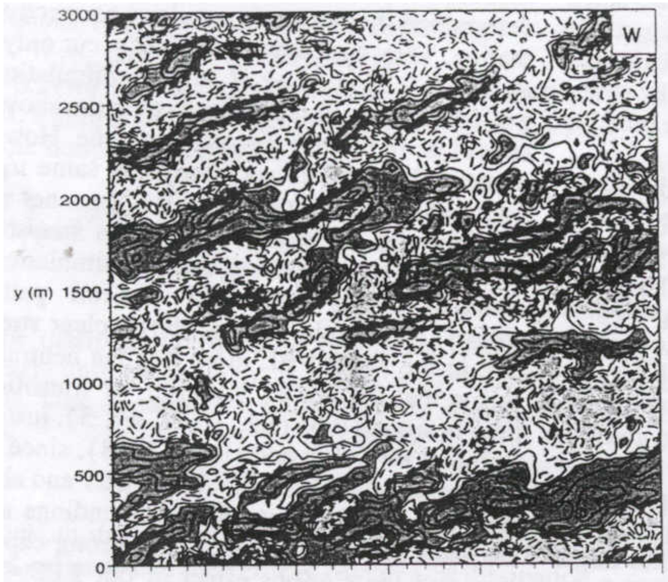
Convection organisée même pour les couches limites non nuageuses.
Mise en évidence dans des « Large Eddy Simulations » ou « Simulation des grands tourbillons », domaine de quelques km, mailles de qq 10m.
Forcé par un flux de chaleur venant de la surface

θ' w'

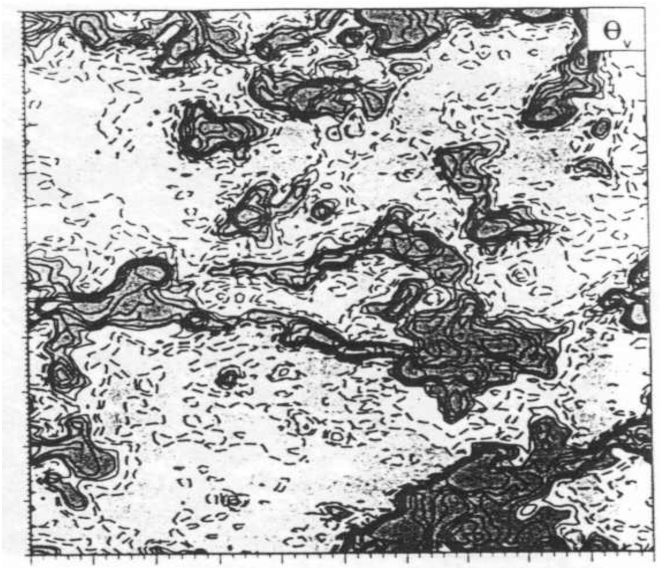
Exemple de résultats de simulations LES. Coupes instantannées au niveau 0.2 Zi où Zi est la hauteur de la couche limite. Moeng et al, 1994

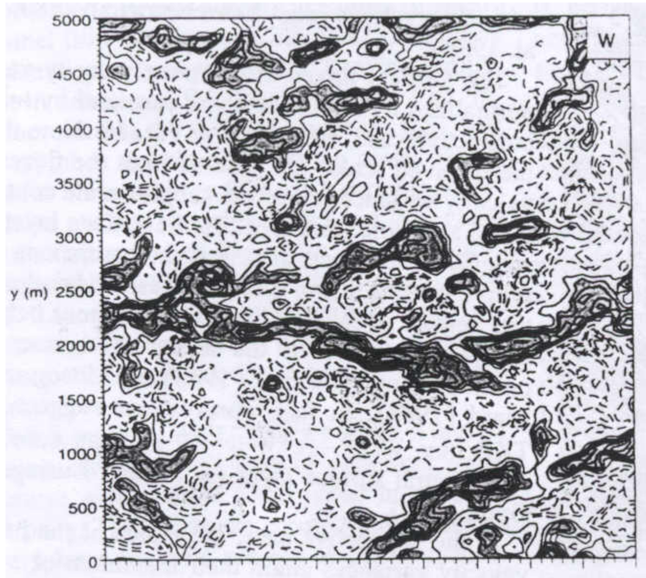
Simulation avec convection + cisaillement





Simulation avec convection sans cisaillement (convection libre)





Parameterization of convective boundary layer and turbulence

Built upon on much finer resolution simulation (LES), here with a mesh of 8m
This movie is all physics : both the simulation of clouds and the rendering
Physical rendering made possible by a recent PhD 2019 (N. Villefranque)
An illustration of state-of-the-art work on parameterizations

Parameterization of convective boundary layer and turbulence

Built upon on much finer resolution simulation (LES), here with a mesh of 8m

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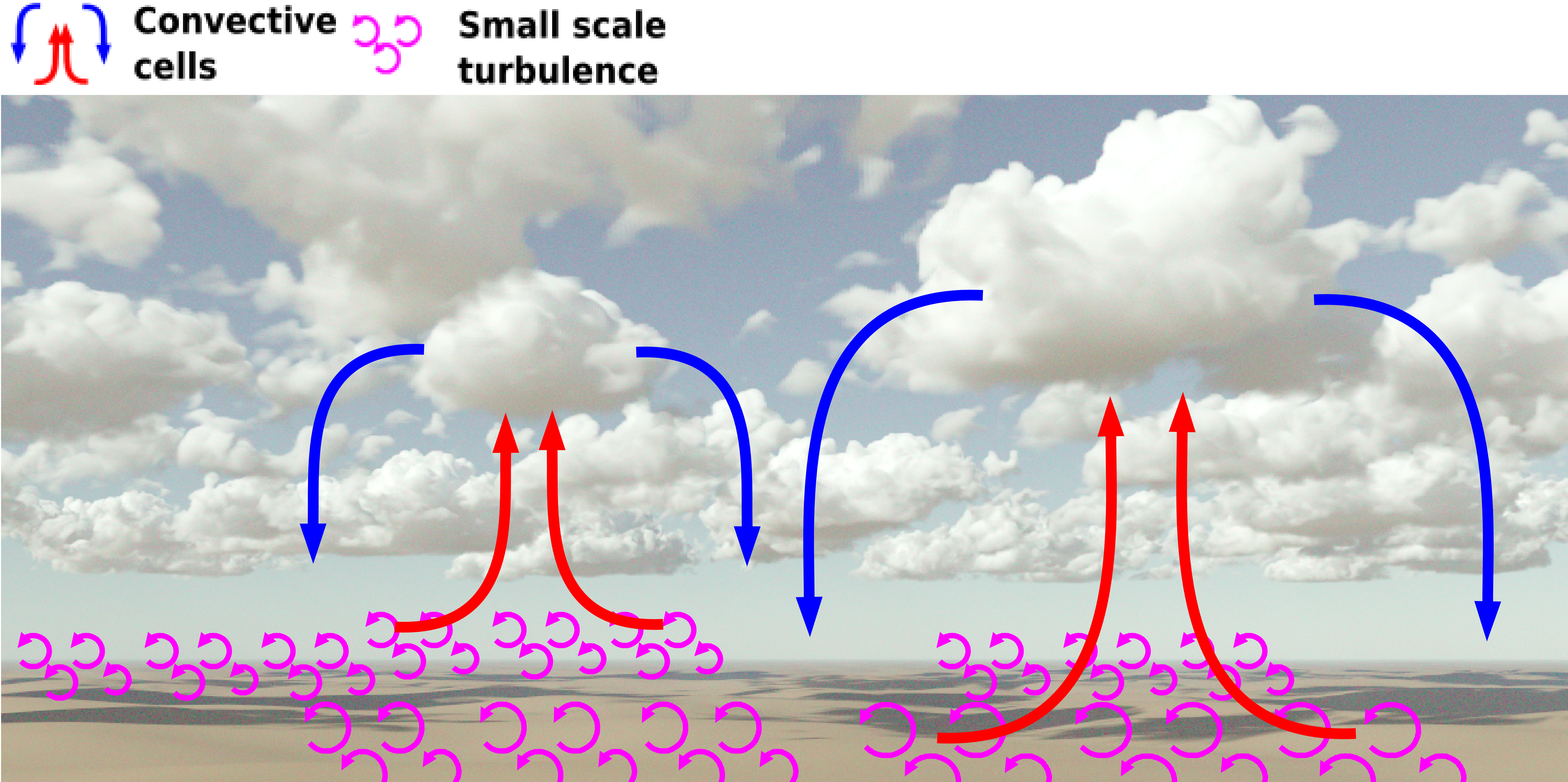
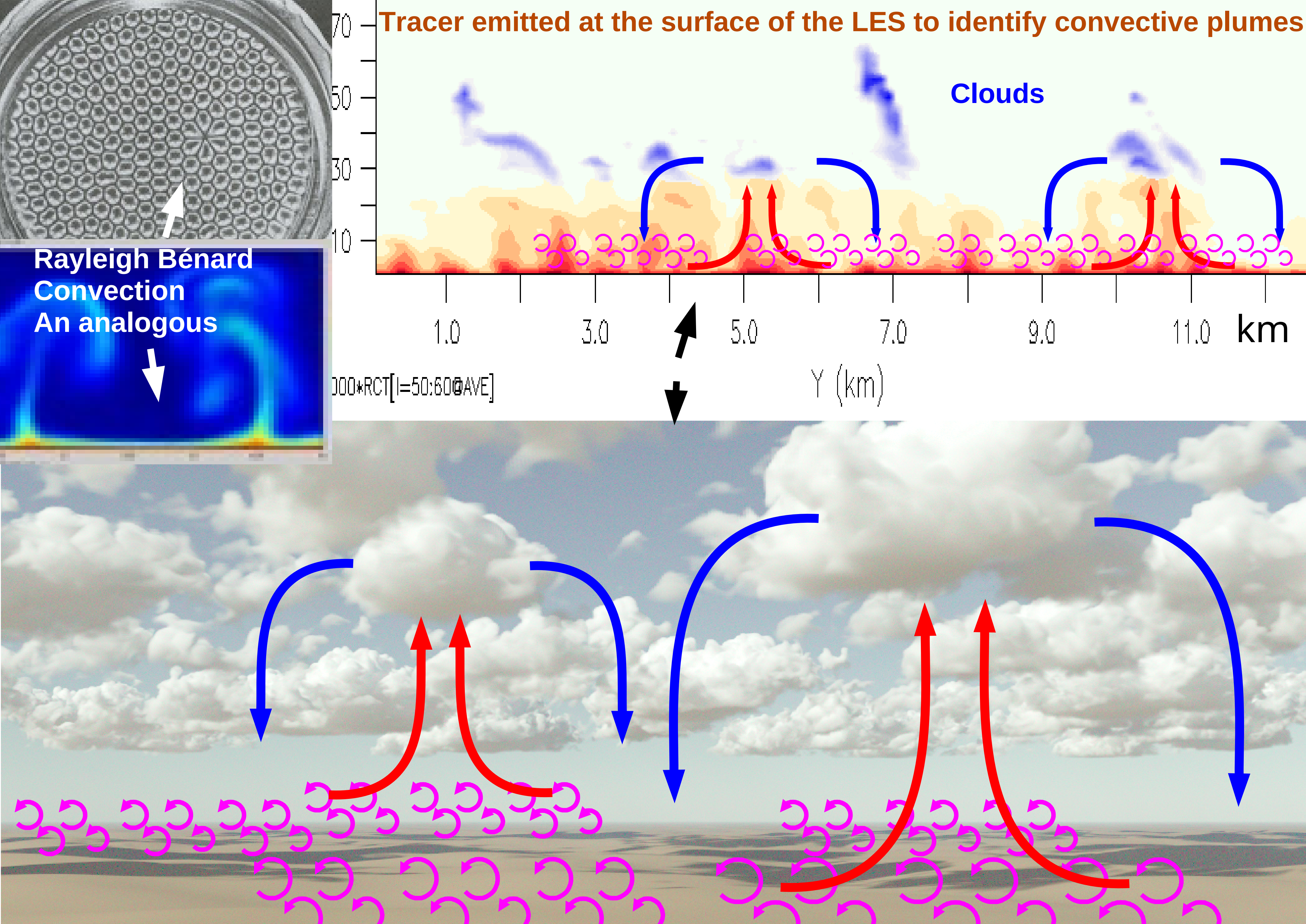
Physical rendering made possible by a recent PhD 2019 (N. Villefranque)

An illustration of state-of-the-art work on parameterizations

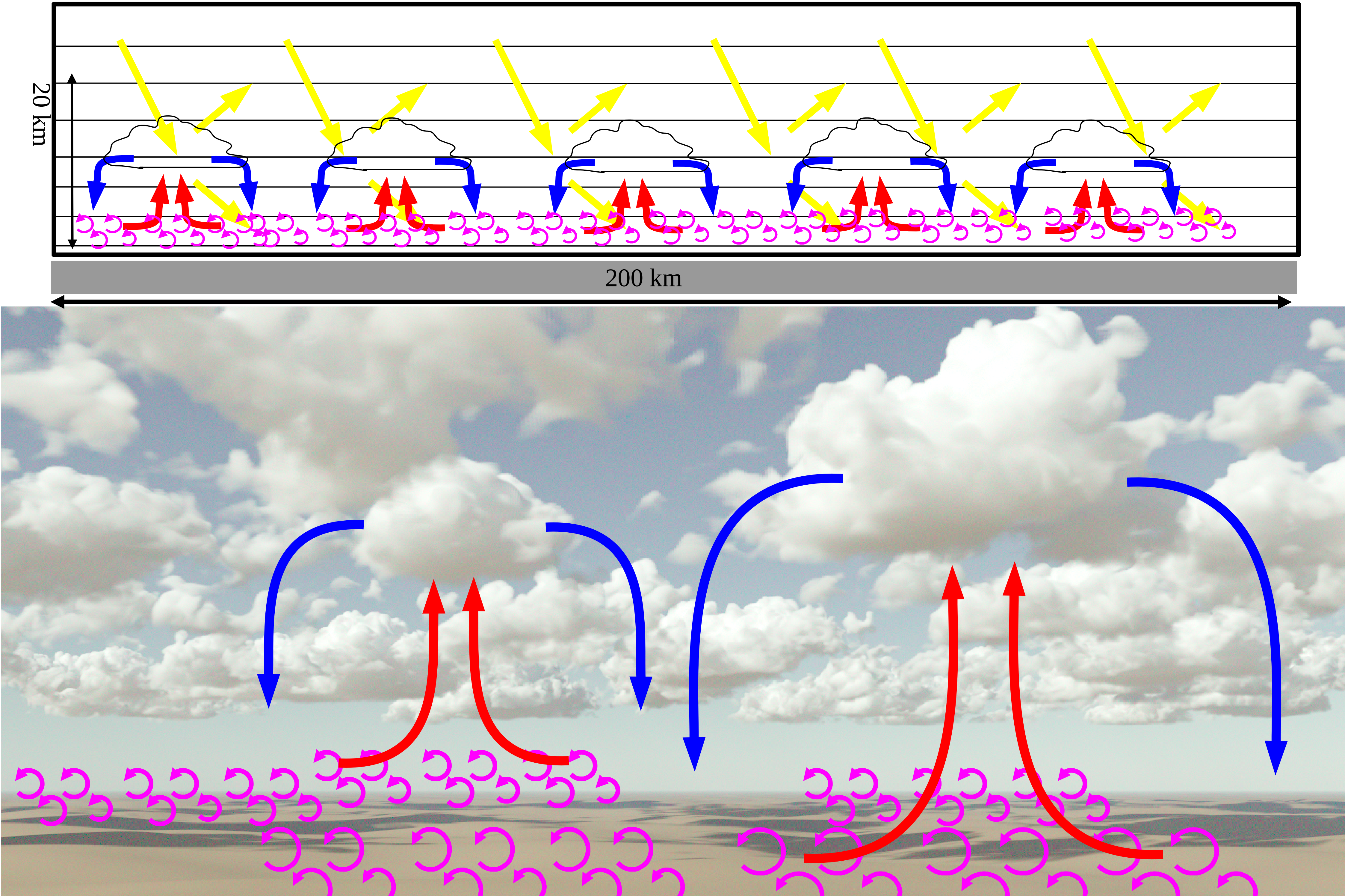
Parameterization of convective boundary layer and turbulence

Large Eddy simulations at 8m of a case of cumulus case (ARM case)
Used to understand the processes at work and idealize them



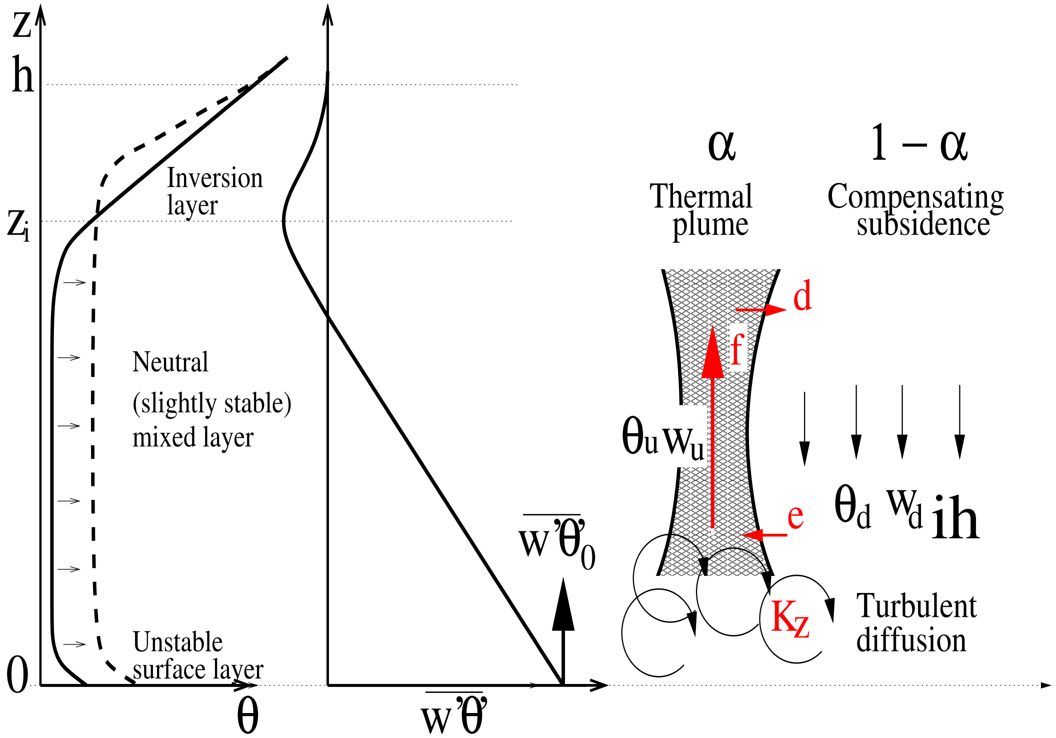

Tracer emitted at the surface of the LES to identify convective plumes
Clouds
Rayleigh Bénard
Convection
An analogous
70
50
30
10
1.0
3.0
5.0
7.0
9.0
11.0
km
Y (km)
000*RCT[I=50:60@AVE]

Parameterization of convective boundary layer and turbulence



The “thermal plume model” equations

An EDMF, combining turbulent diffusion with mass fluxes



$$X = \alpha X_u + (1-\alpha) X_d$$

ascending plume of mass flux

$$f = \alpha \rho w_u$$

$$\frac{\partial f}{\partial z} = e - d$$

$$\frac{\partial f c_u}{\partial z} = e c_d - d c_u$$

$$\rho \overline{w' c'} = -\rho K_z \frac{\partial c}{\partial z} + f\,(c_u - c_d) \qquad (9)$$

Chatfield and Brost, 1987, Hourdin et. al., 2002, Siebesma, Soarez et al, 2004

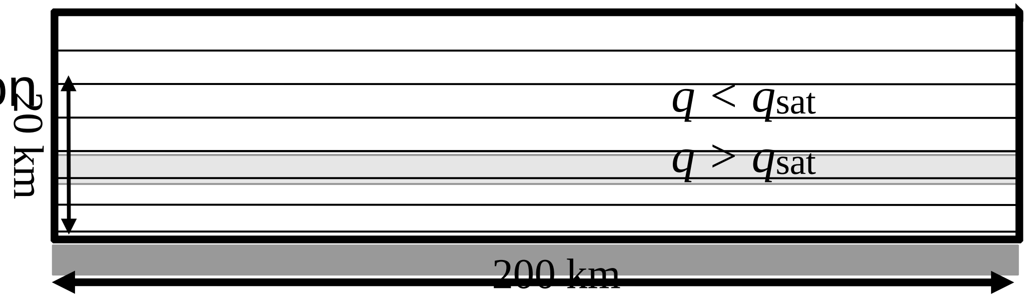
Chatfield, R. B., et Brost, R. A. (1987). A two-stream model of the vertical transport of trace species in the convective boundary layer. Journal of Geophysical Research, 92, 13,263-13,276.

Hourdin, F., Couvreux, F., & Menut, L. (2002). Paramétrage de la couche limite de convection sèche basé sur une représentation du flux de masse des thermiques. Journal of the Atmospheric Sciences, 59, 1105-1123

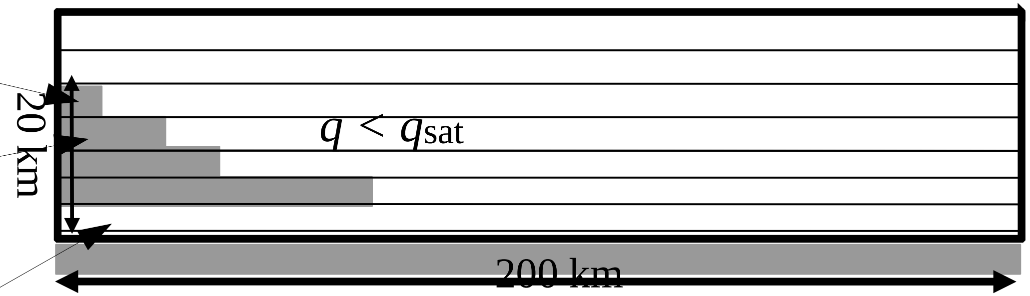
Statistical cloud scheme

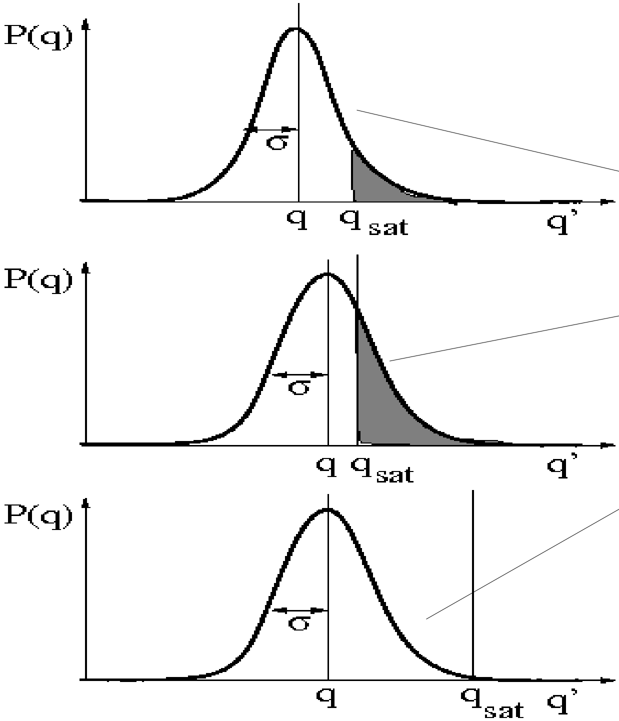
q : water vapor concentration
q_{sat} : maximum concentration at saturation
If $q > q_{sat}$:
→ water condenses = clouds
q *and* q_{sat} are known at the grid scale
→ What is the fractional coverage ?

« all or nothing » model :
If $q > q_{sat}$ cloudy grid cell, else clear sky



« Satistical » cloud scheme :
We assume a subgrid-scale distribution of q' in the grid cell centered on q



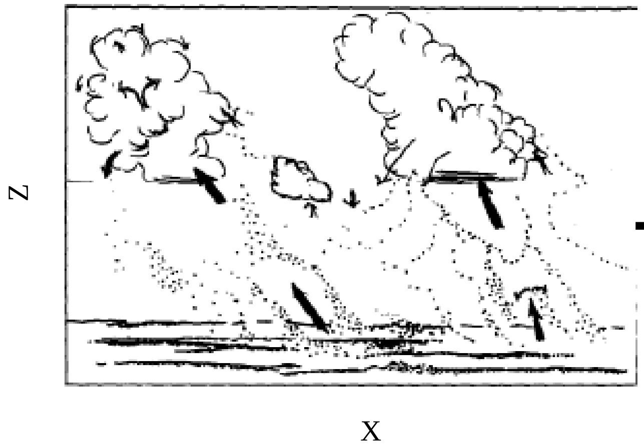


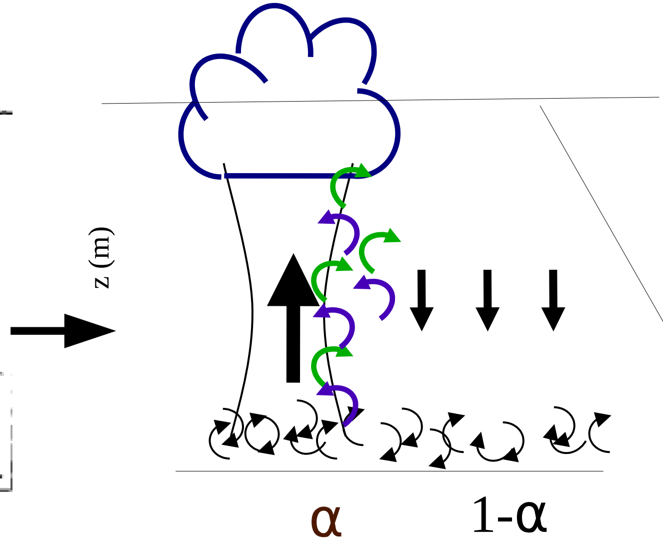
Simple parameterization : gaussian with $\sigma / q = 20\%$

« Mass flux schemes » : example of the thermal plume model boundary layer convection

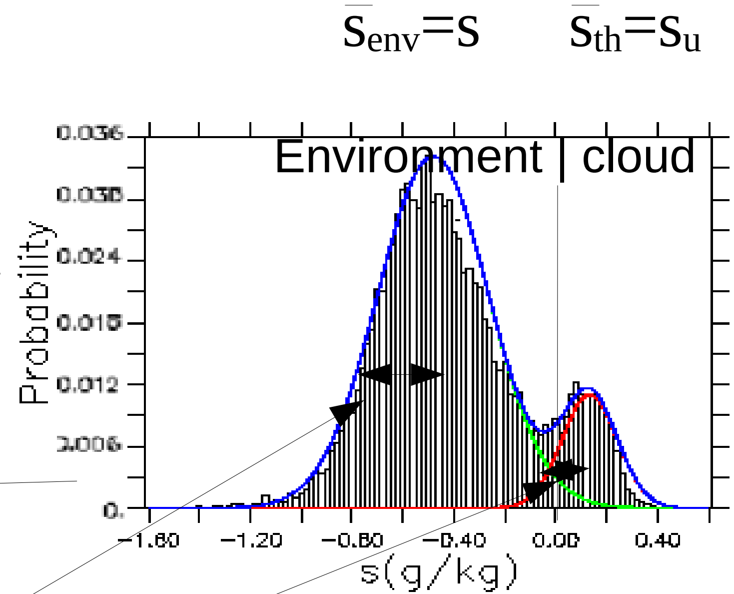
Hourdin et al., JAS, 2002; Rio et Hourdin, JAS, 2008

LeMone and Pennell, MWR, 1976





Parameterization of the subgrid-scale distribution of s=q-qsat

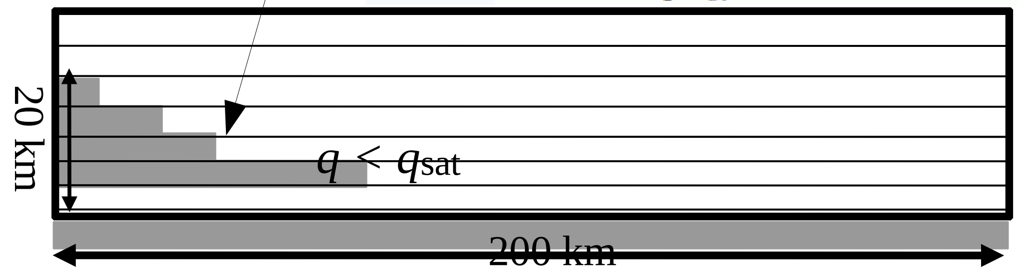


$$\sigma_{s,env} = c_{env} \times \left(\frac{\alpha}{1-\alpha}\right)^{\frac{1}{2}} \times (\bar{s}_{th} - \bar{s}_{env}) + b \times \bar{q}_{t_{env}}$$

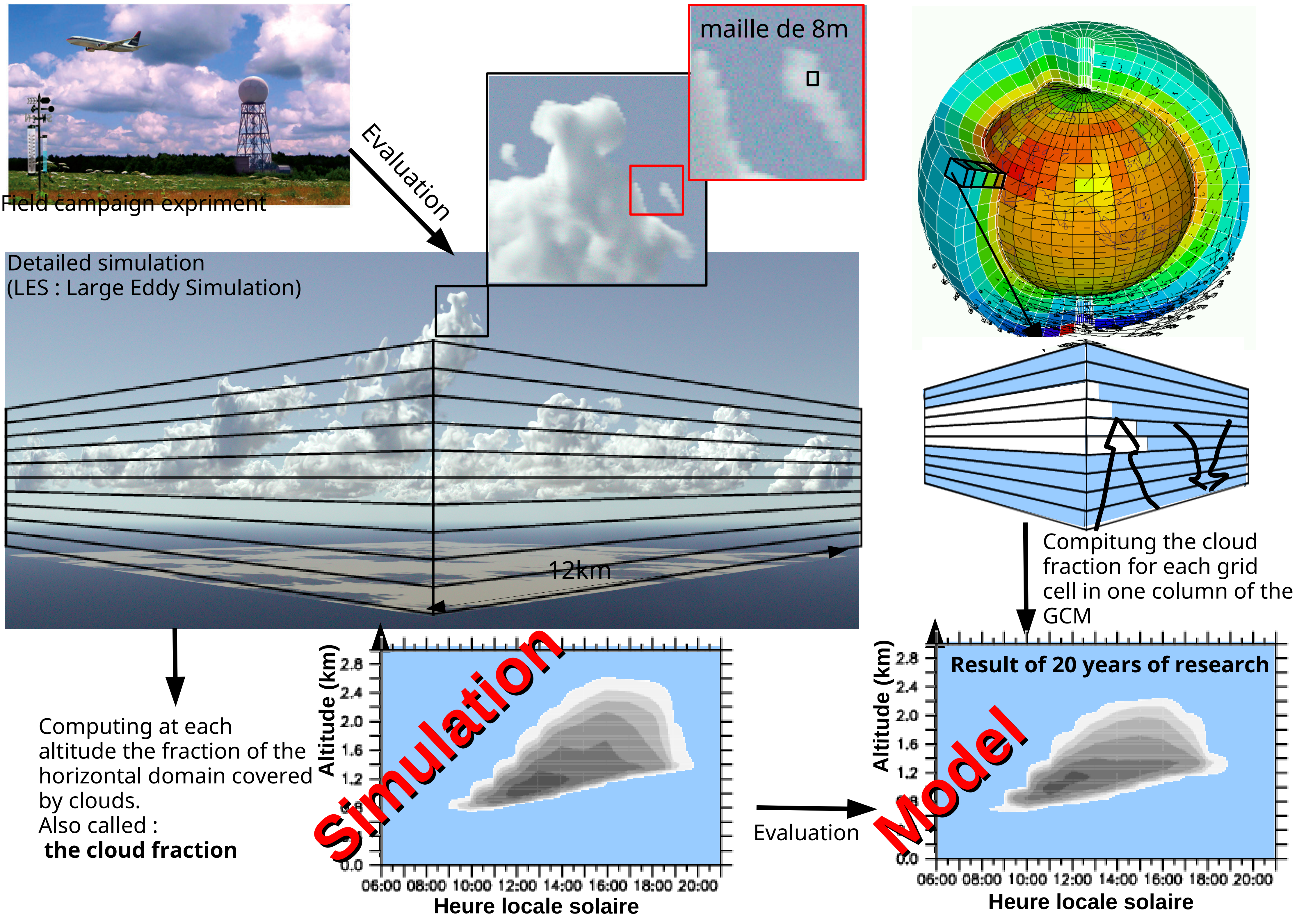
$$\sigma_{s,th} = c_{th} \times \left(\frac{\alpha}{1-\alpha}\right)^{-\frac{1}{2}} \times (\bar{s}_{th} - \bar{s}_{env}) + b \times \bar{q}_{t_{th}}$$

Internal variables

- w: mean vertical velocity within thermals
- α: fractional coverage of thermals
- e: entrainment rate within thermals
- d: detrainment rate from thermals
- qa: concentration of q within thermals



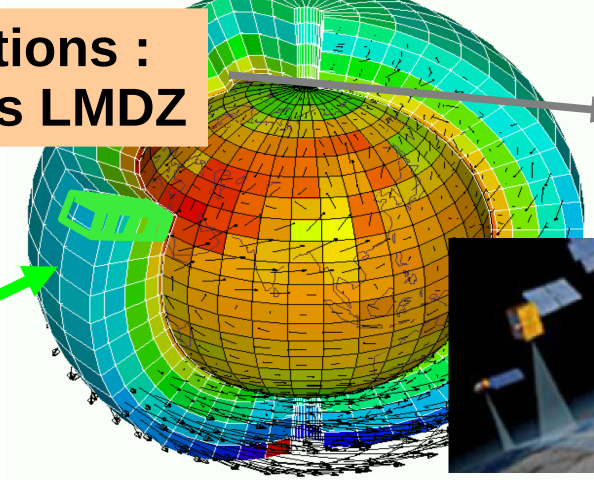
Simple parameterization : Gaussian σ / *q* = 20%



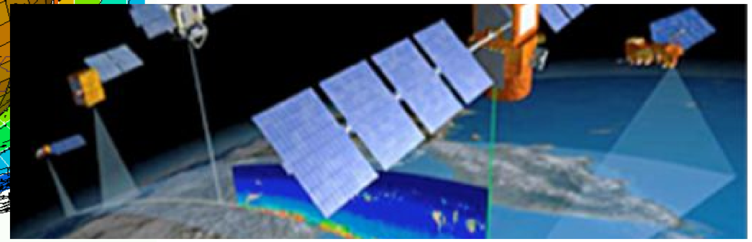
Field campaign expriment
Evaluation
maille de 8m
Detailed simulation
(LES : Large Eddy Simulation)
12km
Compitung the cloud fraction for each grid cell in one column of the GCM
Computing at each altitude the fraction of the horizontal domain covered by clouds.
Also called :
the cloud fraction
Simulation
Altitude (km)
2.8
2.4
2.0
1.6
1.2
0.0
06:00 08:00 10:00 12:00 14:00 16:00 18:00 20:00
Heure locale solaire
Evaluation
Model
Result of 20 years of research
Altitude (km)
2.8
2.4
2.0
1.6
1.2
0.0
06:00 08:00 10:00 12:00 14:00 16:00 18:00 20:00
Heure locale solaire

Amélioration/évaluation des paramétrisations : apport du « modèle du thermique » dans LMDZ

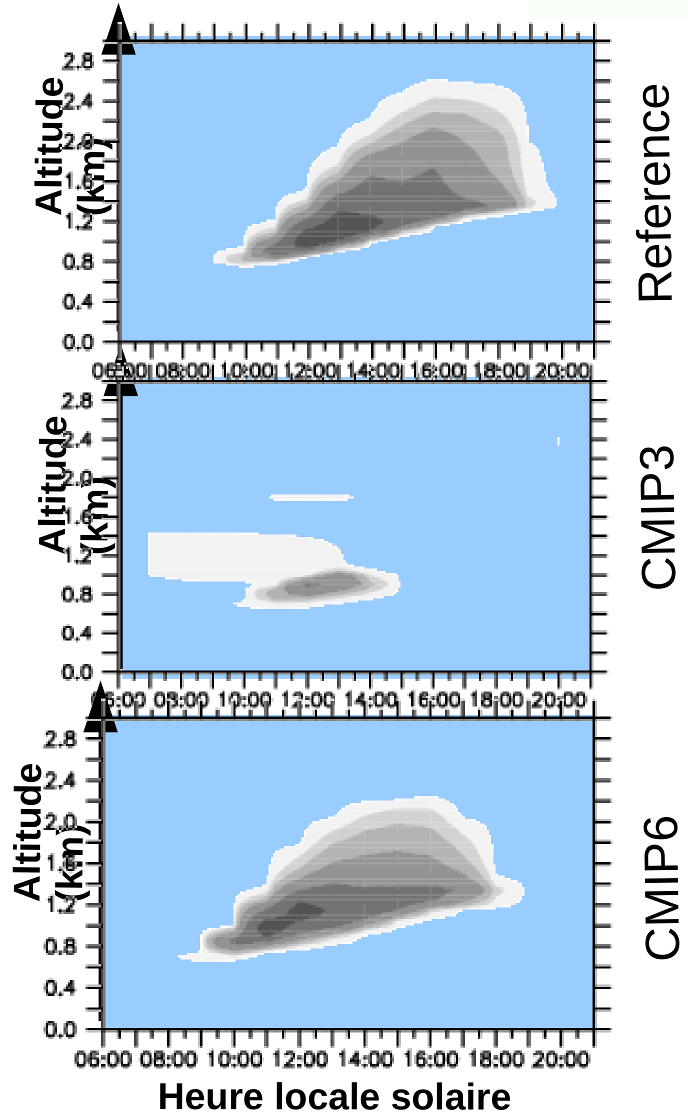
1/ en mode uni-colonne (SCM) vs simulations explicites (LES)

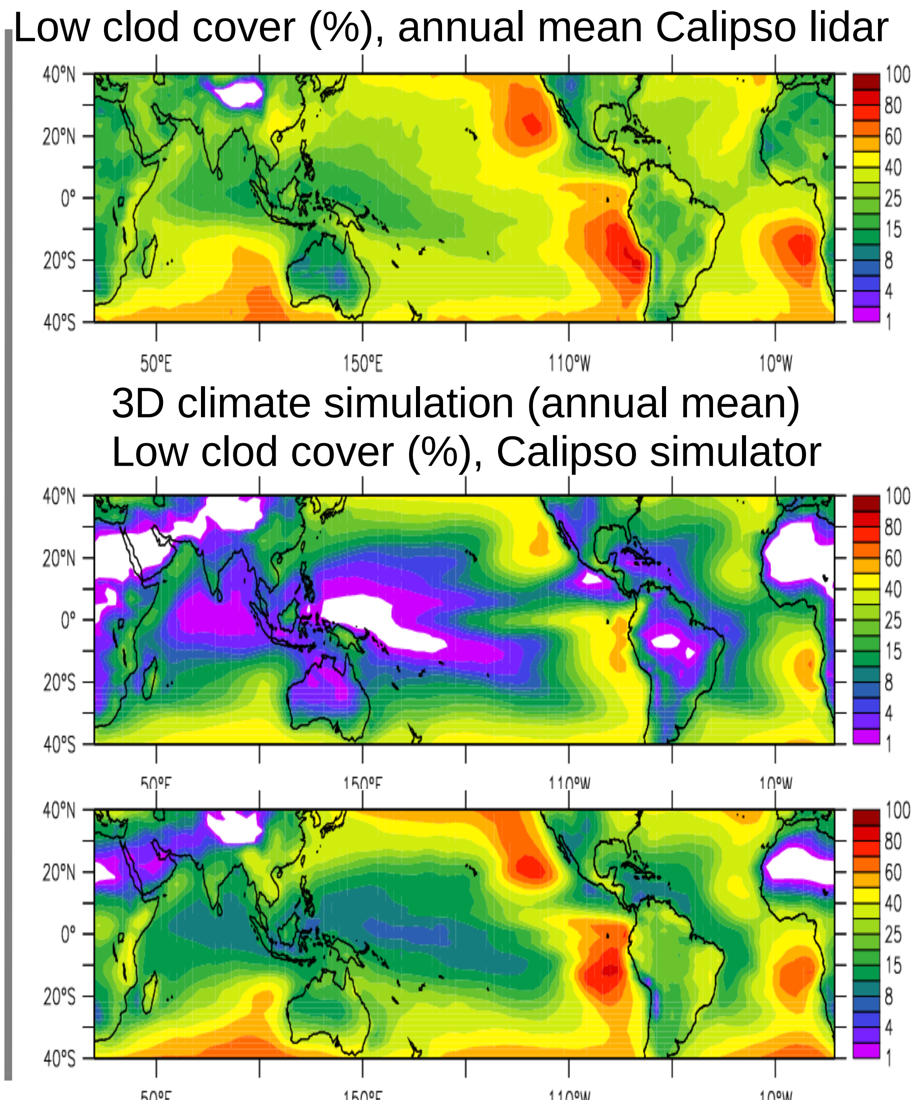


2/ dans le modèle climatique 3D vs satellites



Cas ARM (Oklaoma) de cycle diurne de cumulus

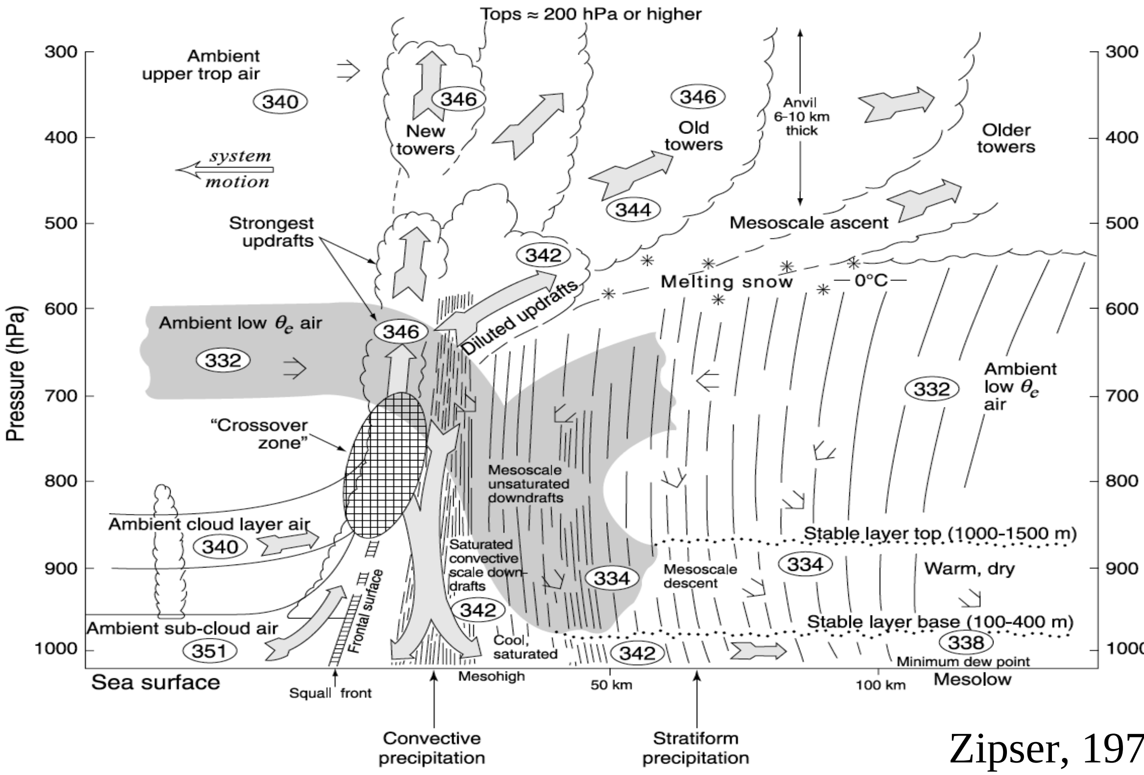




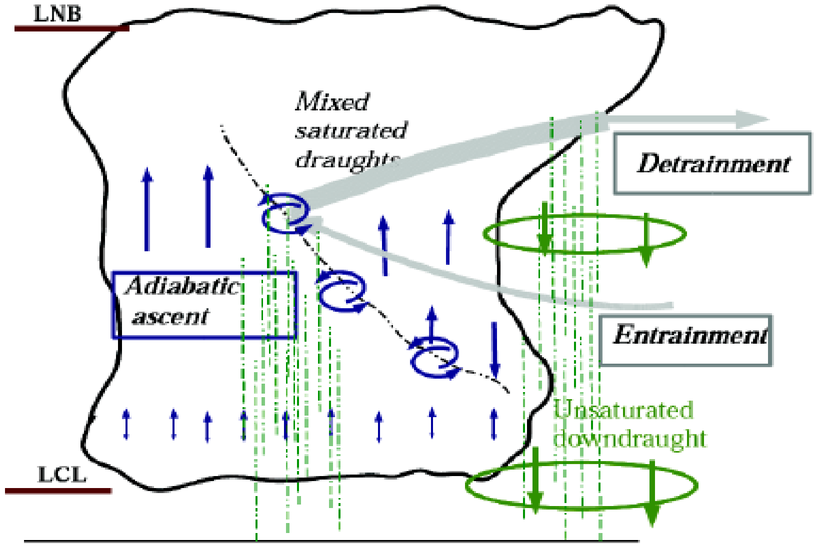
3. La convection profonde

Spécificités de la convection profonde
- Profonde (typiquement jusqu'à la tropopause)
- Instabilité conditionnelle → Processus de déclenchement (triggering)
- Importance de la microphysique. La pluie joue un rôle déterminant.
- Importance de l'organisation méso-échelle (formes variées)

Conceptual model of convection highlighted by field campaigns



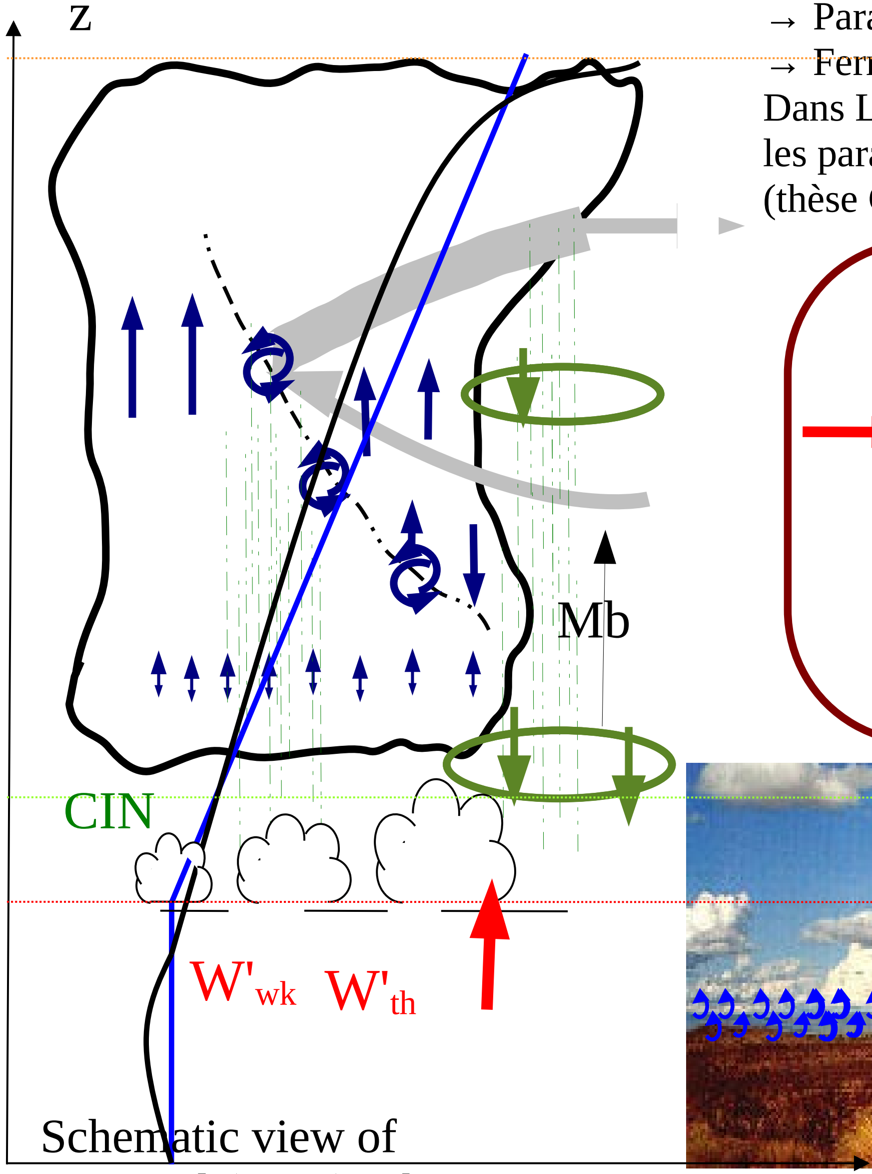
Zipser, 1977



Emanuel, 1991

« Nouvelle physique » : contrôle de la convection par les processus sous-nuageux

→ Paramétrisation des poches froides (Grandpeix and Lafore 2010)
→ Fermeture basée sur les processus sous-nuageux
Dans LMDZ : on se base sur la vitesse verticale W' estimée par les paramétrisations des thermiques et des poches froides.
(thèse Catherine Rio)



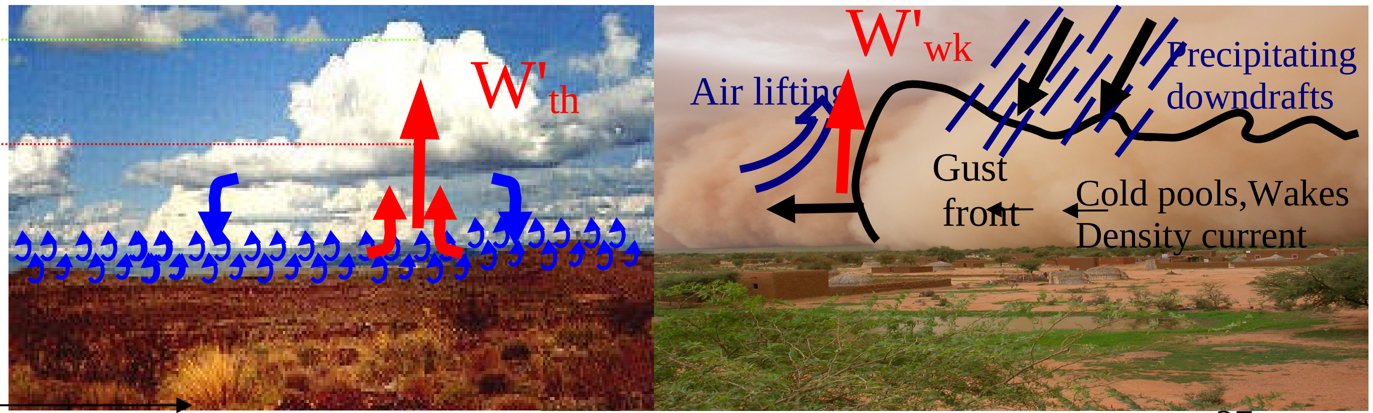
Schematic view of
Emanuel (1993) scheme
Deep convection

K: Energie de soulèvement disponible
ALE en J/kg, proportionnel à w'².

→ **Déclenchement** : max (ALE_{th},ALE_{wk}) > |CIN|

P: Puissance de soulèvement disponible
ALP en W/m², proportionnel à w'³.

→ **Fermeture** : $MB=f(ALP_{th}+ALP_{wk})$



3. La convection profonde

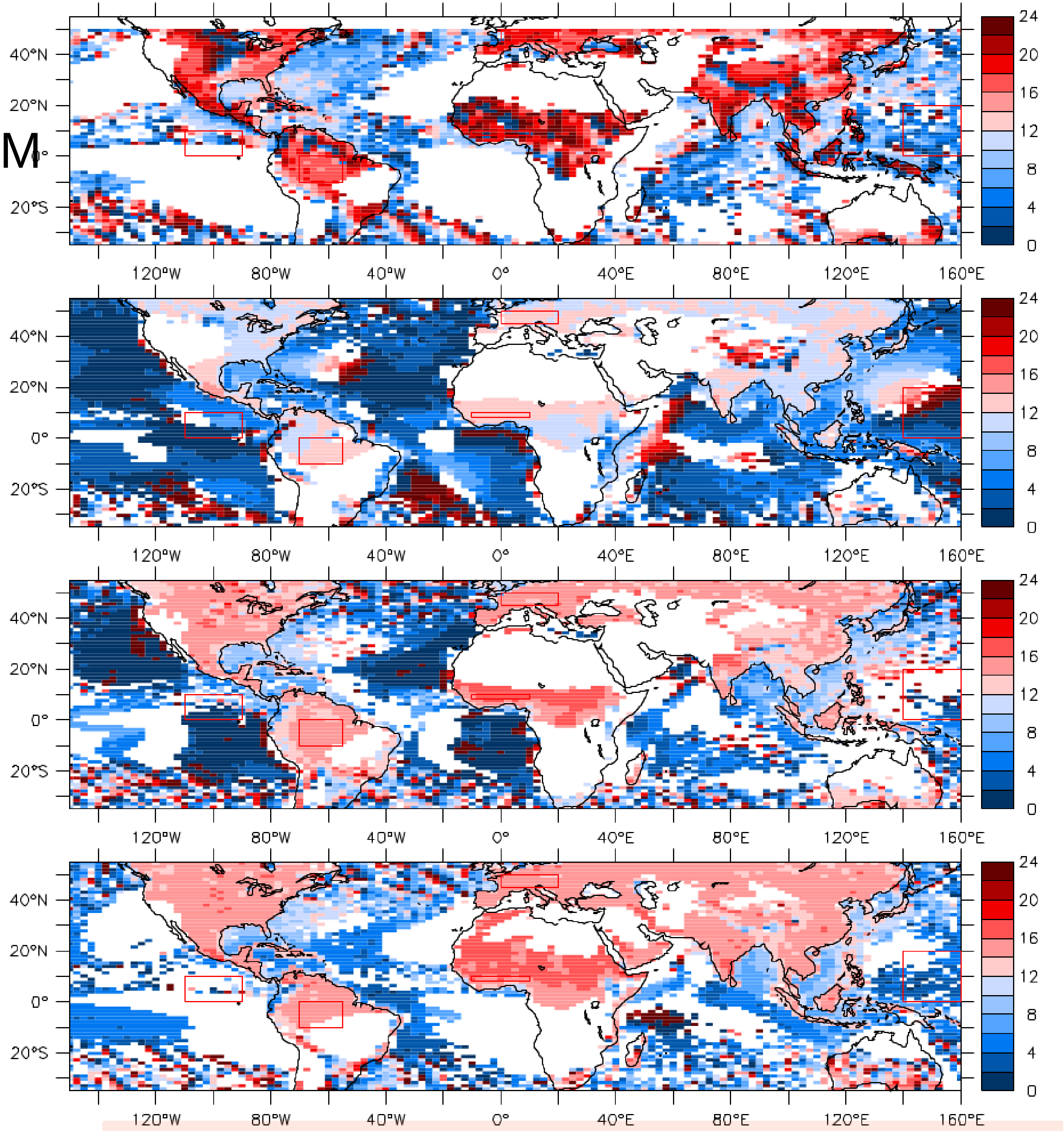
Heure du maximum de précipitation (Juillet Août)

Obs. TRMM

LMDZ5A

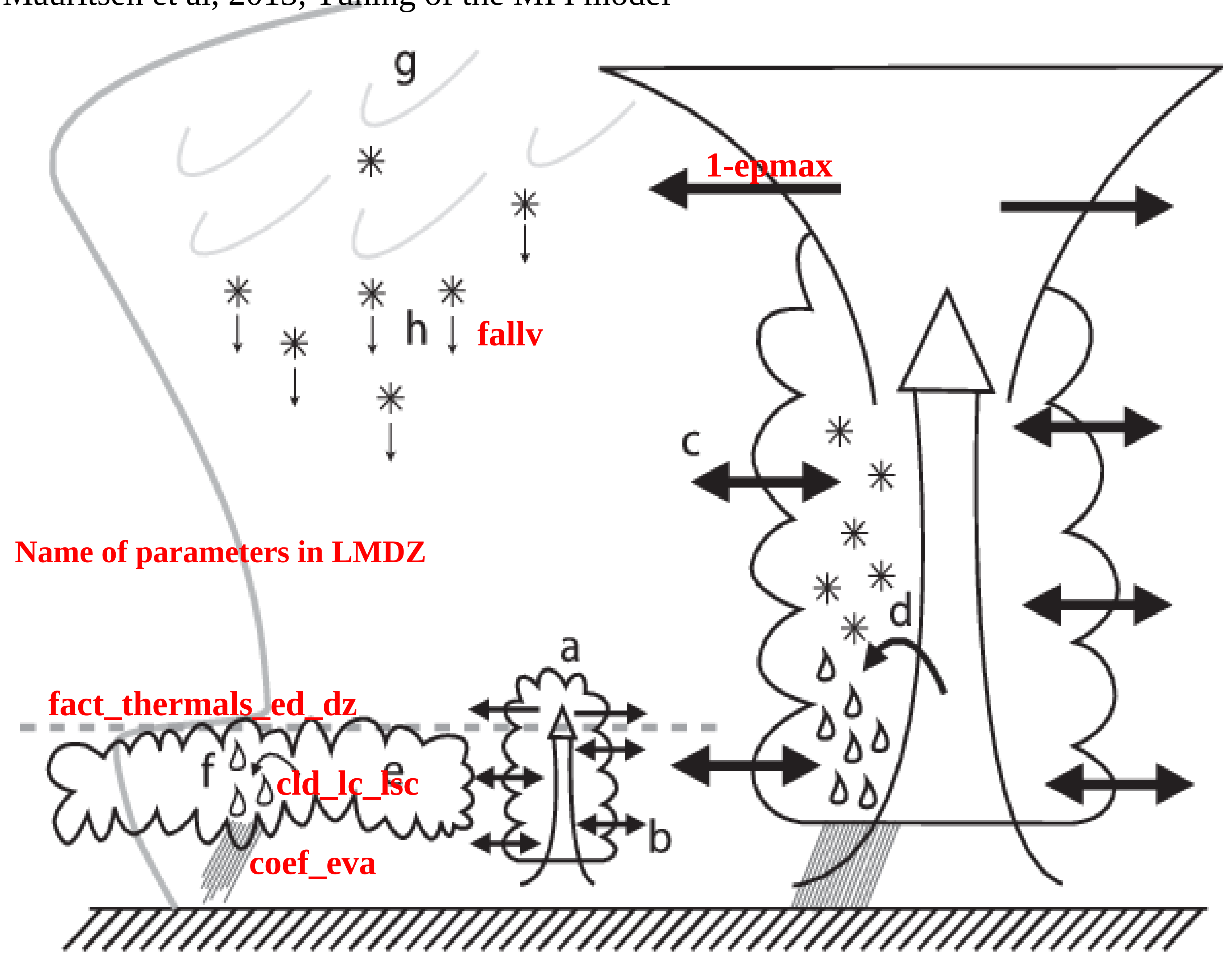
LMDZ5B

LMDZ6A



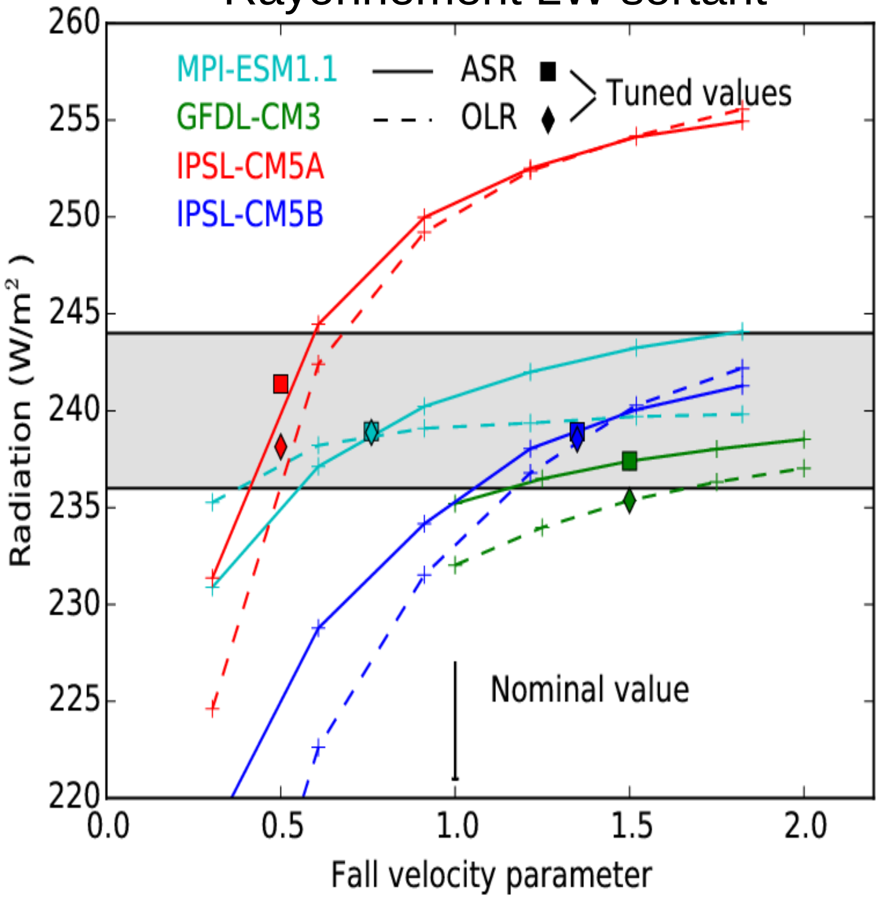
Tuning of cloud parameters

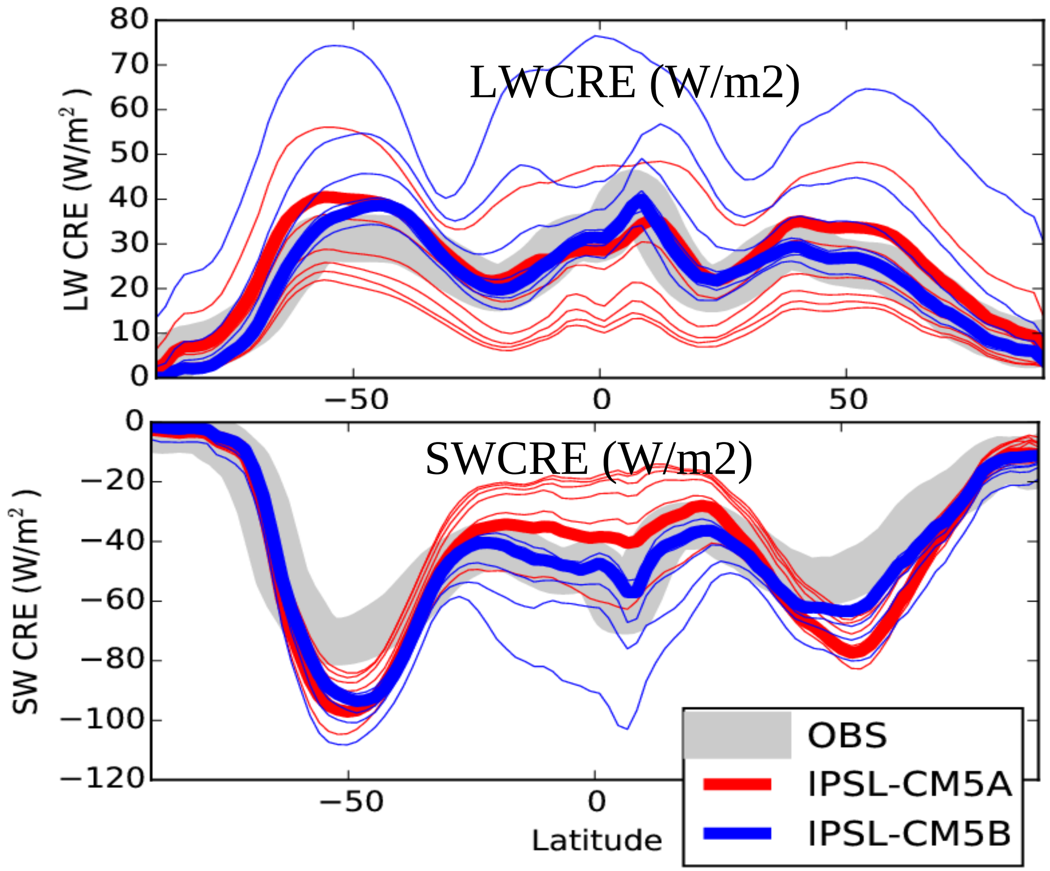
Mauritsen et al, 2013, Tuning of the MPI model



Use of a scaling factor on the fall velocity of cloud ice particles
Impact on global radiative balance and latitudinal radiative forcing of the circulation

Impact sur les flux globaux au sommet
— Rayonnement SW absorbé
- - - Rayonnement LW sortant

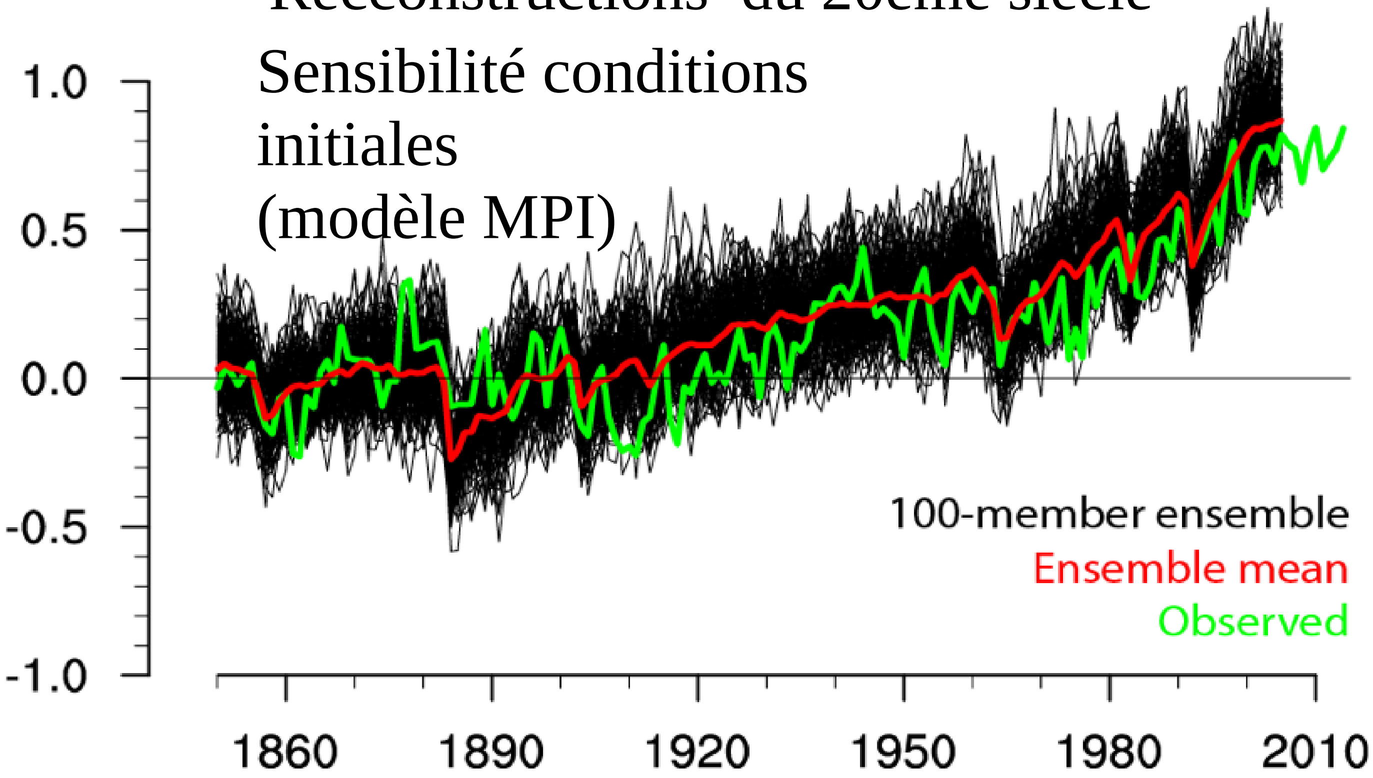


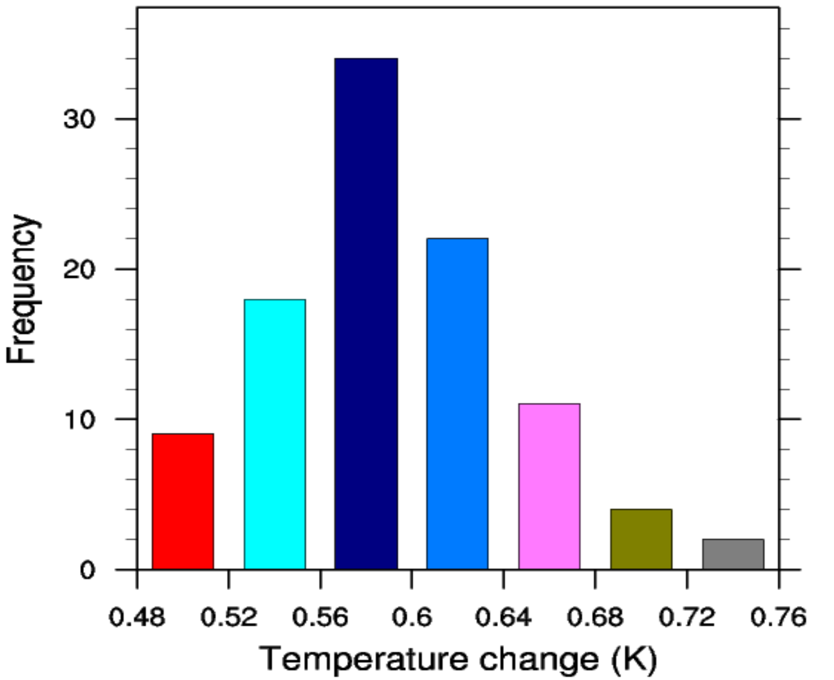


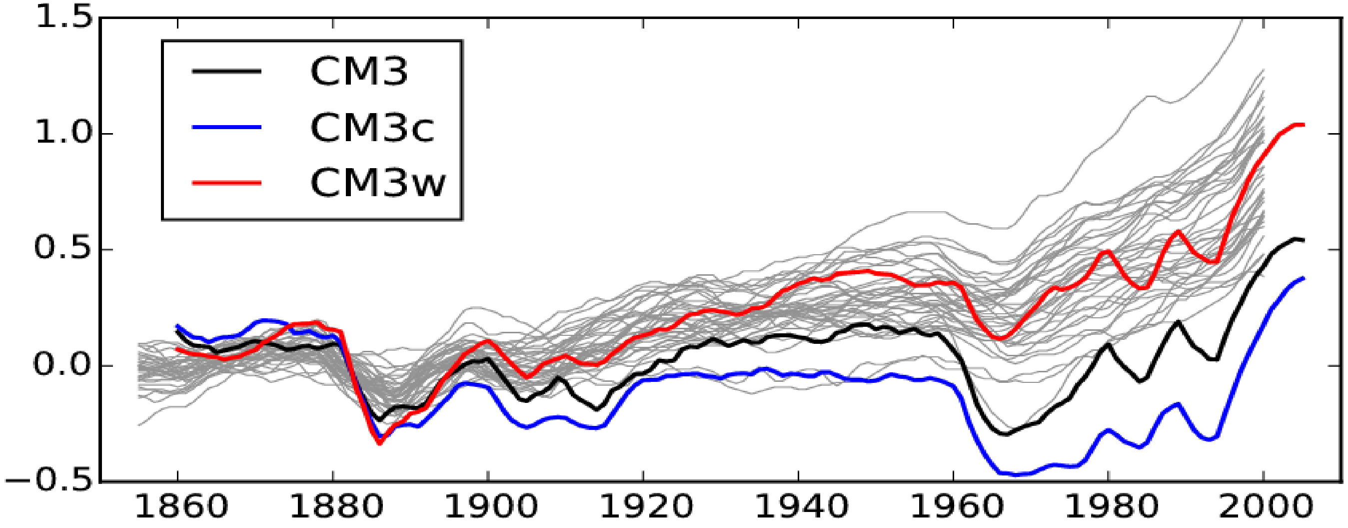
https://www.lmd.jussieu.fr/~hourdin/PUBLIS/bams-d-15-00135.1.pdf
The art and science of climate model tuning

Recconstructions du 20eme siècle

Sensibilité conditions initiales (modèle MPI)

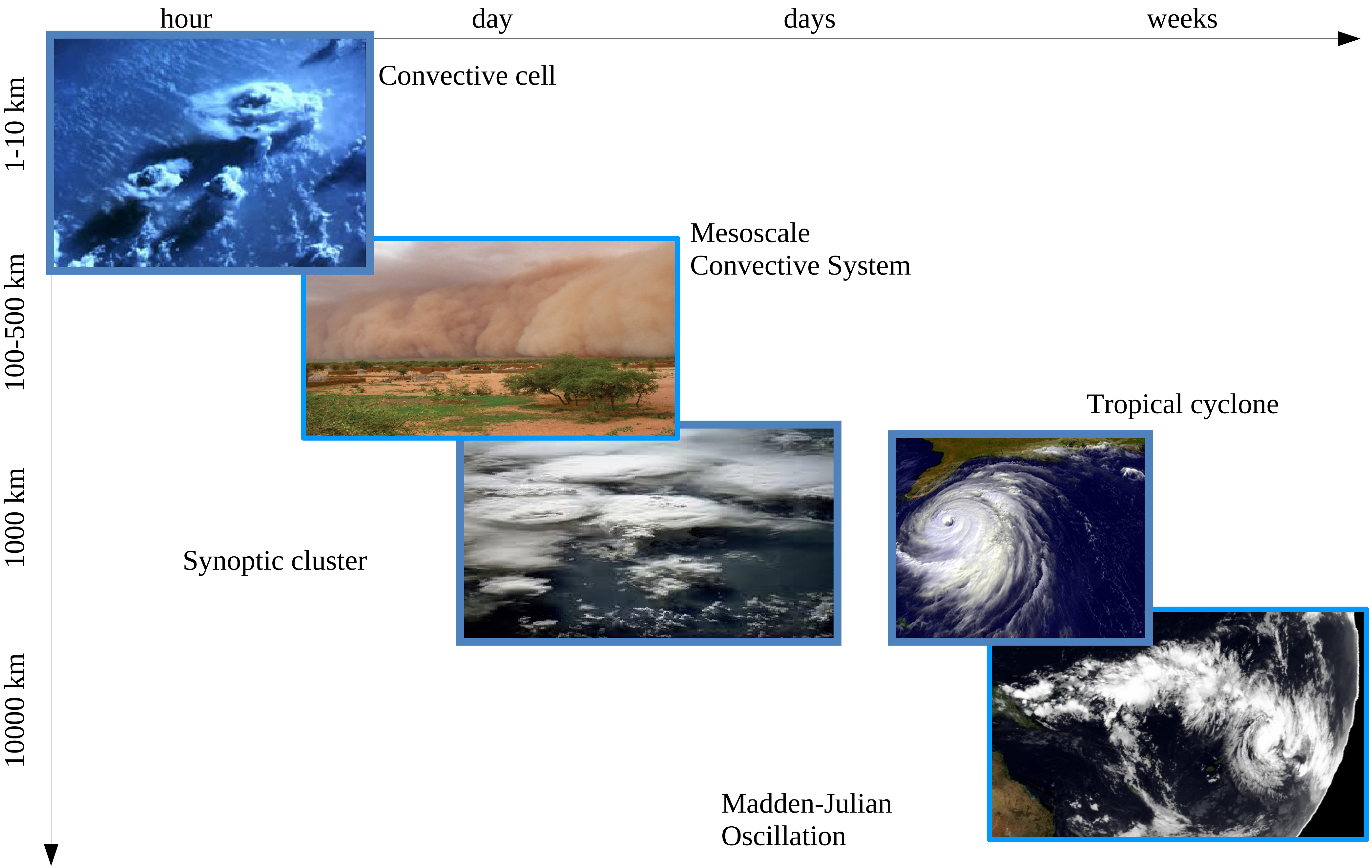


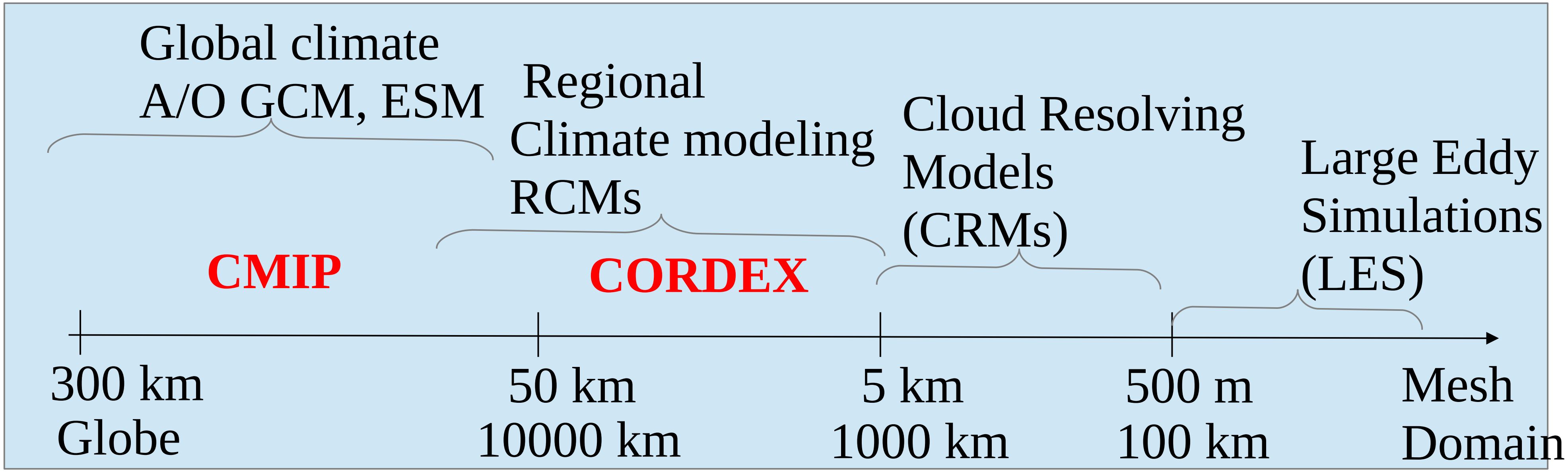




Effet du tuning
Modèle du GFDL

Spatial and temporal scales of convection: a challenge for models





Parameterized convection
Subrid scale clouds, poor microphysics
Climate studies (CMIP)

Explicit convection
1/0 clouds, sophisticated microphysics
Process studies (GASS)

Grey zone for convection

Grey zone for boundary layer

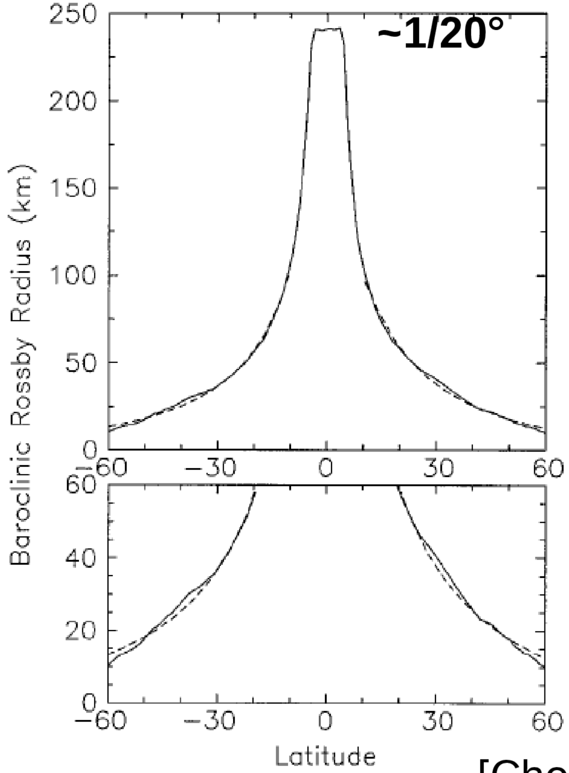
Ocean

Régime « eddying »

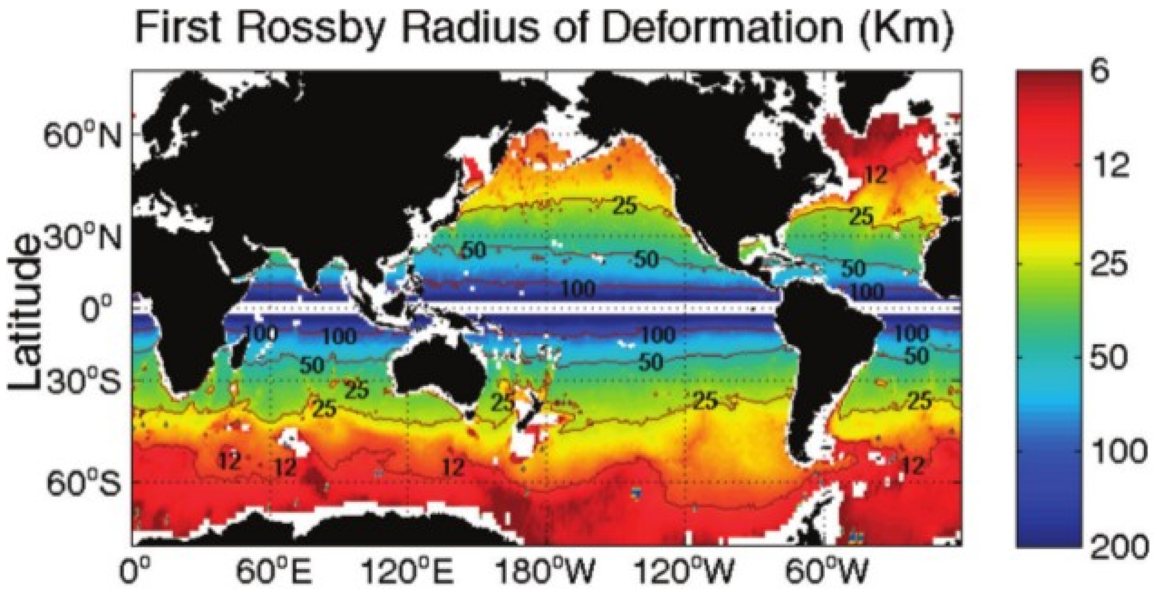
$$R_d = \frac{1}{\pi}\int_{-H}^{0}\frac{N(z)}{f}\,dz$$

Submesoscale permitting	Eddy resolving	Eddy permitting	Grande échelle

$\Delta x / R_d$	1/5	1	5
	~1/20°	~1/4°	~1°



[Chelton et al. 1998]



[Smith 2007]

Concluding remarks / recommendations

Parameterizations

→ Parameterizations are keys in climate modeling, in particular that of subgrid scale processes, cloud, convection ...

→ Parameterizations based on an idealization of the physical processes

→ Turbulent and convective processes may start to be explicitly represented at fine resolution : < 10 km for deep convection, < 500 m for boundary layer convection.

→ Various approaches exist on the way to decompose and approximate the system

→ Use of explicit LES very efficient approach for parameterization development

→ Non local organized turbulence very important for climate

Model and model configurations

→ The model or model configuration you are using should depend on the problem you want to address.

→ All models are wrong and must be assessed specifically for the question you want to address.

→ **A parameterization or a model : Grid configuration + set of equations + tuning**

→ The tuning should be reconsidered if you change the model configuration

→ Tuning should be considered as well for limited area model. It is most often not the case