New developments and approaches for the representation of cloud processes and convection in climate models

Frédéric Hourdin and Jean-Yves Grandpeix

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I Global climate modeling and cloud processes

→ From General Circulation Models to « Earth System »
→ Cloud process studies and the use of high resolution explicit models
→ Key issues for cloud parameterizations

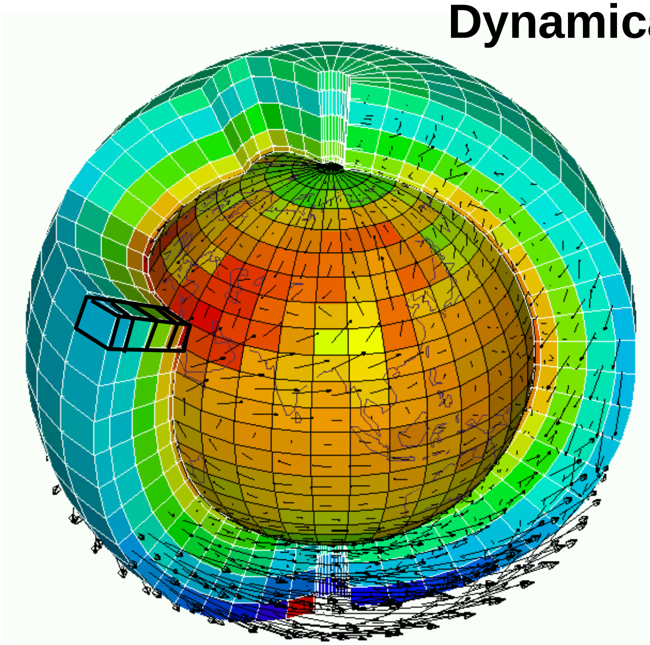
II The LMDZ « New Physics »

→ Thermal plumes and clouds
→ From 1D to 3D and the question of model tuning
→ Deep convection and wakes
→ Impact on climate variability and sensitivity to greenhouse gases

III Current issues in climate modeling and clouds

→ Observations of cloud processes: global (satellites) and local (field campaigns)
→ Global Cloud Resolving Models and super-parametrizations
→ “Stochastic physics”

I.1 From General Circulation Models to “Earth System”



Dynamical core : discretized version of the equations of fluid mechanics

- Conservation de la masse

  $D\rho \,/Dt + \rho \,\mathrm{div}\underline{U} = 0$

- Conservation de la température potentielle

  $D\theta \,/ Dt = Q / Cp \;(p_0/p)^{\kappa}$

- Conservation de la quantité de mouvement

  $D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}p} - \underline{g} + 2\,\underline{\Omega} \wedge \underline{U} = \underline{F}$

- Conservation des composants secondaires

  $Dq/Dt = Sq$

General Circulation Models

→ Developed in the 60s for the purpose of weather forecast
→ Based on a discretized version of the « primitive equations of meteorology »
→ On the Earth but also very rapidly (70s) on other planets (Mars, Venus, ...)
→ Coupling with surface hydrology, ocean, chemistry ... → Earth System models (80s-present)
→ A number of important process are subgrid scale and must be parameterized

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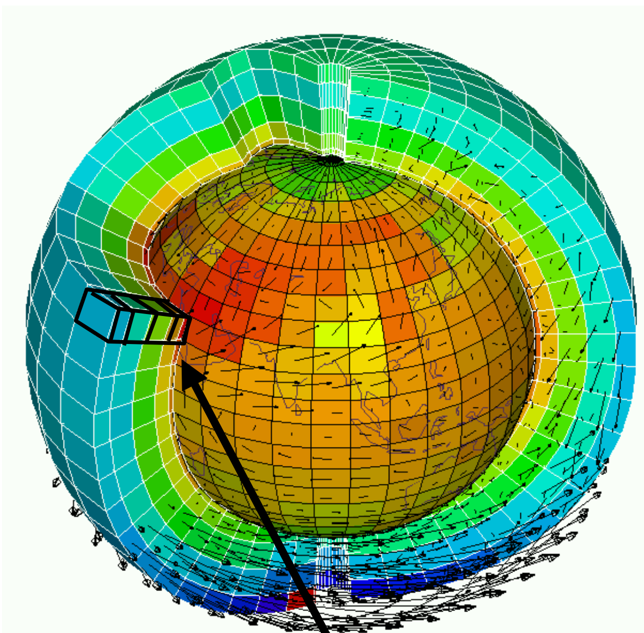

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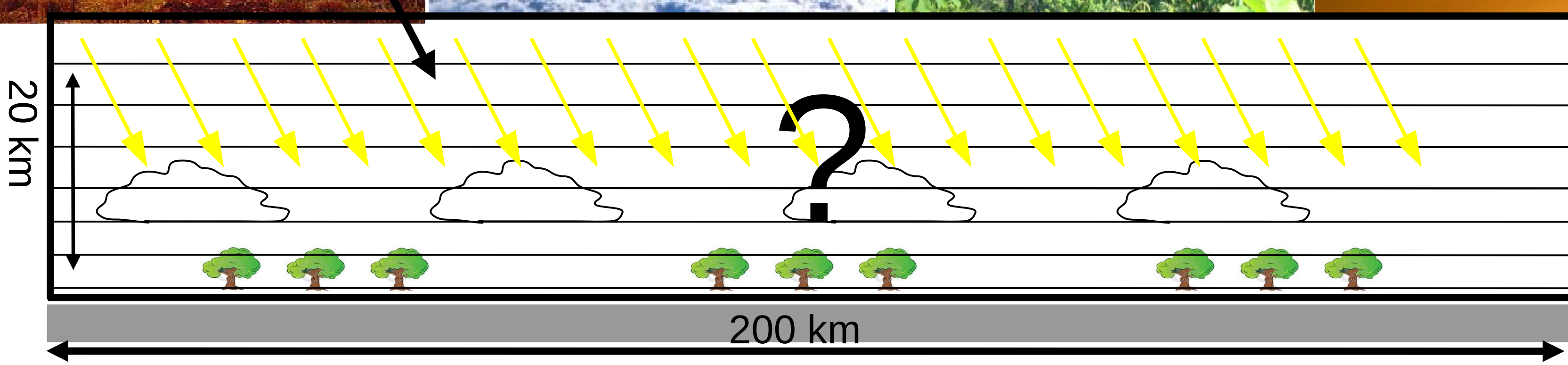
Radiation and sub-grid scale physics : « PARAMETERIZED »

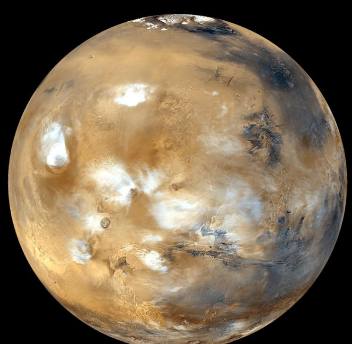
→ **Approximate.**

→ **Based on physical principles not derived from fundamental laws**

→ **Statistical on the horizontal and partly explicit on the vertical**

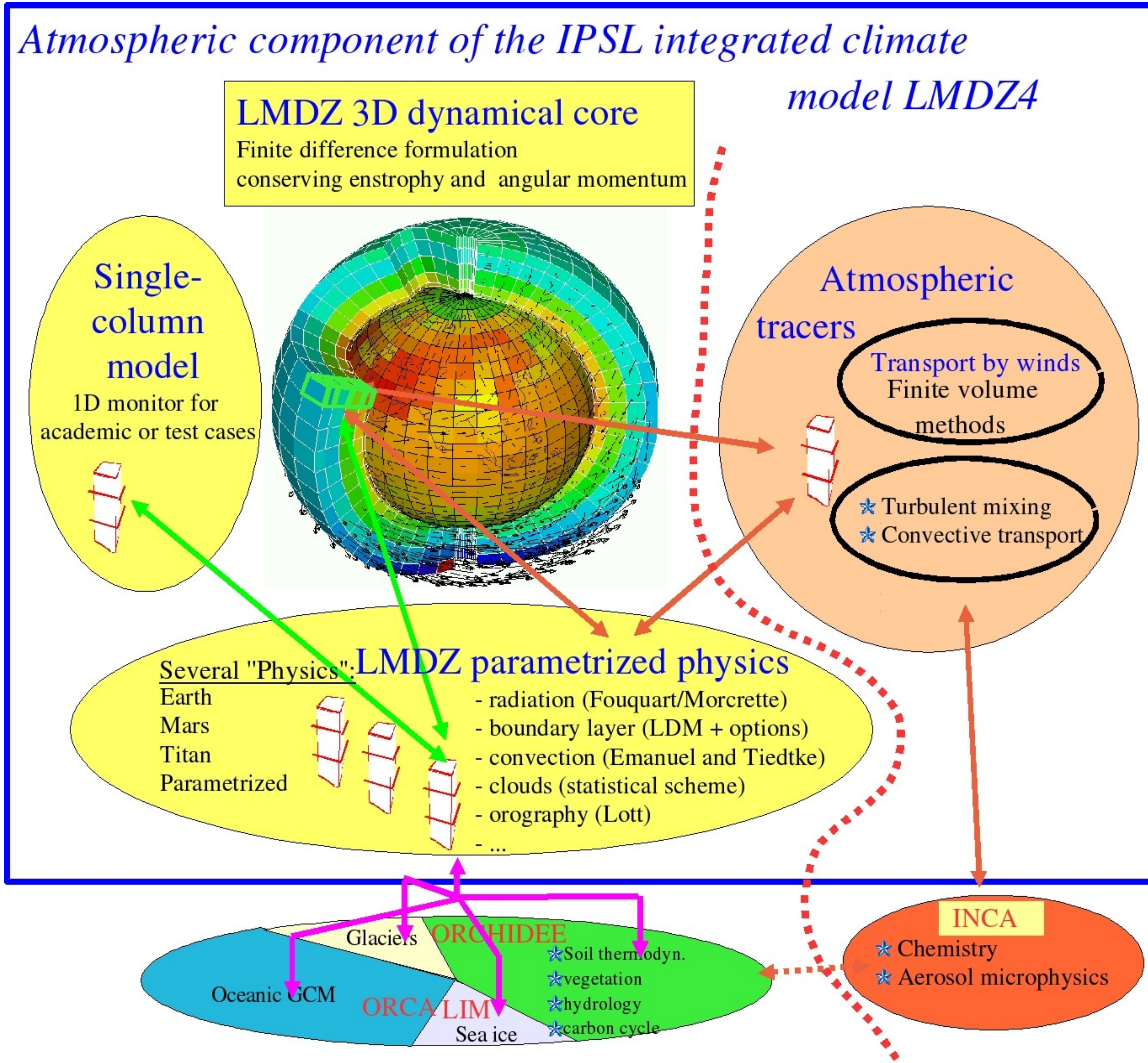


The Earth



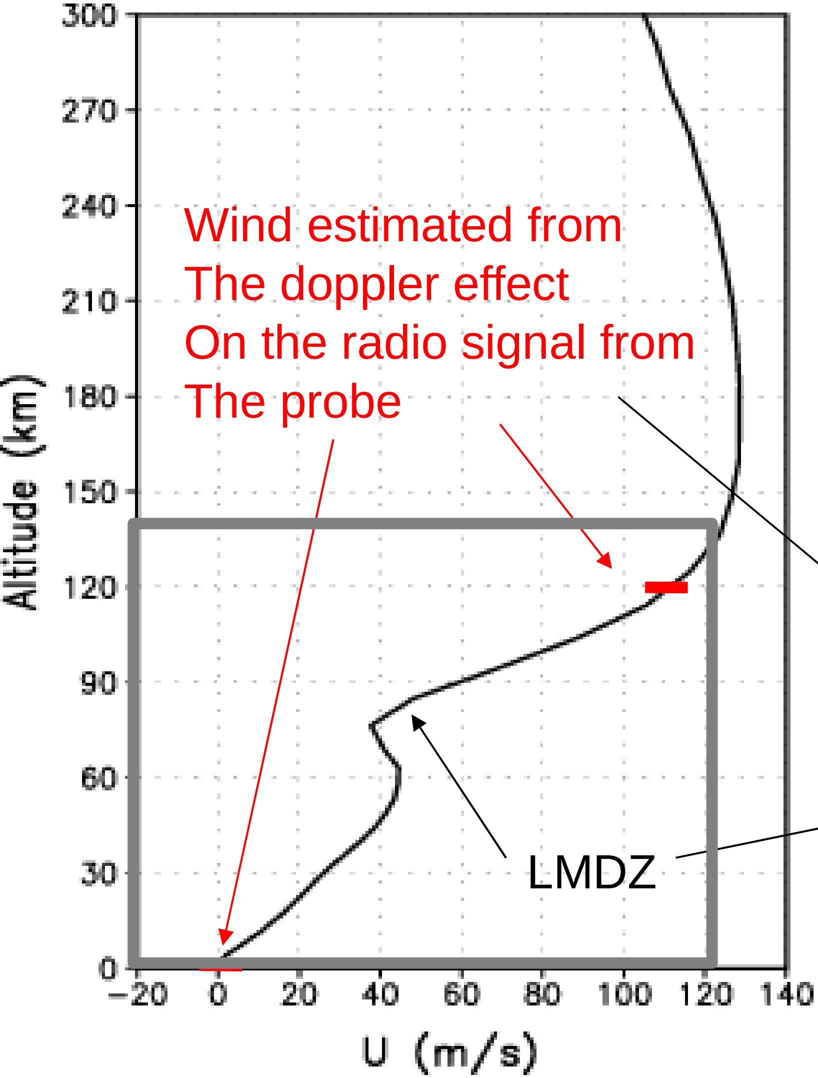
Mars

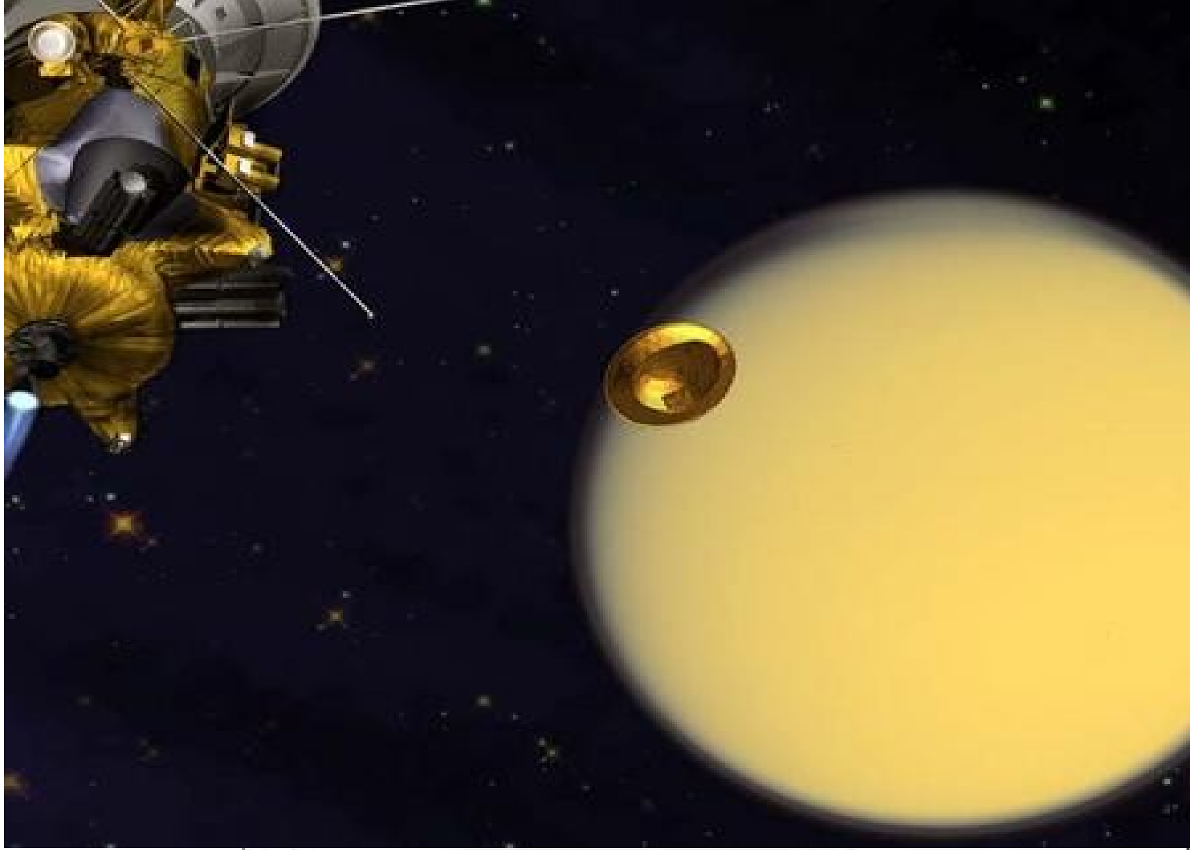
Titan

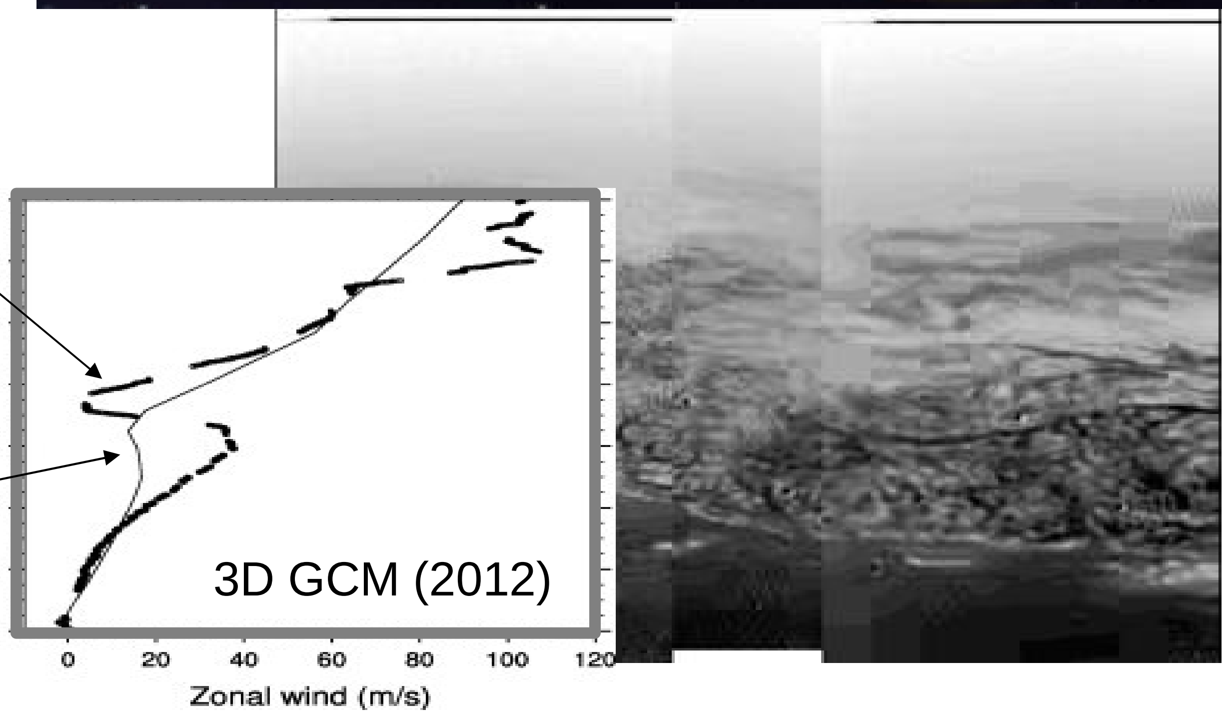


Prediction of Titan atmospheric
Super-rotation with the
LMDZ Titan GCM
(1995, 2005)

An a posteriri comparison with
The Huygens entry profile







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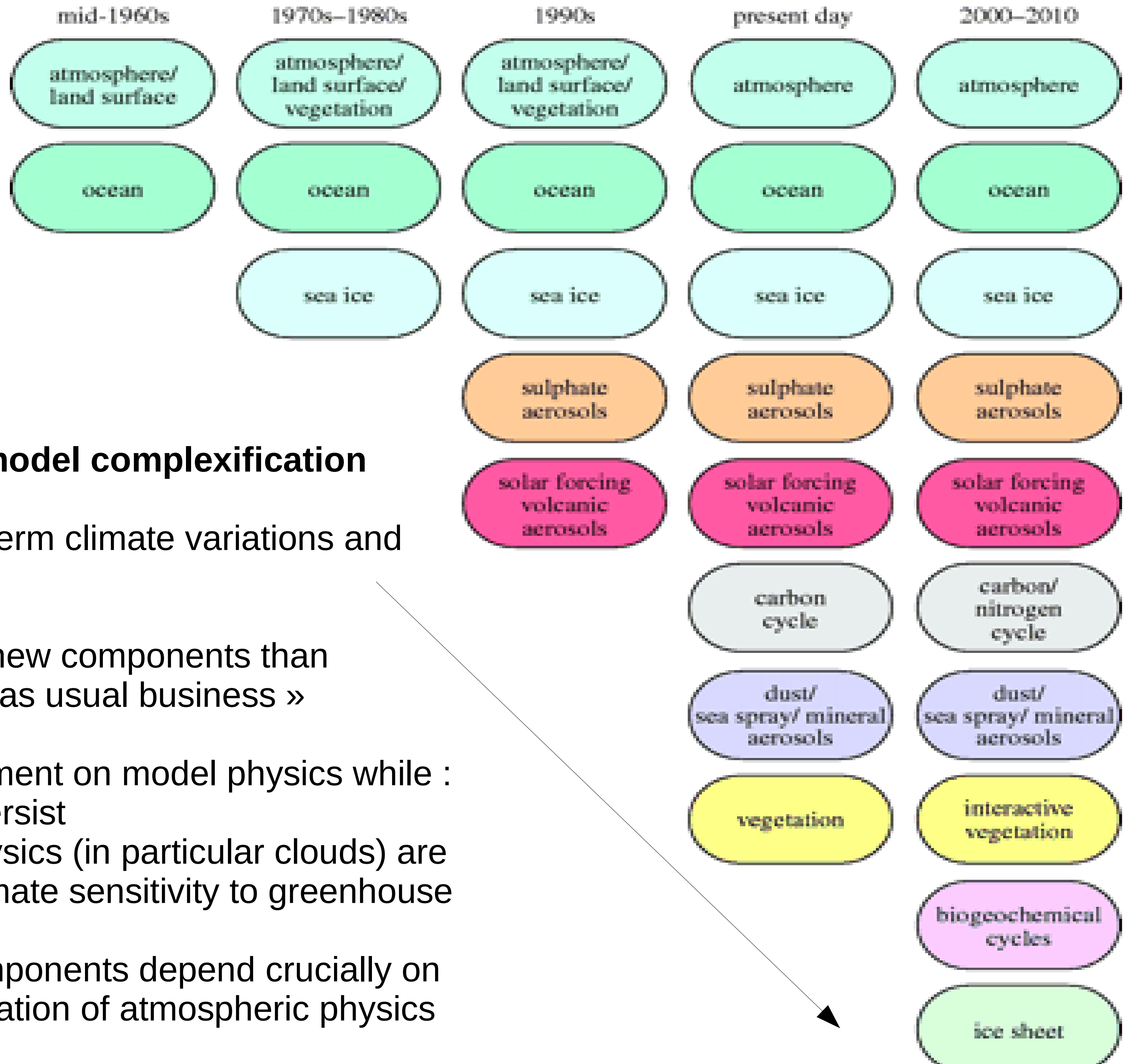


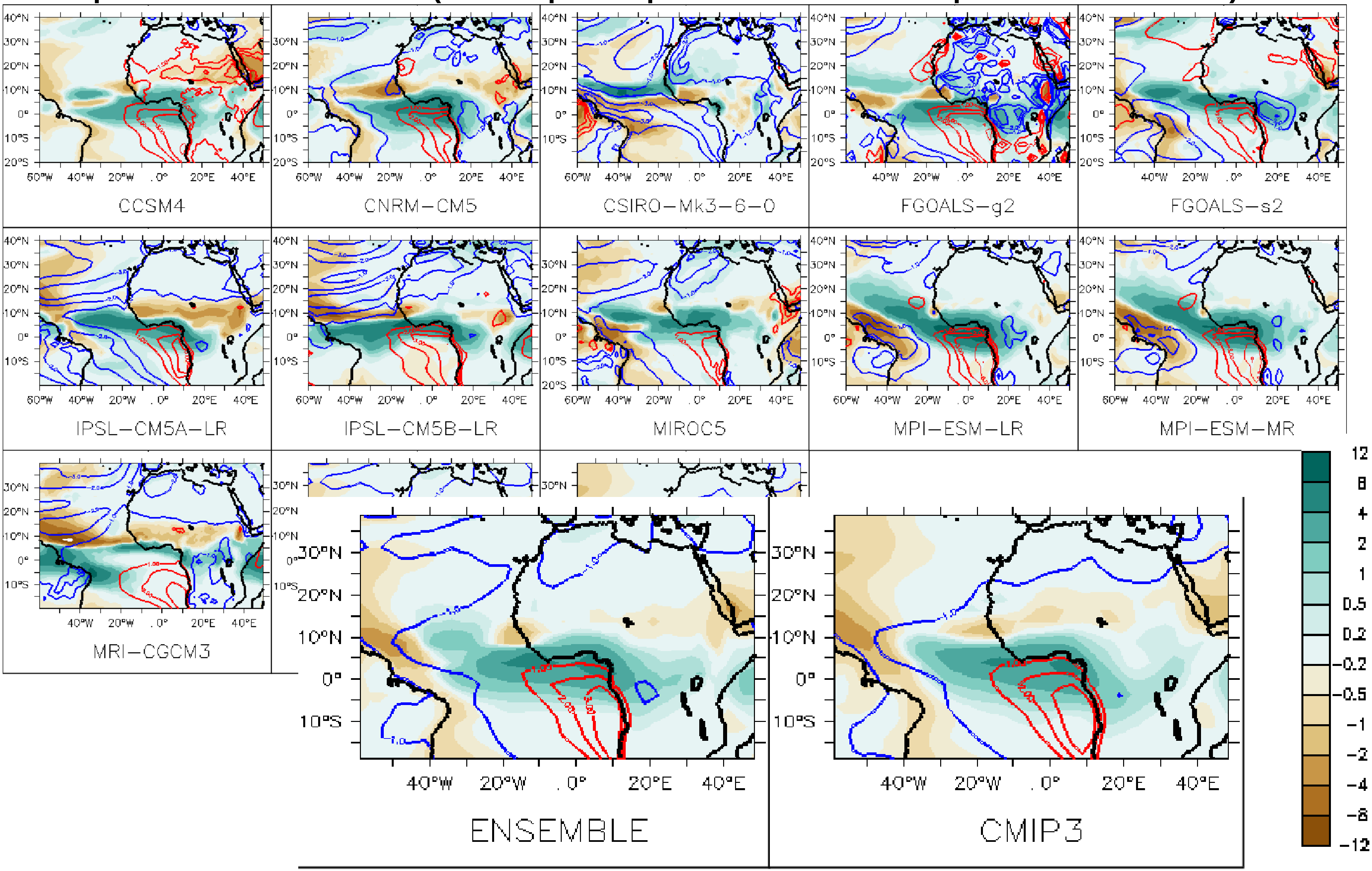
Priority given to model complexification

Motivated by long term climate variations and CO2 cycle

Easier to promote new components than improvements of « as usual business »

Not much improvement on model physics while :
→ strong biases persist
→ atmospheric physics (in particular clouds) are of first order for climate sensitivity to greenhouse gases
→ all the other components depend crucially on the good representation of atmospheric physics

Biases in sea surface temperature (K, contours) and rainfall (mm/day, colors) in coupled atmosphere-ocean simulations (with respect imposed-sea-surface temperature simulations)



CMIP5 average (2012)

CMIP3 average (2006)

I.2 Cloud process studies and the use of high resolution explicit models

Explicit models for turbulent and convective processes

Non hydrostatic on the vertical
« Cloud Resolving Models » : grid cells of 1-3 km, domains 100-1000 km
→ Boundary layer processes parameterized
→ Deep convection and associated clouds are explicitely resolved
« Large Eddy simulations » : grid cells of 10-200 m, domains 10-200 km
→ Small scale turbulence parameterized
→ Cumulus and boundary layer organized structures (large eddies) explicit
« Direct Numerical Simulations » : grid cells of 1mm, domain 1-10 m
→ All the turbulence explicit
→ No use

The GCSS approach (Gewex Cloud System Study)
following Eucrem, Eurocs and others, From 1990

→ The goal of GCSS is to improve the parameterization of cloud systems in GCMs (global climate models) and NWP (numerical weather prediction) models through improved physical understanding of cloud system processes.
→ The main tool of GCSS is the cloud-resolving model (CRM), which is a numerical model that resolves cloud-scale (and mesoscale) circulations in either two or three spatial dimensions. The large-eddy simulation (LES) model is closely related to the 3D CRM, but resolves the large turbulent eddies.
→ The primary approach of GCSS is to use single-column models (SCMs), which contain the physics parameterizations of GCMs and NWP models, in conjunction with CRMs, LES models, and integrated, high-quality observational datasets, to evaluate and improve cloud system parameterizations.
→ Integrated, high-quality observational datasets are required to run the models and to evaluate their results. GCSS and collaborating programs (such as DOE ARM) produce these valuable datasets, which are available from GCSS-DIME (Data Integration for Model Evaluation) (http://gcss-dime.giss.nasa.gov).
In addition, GCSS has recently begun to lead diagnostic studies of the representation of cloud processes in GCMs.

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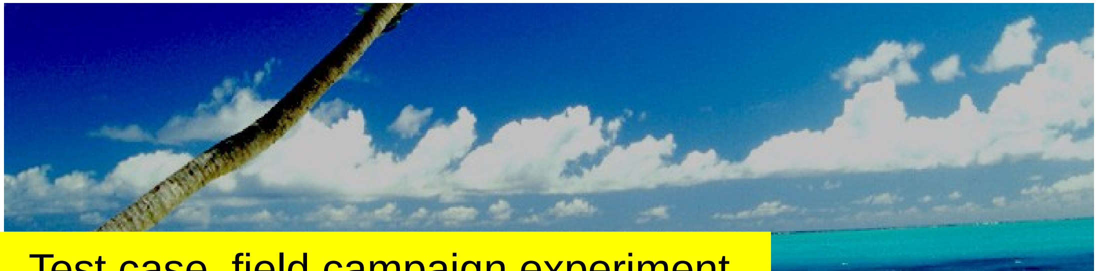
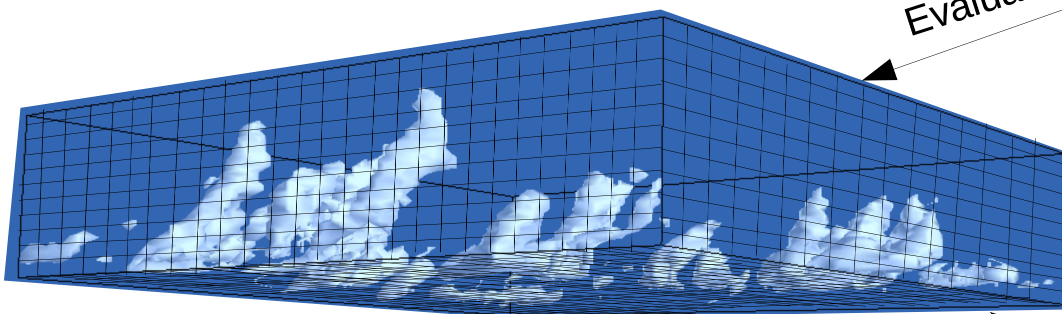


Test case, field campaign experiment

Observation

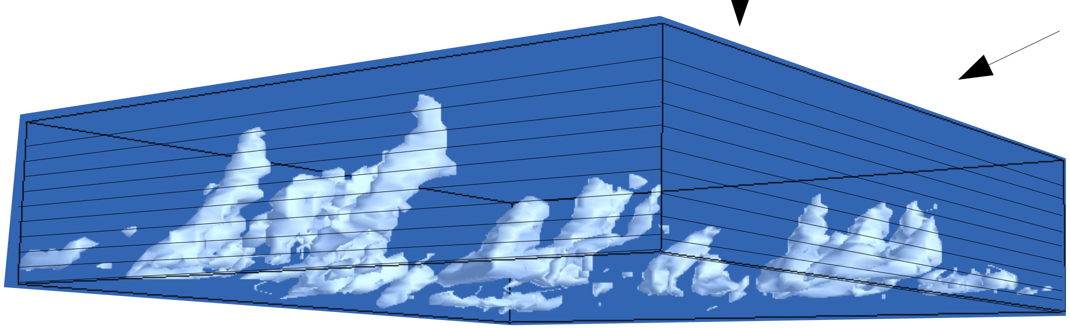
Evaluation

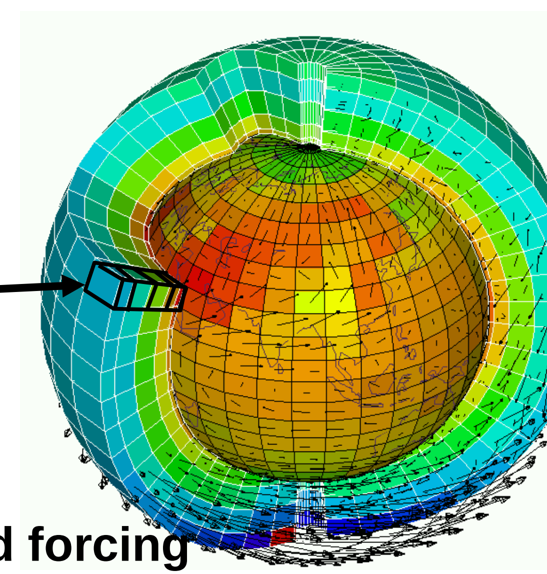


Explicit simulations, Grid cell, 20-100 m

Evaluation

« Large scale » conditions imposed





Climate model, parameterizations, « single-column » mode

→ **Parameterizations are evaluated against other models**

→ **Can be done for realistic test cases but also with more idealized forcing (check the response of the parameterization to perturbations)**

I.3 Key issues for cloud and convective parameterizations

→ strong biases persist in climate models (in particular in coupled atmosphere/ocean models)

→ Underestimation of cumulus and strato-cumulus clouds

→ Bad representation of convection diurnal cycle and intra-seasonal variability of tropical rainfall

→ Important processes like sensitivity of the convection to tropospheric humidity, propagation of convective systems, role of convective organization are not or badly accounted for.

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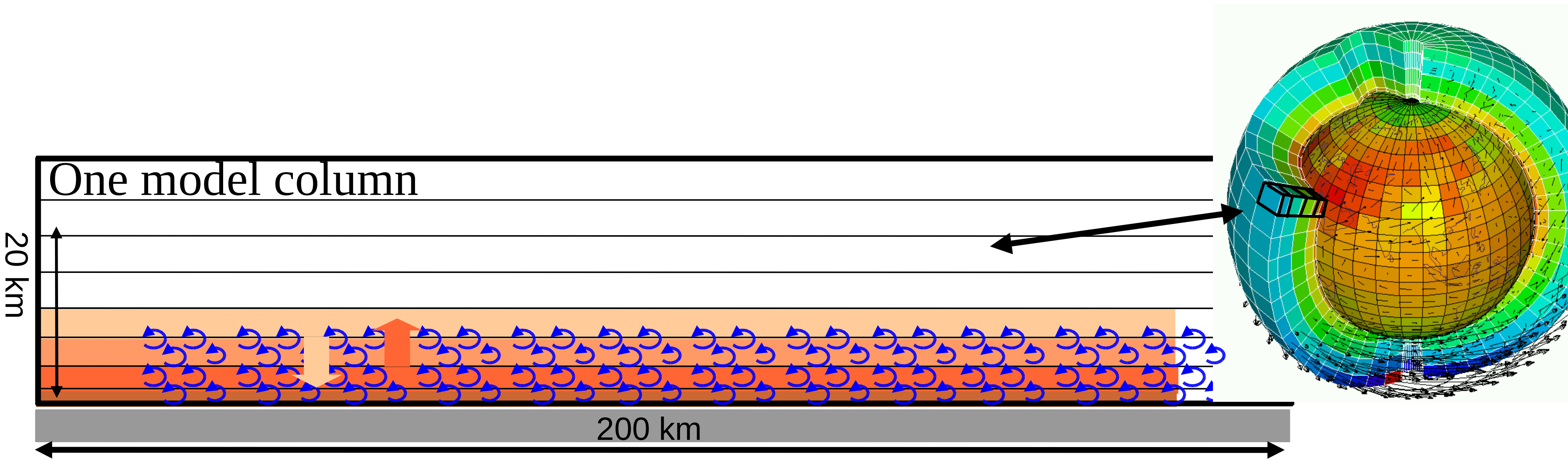
II.1 Thermal plumes and clouds



Classical approach :

→ **« Turbulent mixing » or diffusion**

Mixing by small scale random motion

Analogous to molecular diffusion

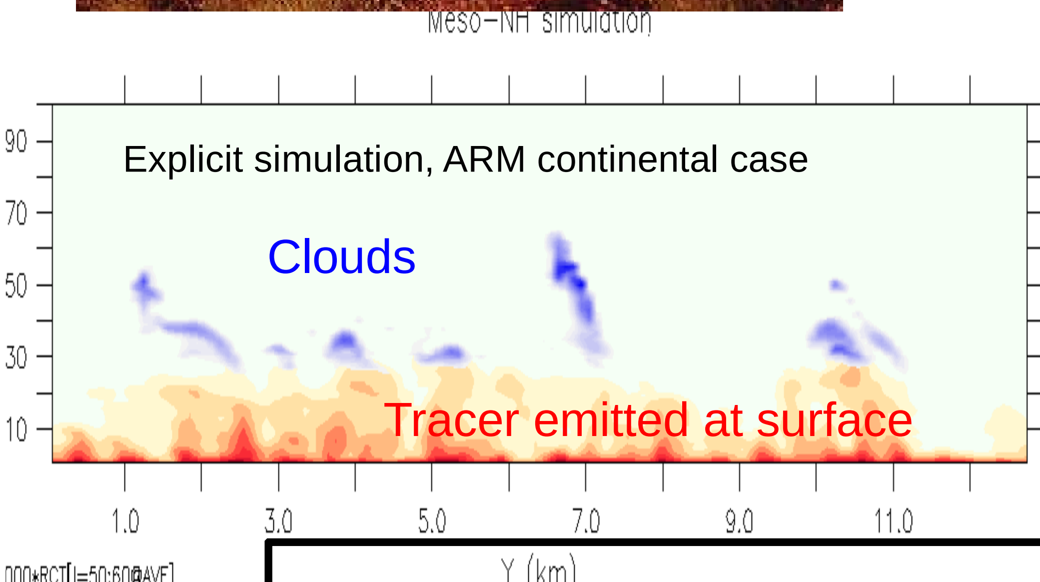
$Dq/Dt = Sq$ avec $Sq = \frac{\partial}{\partial z}\left(K_z \frac{\partial q}{\partial z} \right)$

→ Computation of Kz : a field of research

Kz = f (dU/dz, dθ /dz,e,...)

New equations, new parameters ...

II.1 Thermal plumes and clouds



Turbulent diffusion :
for isotropic small scale turbulence

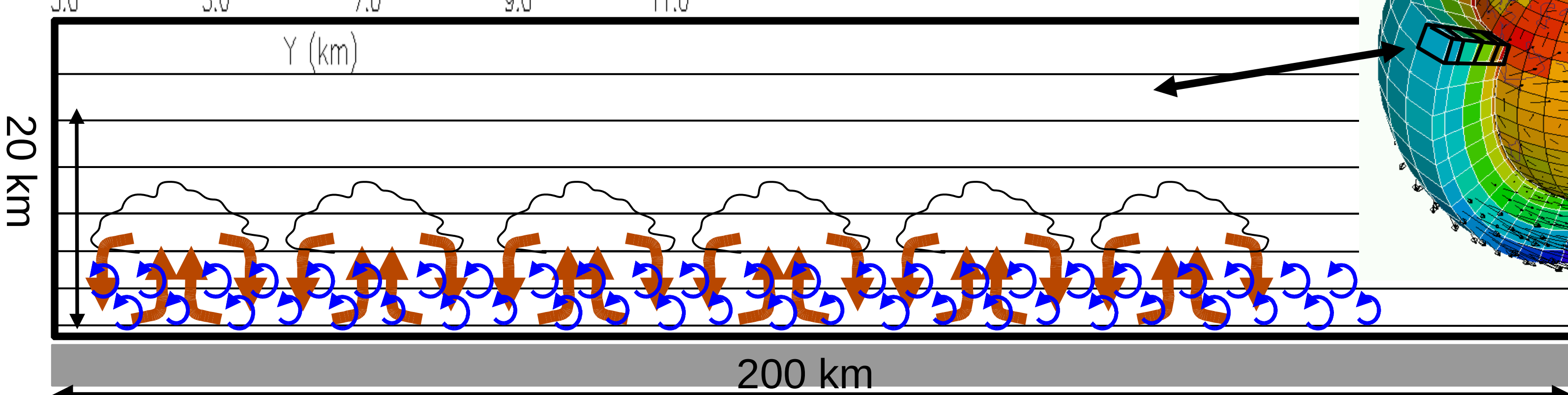
Atmospheric turbulence :
"meso-scale", organized and anistrop

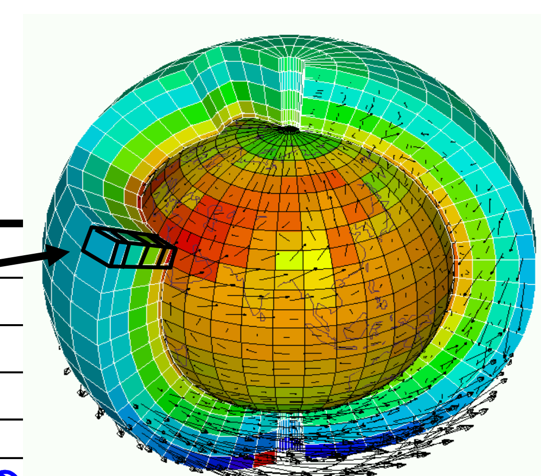
→ **« Thermal plume model »**

Each atmospheric column is divided in 2 :

- plume of air rising from the surface
- air subsiding around the plume

A « mean plume » is represented, at the top of which a « mean cumulus » can appear.





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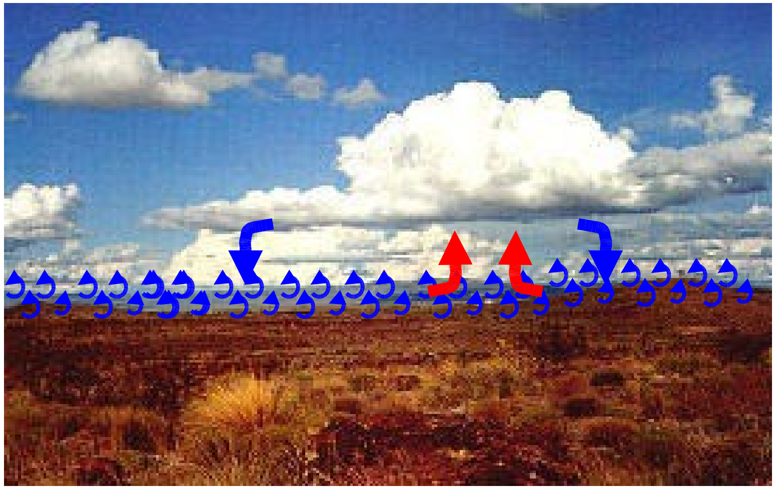

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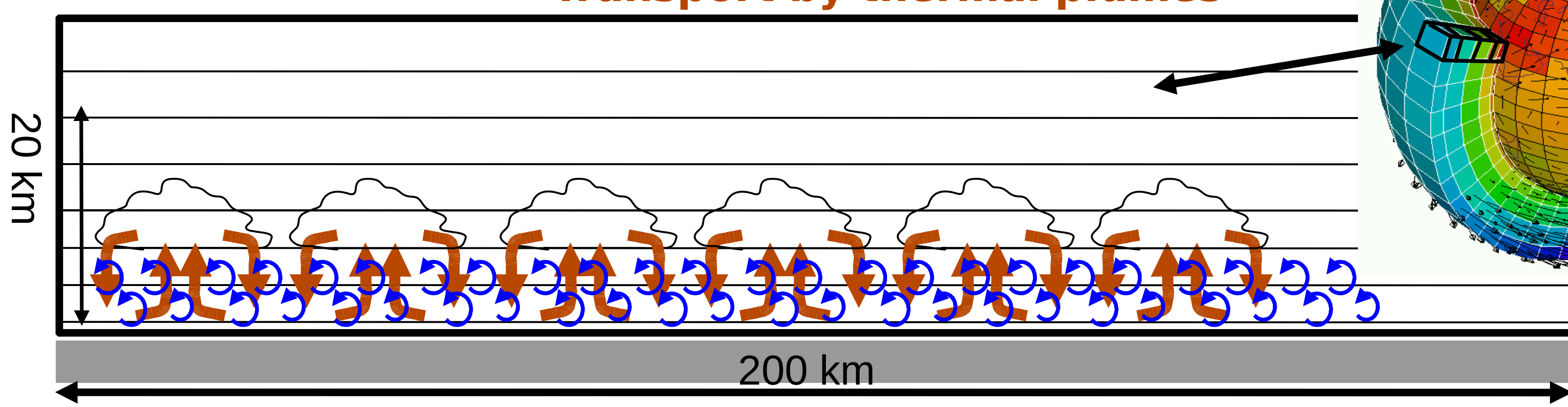
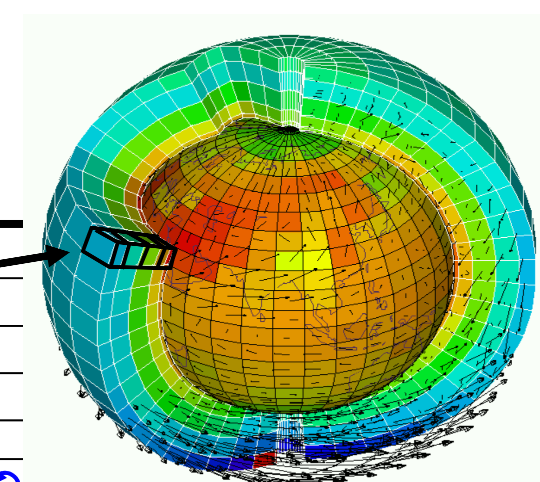
$$S_q = -\frac{1}{\rho}\frac{\partial}{\partial z}\rho\overline{w'q'} = -\frac{1}{\rho}\frac{\partial}{\partial z}\rho K_z \frac{\partial q}{\partial z} + -\frac{1}{\rho}\frac{\partial}{\partial z}\left[\rho \alpha w (q_a - q)\right]$$

Turbulent diffusion

Transport by thermal plumes





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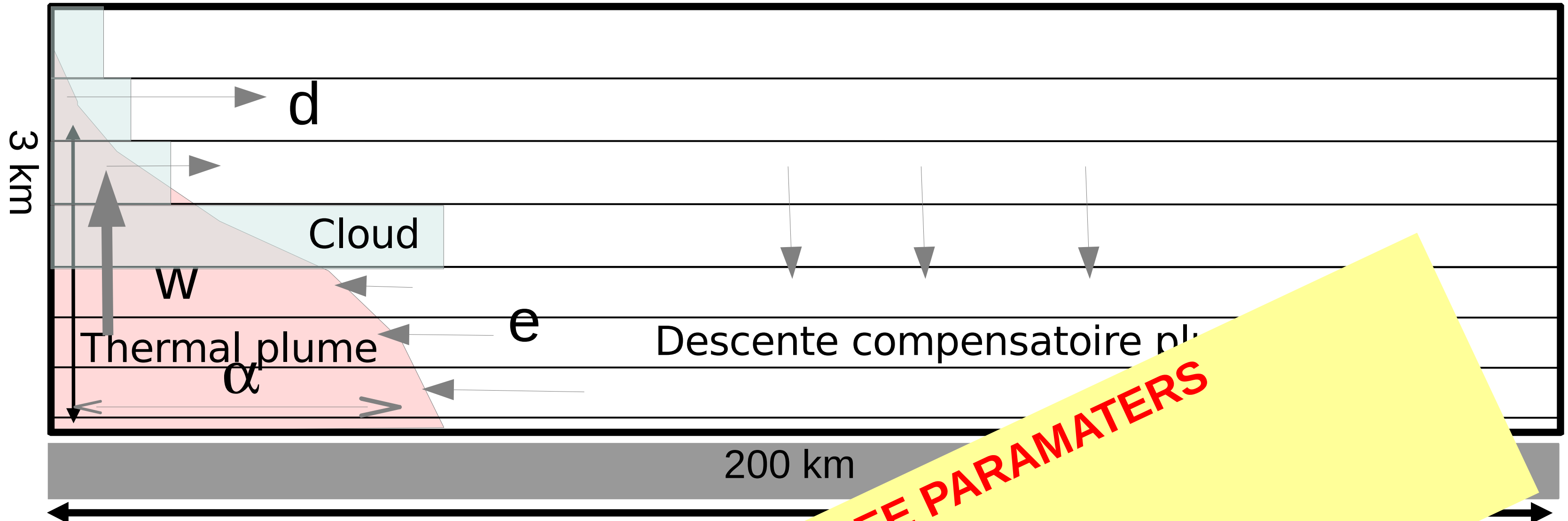


NEW EQUATIONS , NEW FREE PARAMATERS
LES are used for
→ Guide for formulations
→ Choice of free parameters
→ Evaluation

Variables internes de la paramétris

w : vitesse moyenne des panache

α : fraction de la surface

e : taux d'entrée l ... ment)

d : sorties d'air de

q_a : concentration d ... ascendance

... la masse :

$$\frac{\partial f}{\partial z} = e - d \qquad \text{avec} \quad f = \alpha \rho w$$

Conservation de la masse du composant q

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

Equation du mouvement

$$\frac{\partial f w}{\partial z} = -d w + \alpha \rho B$$

B étant la poussée d'Archimède

$$B = g \frac{\theta_{va} - \theta_v}{\theta_v}$$

Terme source pour ... ations explicites

$$S_q = -\frac{1}{\rho}\frac{\partial}{\partial z}\rho \overline{w'q'} = \frac{1}{\rho}\frac{\partial}{\partial z}\rho K_z \frac{\partial q}{\partial z} + -\frac{1}{\rho}\frac{\partial}{\partial z}\left[\rho \alpha w (q_a - q)\right]$$

Diffusion turbulente

Transport par le modèle de panache

$$e = f \max(0, \frac{\beta_1}{1+\beta_1}(a_1 \frac{B}{w^2} - b))$$

4 Paramètres libres :

$a_1 = \frac{2}{3}$, $\beta_1 = 0.9$, $b = 0.002$, $c = 0.012 m^{-1}$, $d = 0.5$

$$d = f \max(0, -\frac{a_1 \beta_1}{1+\beta_1}\frac{B}{w^2} + c(\frac{(q_a - q)/q_a}{w^2})^d)$$

Etc ...

II.1 Thermal plumes and clouds

<u>**Genesis of the thermal plume approach**</u>

Mass flux schemes

→ mass flux schemes already used but essentially for clouds and deep convection

→ dry convective boundary layer were given a weaker priority

Origin of the LMD thermal plume model (2002) :

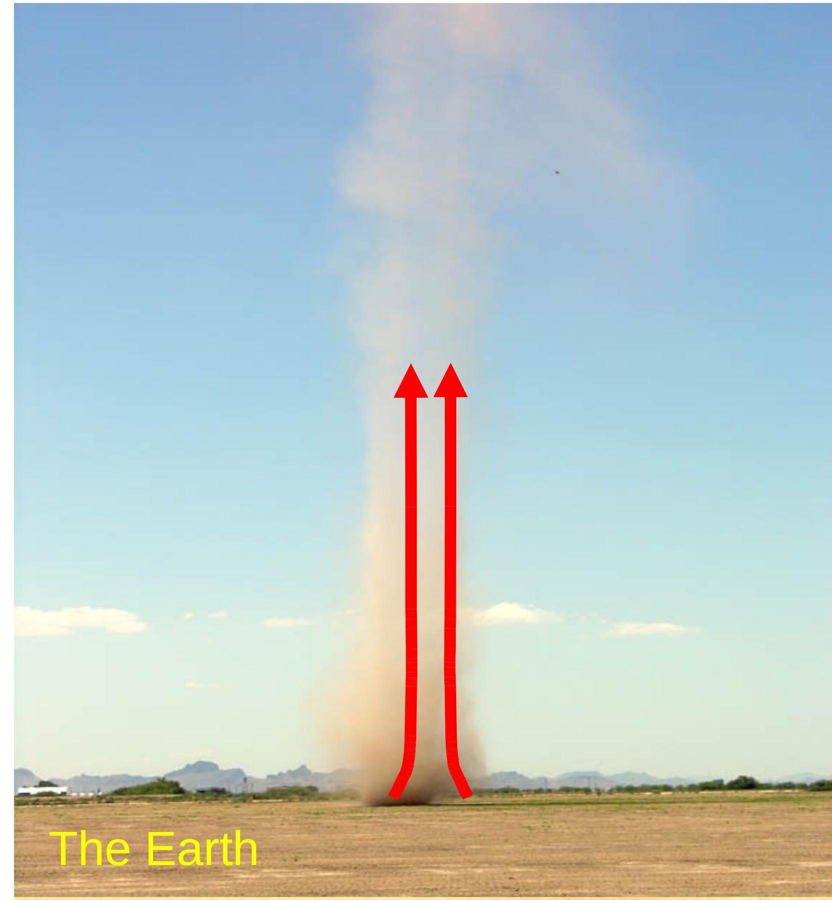
→ motivated by the Martian climate : Mars is a global desert with very strong and frequent dry convection

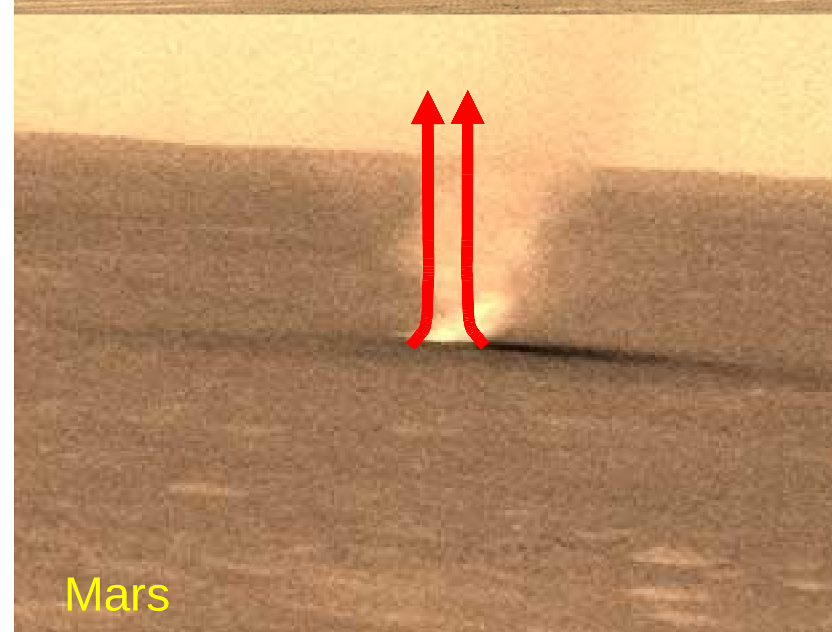
→ Inspired by air plane observations during the Trac campaign (Paris area)

Other origins :

→ First paper proposing the combination of a diffusive approach and mass flux scheme for the convective boundary layer (Chatfield, 1985)

→ Independent parameterization issued from the GCSS and eurocs community (Siebesma and collaborators, 2004)





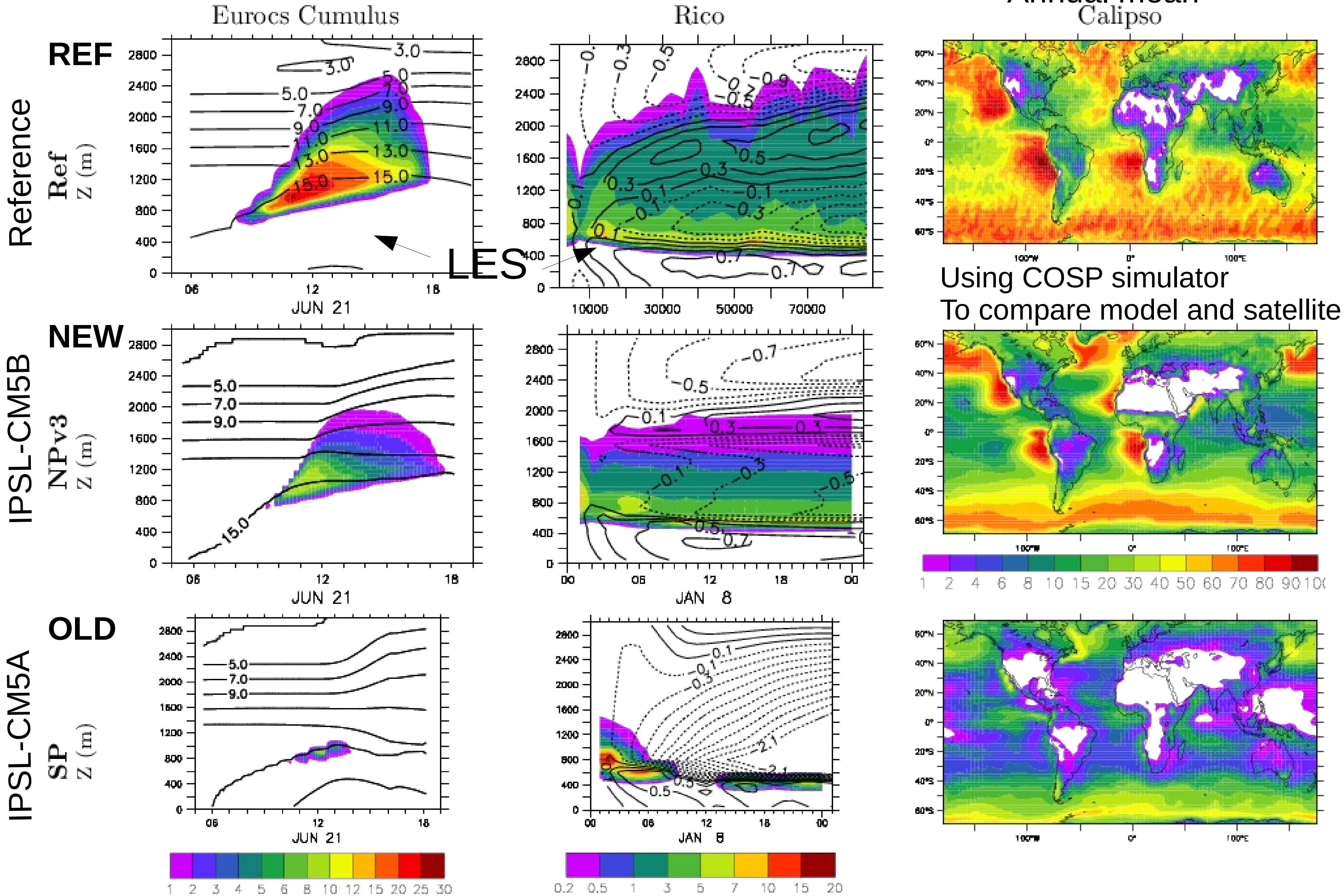
II.2 From 1D to 3D and the question of model tuning

1D test cases

Cloud fraction (%) and water vapor (g/kg)

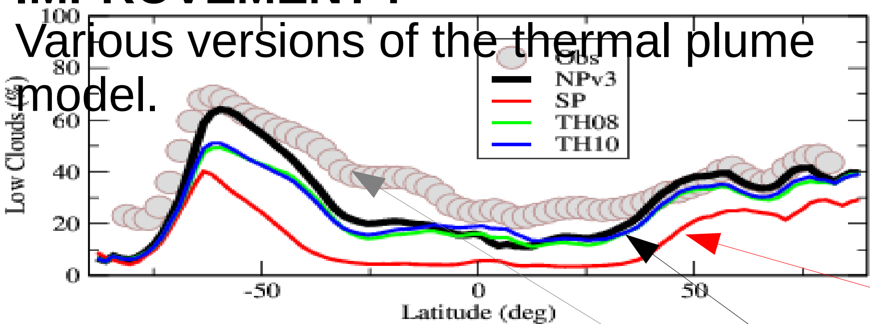
3D simulations

Low-level cloud cover (%)
Annual mean

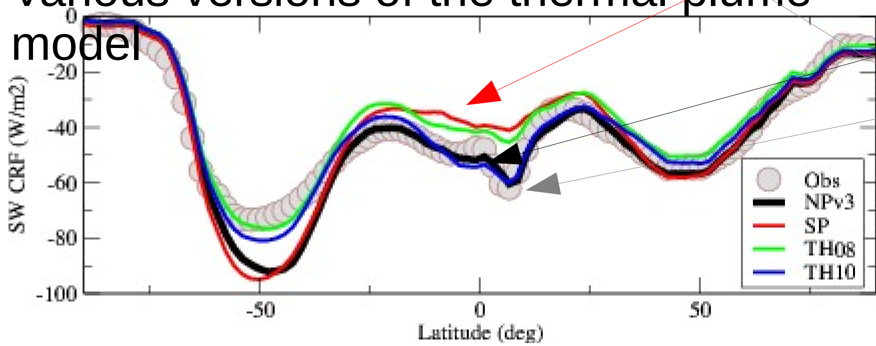


II.2 From 1D to 3D and the question of model tuning

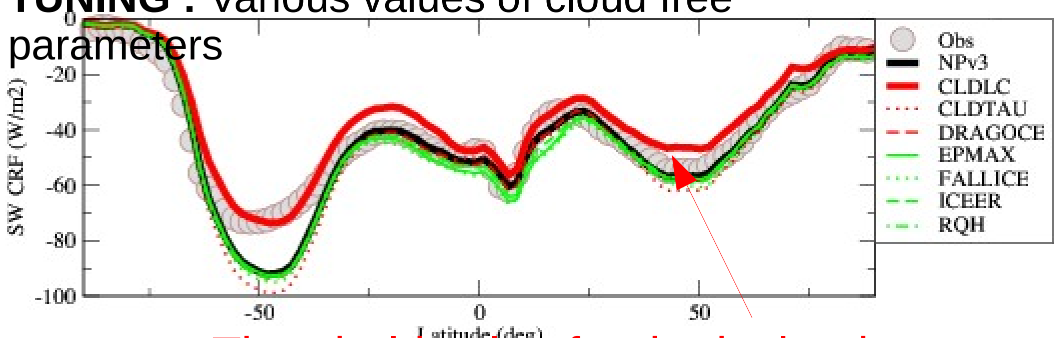
Mean latitudinal distribution of low level clouds for observations ; **MODEL IMPROVEMENT :**
Various versions of the thermal plume model.



Solar radiation reflected to space by clouds
Various versions of the thermal plume model



Solar radiation reflected to space by clouds
TUNING : Various values of cloud free parameters



Threshold value for the incloud water

SP : Standard Physics (OLD) No thermals CMIP3

NPv3 : “New Physics” CMIP5

OLD

TH08

TH10

NEW

Obs

A new paradigm for model development

1. Development and evaluation of cloud parameterizations in single column configuration based on LES simulations of a series of relevant and “representative” test cases.

2. First tuning of internal parameters with respect to LES

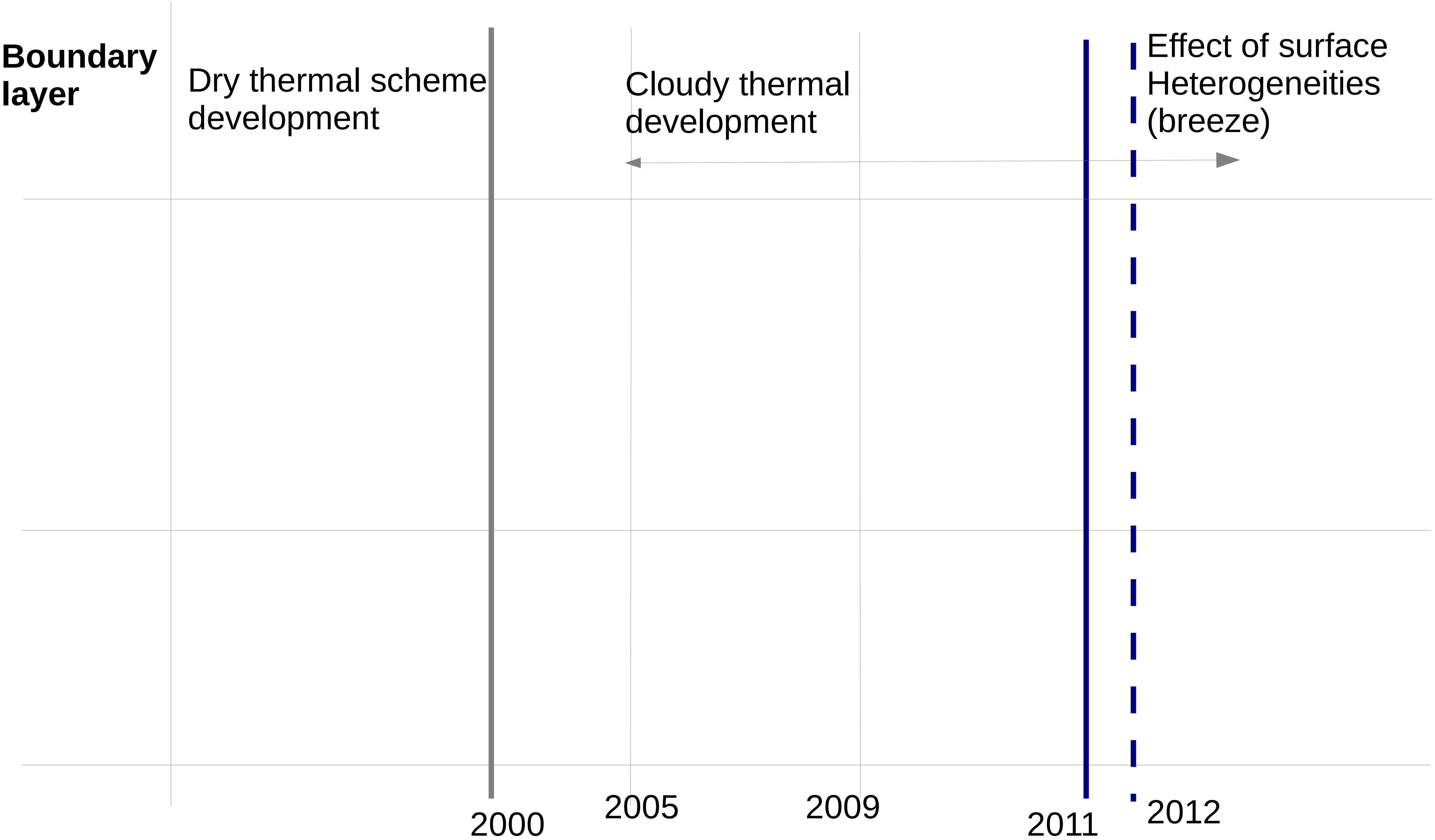
3. Activation in the full 3D GCM : must be computationally efficient, numerically reliable, applicable to a large variety of situations

4. Final tuning of the free parameters in the 3D model so as to fit observations of the “global climate”, under the constraint of test cases.

New =
Starting to be used systematically as a methodology for model physics improvement in climate models.

Time constant : 10 years

Time and duration



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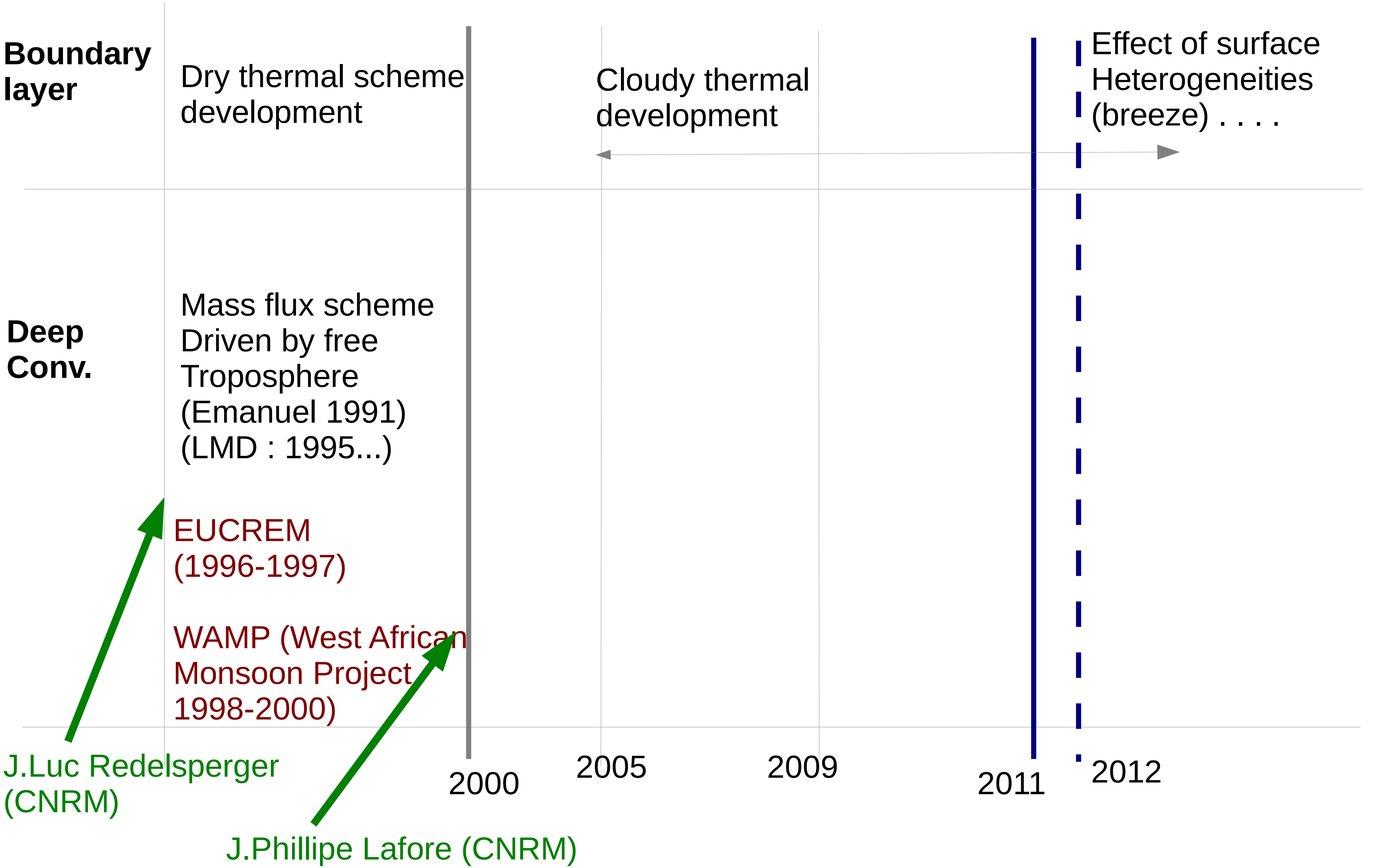

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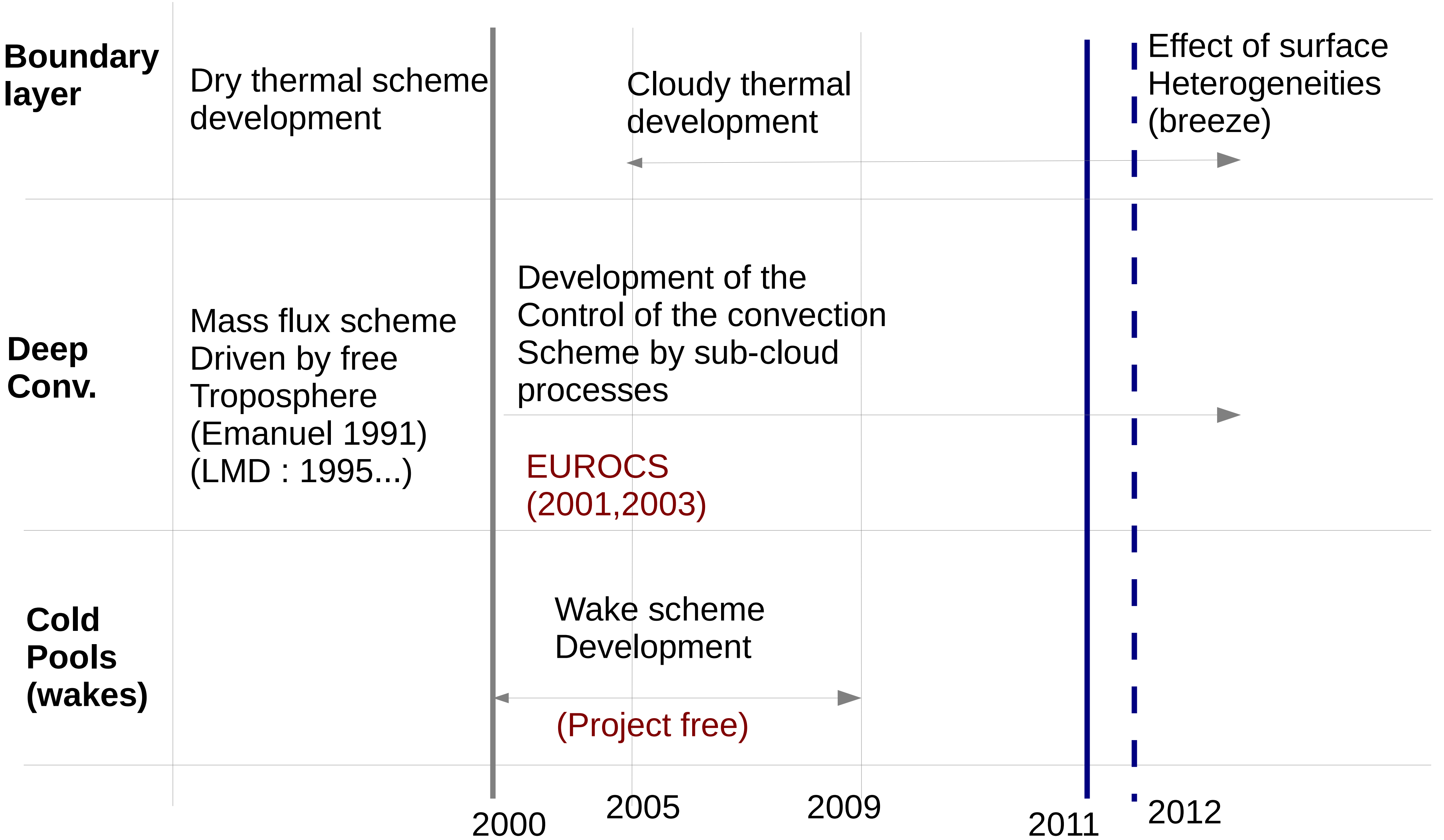
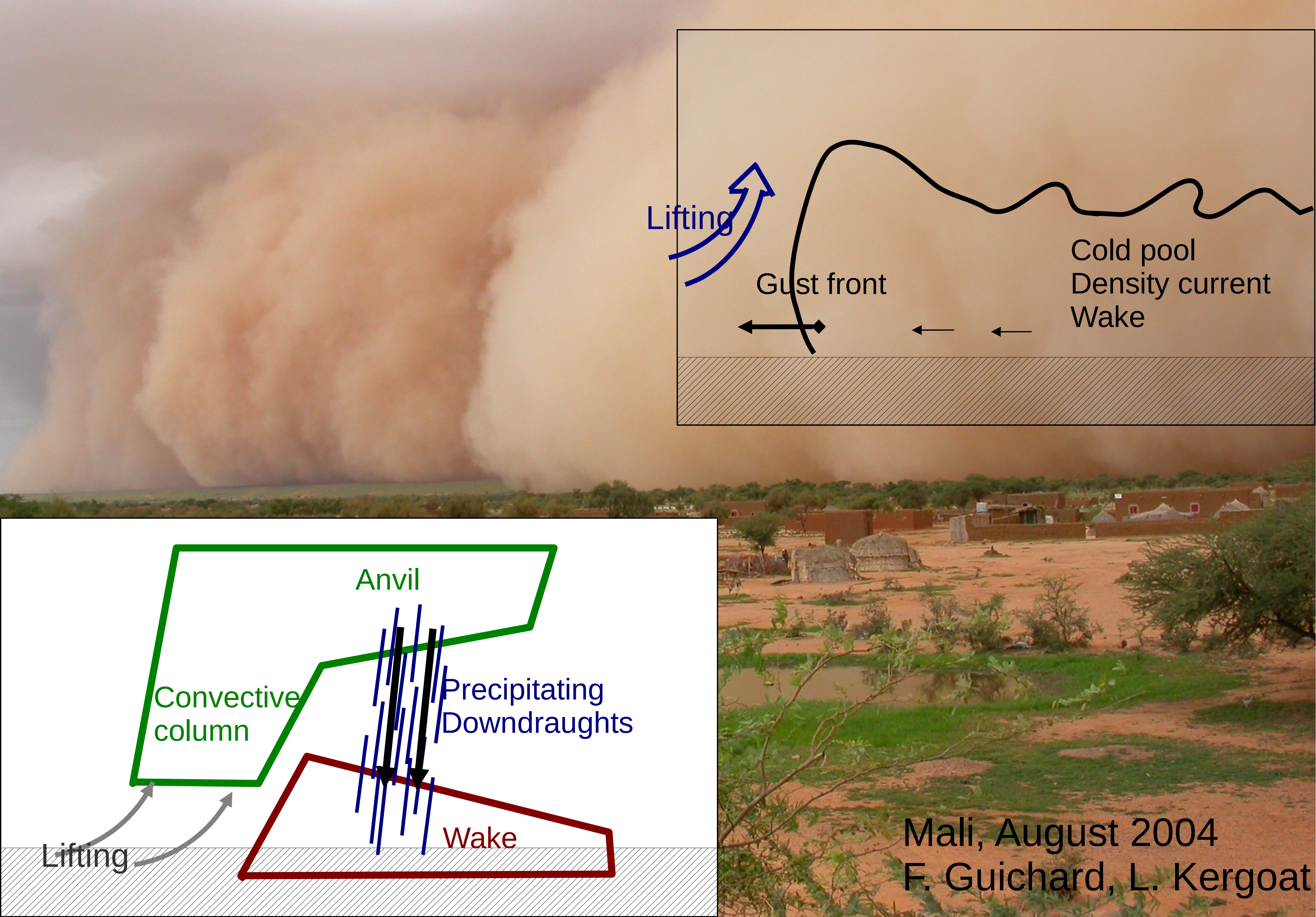
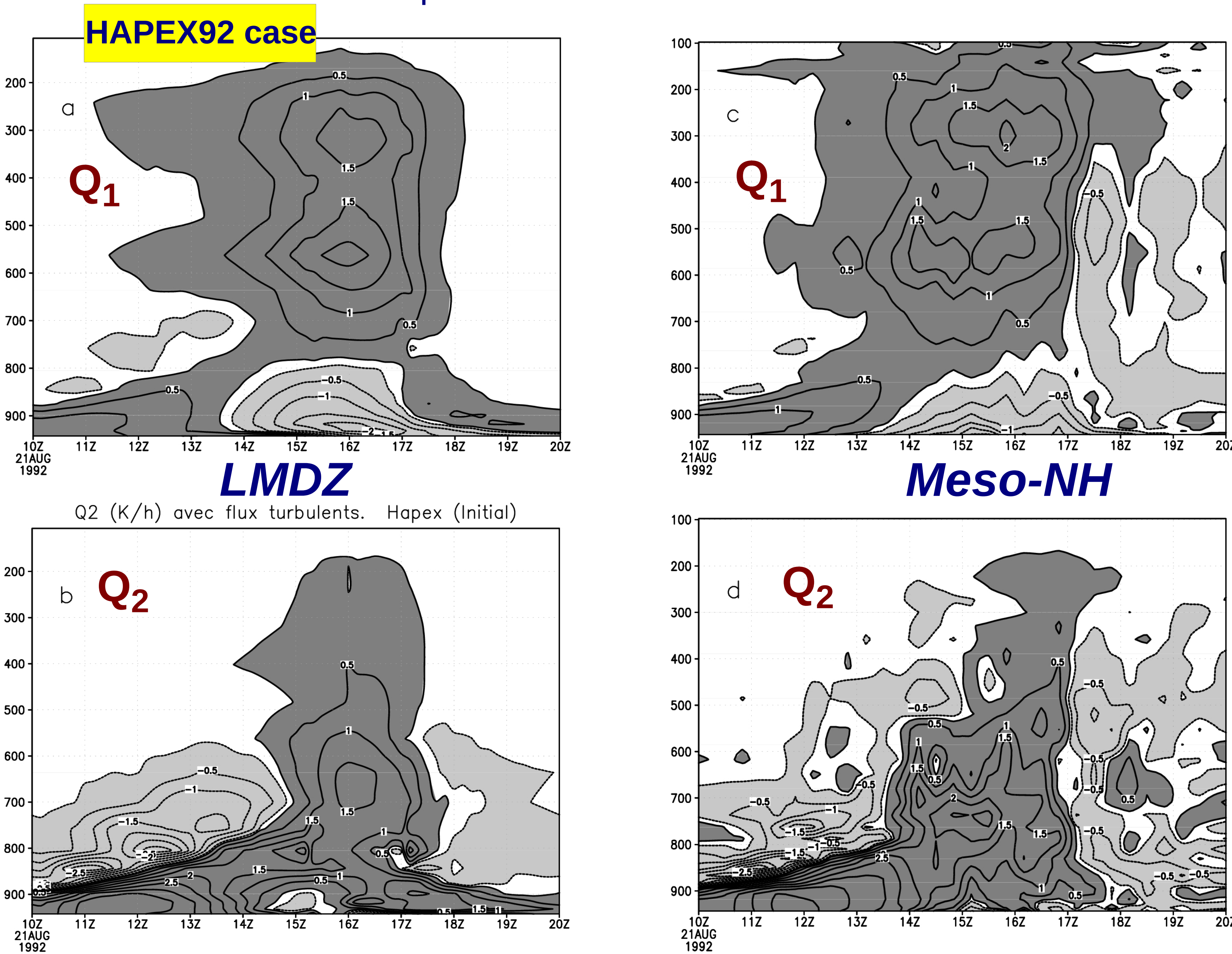


II.3 Deep convection and wakes



II.3 Deep convection and wakes

Comparison between LMDZ SCM and Meso-NH CRM



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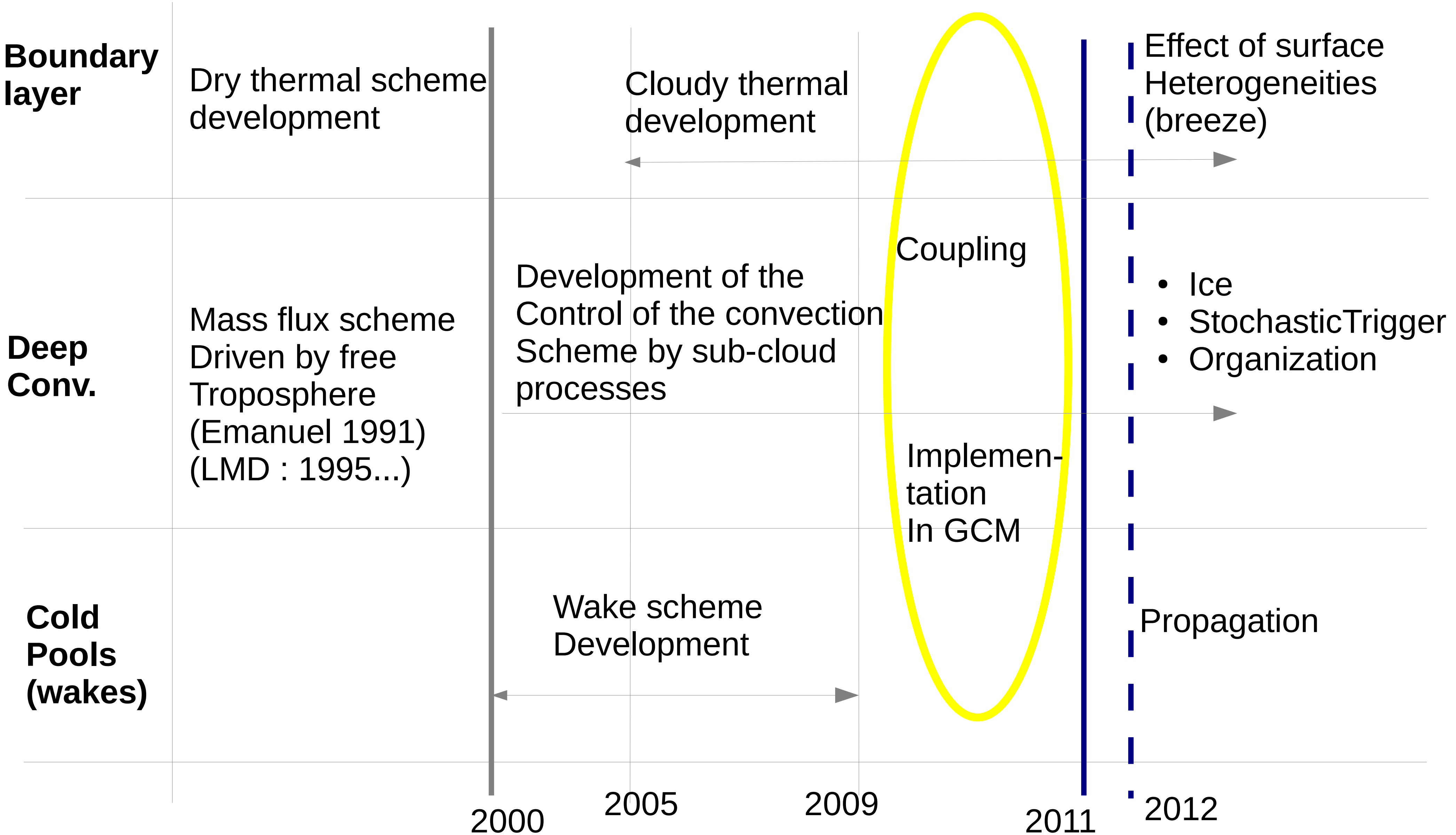


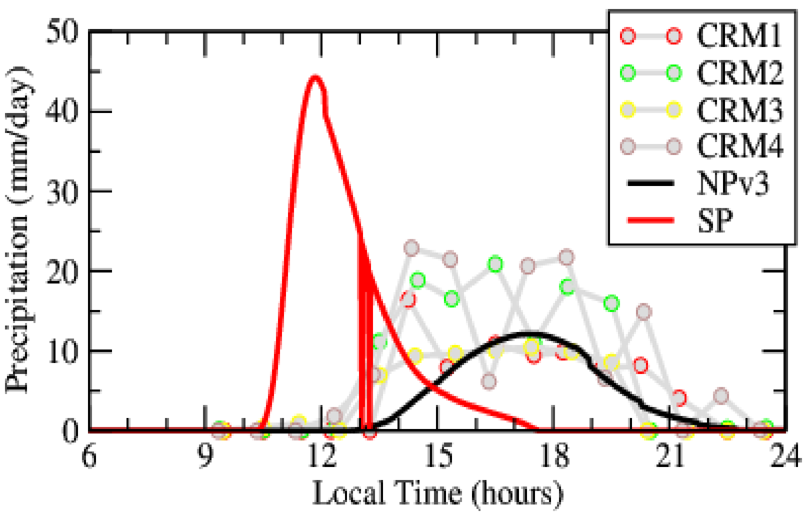
Développement thermique nuageux

II.4 Illustration with the LMDZ climate model : robust improvements

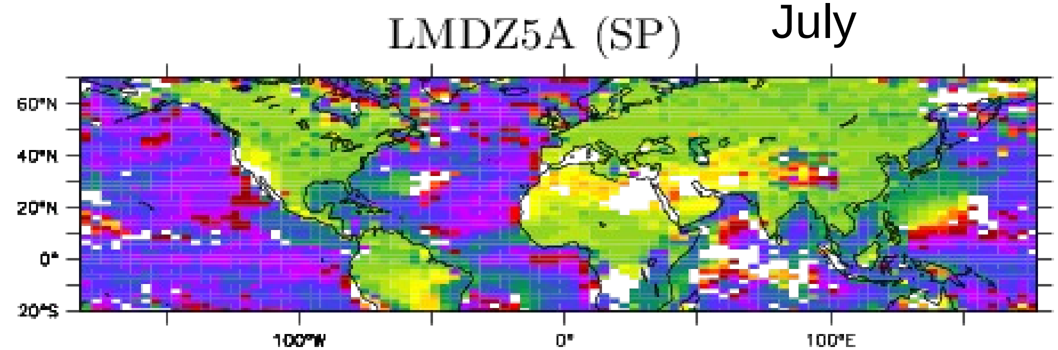
Diurnal cycle of rainfall
Directly linked to the change in convection schemes

Local time of maximum convection

1D tests compared with
Cloud resolving models (mesh of ~1km)
Continental convection in Oklaoma



July



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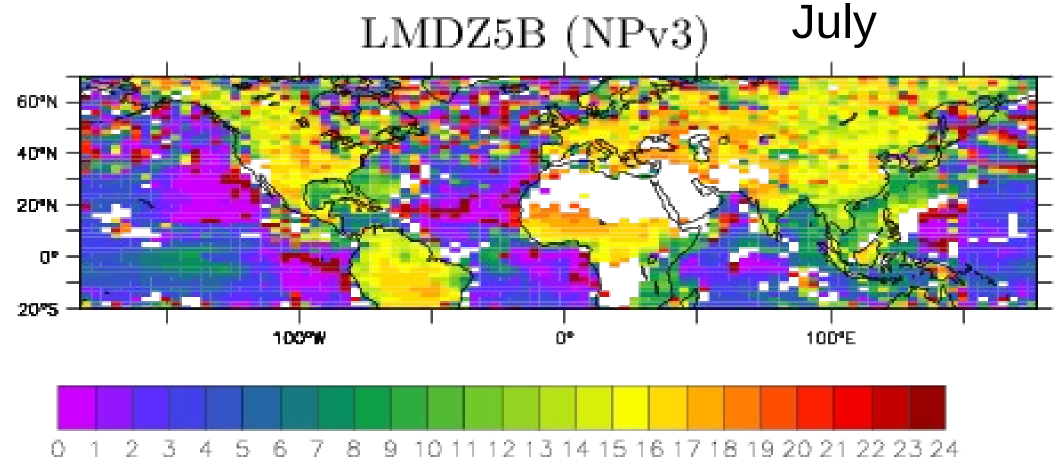
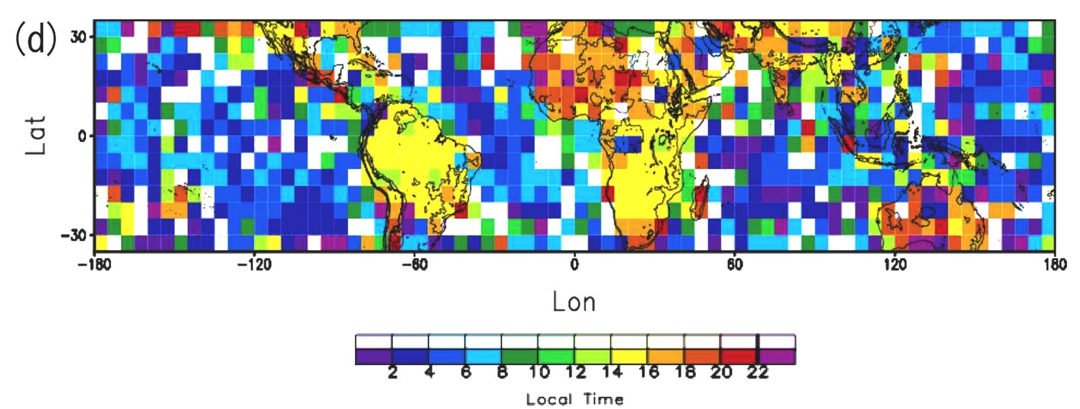
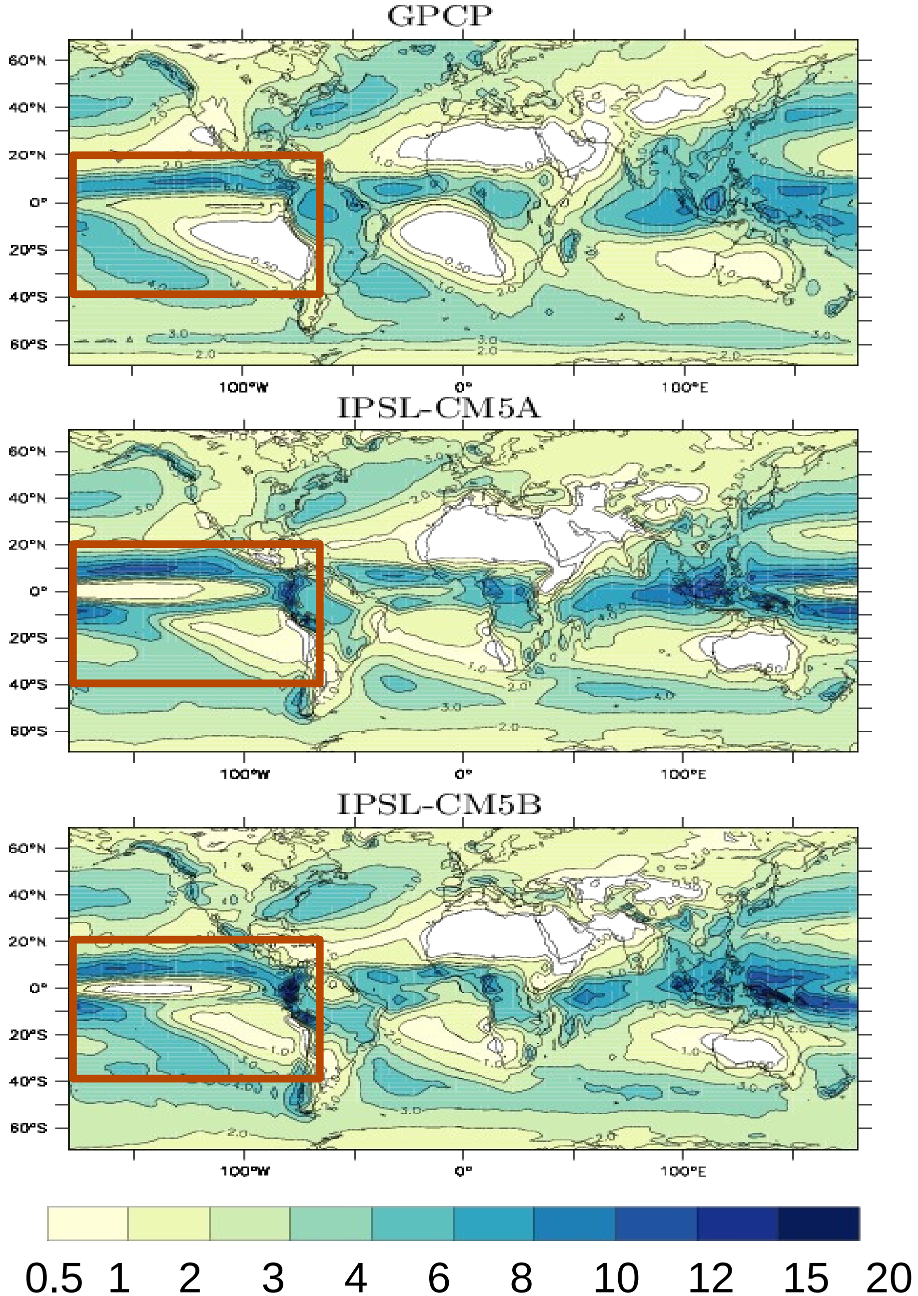


TRMM satellite obs., Hirose et al. 2008, annual

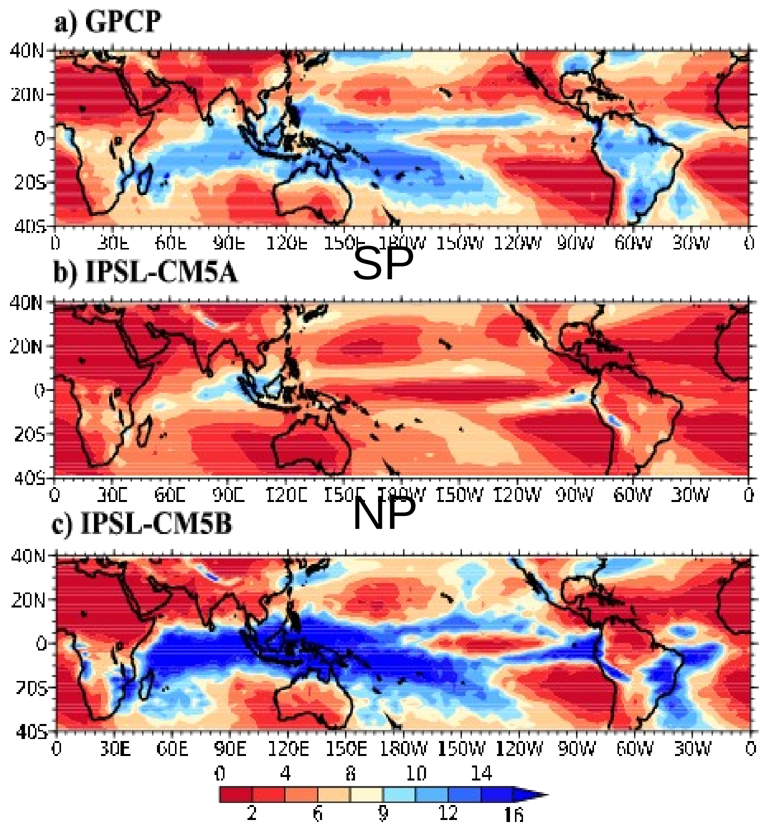


II.4 Illustration with the LMDZ climate model : biases

Slight bias reduction for
Annual mean rainfall (mm/day)

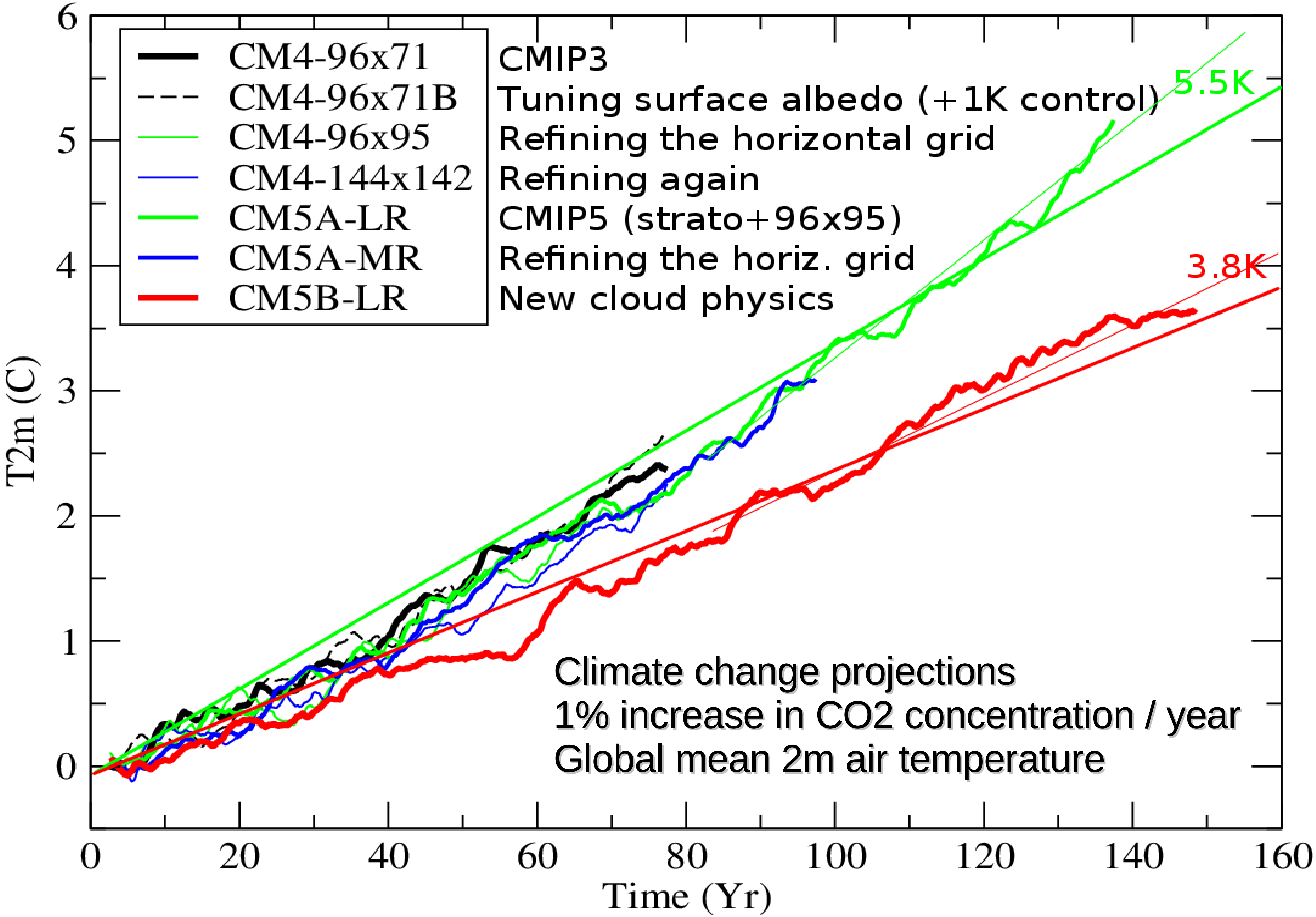


Large positive impact on the
Intraseasonnal rainfall variability



Standard deviation of daily rainfall anomalies (mm/day) of the a) GPCP dataset (1996-2009), b) IPSL-CM5A and c) IPSL-CM5B preindustrial simulations, for the winter season (November to April - NDJFMA)

II.4 Illustration with the LMDZ climate model : Climate change projections



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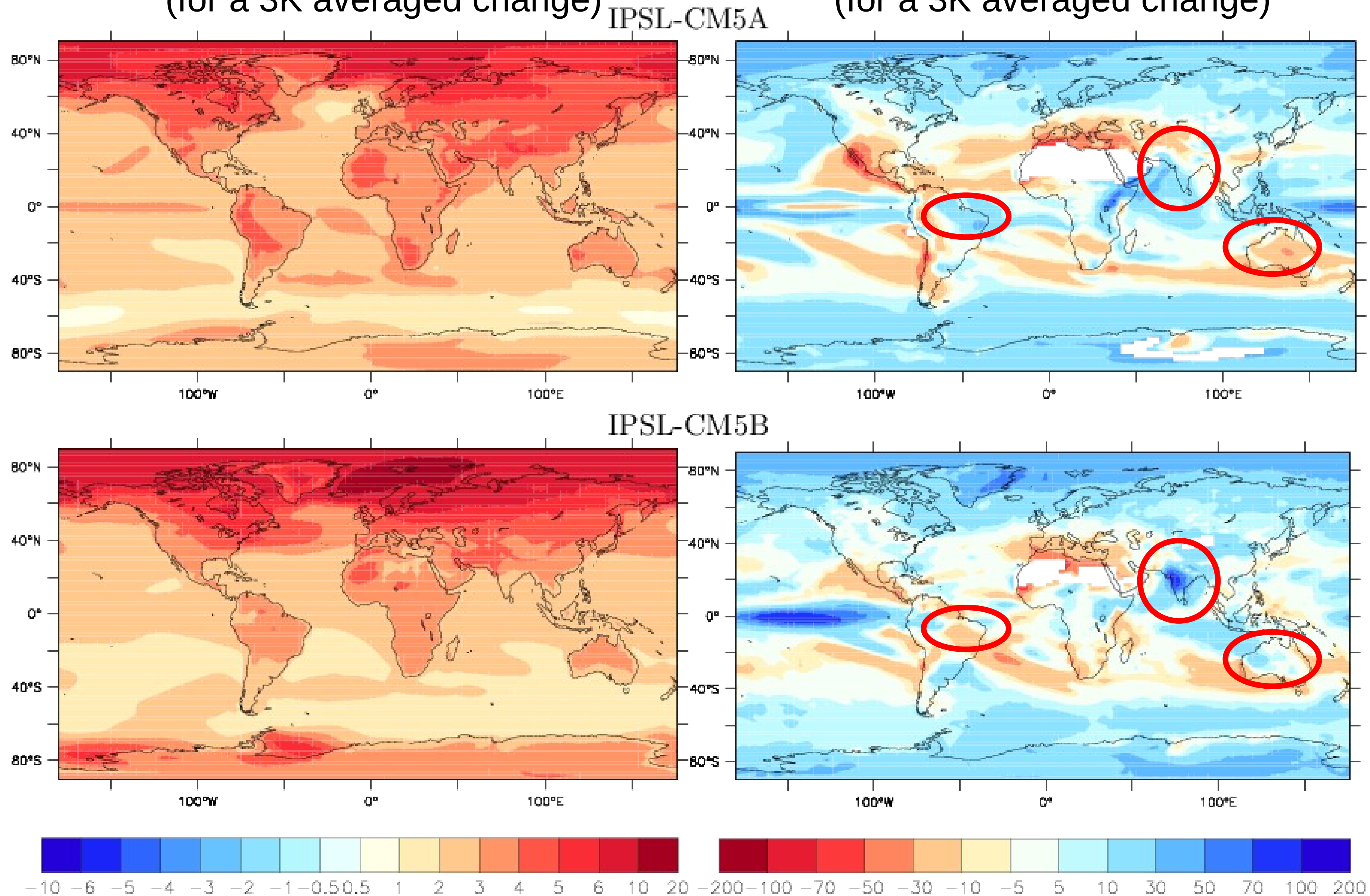
Change in surface temperature (K) (for a 3K averaged change)

Change in annual mean rainfall (mm/day) (for a 3K averaged change)



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→ “Stochastic physics”

III-1 Global observation of cloud processes: Satellites and parametrizations

Up to now **satellite** observations and **GCM** simulations are compared at the global and plurianual scales. CRMs, LES and parametrization developments do not use satellite data.
At smaller scale GCM are too far from satellite observations.

What is keeping satellite observations and parametrization results so far away?

In most GCMs:

- Bad diurnal cycle of deep convection over land.
- Poor low cloud simulation (Cumulus and stratocumulus).
- Poor anvil simulation or lack of anvil representation.
- Lack of autonomy of deep convection (there are no convective systems).
- Lack of convection propagation.

Progress made in LMDZ:

- Density current parametrization together with PBL thermal parametrization ==> better representation of deep convection diurnal cycle and better simulation of low clouds. Deep convection becomes autonomous.

Huge problems remain:

- Still no proper anvil representation.
- Still no representation of the propagation of deep convection.

III-1 Global observation of cloud processes: Satellites and parametrizations

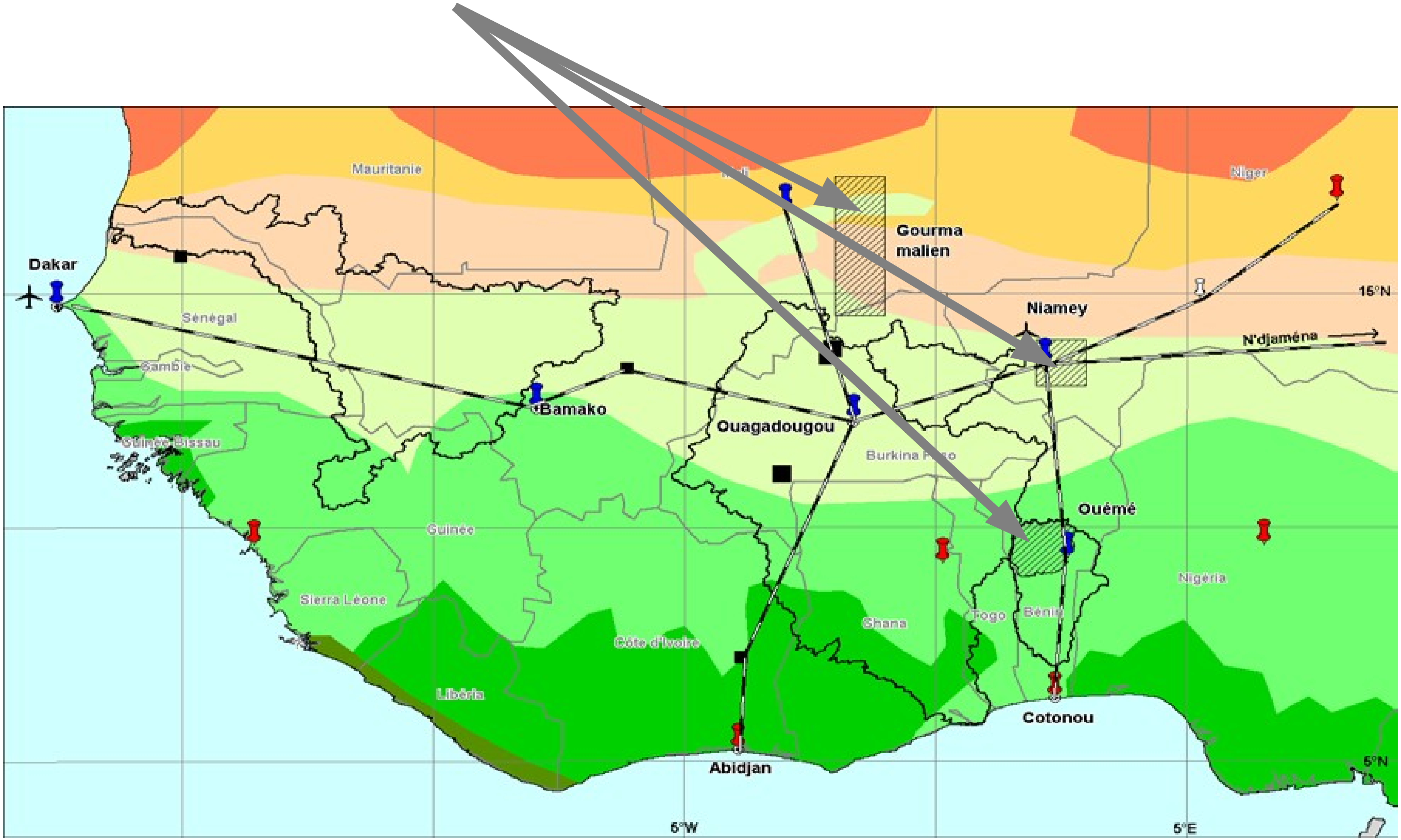
Major changes in the near future:

- **Large domain CRMs and LES** are coming ==> use of satellite data.

- Satellites like **Megha-Tropiques** will make it possible to analyse the life cycle of convective systems.

III-1 Local observation of cloud processes: Field campaigns and parametrizations

Super-sites



III-2 Global Cloud Resolving Models and super-parameterizations

Arakawa (1974, 2004): Convective parametrizations are based on Quasi-Equilibrium

Bretherton, Neelin, Randall and others (2005,2008, 2011): Quasi-Equilibrium entails an exceedingly low variability.

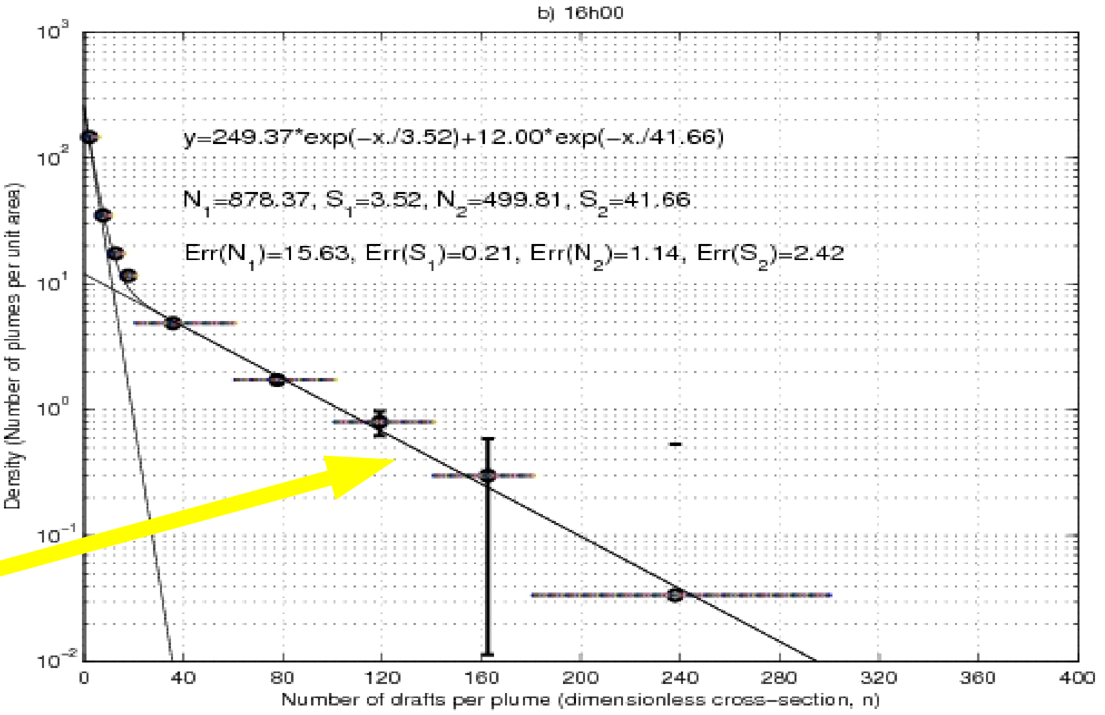
==> In th US :super-parametrizations (one 2D CRM in each GCM grid cell).
==> In Europe stochastic physics

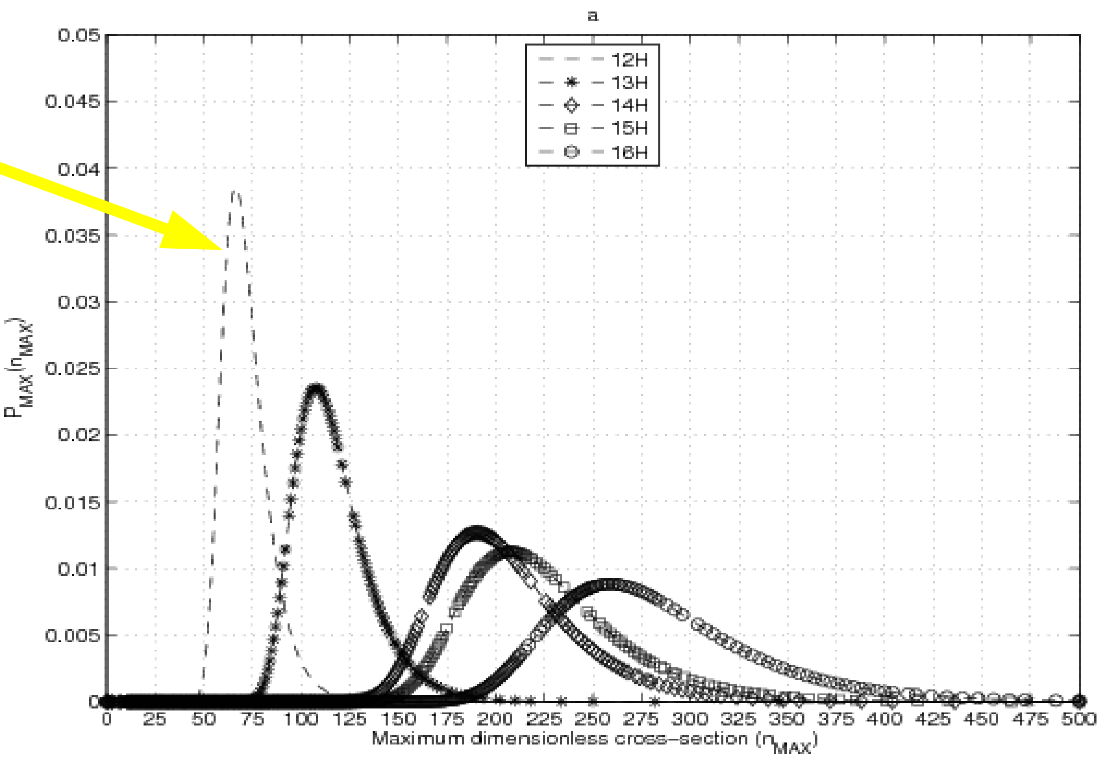
The other solution is global CRM.

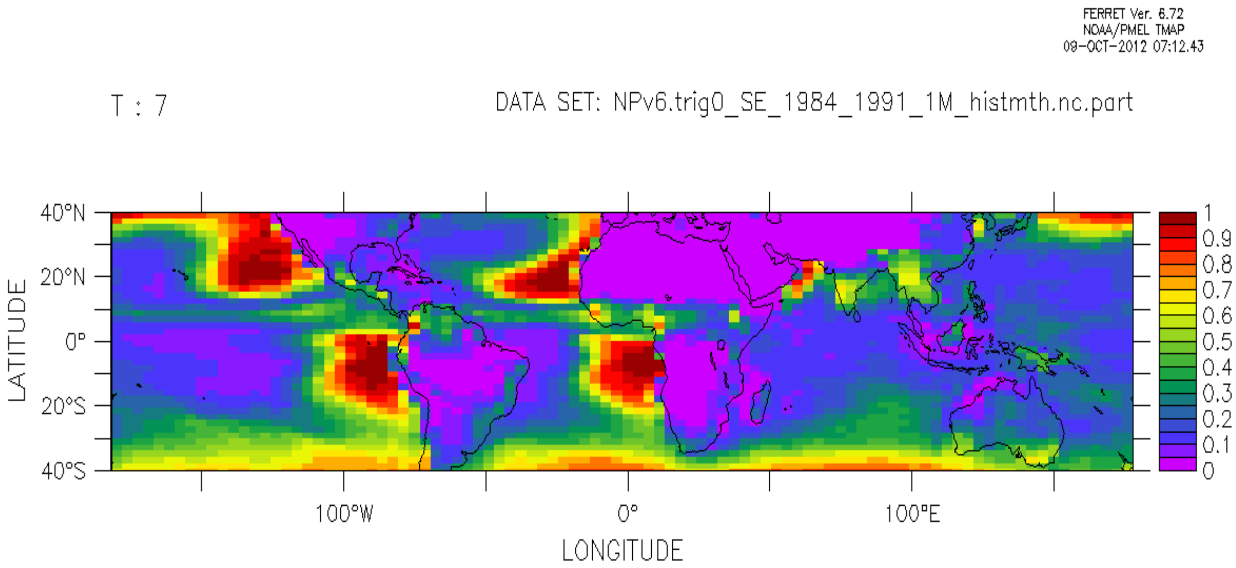
III-3 Stochastic physics: Deep convection triggering

Stochastic trigger

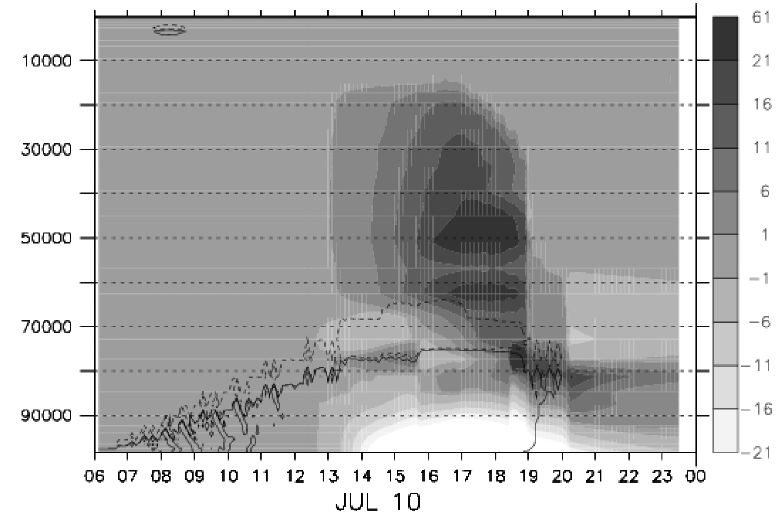
- Analysis of LES of 10 July 2006 case over Niamey :
  1. PDF of cumulus sizes is exponential.
  2. deep convection triggers when there are large cumulus.
- Trigger = "largest cumulus size exceeds a given threshold"
- From PDF of Cu size ⟶ PDF of largest cumulus size
- ⟹ probability of triggering ; use of a random number generator to implement this probability.



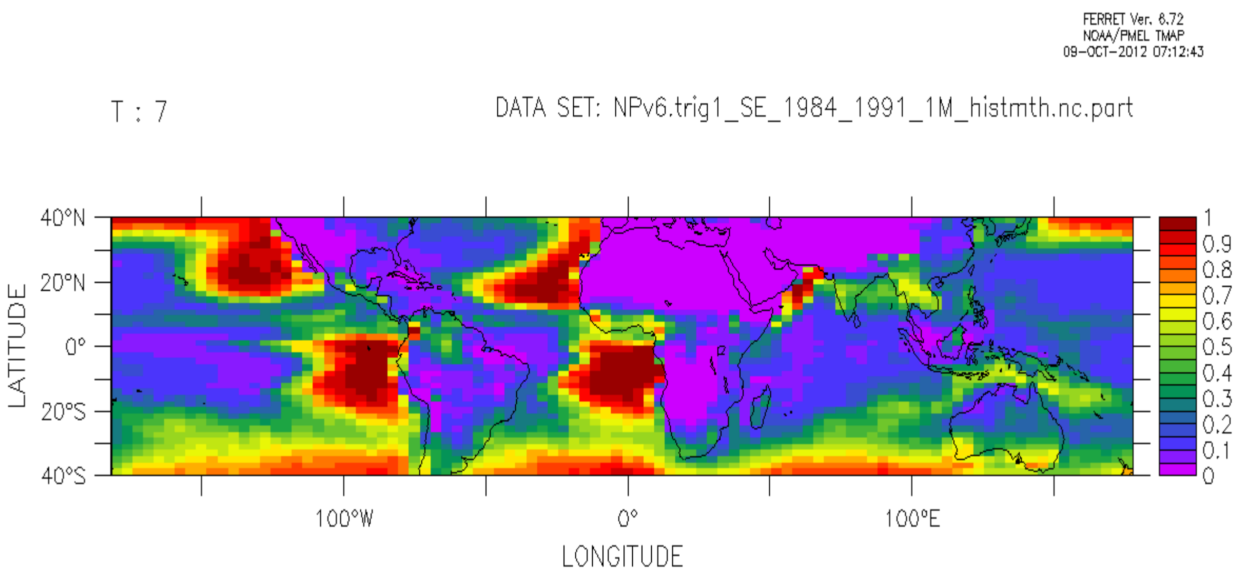




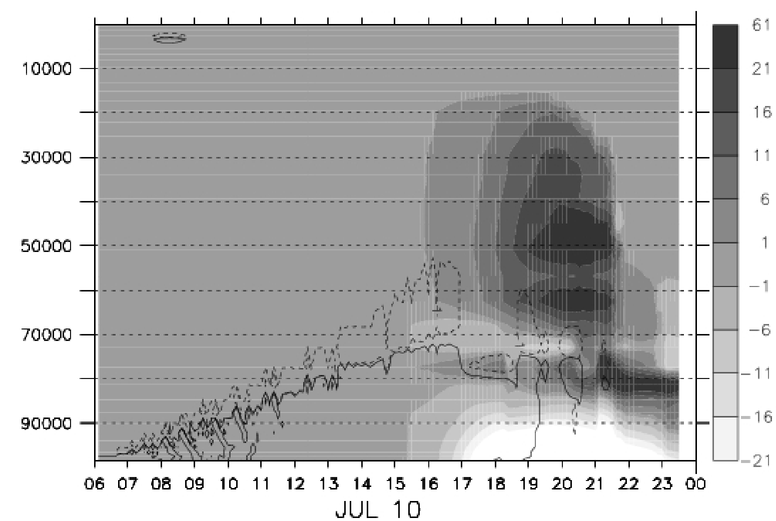
Low-level cloudiness, jul, DET



Q1 CV & Q1 BL (K/day): DET



Low-level cloudiness, jul, STOCH



Q1 CV & Q1 BL (K/day): STAT

IV Conclusions

Scientific results :

- New model with a much better representation of cloud and convective processes.
- A new (starting to be really at work in the modeling groups) methodology : 1D versus explicit 3D simulations on test cases.
- Robust improvements = both in 1D and 3D + we improve what we wanted to improve (!)
- Free parameter tuning is an essential step of climate change modeling, often hidden aspect.
- Some mean biases increased (question of tuning or non compensation of errors)

2 model versions that

1. differ only by the representation of clouds physics and free parameter tuning
2. contrasted response to greenhouse gas increase (global temperature and rainfall distribution), quite similar to CMIP3 multi-model dispersion

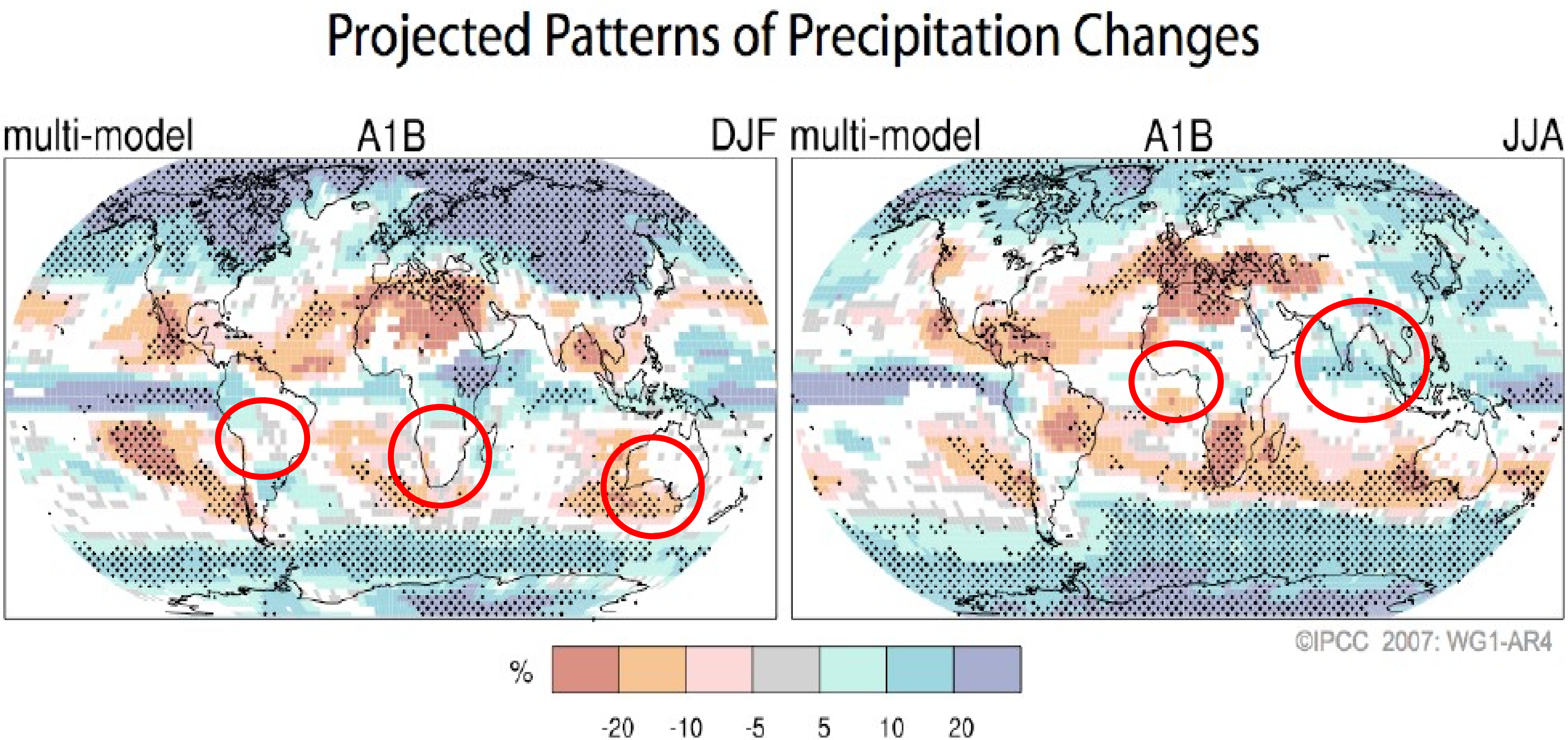
How to reduce uncertainty in future projections ?

→ None of the development or tuning was done to adjust the climate sensitivity (response to greenhouse gas increase).

→ What weight must be given to the mean biases, robust improvements or physics content ?

→ How to asses the models response ?

I. Uncertainties in climate change projection : dispersion of results



Evolution of cumulated ranfall over monsson region : unknown (even the sign)

FIGURE SPM-6. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}

Source: GIEC 2007

III Illustration with the LMDZ climate model : robust improvements

Test of 2 version of the IPSL climate model (atmospheric component LMDZ)

1. **IPSL-CM5A** : standard version **SP**. Physics already used in CMIP3

2. **IPSL-CM5B** : « new physics » **NP**
parameterizations of convection, turbulence and clouds based on new concept (10-year reasearch). Includes the thermal plume model + new parameterizations of cold pools created below

apparences

théories (physique, chimie, biologie, économie)

mathématique

numérique

informatique

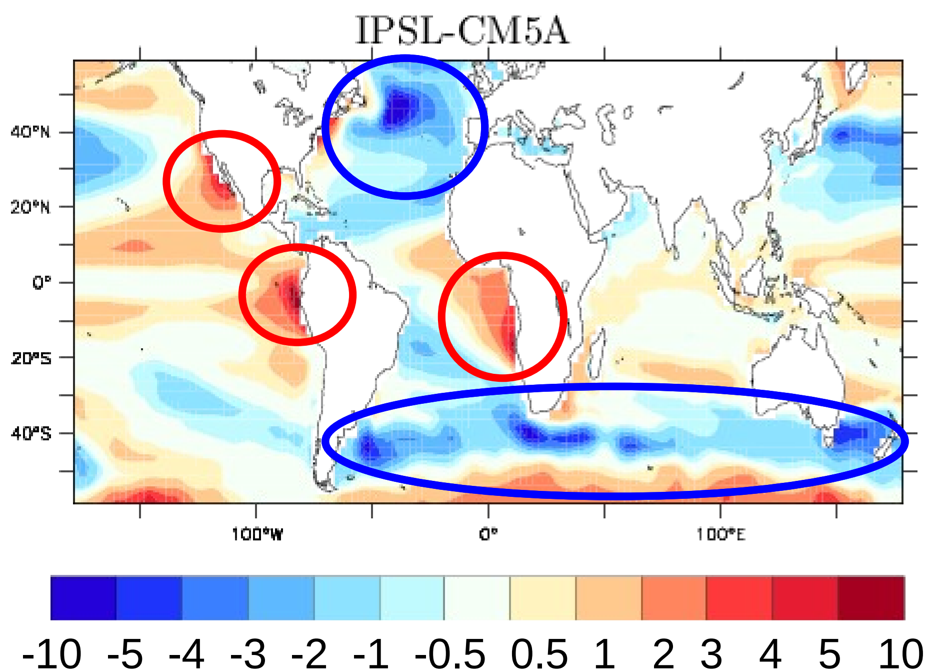
Les mathématiques constituent un langage commun.

La modélisation concerne l'ensemble de ces couches.
Il faut toujours essayer de mettre en évidence les liens avec les couches supérieures.
Il faut en même temps être capable de bien séparer ces différentes couches (savoir dans laquelle on se trouve).

I. Uncertainties in climate change projection : biases in the representation of the present day climate

Results from control experiments with the IPSL-CM5A model used in CMIP3
→ Good in view of the fact that it is a fully consistent model based on physics
→ But large biases

Sea surface temperature bias (K)
10-year mean



Annual mean rainfall (mm/day)