Master Sciences de la Terre et des Planètes, Environnement
Parcours Sciences pour l'Atmosphère et le Climat

# Prévision Numérique

## Partie II:
## Introduction à la modélisation numérique du climat

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# Useful references


- Hélène GUILLEMOT, Frédéric HOURDIN, "MODÉLISATION DU CLIMAT", Encyclopædia Universalis, https//www.universalis.fr/encyclopedie/modelisation-du-climat/
- https://www.infoclimat.fr/
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- Balaji et a. (2022), Are General Circulation Models obsolete? Proc Natl Acad Sci, Nov 14;119(47):e2202075119. doi: 10.1073/pnas.2202075119
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- Hourdin, F., Mauritsen, T., Gettelman, A., Golaz, J.-C., Balaji, V., Duan, Q., et al. (2017). The art and science of climate model tuning. Bulletin of the American Meteorological Society, 98, 589–602. https://doi.org/10.1175/BAMS-D-15-00135.1
- Mignot, J., Hourdin, F., Deshayes, J., Boucher, O., Gastineau, G., Musat, I., et al. (2021). The tuning strategy of IPSL-CM6A-LR. Journal of Advances in Modeling Earth Systems, 13, e2020MS002340. https://doi.org/10.1029/2020MS002340

# Modelling tools

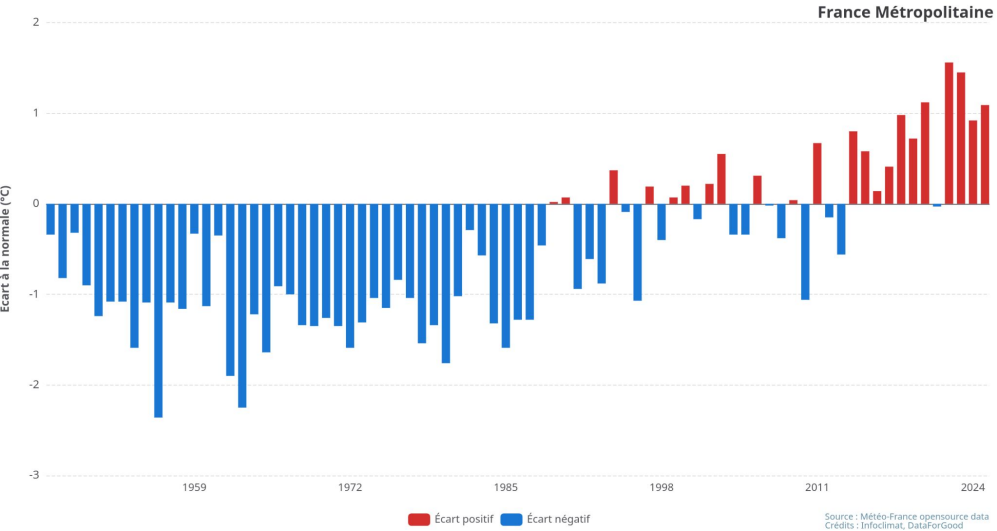
**LMDZ Atmospheric General Circulation Model**
**https://lmdz.lmd.jussieu.fr/**

eduplanet framework (LMDZ for teaching purposes)

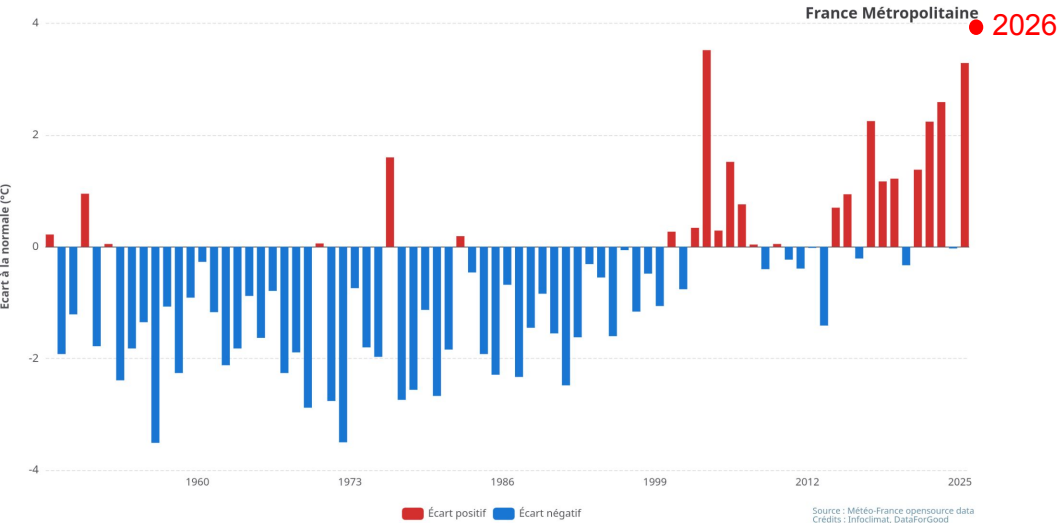
https://gitlab.in2p3.fr/ipsl/projets/eduplanet

you'll find a jupyter notebooks with instructions here:

https://gitlab.in2p3.fr/ipsl/projets/eduplanet/LMDZ/-/blob/master/docs/cours_clermont_modelisation_climatique.ipynb?ref_type=heads


France Métropolitaine
Ecart à la normale (°C)
2
1
0
-1
-2
-3
1959
1972
1985
1998
2011
2024
Écart positif
Écart négatif
Source : Météo-France opensource data
Crédits : Infoclimat, DataForGood

annual


France Métropolitaine
2026
Ecart à la normale (°C)
4
2
0
-2
-4
1960
1973
1986
1999
2012
2025
Écart positif
Écart négatif
Source : Météo-France opensource data
Crédits : Infoclimat, DataForGood

june




Président Emmanuel Macron, official 31st 2023 TV speech

2026 per se what not predictable, but the increase in very hot summer season yes!

-> we will understand why

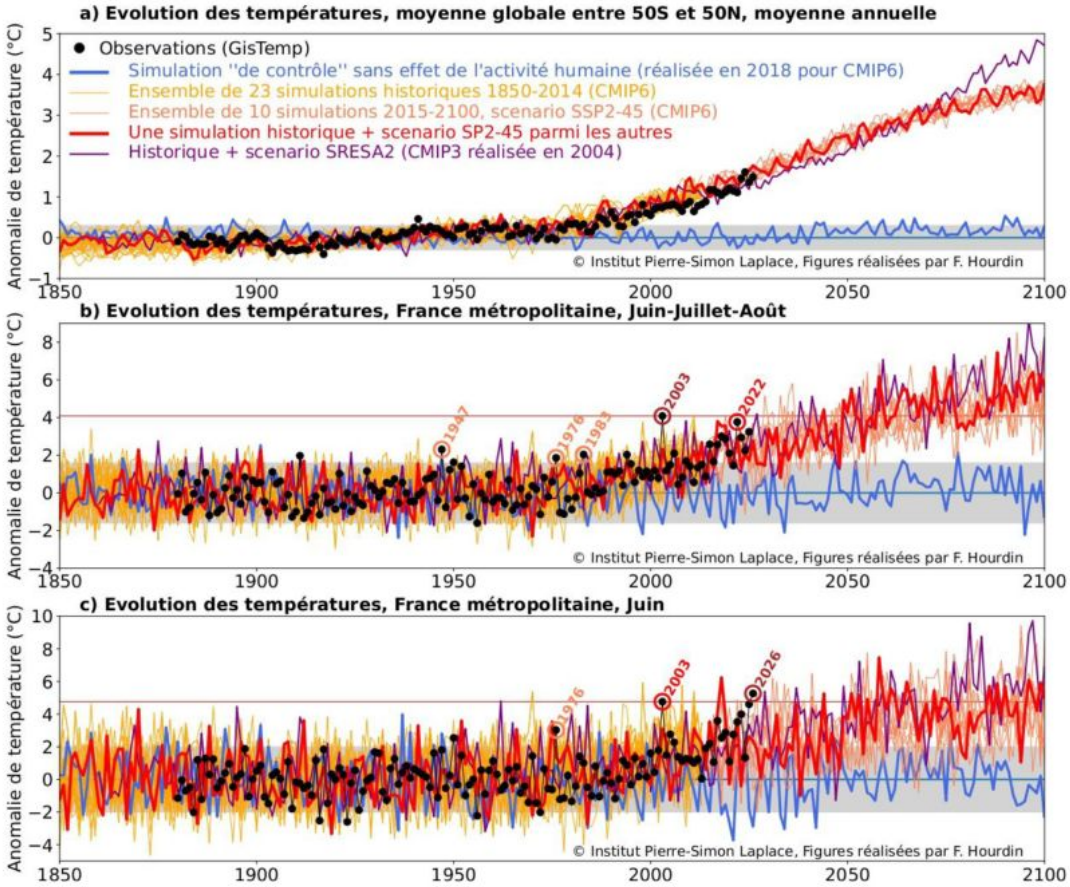



Figure 1. Évolution des anomalies de températures (référence 1900-1960) observées [1] et simulées avec le modèle couplé de l'IPSL pour CMIP3 et CMIP6.

éclairage, la vague de chaleur de juin 2026, centre du climat pour la société IPSL, courtesy of F. Hourdin

# Objectives:

- Figure out what is the science of climate modelling and how climate models are built
- Understand how climate simulations are designed and run to inform Society

# Outline

- **Chapter 1** What are climate models and where do they come from?
- **Chapter 2** Physical parameterizations in climate models
- **Chapter 3** Climate Modelling for the benefit of society

# Chapter 1:
## What are climate models and where do they come from?

- A bit of history ....
- The 5 layers of climate modelling
- How climate models have been (and are still) built
- First steps in practice

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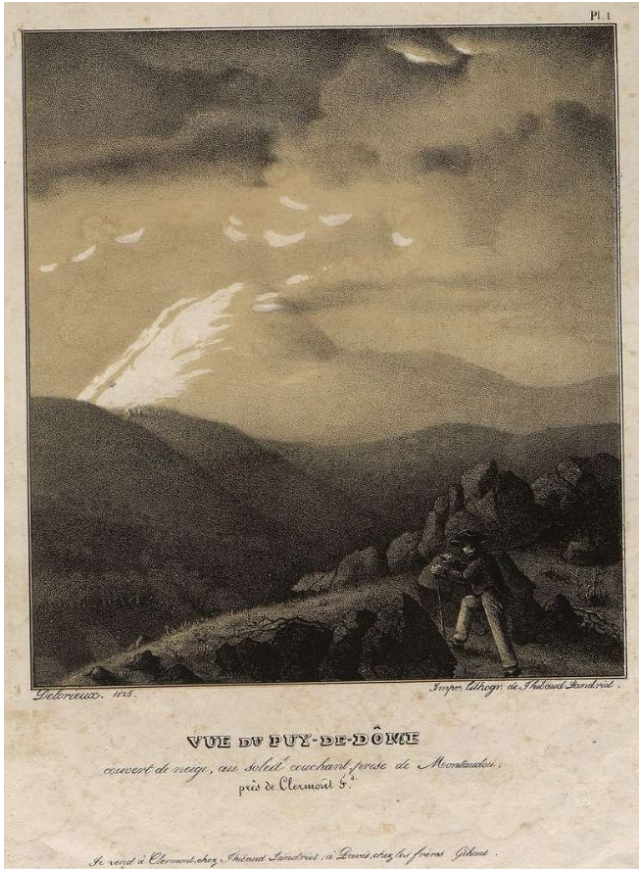
# A bit of History

**XVI century:** development of descriptive meteorology

- Development of instruments among which thermometers and Torricelli's barometer. Puy de Dôme Pascal's experiment (la grande expérience de l'équilibre des liqueurs) by his brother in law Florin Périer in September 1643.
- First observatories by Ferdinand de Medicis
- First map of oceanic winds and currents by Edmund Halley

**XVIII century:** First analytical model of atmospheric circulation (trade winds): warm air rises at the equator + effect of Earth's rotation by Georges Hadley

**XIV century:** development of systematic (climatologic) measurements + standardized meteorological map (creation of World Meteorological Organization)




@bibliothèque de Clermont Ferrand

# A bit of History

## XIX century:

### according to English history:

A storm in October 1859 that caused the loss of the *Royal Charter* inspired Robert FitzRoy to develop charts to allow predictions to be made, which he called "forecasting the weather". 15 stations were established to use the telegraph to transmit to him daily reports. His warning service for shipping was initiated in February 1861 (published in The Times), with the use of telegraph communications. ”

### according to French history:

On November 14, 1854, a terrible storm, striking without the slightest warning during the Crimean War, swept across Europe from west to east, causing the loss of 41 ships in the Black Sea. At the request of Napoleon III, Urbain Le Verrier established a network of meteorological observatories, 13 of which were connected by telegraph. Le Verrier had discovered that a weather event occurring in one location was the result of physical phenomena moving on a global scale. This marked the birth of modern meteorology.

## XX century:



beginning of dynamic meteorology with **Wilhelm Bjerkness**
-> Norwegian school of meteorology (**Carl-Gustaf Rossby**) -> explained the mid-latitude circulation
-> weather forecasting based on physics laws: **primitive equations for the atmosphere**

**Lewis Richardson** proposes a set of equations to predict the state of the atmosphere from an initial state:
-> first attempt to predict the weather 6h later (1910)
-> numerical scheme to solve differential equations to predict the weather globally... with no computers

# A bit of History

The first model of weather forecast model: The Richardson's weather factory



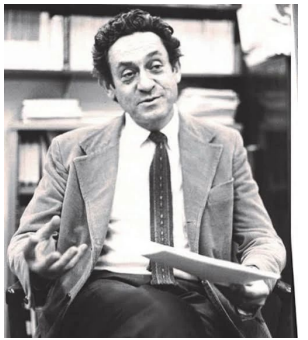
FIGURE 1: "Weather Forecasting Factory" by Stephen Conlin, 1986. Based on the description in Weather Prediction by Numerical Process, by L.F. Richardson, Cambridge University Press, 1922, and on advice from Prof. John Byrne, Trinity College Dublin. Image: ink and water colour, c. 50 x 38.5 cm. © Stephen Conlin 1986. All Rights Reserved ´. (Courtesy: Hendrik Hoffmann, School of Mathematics & Statistics, University College Dublin)

# A bit of History

## The tipping point: The World War II

- lots of new measurements (radiosondes) + training of many meteorologists in the USA (for aviation purposes)
- development of first computers
- **John von Neumann** (hungarian-american mathematician) developed the first computers to develop the A and H bomb....was convinced that computers can serve to solve atmospheric dynamical systems.
- He founded in 1946 the Numerical Meteorology Project at **Princeton**, with CG Rossby and **Jules Charney**
- In 1950, first numerical weather forecast over the USA using the ENIAC computer (numerical integration of the Barotropic vorticity equation = Charney's model) 24h of computation time for a 24h range forecast
- In 1956, **Norman Philipps** created the first general circulation model (2-layer quasi-geostrophic cylinder model, 130 day simulation)





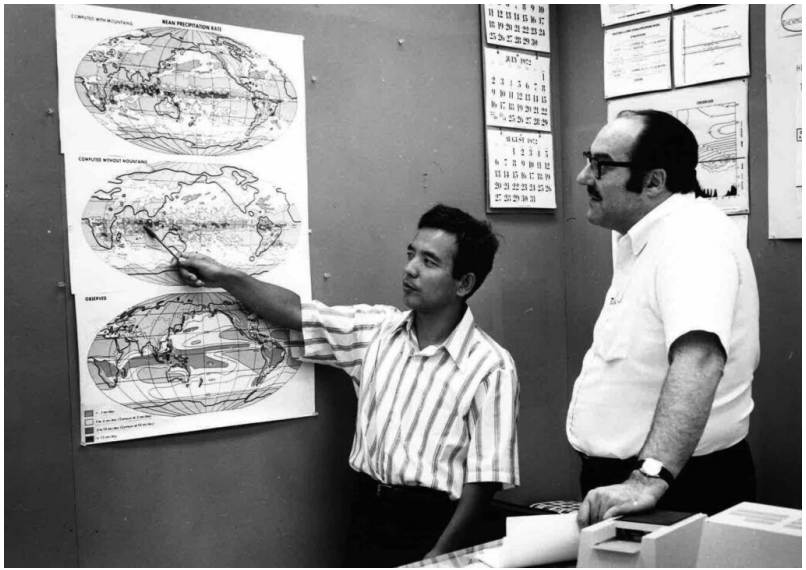
# A bit of History

**Modern history: towards current climate model**

**1960's:** pioneering work by **Joseph Smagorinsky** and **Syukuro Manabe** (nobel price in 2021) at GFDL -> spherical models, vertical discretisation AND missing processes (radiation, hydrological cycle, convection)

**in 1969:** first simulation atmosphere coupled with the ocean

-> we entered the era of coupled climate models

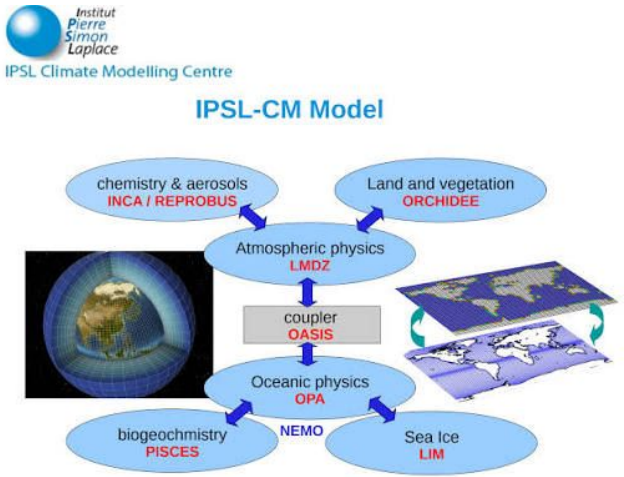


**In France**, creation of the Laboratoire de Météorologie Dynamique (LMD) in 1968 and first general circulation model of the atmosphere by R. Sadourny and K. Laval in 1980

# A bit of History

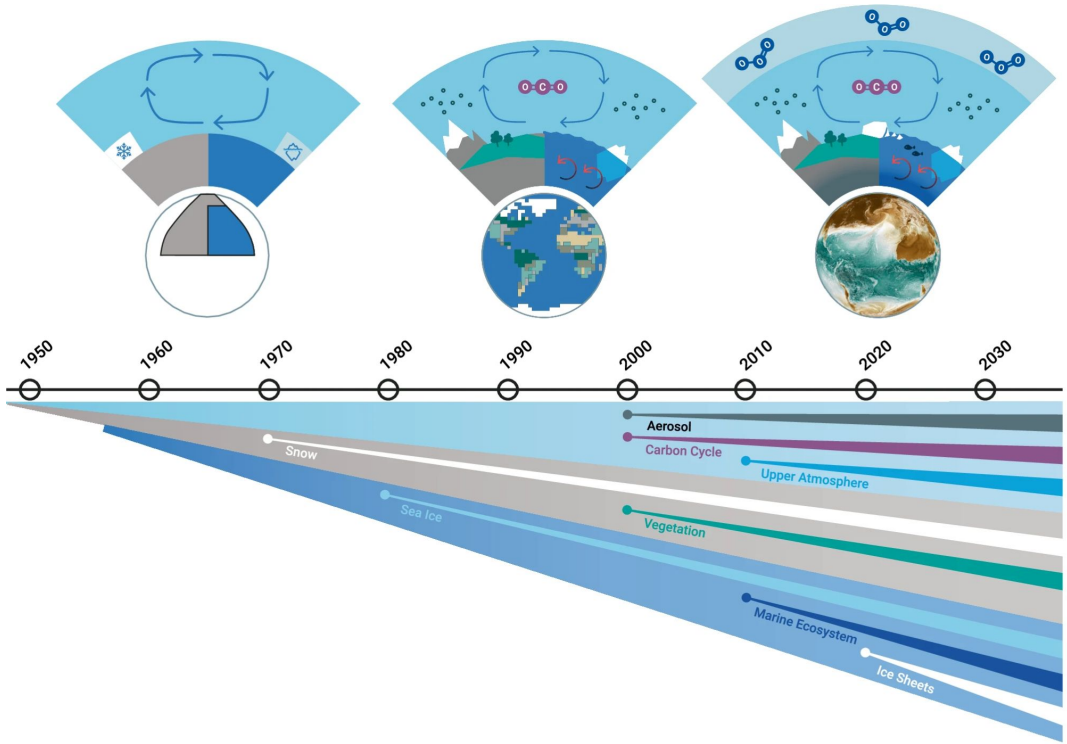
**Today:** about 150 climate models from about 50 climate modelling centers

In France, 2 centers IPSL (Institut Pierre Simon Laplace) and Météo France



# A bit of History

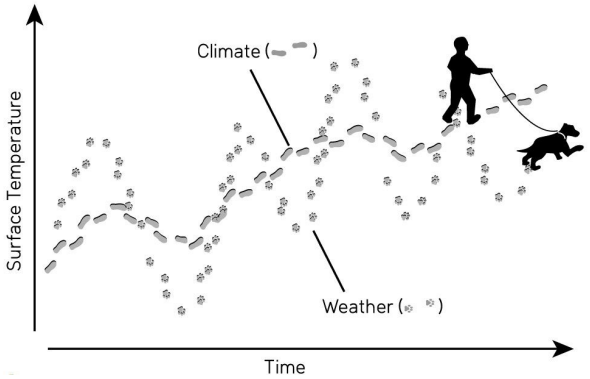
Quest for exhaustivity and quest for 'realism' led to a gradual increase in complexity.
From atmospheric models to Earth System Models




Bordoni et al. 2025

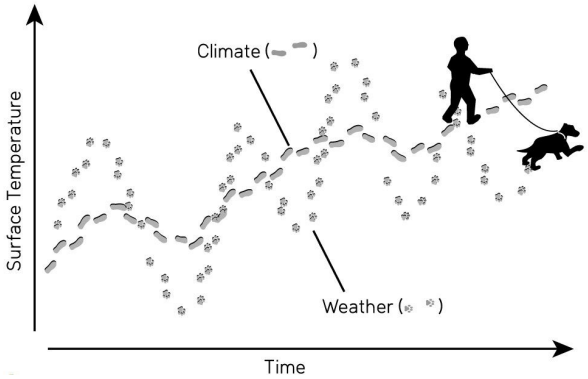
# A bit of History

| Climate Modelling | Weather Forecasting |
|---|---|
| "Boundary conditions" problem (Earth orbital configuration (solar forcing), GES emissions (anthropic forcing) ... ) | "Initial conditions" problem (weather is very dependent on initial state, challenge of accurately predicting the initial state, Lorenz chaos) |
| decades to centuries projections | a few hours to a few days predictions |
| Aim: predict the evolution of weather statistics (mean, extremes, return periods)<br>–> evolution of the weather system equilibrium point of the attractor | Aim: determine the exact trajectory of the weather |



# A bit of History

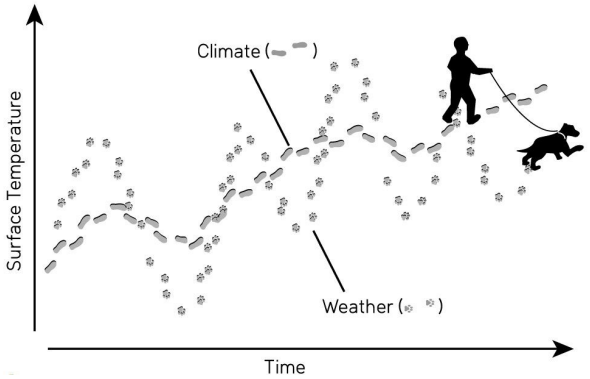
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**Predicting the climate is not predicting the weather!**
**It is possible to predict the long-term trajectory of the dog master (determined by forcing) but not that of the dog itself (high variability and chaos)**

# A bit of History

| Climate Modelling | Weather Forecasting |
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**Weather forecast models and climate models are historically the same models**

Today they still have a lot in common but weather forecast models at higher resolution
(But things are changing very quickly with AI-based weather forecast -> move from deterministic physical models to AI models, much more efficient numerically and with similar accuracy but require advanced physical models and observation assimilation systems to learn on)

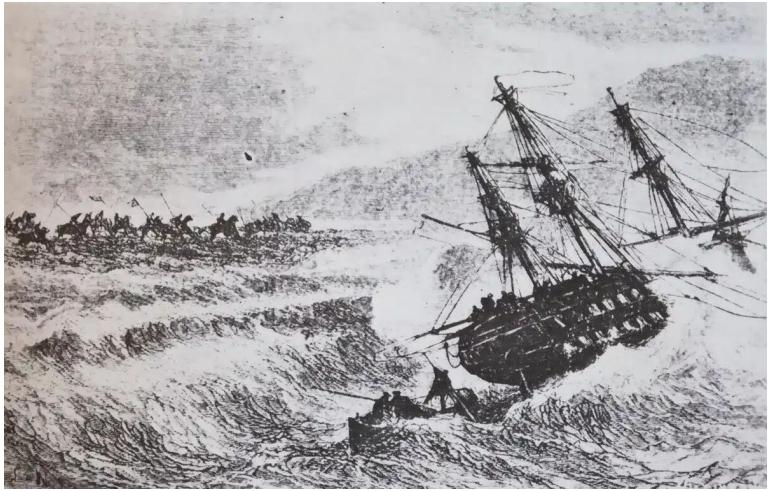
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# The 5 layers of climate modelling



# The 5 layers of climate modelling



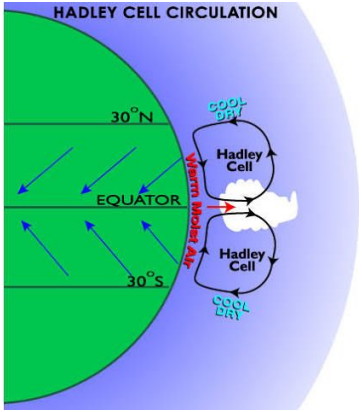
The world of phenomena



# The 5 layers of climate modelling

ex: conservation of angular Momentum
acceleration by pressure gradients

-> Georges Hadley' cells conceptual model for trade winds




The world of theories

The world of phenomena



# The 5 layers of climate modelling



$$\frac{du}{dt} - \left(f + \frac{u\tan\phi}{a}\right)v + \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x = 0$$

$$\frac{dv}{dt} + \left(f + \frac{u\tan\phi}{a}\right)u + \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y = 0$$

$$p = R\rho T$$

$$\frac{\partial p}{\partial z} + g\rho = 0$$

$$\frac{dT}{dt} + (\gamma - 1)T\nabla \cdot \mathbf{V} = \frac{Q}{c_p}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho\mathbf{V} = 0$$

$$\frac{\partial \rho_w}{\partial t} + \nabla \cdot \rho_w\mathbf{V} = [\text{Sources} - \text{Sinks}]$$

The world of mathematics

The world of theories

The world of phenomena



# The 5 layers of climate modelling

Richardson's equations on a discretized grid
(from continuous to discretized world)



FIGURE 1: "Weather Forecasting Factory" by Stephen Conlin, 1986. Based on the description in Weather Prediction by Numerical Process, by L.F. Richardson, Cambridge University Press, 1922, and on advice from Prof. John Byrne, Trinity College Dublin. Image: ink and water colour, c. 50 x 38.5 cm. © Stephen Conlin 1986. All Rights Reserved . (Courtesy: Hendrik Hoffmann, School of Mathematics & Statistics, University College Dublin)

The world of numerics

The world of mathematics

The world of theories

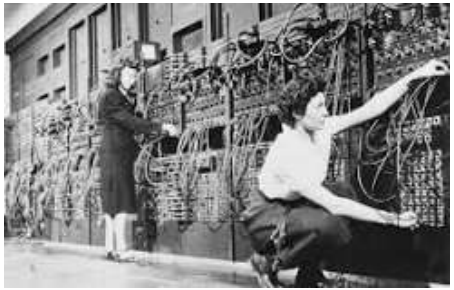
The world of phenomena



# The 5 layers of climate modelling

```
DO ilay=1,nlay
    DO igrid = 1, ngrid
        theta(igrid,ilay)=temp(igrid,ilay)*(preff/play(igrid,ilay))**(rd/rcpd)
    END DO
END DO
```

ENIAC computer



The world of computers

The world of numerics

The world of mathematics

The world of theories

The world of phenomena



# The 5 layers of climate modelling

The world of computers

The world of numerics

The world of mathematics

The world of theories

The world of phenomena

The 5 worlds of climate modelling

Climate modelling IS a permanent journey through all of the 5 worlds

# The 5 layers of climate modelling

***Take home messages***

- Climate modelling and Weather Forecasting have a common history and still have a lot in common
- Climate modelling is a fundamental science with a tight and historical link with Society (understand the climate system AND inform Society on the present and future states of the climate)
- Climate models are first and foremost physical models based on fundamental physics laws that aim to explain the functioning of a complex physical system, for research AND teaching purposes
- Climate modelling is a scientific discipline per se and founded on 5 interconnected 'layers'

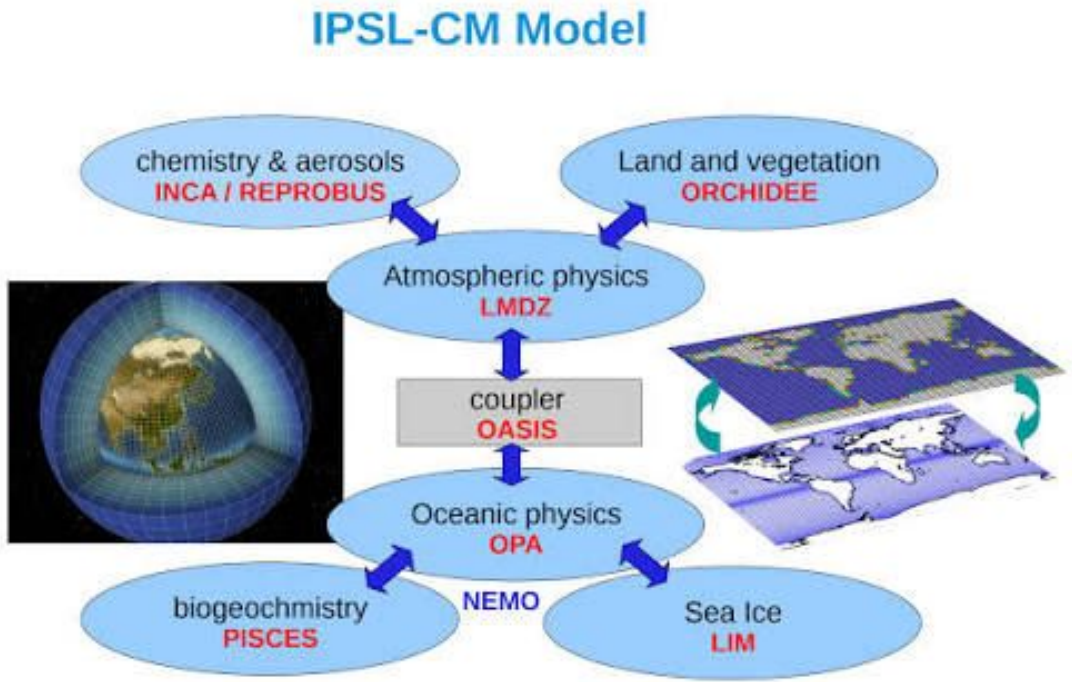
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# How climate models have been (and are still) built?

The concept of "coupled models"

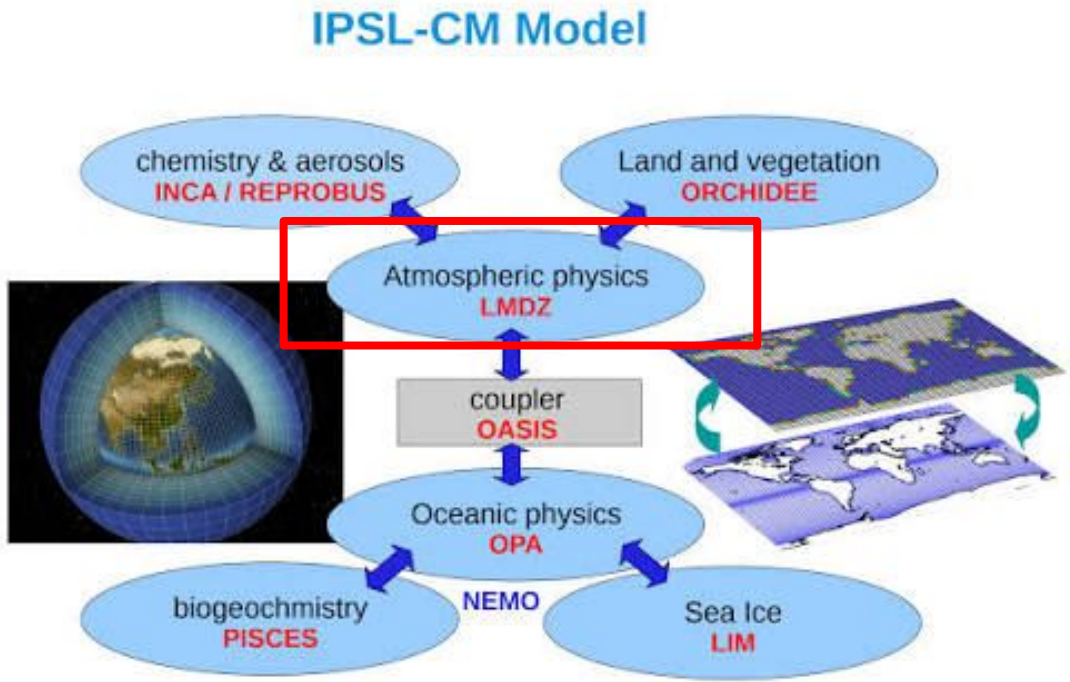
Institut Pierre Simon Laplace
IPSL Climate Modelling Centre



# How climate models have been (and are still) built?

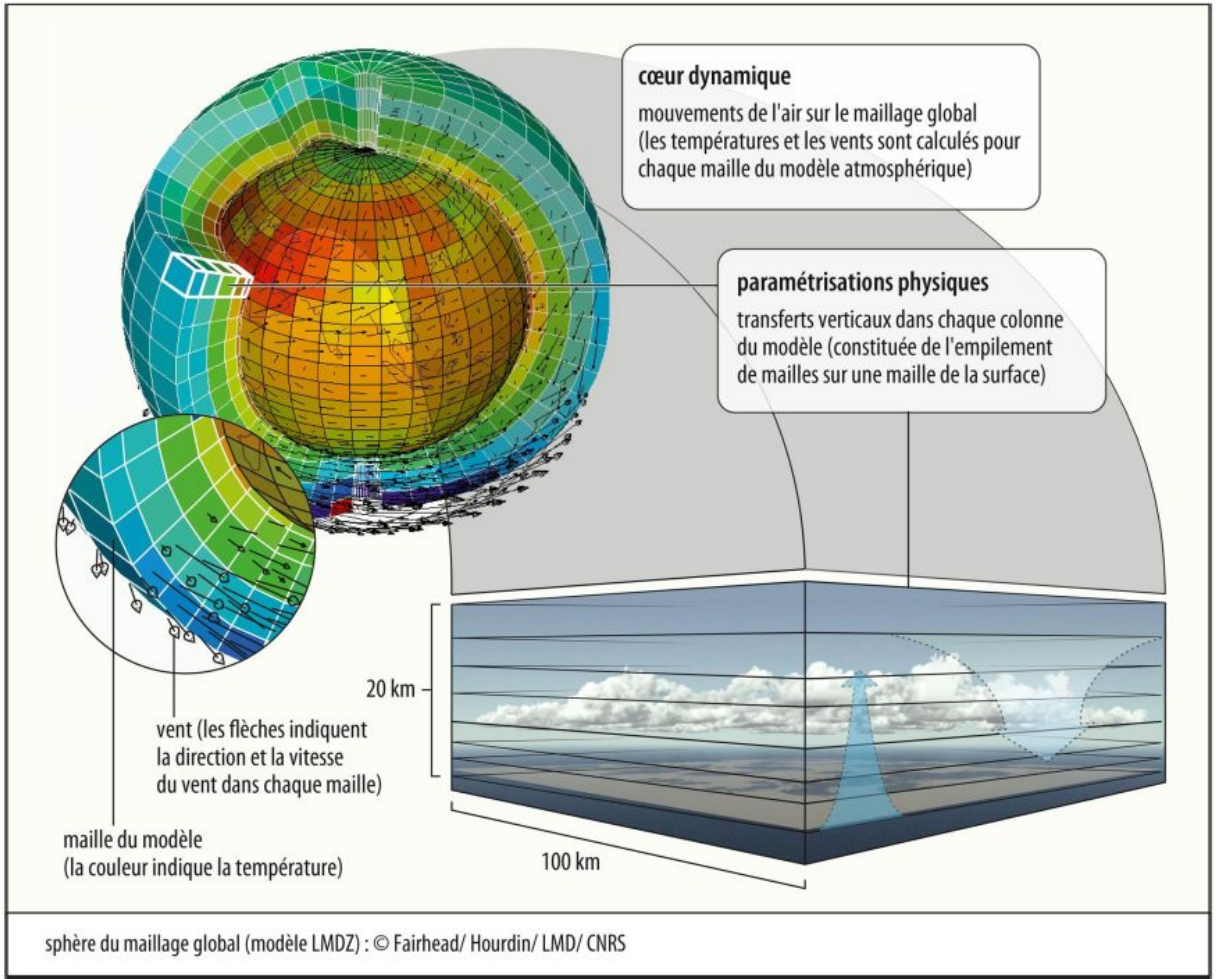
The concept of "coupled models"

Institut Pierre Simon Laplace
IPSL Climate Modelling Centre



# How climate models have been (and are still) built?

Conceptual and dynamical splitting between 2 components



# How climate models have been (and are still) built?

## Dynamical core or model's 'dynamics'

primitive equation discretized on the sphere

Different meshes

also spectral methods (e.g., CNRM model in Toulouse)

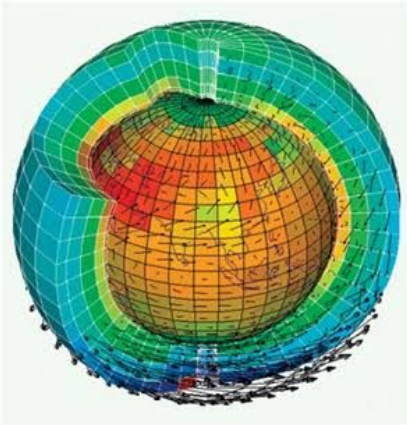
- Mass conservation

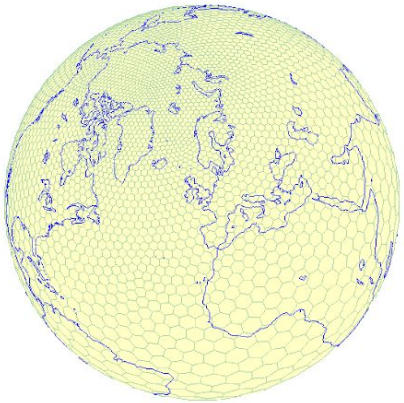
  $D\rho/Dt + \rho \, \mathrm{div}\underline{U} = 0$
- Potential temperature conservation

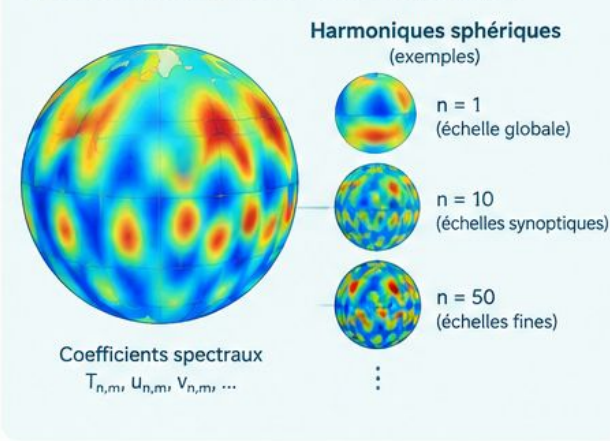
  $D\theta / Dt = Q / Cp \ (p0/p)^{\kappa}$
- Momentum conservation

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

  $Dq/Dt = Sq$

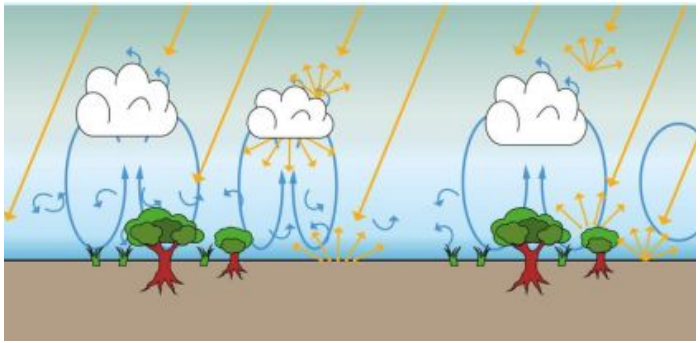






# How climate models have been (and are still) built?

## Physical parameterizations or model's 'physics'



- Mass conservation

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

- Potential temperature conservation

  $D\theta / Dt = Q / Cp\ (p0/p)^{\kappa}$

- Momentum conservation

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

- Secondary components conservation

  $Dq/Dt = Sq$

**Parameterizations purpose :** account for the effect of processes non resolved by the dynamical core

→ **Traditional « source » terms in the equations**

- $Q$ : Heating by radiative exchanges, thermal conduction (neglected), condensation, sublimation, **subgrid-scale motions (turbulence, clouds, convection)**
- $\underline{F}$ : Molecular viscosity (neglected), **subgrid-scale motions (turbulence, clouds, convection)**
- $Sq$ : condensation/sublimation (q= water vapor or condensed), chemical reactions, photo-dissociation (ozone, chemical species), micro physics and scavenging (pollution aerosols, dust, ...), **subgrid-scale motions (turbulence, clouds, convection)**

# How climate models have been (and are still) built?

An atmospheric model can be summarized as:

$$\frac{\partial \boldsymbol{x}}{\partial t} = \mathcal{D}(\boldsymbol{x}) + \sum_p \mathcal{P}_p(\boldsymbol{x}, \boldsymbol{\lambda}_p)$$

$\mathbf{x}$ = state variables (temperature, humidity, wind components), $D$ = discretized form of the fluid dynamic equations, $Pp$ = source term provided by the parameterization of the process p and $\lambda p$ the associated 'free' parameters.

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## Model tendencies

for any state variable of the model:

$$X_{t+\Delta t} = X_t + \left(\frac{\partial X}{\partial t}\right)_{\text{dyn}} \Delta t \text{ (dynamical core)}$$
$$+ \left(\frac{\partial X}{\partial t}\right)_{\text{param}} \Delta t \text{ (parameterizations)}$$

# How climate models have been (and are still) built?

## Forcings and initial conditions

- Initial conditions of state variables
- Eventually atmospheric composition prescriptions (aerosols, GHGs, ozone ...)
- For atmosphere-only simulations: surface conditions (sea surface temperature and sea ice cover)

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# First steps in practice

Let's use one AGCM to understand the basics of the atmospheric circulation: the Hadley cells

# Chapter 2:
## Physical parameterizations in climate models

- The basics of physical parameterizations
- Parameterizations of subgrid atmospheric motions
- Parameterizations of clouds
- Parameterization development: one approach
- Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

# Chapter 2:
## Physical parameterizations in climate models

- **The basics of physical parameterizations**
- Parameterizations of subgrid atmospheric motions
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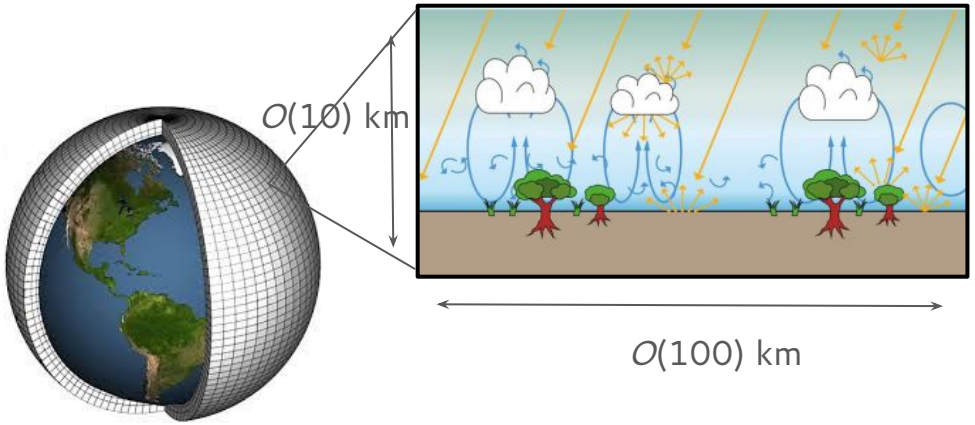
## Why a focus on physical parameterizations?

- What makes the **identity** of a model is **first and foremost** its **physics** (ensemble of parameterisations)
- The reliability and 'realism' of a model mostly depend on them
- **Parameterization development and tuning:** A scientific discipline per se, an important part of atmospheric research and climate modelling. Many challenges regarding their conceptualisation and calibration
- A national working group dedicated to it (DEPHY, https://web.lmd.jussieu.fr/DEPHY/dephy.html)

# The basics of physical parameterizations

**3 main parameterizations groups:**

- transport by subgrid and unresolved motions
- clouds, precipitation and aerosols
- radiative transfer



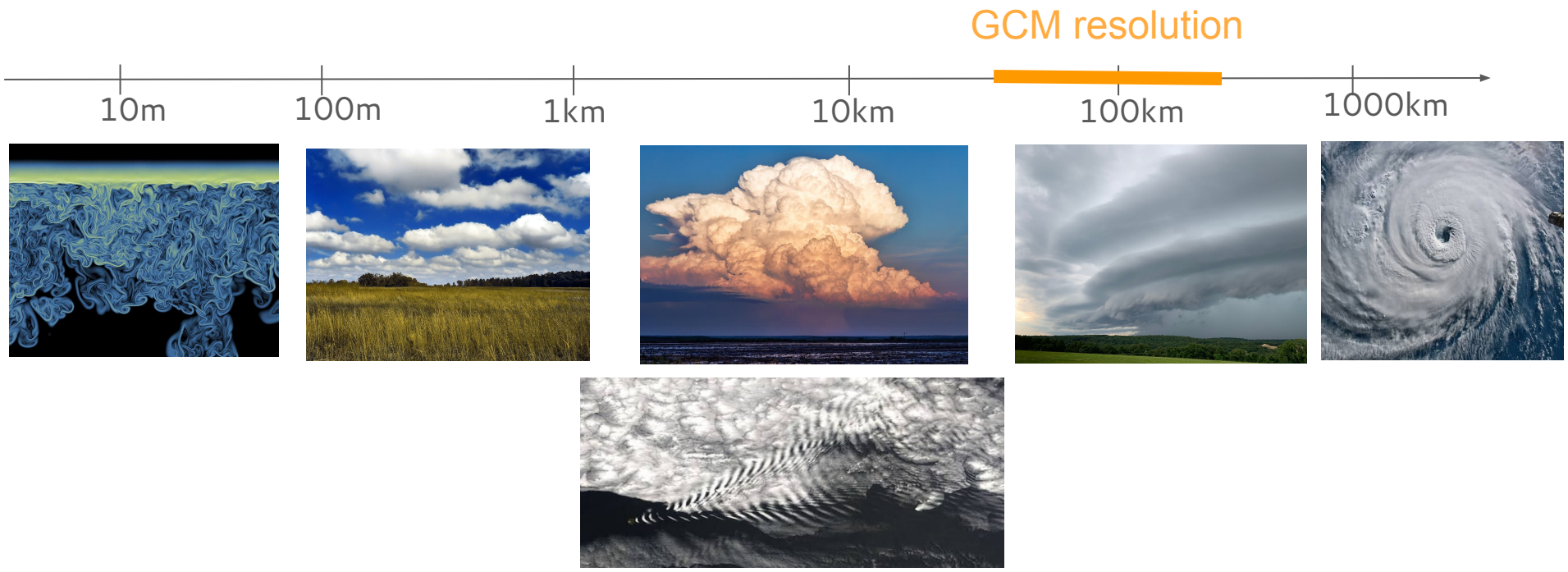

The paradigm of **'verticality' and column independency** in models' physics

– > subgrid vertical motions mostly contribute to transport quantities along the vertical
–> radiative fluxes do not see neighbouring columns (aspect ratio in standard resolutions ok)

# Chapter 2:
## Physical parameterizations in climate models

- The basics of physical parameterizations
- **Parameterizations of subgrid atmospheric motions**
- Parameterizations of clouds
- Parameterization development: one approach
- Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

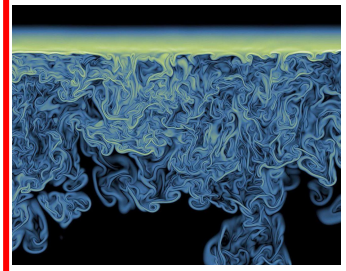
# Parameterization of subgrid atmospheric motions



# Parameterization of subgrid atmospheric motions

GCM resolution

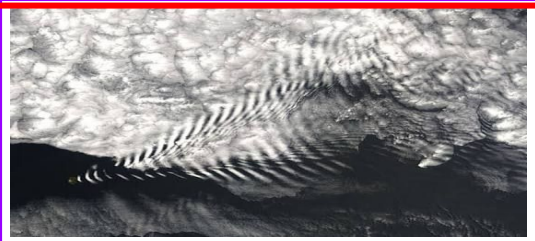
10m 100m 1km 10km 100km 1000km





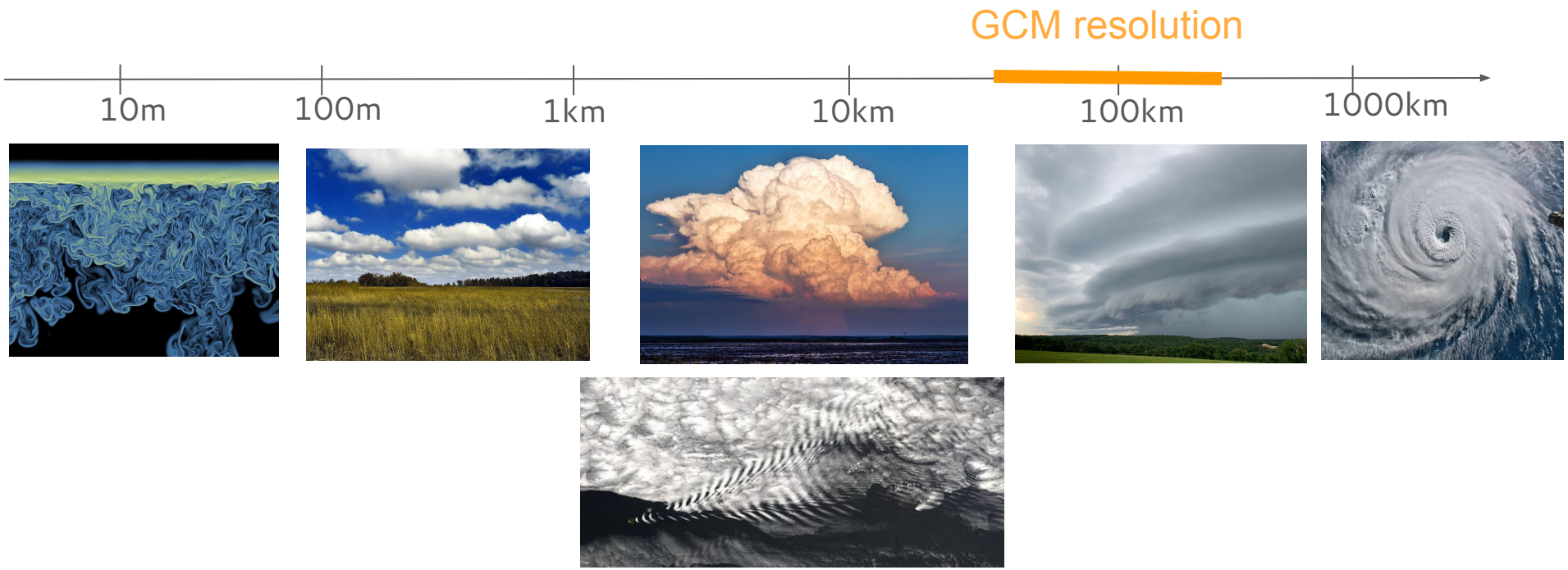


Atmospheric turbulence



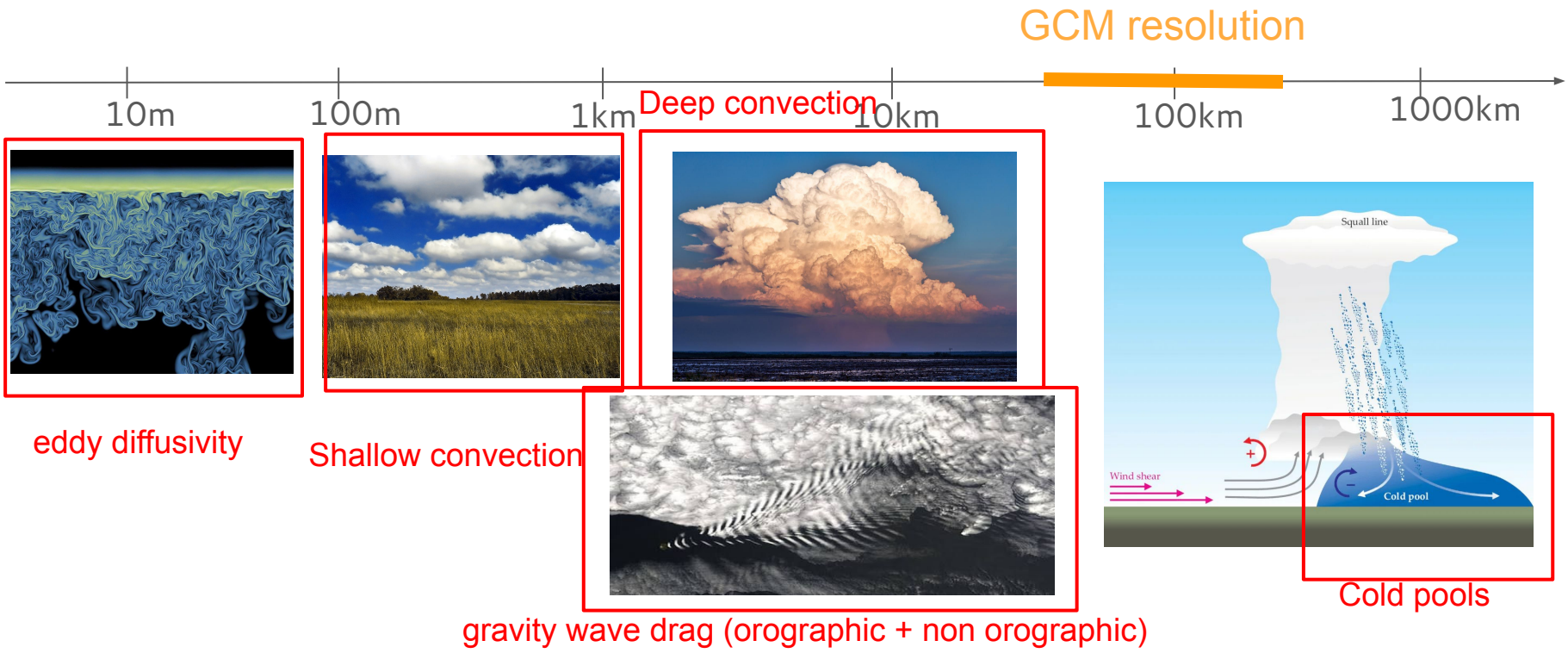
Atmospheric waves

# Parameterization of subgrid atmospheric motions




How to **categorize** the different types of subgrid motions (turbulence and waves) and to **parameterize** them is a research per se.
–> different choices in different models

# Parameterization of subgrid atmospheric motions




**Example of the french LMDZ model**

Separating the treatment of turbulent mixing allows for scale-interactions studies (i.e. triggering of deep convection by shallow convection and cold pools)

# Parameterization of subgrid atmospheric motions

Mathematical framework: the Reynold's equations

$$\frac{\partial \rho c}{\partial t} + \vec{\nabla}(\rho \vec{u} c) = P_c$$

$$\tilde{c} \equiv \frac{\overline{\rho c}}{\overline{\rho}}$$ $\tilde{c}$ is an extensive physical quantity per mass unit.

$$c = \tilde{c} + c'$$

$$\underbrace{\frac{\partial \overline{\rho}\tilde{c}}{\partial t} + \vec{\nabla}\left(\overline{\rho}\tilde{c}\tilde{\vec{u}}\right)}_{(1)} = \underbrace{-\vec{\nabla}\left(\overline{\rho \vec{u}' c'}\right)}_{(2)} + \overline{P_c}$$

when assuming statistical average ↔ spatial (mesh) average (Ergodicity)

Handled by the dynamical core

Handled by the model's physics

# Parameterization of subgrid atmospheric motions

Mathematical framework: the Reynold's equations

$$\frac{\partial \overline{\rho}\tilde{c}}{\partial t} + \vec{\nabla}\left(\overline{\rho}\tilde{c}\tilde{\vec{u}}\right) = -\vec{\nabla}\left(\overline{\rho\vec{u}'c'}\right) + \overline{P_c}$$

$$\vec{\nabla}\left(\overline{\rho\vec{u}'c'}\right) \approx \partial_z\left(\overline{\rho w'c'}\right)$$

$$\left.\frac{\partial \tilde{c}}{\partial t}\right|_{turbulence} = -\frac{1}{\overline{\rho}}\frac{\partial \overline{\rho w'c'}}{\partial z}$$

for large scale atmospheric models of resolution O(10–100km), we **assume horizontal homogeneity**

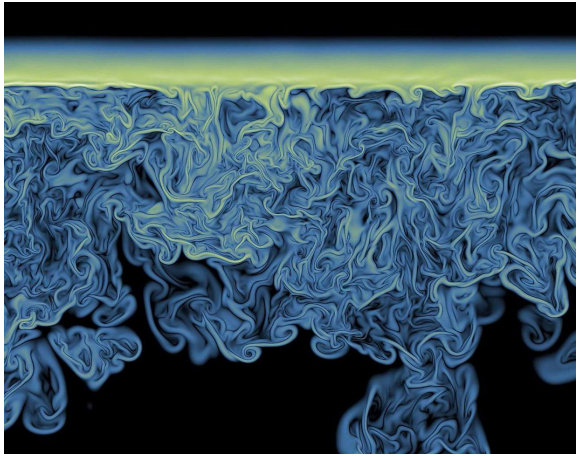
**Modelling choice:** treating this tendency as the sum of different tendencies corresponding to different **arbitrarily separated** processes (vertical turbulent diffusion (small eddies), shallow convection and deep convection, gravity waves ...)

# Parameterization of subgrid atmospheric motions

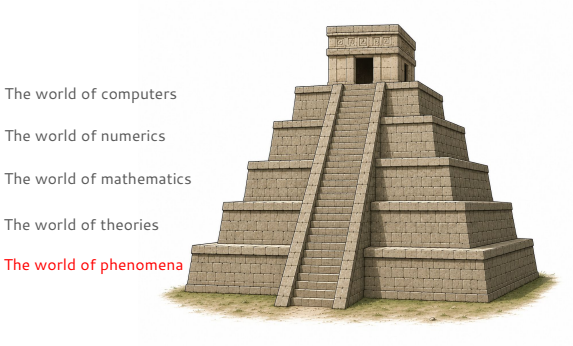
## Example: building a parameterization for turbulent mixing by small scale eddies:



Turbulent Kelvin-Helmholtz instability

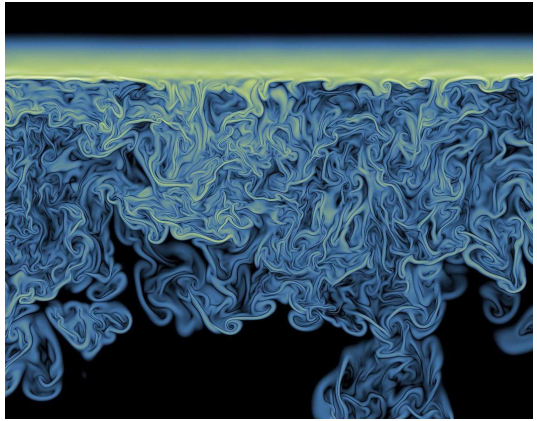


Mixing at cloud boundaries, DNS Juan Pedro Mellado
The evaporatively driven cloud-top mixing layer", J. Fluid Mech., 660



# Parameterization of subgrid atmospheric motions

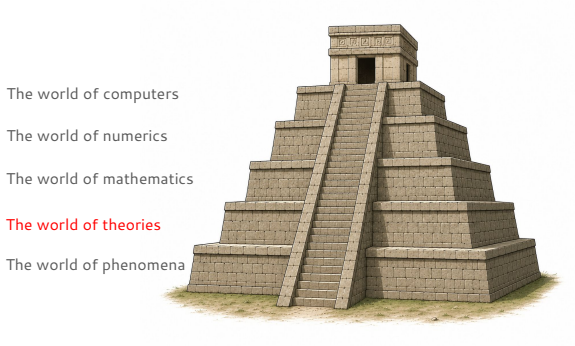
## Example: building a parameterization for turbulent mixing by small scale eddies:



High concentration of liquid water

fluid dynamics: diffusive transport from high to low concentration by turbulence

Low concentration



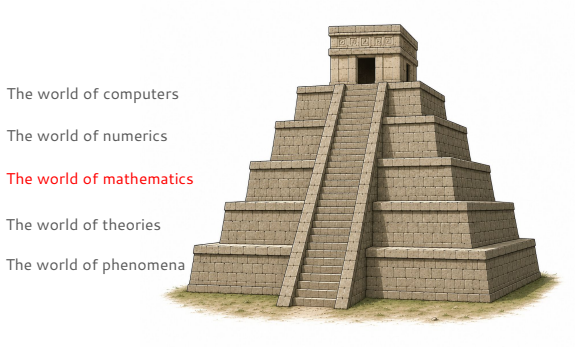
# Parameterization of subgrid atmospheric motions

## Example: building a parameterization for turbulent mixing by small scale eddies:

**Conceptual model** of Fick type diffusion law
counter-gradient diffusion

$$\overline{\rho w' c'} = -\rho K_c \partial_z c$$

turbulent diffusion coefficient

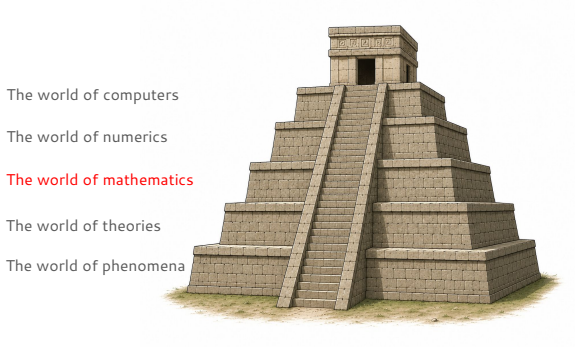


# Parameterization of subgrid atmospheric motions

## Example: building a parameterization for turbulent mixing by small scale eddies:

**Conceptual model** of Fick type diffusion law
counter-gradient diffusion

$$\overline{\rho w' c'} = -\rho K_c \partial_z c$$




Different formulations for $K_c$

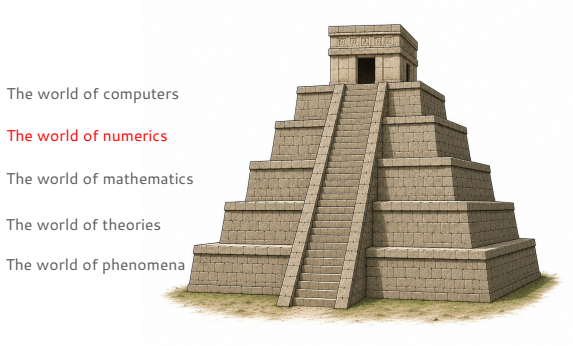
1st order closure
2nd order closure
⟶ introduction of semi-empirical parameters

# Parameterization of subgrid atmospheric motions

## Example: building a parameterization for turbulent mixing by small scale eddies:

$$\frac{\partial c}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(-\rho K_c \frac{\partial c}{\partial z}\right).$$

$$F^n_{i+1/2} = -\rho_{i+1/2} K_{c,i+1/2} \frac{c^n_{i+1} - c^n_i}{\Delta z}.$$




Resolution **explicit** in time

$$\frac{c^{n+1}_i - c^n_i}{\Delta t} = -\frac{1}{\rho_i}\frac{F^n_{i+1/2} - F^n_{i-1/2}}{\Delta z}.$$

**conditionally stable**
**requires time steps of a few tens of s ….**
**-> not applicable in GCMs**

Resolution **implicit** in time
(more complex, requires inverting a tri-diagonal matrix)

$$\frac{c^{n+1}_i - c^n_i}{\Delta t} = -\frac{1}{\rho_i}\frac{F^{n+1}_{i+1/2} - F^{n+1}_{i-1/2}}{\Delta z}.$$

**always stable but more diffusive**

# Parameterization of subgrid atmospheric motions

## Example: building a parameterization for turbulent mixing by small scale eddies:

```
module lmdz_atke_exchange_coeff

implicit none

contains

subroutine atke_compute_km_kh(ngrid,nlay,dtime, &
                        wind_u,wind_v,temp,qvap,play,pinterf,cdrag_uv, &
                        tke,eps,tke_shear,tke_buoy,tke_trans,Km_out,Kh_out)
!$gpum horizontal ngrid

!=======================================================================
! Routine that computes turbulent Km / Kh coefficients with a
! 1.5 order closure scheme (TKE) with or without stationarity assumption
!
! This parameterization has been constructed in the framework of a
! collective and collaborative workshop,
! the so-called 'Atelier TKE (ATKE)' with
! K. Arjdal, L. Raillard, C. Dehondt, P. Tiengou, A. Spiga, F. Cheruy, T Dubos,
! M. Coulon-Decorzens, S. Fromang, G. Riviere, A. Sima, F. Hourdin, E. Vignon
!
! Main assumptions of the model :
! (1) horizontal homogeneity (Dx=Dy=0.)
!=======================================================================

USE lmdz_atke_turbulence_ini, ONLY : iflag_atke, kappa, l0, ric, cinf, rpi, rcpd, atke_ok_virtual, ri0, ri1
USE lmdz_atke_turbulence_ini, ONLY : cepsilon, pr_slope, pr_asym, pr_neut, ctkes, rg, rd, rv, atke_ok_vdiff
USE lmdz_atke_turbulence_ini, ONLY : viscom, viscoh, clmix, clmixshear, iflag_atke_lmix, lmin, smmin, cn
```

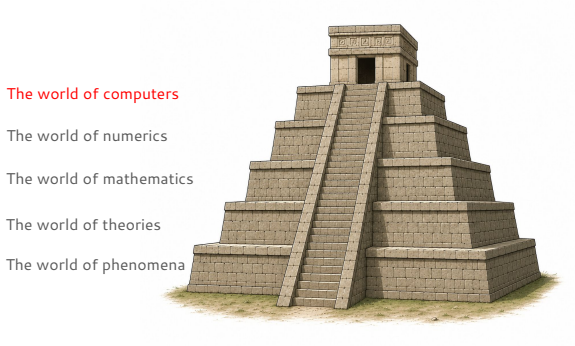



illustration notebook

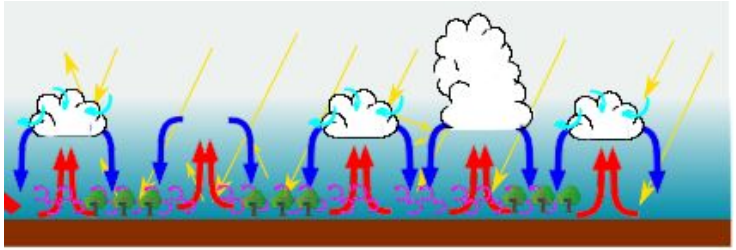
# Parameterization of subgrid atmospheric motions

**Example: building a parameterization for turbulent mixing by small scale eddies:**

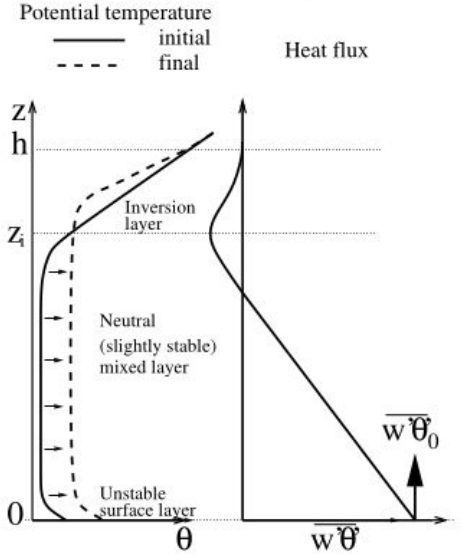
How does the turbulent mixing of temperature occurs over the Saharan desert or over the Amazonian forest?

# Parameterization of subgrid atmospheric motions

## Shallow convection (organized convective cells)



Idealized view of the dry convective boundary layer.




**In the mixed layer**

- Diffusive formulation

$$\overline{w'\theta'} = -K_z \frac{\partial \theta}{\partial z} = 0 \quad \text{or slightly} \quad < 0$$

- Uniform heating by the surface

$$\frac{\partial \theta}{\partial t} \simeq \frac{\overline{w'\theta'}_0}{z_i} (\text{Cste} > 0)$$

$$\overline{w'\theta'} \simeq \frac{z - z_i}{z_i} \overline{w'\theta'}_0 > 0$$

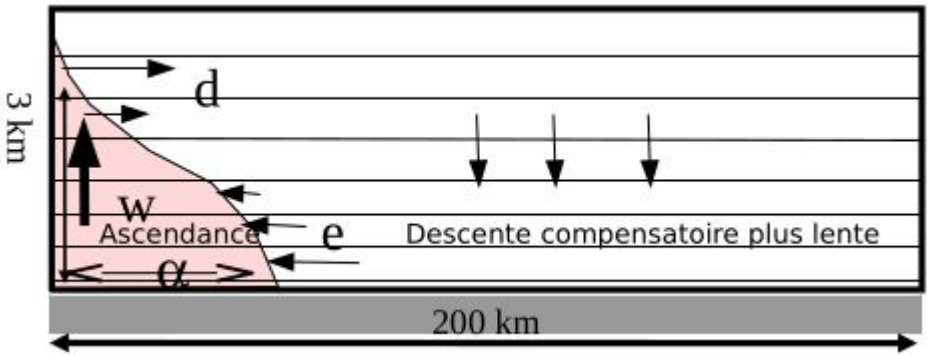
Historical approach:
counter gradient term

$$\overline{w'\theta'} = K_z \left[ \Gamma - \frac{\partial \theta}{\partial z} \right]$$

# Parameterization of subgrid atmospheric motions

## Shallow convection

now: mass-flux approaches (from original work of Arakawa & Schubert 1974, for deep convection)




combination eddy-diffusivity and mass flux (EDMF):

$$\rho\overline{w'q'} = \rho\hat{\alpha}\hat{w}(\hat{q}-q) - \rho K_q \frac{\partial q}{\partial z}$$

mass-flux

turbulent diffusion

**based on 3 equations:**

mass conservation

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

quantity (tracer) q conservation

$$\frac{\partial f q_a}{\partial z} = eq - dq_a$$

motion equation

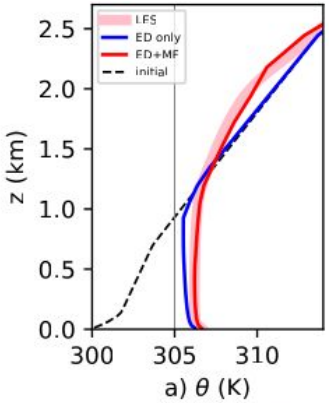
$$\frac{\partial f w}{\partial z} = -dw + \alpha\rho B$$

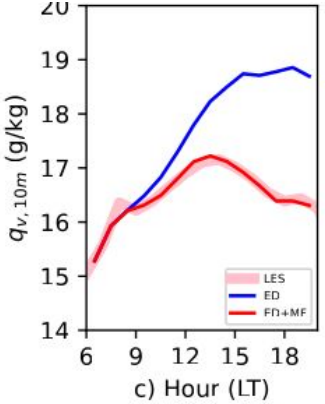
e: entrainment, d: detrainment, w vertical velocity, f: mass flux, B: buoyancy

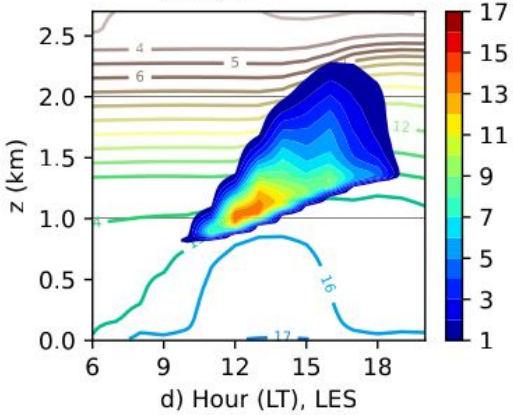
# Parameterization of subgrid atmospheric motions

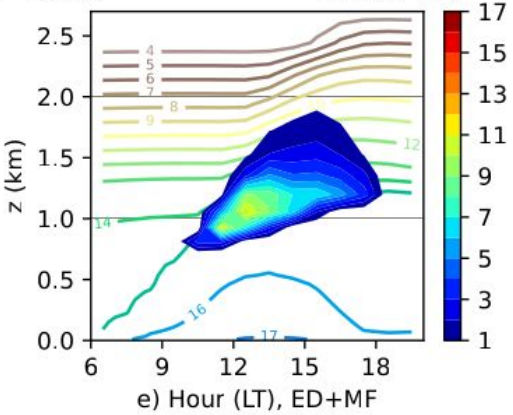
**Example of the introduction of mass-flux scheme for shallow convection to reproduce the convective boundary layer and cumulus clouds over land**





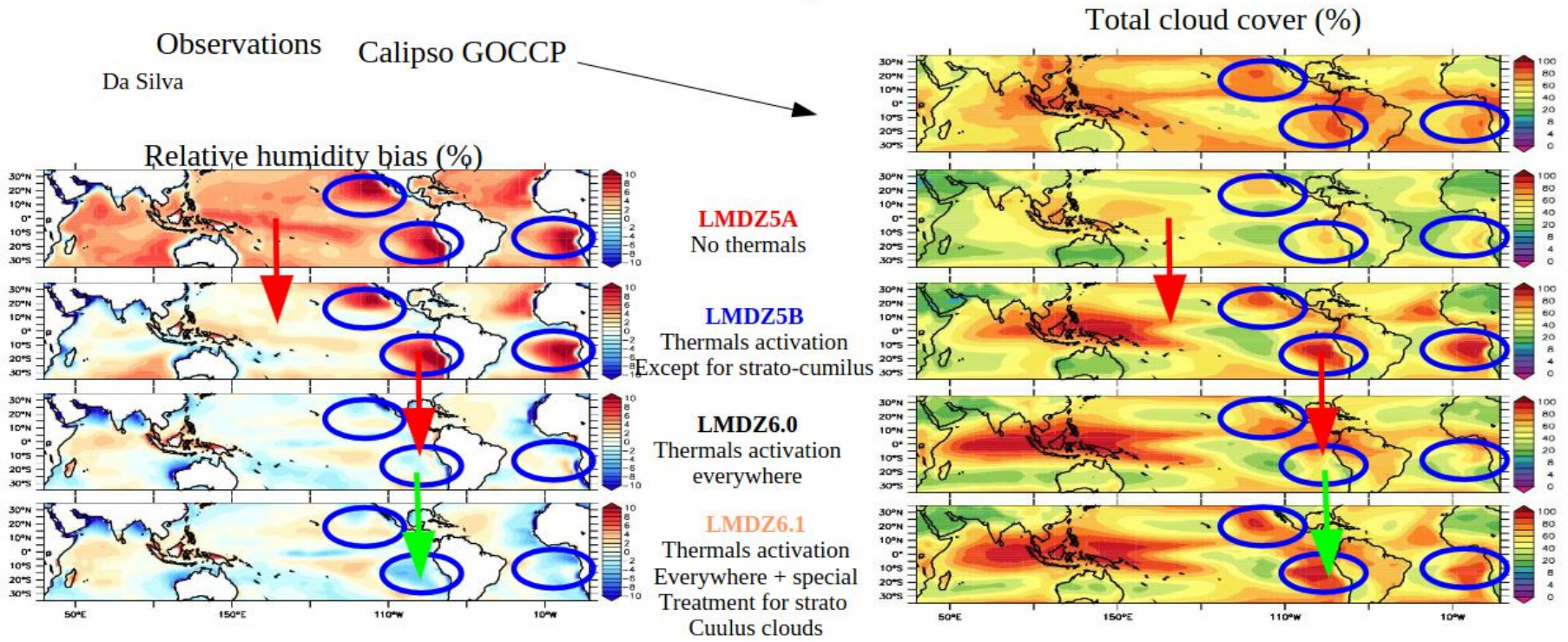



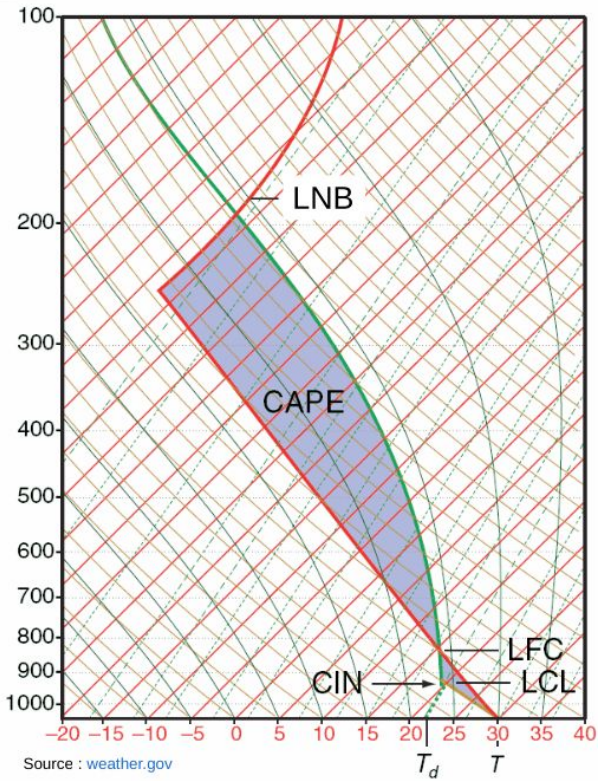
# Parameterization of subgrid atmospheric motions

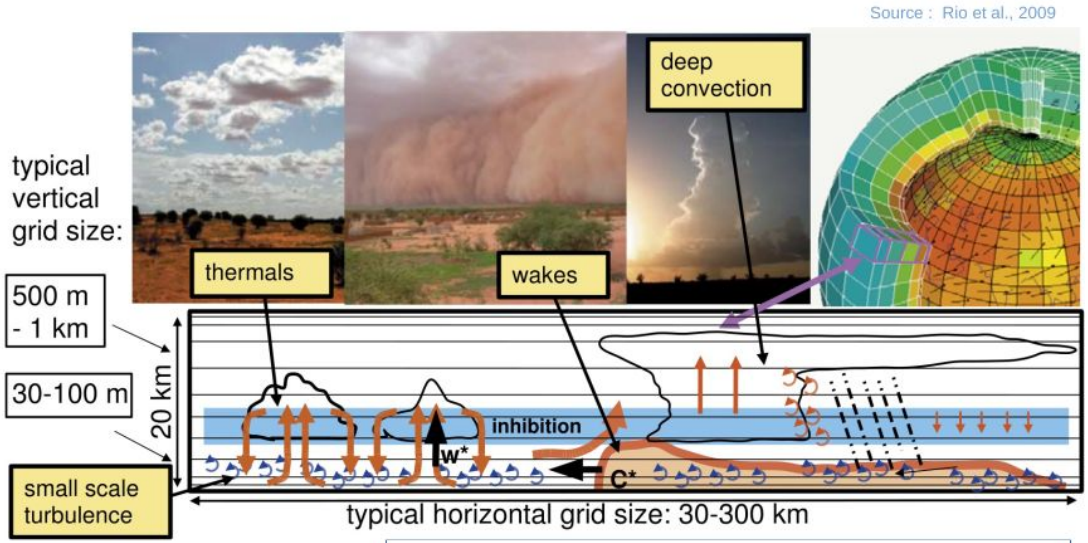
## And then … consequences in 3D (global) version of the model



# Parameterization of subgrid atmospheric motions

## From shallow to deep convection: interactions between parameterizations




$$\mathrm{ALE}^{\mathrm{th}} = w_*^2/2$$

$$\mathrm{ALE}^{\mathrm{wk}} \simeq C_*^2$$

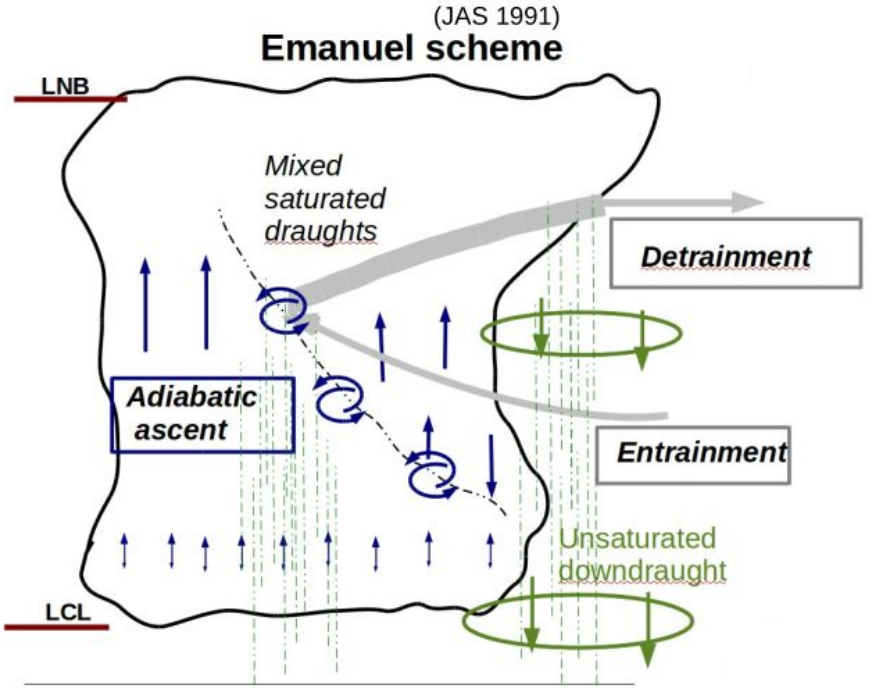
Deep convection is triggered :

IF : $\max(\mathrm{ALE}^{\mathrm{th}}, \mathrm{ALE}^{\mathrm{wk}}) > |\mathrm{CIN}|$

AND **AND IF** : at least one cloud reaches a given threshold size (stochastic triggering scheme, Rochetin et al., 2014)

# Parameterization of subgrid atmospheric motions

## Deep convection



# Chapter 2:
## Physical parameterizations in climate models

- The basics of physical parameterizations
- Parameterizations of subgrid atmospheric motions
- **Parameterizations of clouds**
- Parameterization development: one approach
- Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

# Parameterization of clouds



Picture by Oleg Artemyev taken from the ISS

# Parameterization of clouds

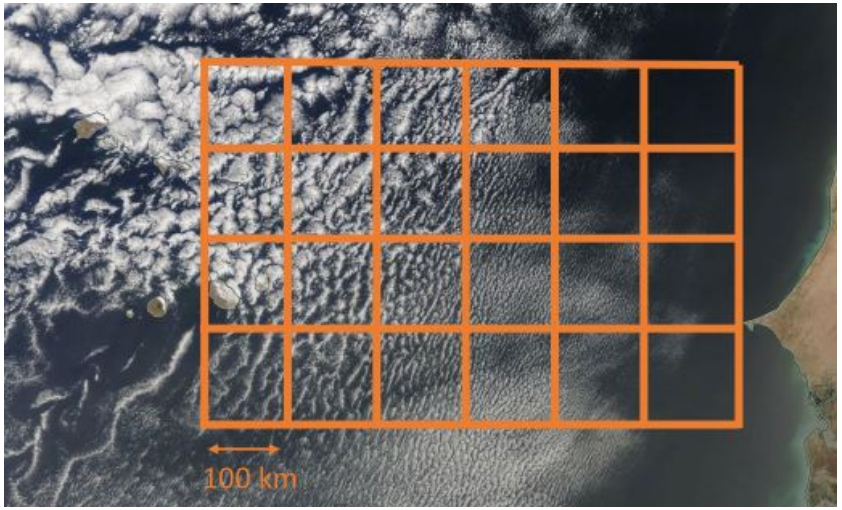
**Challenges** of cloud parameterization

- prediction of cloud cover (for interaction with radiations)
- prediction of condensates properties (mass, size, phase ...)
  -> microphysics
- prediction of precipitation

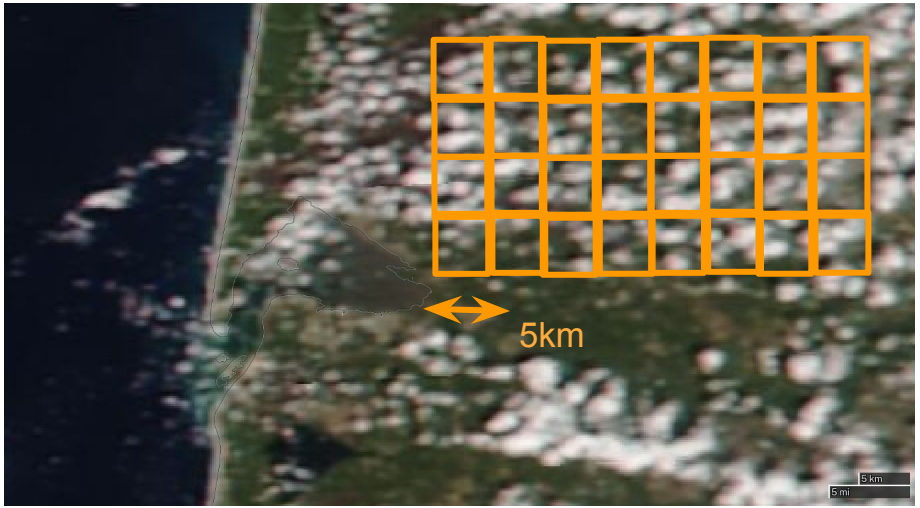
-> Earth's radiative budget
-> water cycle
-> atmospheric dynamics (diabatic effects)

# Parameterization of clouds

off the African coast



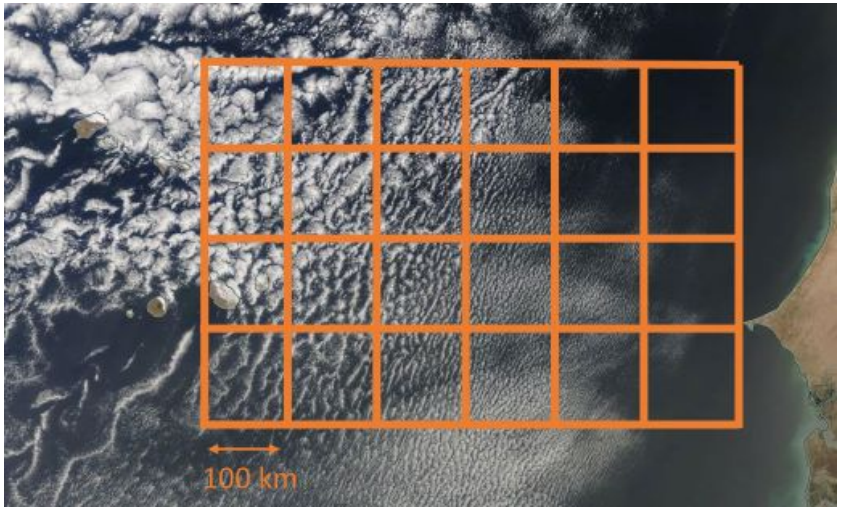

Near the Arcachon Basin



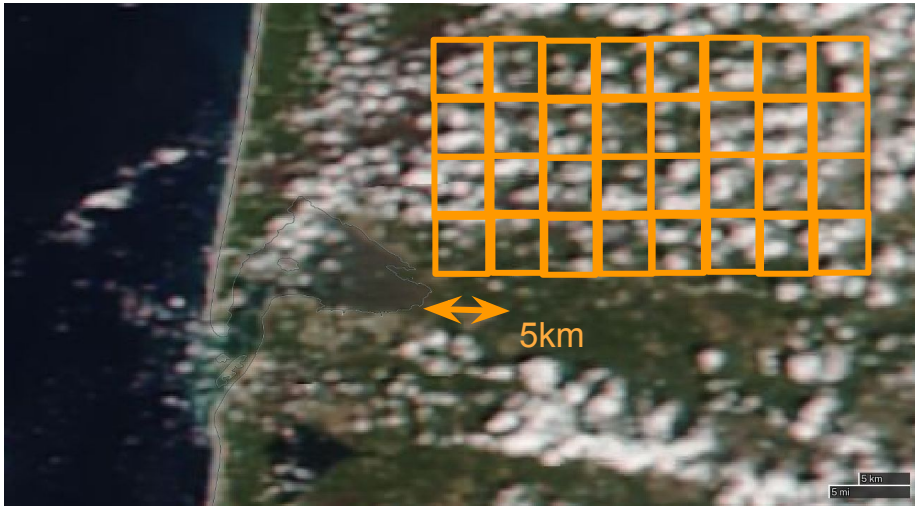

nasa worldview, viirs image, true color

# Parameterization of clouds

off the African coast




Near the Arcachon Basin



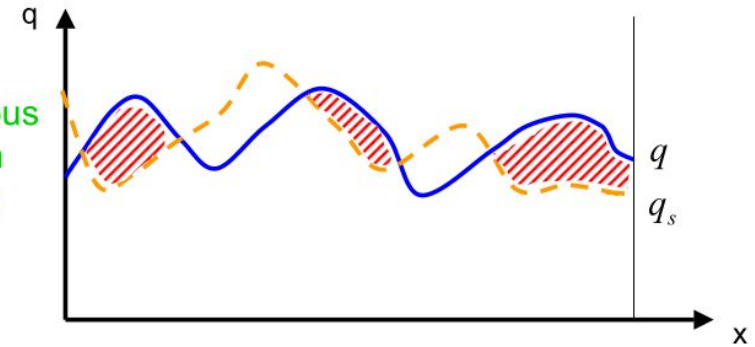

**at 100 km resolution and even at a few km resolution**
**–> atmospheric water (and temperature) are not homogeneous within one mesh**
**–> need to account for subgrid variability to estimate cloud quantities and properties**

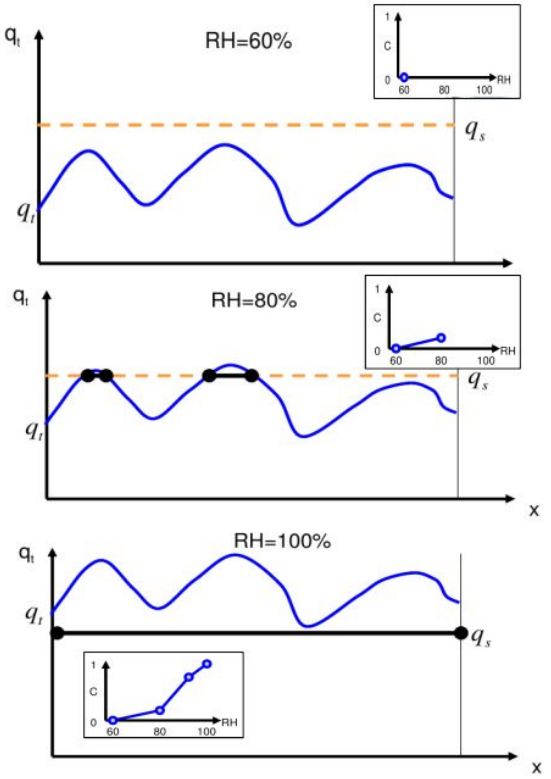
nasa worldview, viirs image, true color

# Parameterization of clouds

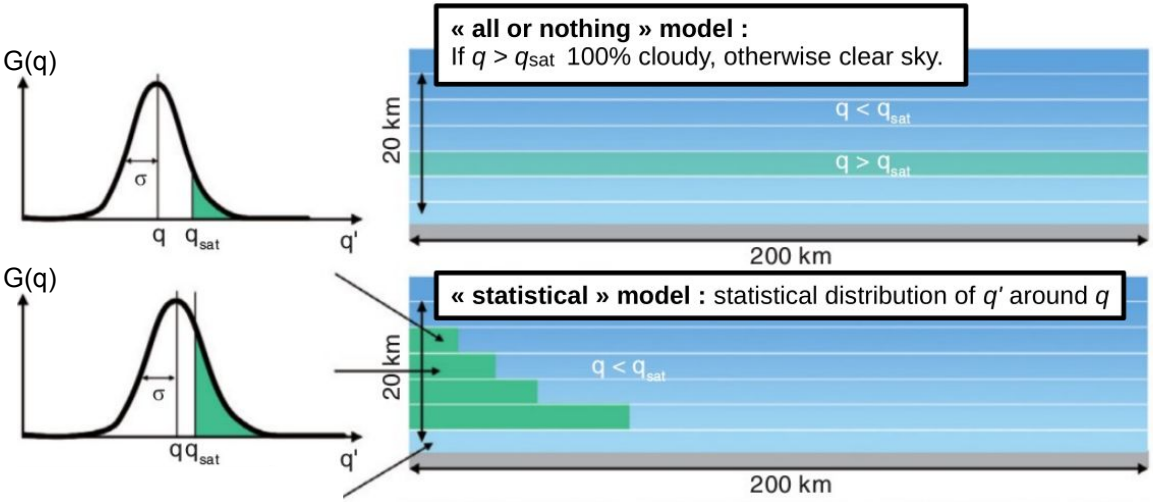
## Fundamentals of statistical cloud parameterizations

Heterogeneous distribution of T and q



## Fundamentals of statistical cloud parameterizations




cloud fraction

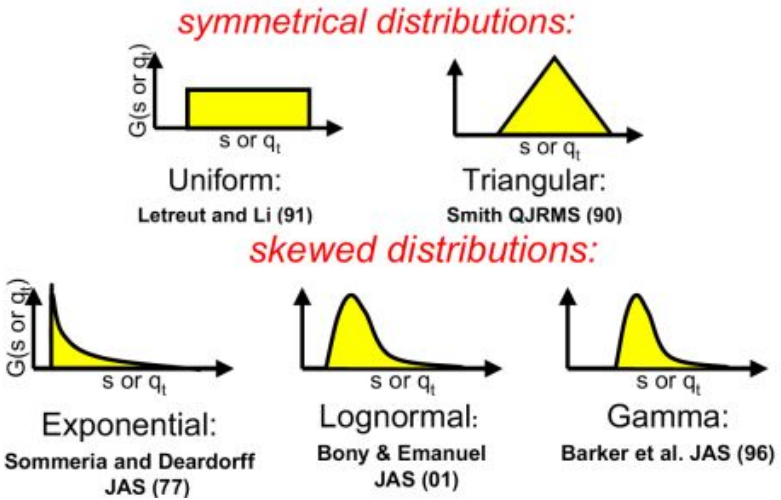
$$C = \int_{q_s}^{\infty} G(q_t) dq_t .$$

condensed cloud water content

$$\bar{q}_c = \int_{q_s}^{\infty} (q_t - q_s) G(q_t) dq_t .$$

## Fundamentals of statistical cloud parameterizations

different types of distributions




cloud fraction

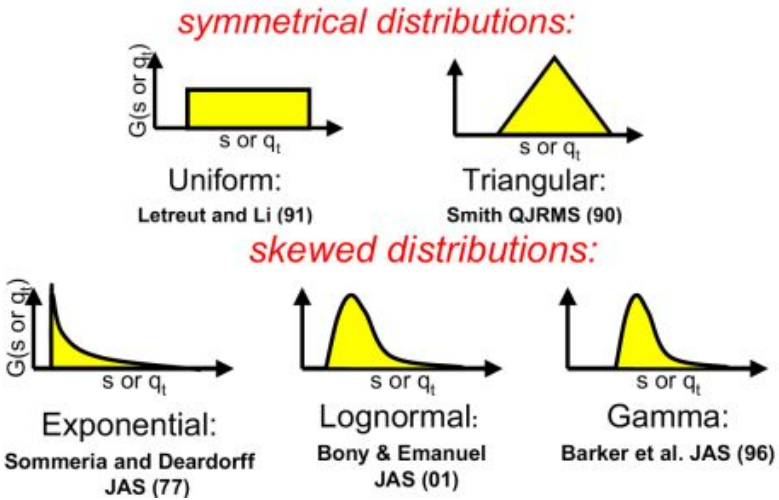
$$C = \int_{q_s}^{\infty} G(q_t)dq_t.$$

condensed cloud water content

$$\bar{q}_c = \int_{q_s}^{\infty} (q_t - q_s)G(q_t)dq_t.$$

## Fundamentals of statistical cloud parameterizations

different types of distributions




σ is either diagnosed or predicted (Klein et al. 2005)

$$\frac{\partial \sigma^2(q_t)}{\partial t} = D(q_{td} - q_t)^2 + D(\sigma^2(q_{td}) - \sigma^2(q_t)).$$

cloud fraction

$$C = \int_{q_s}^{\infty} G(q_t) dq_t.$$

condensed cloud water content

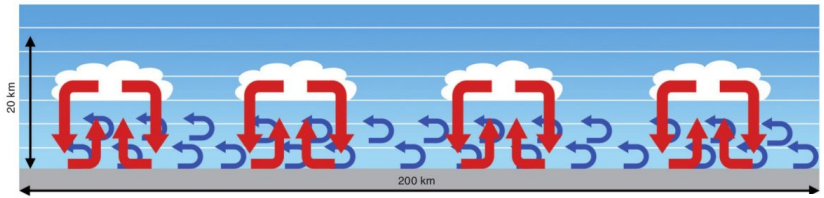
$$\bar{q}_c = \int_{q_s}^{\infty} (q_t - q_s) G(q_t) dq_t.$$

# Parameterization of clouds

## Fundamentals of statistical cloud parameterizations

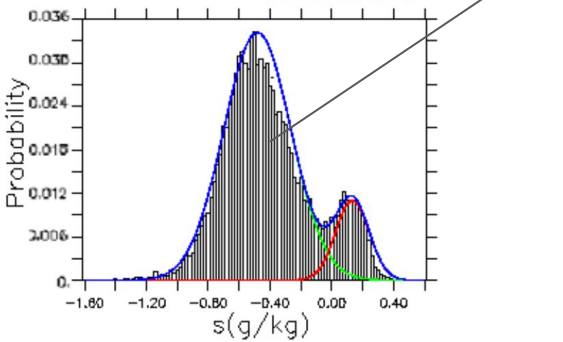
Need to account for temperature variability

temperature highly variable in the boundary layer
anti-correlation of temperature anomalies with moisture anomalies

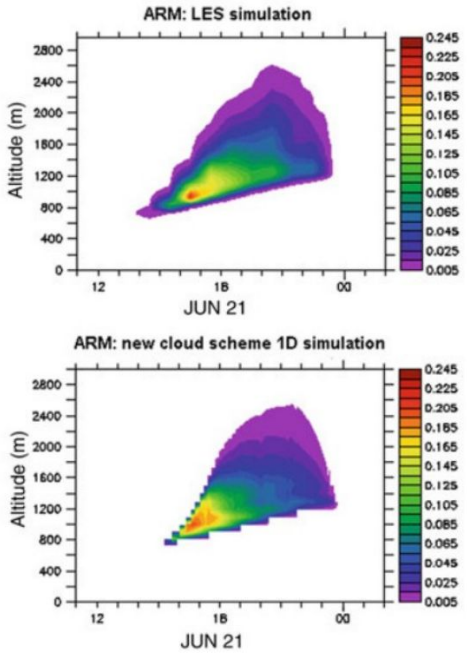



saturation deficit:
s=q-qsat(T)

[Jam & al., BLM, 2013]




simulation of cumulus clouds
(cloud fraction)



# Parameterization of clouds

## Fundamentals of statistical cloud parameterizations

### Cloud phase

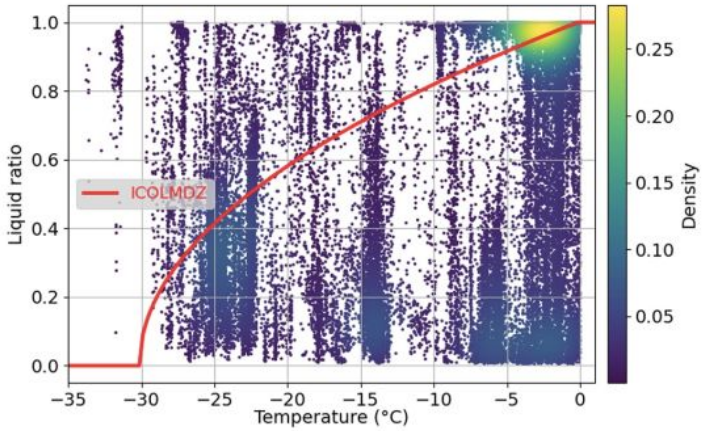
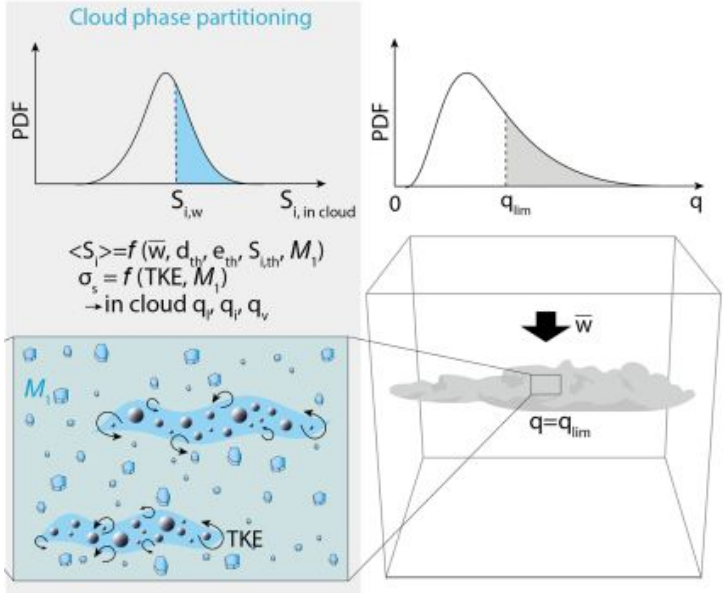



**Figure 9.** Scatter plot of cloud liquid ratio (LWC/(IWC + LWC)) as a function of temperature for the in situ measurements (color shading indicates the density of points) and function used for cloud phase partitioning in ICOLMDZ (red curve).

Function of temperature (Raillard et al. 2024)




More complex estimation based on subgrid turbulence and ice crystal properties (Raillard et al. 2026, Vignon et al. 2026)

# Parameterization of clouds

## Main limits of statistical cloud parameterizations

- no representation of out-of-equilibrium conditions e.g., ice supersaturation (as there is saturation adjustment) ;
- possible horizontal heterogeneities (checkerboard patterns) in cloud fraction fields (no advection)
- microphysics missing (limited process-oriented studies)

# Parameterization of clouds

## Prognostic cloud parameterizations

$$\frac{\partial CC}{\partial t} = Adv(CC) + Diff(CC) + Detr(CC)_{conv} + Turb(CC)_{PBL} + Cond(CC)_{strat} - Evap(CC)$$

Tracer Advection

Cloud Microphysics

$$\frac{\partial q_j}{\partial t} = Adv(q_j) + Diff(q_j) + \sum_j [sources_j(q_j, T, \rho) - sinks_j(q_j, T, \rho)] + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\, q_j\, V_j(q_j, T, \rho)\right)$$

physical processes (grid-point-wise)

sedimentaion

with $q_j = \{q_v, q_c, q_i, q_s, q_g, q_r\}$,

and $q_v$ = water vapour, $q_c$ = cloud liquid water, $q_i$ = cloud ice, $q_r$ = rain and $q_s$ = snow

## Prognostic cloud parameterizations

# Clouds as a Collection of Particles

Clouds are condensed water species (cloud drops, ice crystals, snowflakes) in control volume (grid box).



A microphysics scheme aims at describing the evolution of particle size distribution (PSD) for each species with equations. PSD is the output of the scheme.

Most microphysical processes depend on the PSD (size, surface area, volume)

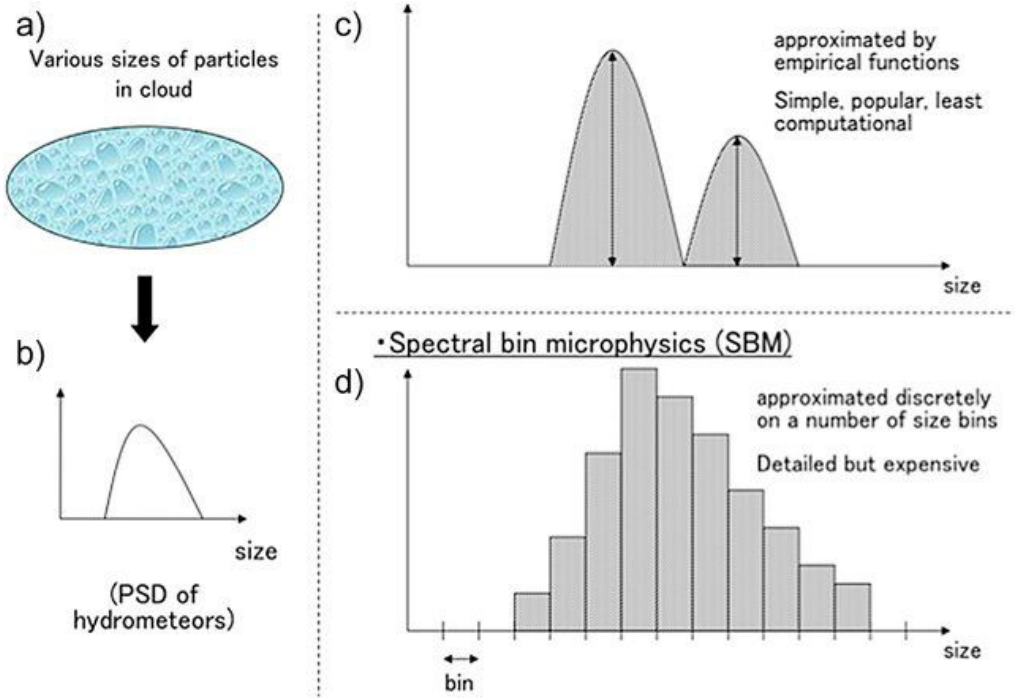
Popular models are:

1. Parameterize the PSD with a histogram. -> each bin is a prognostic variable (spectral bin method)
2. Monte-Carlo approach

Both approaches too expensive for operational weather and climate models (time to solution constraint).
Operational models thus usually **assume a PSD and predict its parameters**.

# Parameterization of clouds

## Prognostic cloud parameterizations



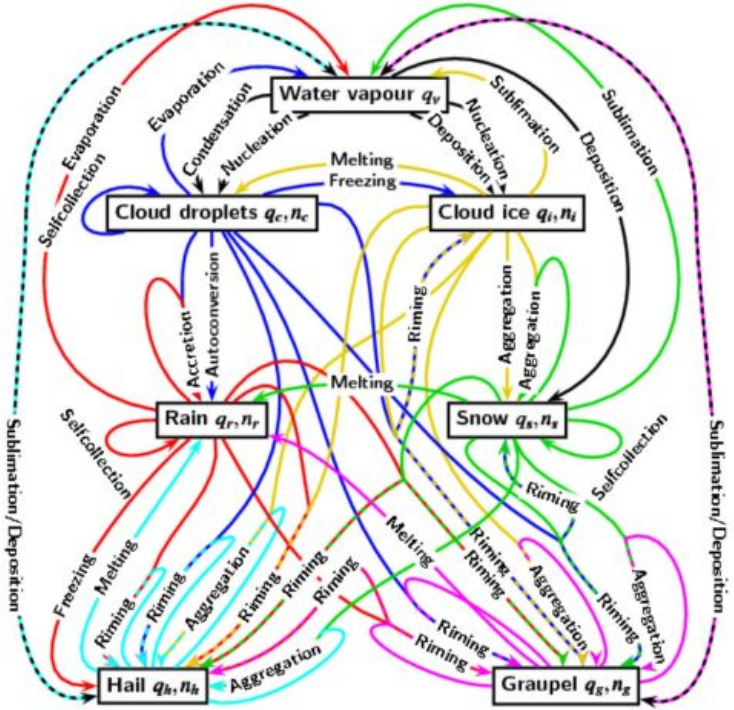
# Parameterization of clouds

## Prognostic cloud parameterizations

it is getting quite complicated.... even more when adding interactive aerosols

- > complexity of interpretation

-> complexity of model tuning




Seifert and Beheng (2006) scheme

# Parameterization of clouds

## Prognostic cloud parameterizations

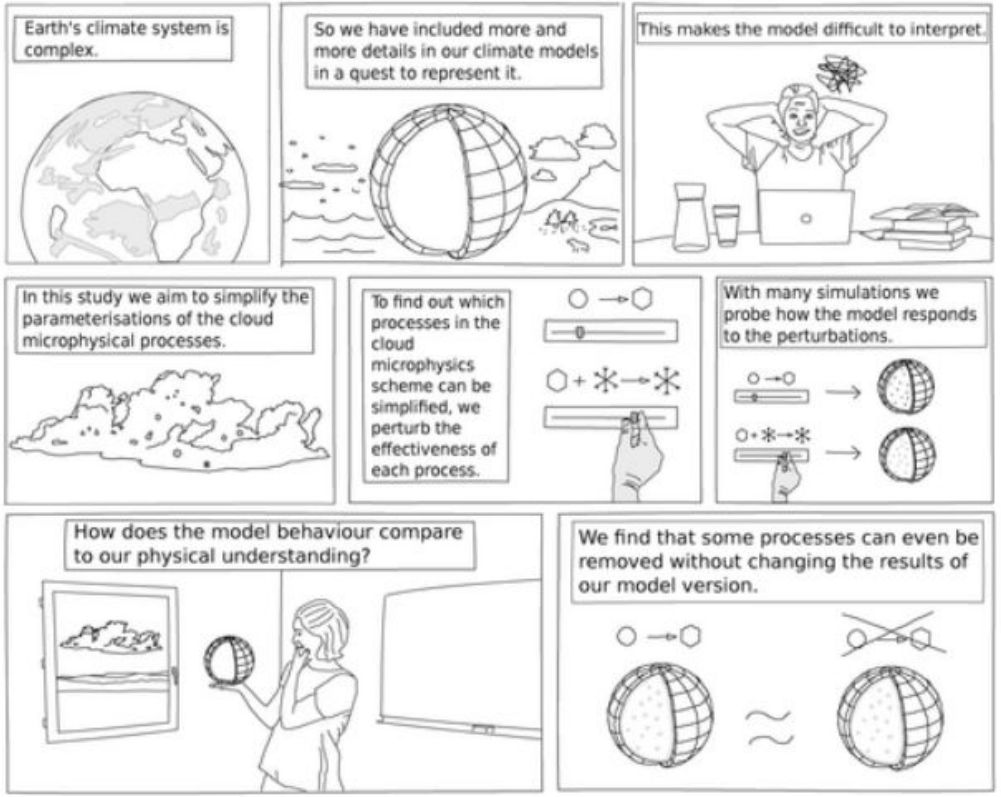
JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access

**Addressing Complexity in Global Aerosol Climate Model Cloud Microphysics**

Ulrike Proske, Sylvaine Ferrachat, Sina Klampt, Melina Abeling, Ulrike Lohmann

First published: 29 April 2023 | https://doi.org/10.1029/2022MS003571 | VIEW METRICS



# Parameterization of clouds

Let’s analyse altogether how the different parameterizations shape the representation of atmospheric boundary layer structure and clouds in a 3D global simulation

# Chapter 2:
## Physical parameterizations in climate models

- The basics of physical parameterizations
- Parameterizations of subgrid atmospheric motions
- Parameterizations of clouds
- **Parameterization development: one approach**
- Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

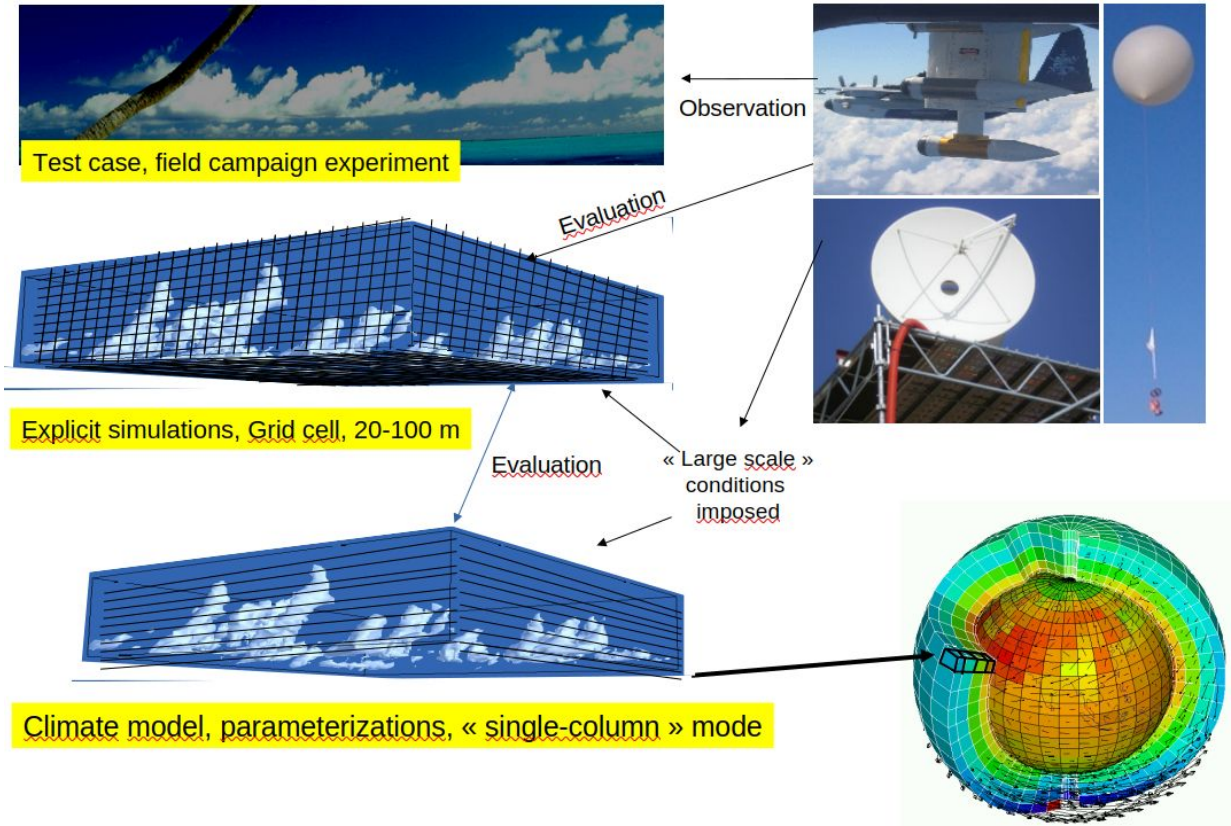
# Parameterization development: one approach

**Challenges:**

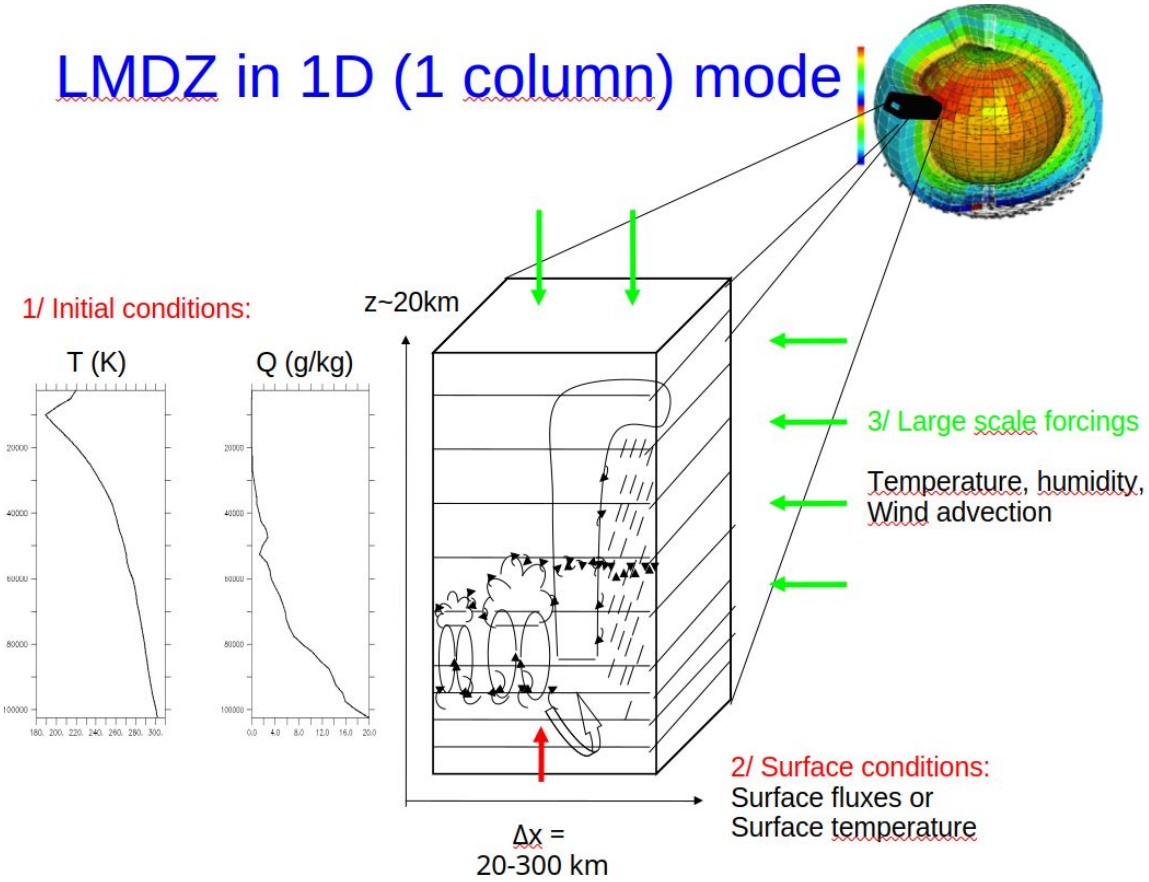
- evaluation of the parameterization and its effect on the model fields
- not only state variables of the model (temperature, humidity ...) but also internal variables of the parameterization
- with ideally no uncertainties/errors inherited from large scale dynamics
- reference to tune (calibrate) the free parameters of the parameterization

# Parameterization development: one approach

## Synergy between Single Column Model version of GCMs, Large Eddy Simulations and observations



# Parameterization development: one approach



# Chapter 2:
## Physical parameterizations in climate models

- The basics of physical parameterizations
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- Parameterization development: one approach
- **Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline**

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline



# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

## An atmospheric model can be summarized as:

$$\frac{\partial \boldsymbol{x}}{\partial t} = \mathcal{D}(\boldsymbol{x}) + \sum_p \mathcal{P}_p(\boldsymbol{x}, \boldsymbol{\lambda}_p)$$

$\mathbf{x}$ = state variables (temperature, humidity, wind components), $D$ stands for the discretized form of the fluid dynamic equations, $Pp$ for the source term provided by the parameterization of the process p and $\lambda p$ for the associated 'free' parameters.

**$\lambda p$ are often defined with a range of uncertainties, or a range of plausible values.**

Example: assuming uniformly distributed ice crystals, which fall velocity value? (somewhere between 0.3 and 1.5 m/s)

**There is a priori no "one good" value. It is a matter of choice (subjective process)**

**How to choose? –> answer depends on the target/objective or metrics**

There is no ugly "cuisine" here. It is recognized as a **discipline per se** in climate science

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

## Why all global climate models are necessarily tuned?

Ideally one can adjust the top-of-atmosphere (TOA) radiative balance in atmosphere-only simulations exposed to observed sea surface temperatures (atmospheric component tuning) and check if the temperature obtained in atmo-ocean coupled models is realistic.

but .....

**1 W/m2 of error in TOA radiative balance <-> 1 K of mean surface temperature**

uncertainties of TOA radiation measurements .... several W/m2

Surface temperature in CMIP models precise at about 0.1 K

..... CMIP models are necessarily tuned!

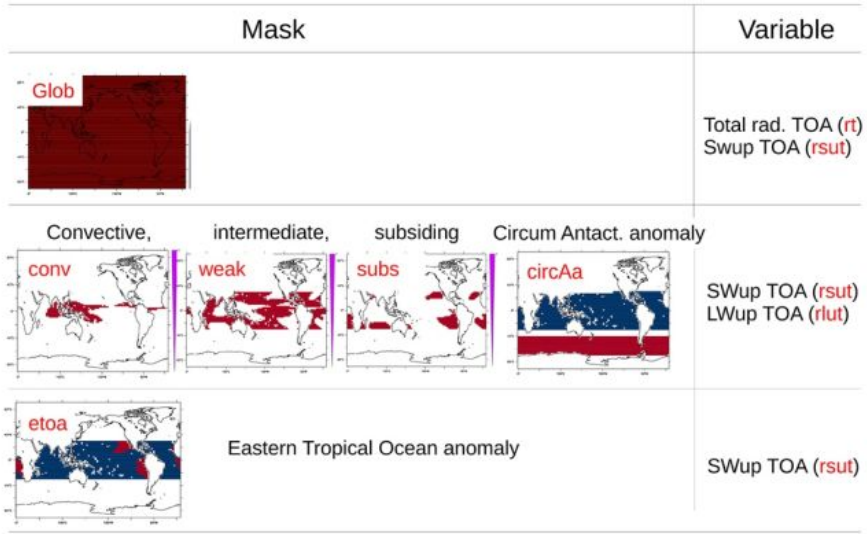
# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

How to tune climate models? (cf Hourdin et al. 2021, Mignot et al. 2021)

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

How to tune climate models? (cf Hourdin et al. 2021, Mignot et al. 2021)

(arbitrary) **list of metrics**




| Metrics | target $W\ m^{-2}$ | error $W\ m^{-2}$ |
|---|---|---|
| glob.rt | 2.5 | 0.2 |
| glob.rsut | 99.6 | 5 |
| circAa.rsut | 24.0 | 5 |
| circAa.rlut | -48.6 | 5 |
| subs.rsut | 84.9 | 5 |
| weak.rsut | 81.8 | 5 |
| conv.rsut | 103.2 | 5 |
| subs.rlut | 274.6 | 5 |
| weak.rlut | 264.3 | 5 |
| conv.rlut | 235.8 | 5 |
| etoa.rsut | 11.0 | 5 |

**Figure 3.** Metrics retained for the GCM tuning consisting in radiative fluxes at top-of-atmosphere averaged over a mask, shown in red on the left hand side of the figure, or a difference between a red and blue mask (anomalies). The target and $\sigma$ error retained for the history matching are shown in the table on the right hand side. The target values are computed from the CERES-EBAF L3b observational data set (Loeb et al., 2009). GCM, General Circulation Model.

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

How to tune climate models? (cf Hourdin et al. 2021, Mignot et al. 2021)

**list of key free parameters** with uncertainty range (modelers'expertise)

**Table 1**
*Parameters Involved in the Iterative Refocusing*

| Name | Min | Max | Ref | Sampling | Controls |
|---|---|---|---|---|---|
| **A1** | 0.5 | 1.2 | 2./3. | Linear | Contribution of buoyancy to the plume acceleration |
| **A2** | 1.5e-3 | 4.e-3 | 2.e-3 | Linear | Drag term in the plume acceleration |
| **B1** | 0. | 1. | 0.95 | Linear | Scaling factor for entrainment and detrainment |
| **CQ** | 0. | 0.02 | 0.012 | Linear | Influence of humidity contrast on detrainment |
| **DZ** | 0.05 | 0.2 | 0.07 | Linear | Environmental air altitude shift for buoyancy computation |
| **BG1** | 0.4 | 2. | 1.1 | Linear | Width of the environment subgrid scale water distribution |
| **BG2** | 0.03 | 0.2 | 0.09 | Linear | Width of the plume subgrid scale water distribution |
| **EVAP** | 5e-5 | 5e-4 | 1e-4 | Log | Reevaporation of rainfall |
| **CLC** | 1e-4 | 1e-3 | 6.5e-4 | Linear | Autoconversion of cloud liquid water to rainfall |

*Note*. The minimum and maximum values explored are given as well as the reference value used in the 6A configuration of LMDZ, the information on whether the parameter is explored with a linear or logarithmic sampling and the meaning of each parameter.

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

How to tune climate models? (cf Hourdin et al. 2021, Mignot et al. 2021)

-> Perturbed Parameter Ensemble experiments

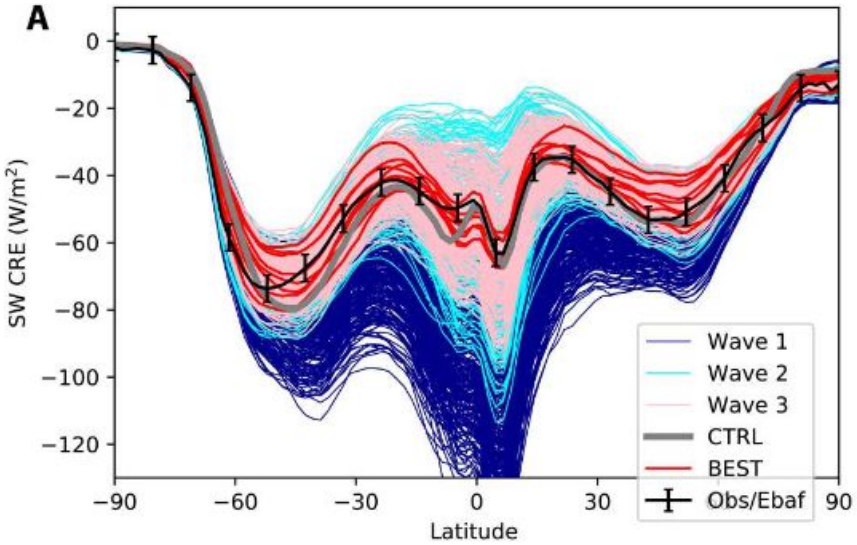
-> exclude configurations that are not plausible

-> by hand (very expensive and subjective) or semi-automatic procedure using statistical iterative History Matching method

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

How to tune climate models? (cf Hourdin et al. 2021, Mignot et al. 2021)

SW CRE= Short Wave Cloud radiative effect

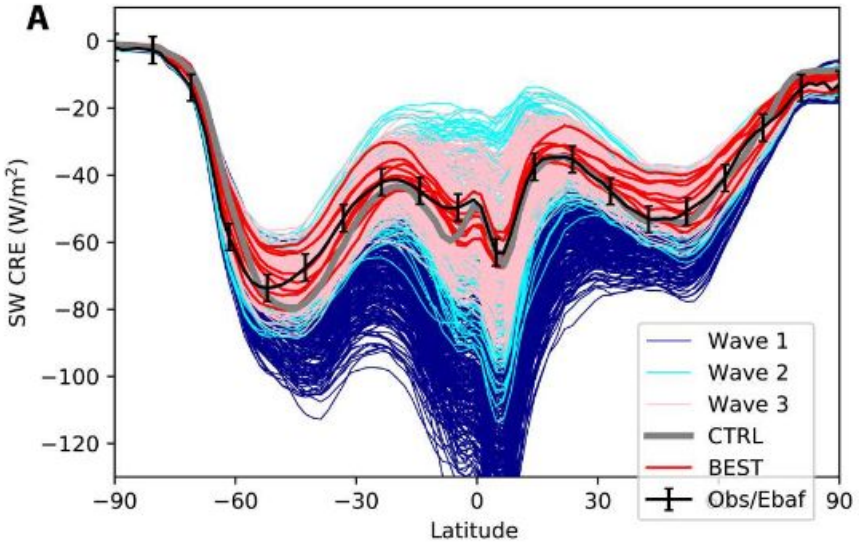


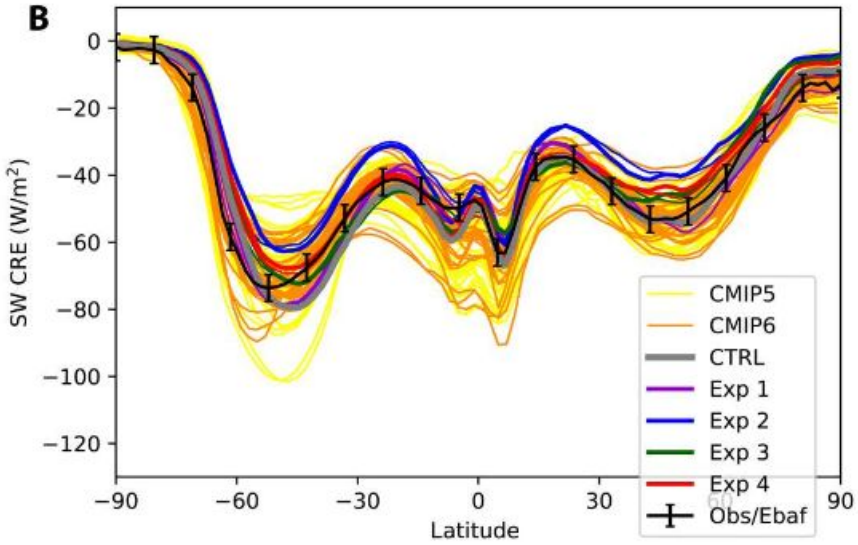

Hourdin et al. 2023

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

A taste of parametric uncertainty ....

SW CRE= Short Wave Cloud radiative effect

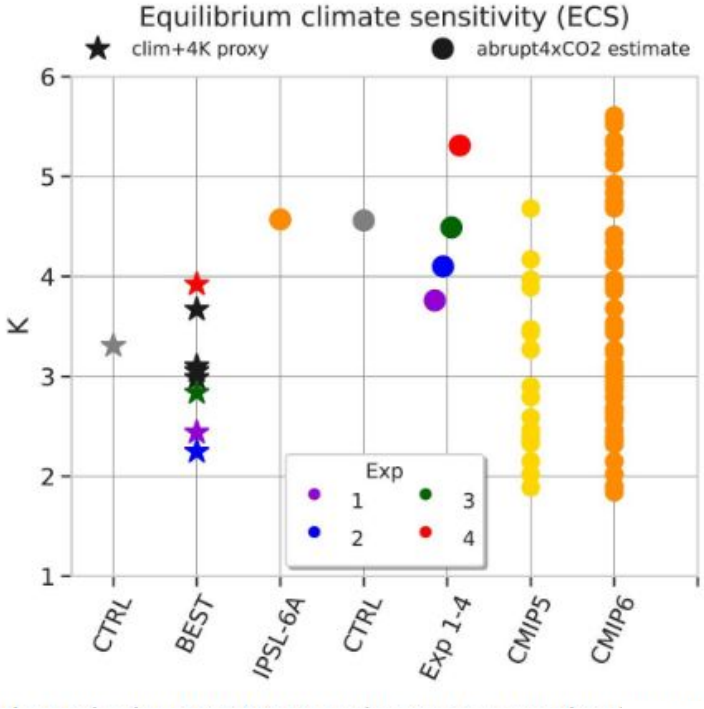



Hourdin et al. 2023

# Model tuning: inevitable and necessary ~~cuisine~~ scientific discipline

A taste of parametric uncertainty ....



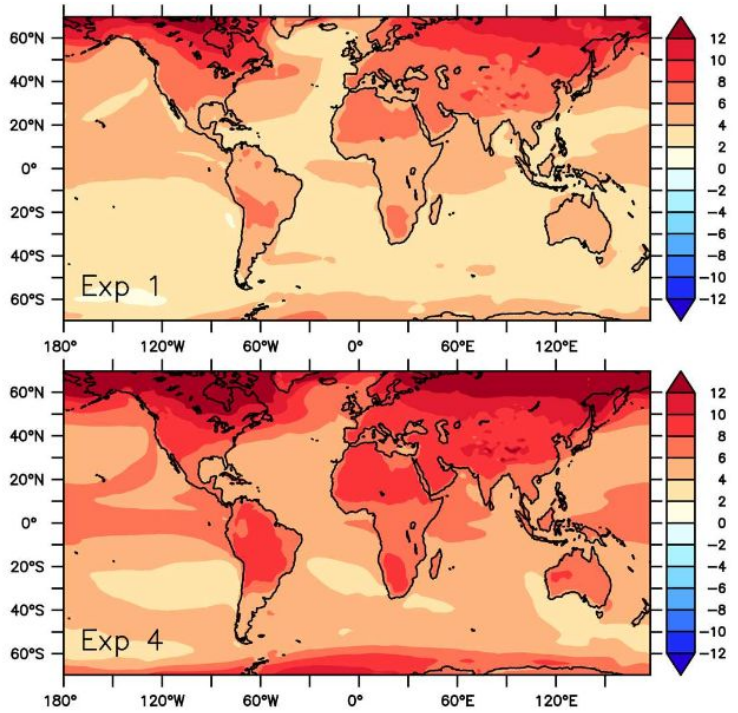




**Fig. 4. Two-meter temperature (K) change in coupled simulations CTRL (IPSL-6A configuration), Exp 1, and Exp 4.** The maps correspond to differences between the abrupt4×$CO_2$ and piControl simulations, averaged over 21 consecutive years. For the left column, this time is centered at year 30 of the simulations. For the right column, it

Hourdin et al. 2023

# Chapter 3:

## Climate modelling for the benefit of society:

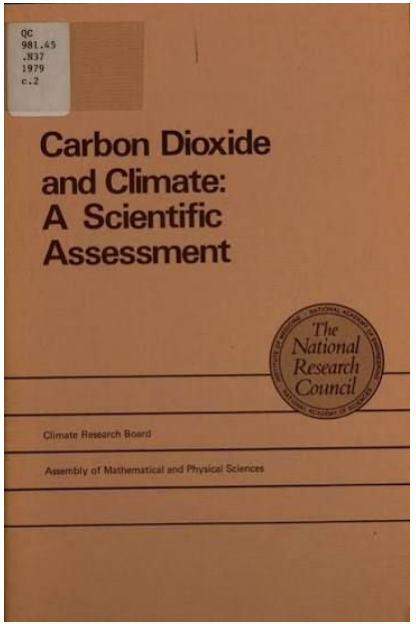
- Climate models to predict climate change
- How to set-up a CMIP type global model configuration?
- The future of climate modelling

# Climate models to predict climate change

- 1896, Swedish physicist **Svante Arrhenius**: link between CO2 variations, surface temperature, and glacial/interglacial periods (from original works by Joseph Fourier and John Tyndall)
  With a simple calculation, **CO2 doubling** due to human activities -> temperature increase of **about 4K**

- **1979: Charney report (**'Carbon Dioxide and Climate: A Scientific Assessment')
  No consensus on impact of human activity on climate. Imperceptible global warming but predicted by emergent numerical climate model from Manabe (GFDL, NOAA) or Hansen (GISS, NASA). Contradictory theories (climate will cool due to aerosols ...)

  Command from White House through National Academy of Science to Jules Charney (team of 9 people)
  Models from Manabe and Hansen -> **equilibrium climate sensitivity** (ECS) between 1.5 and 4.5 K.



# Climate models to predict climate change

## Can we trust models?

Predicting climate change
before we feel it !

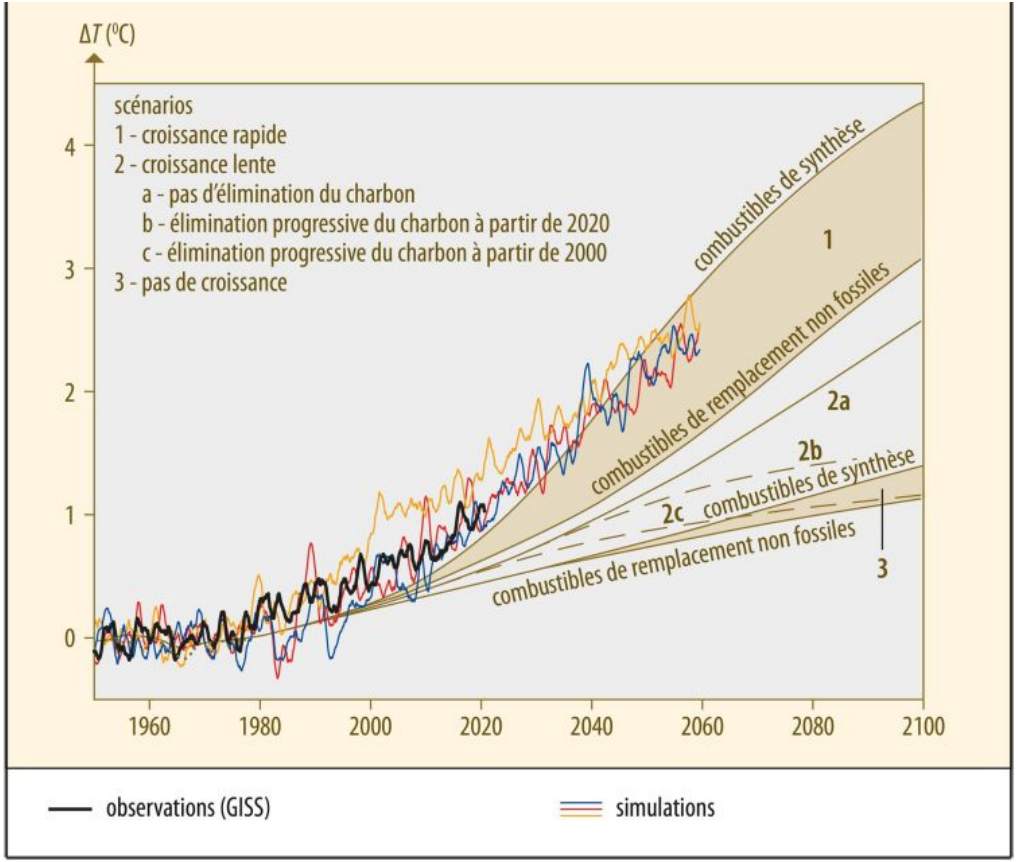
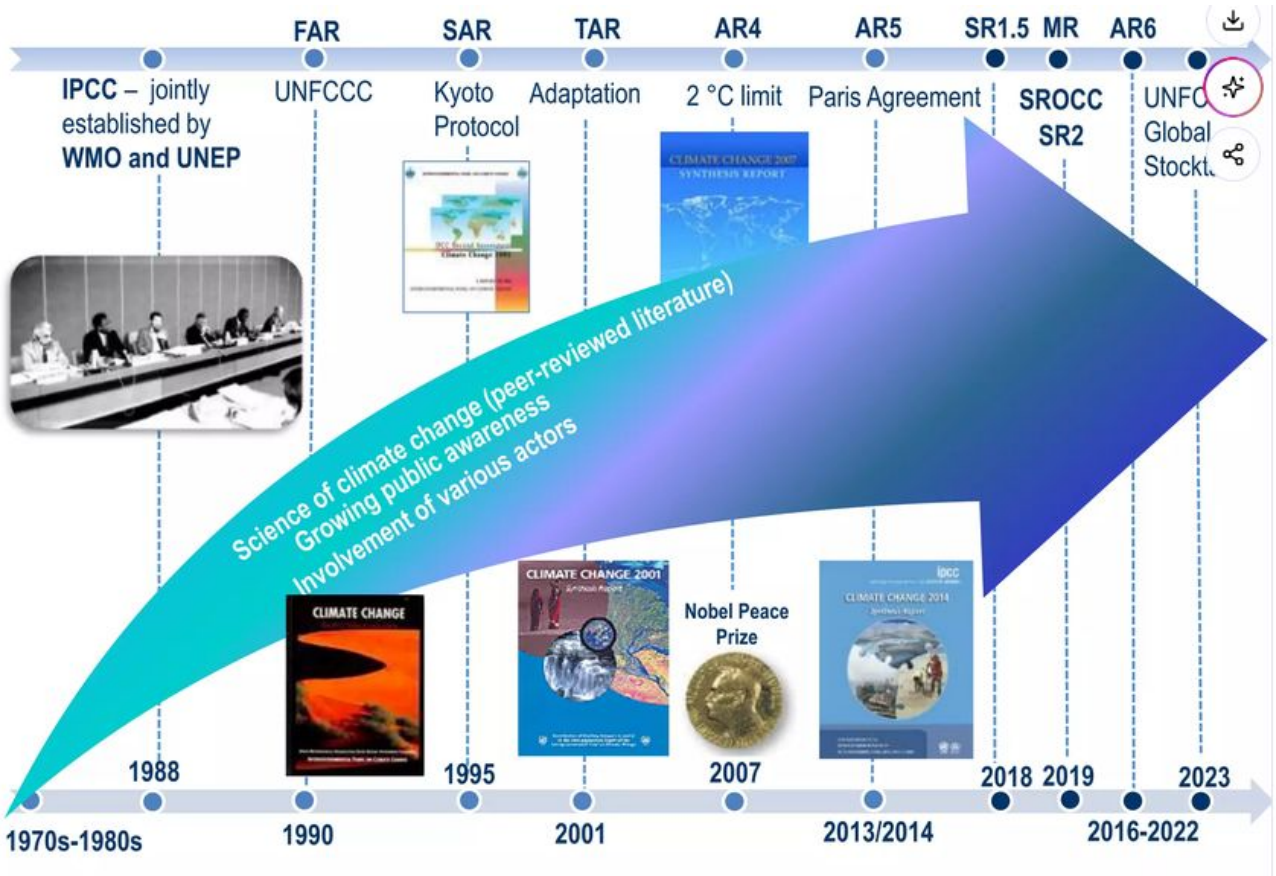



FIGURE 8 – **Le réchauffement global prévu dès les années 1980**
Cette figure superpose à l'une des premières projections du réchauffement global – réalisée en 1980 par James Hansen et ses collaborateurs – des simulations produites par un modèle de climat actuel (courbes en couleurs) montrant l'évolution de la température globale sous l'effet de de l'accroissement des gaz à effet de serre (il s'agit des résultats de la figure précédente, panneau du milieu). Les courbes de la figure de 1980 correspondent à différentes hypothèses sur le taux de croissance et les sources d'énergie de l'avenir (on prévoyait alors une raréfaction du pétrole et du gaz et leur remplacement par des combustibles de synthèse fossiles ou non fossiles). Le réchauffement n'était pas encore perceptible dans les observations de la température globale en 1980, mais on voit que la projection la plus pessimiste d'alors (la courbe qui augmente le plus vite) correspond à peu près à l'évolution réelle observée depuis (courbe noire jusqu'à 2020), ou à celle provenant de calculs réalisés plus récemment (courbes rouge, bleue et orange issues du modèle IPSL-CM du CNRS). Le fait que le réchauffement ait d'abord été prédit avant d'être confirmé par l'observation est une grande source de confiance dans les modèles.

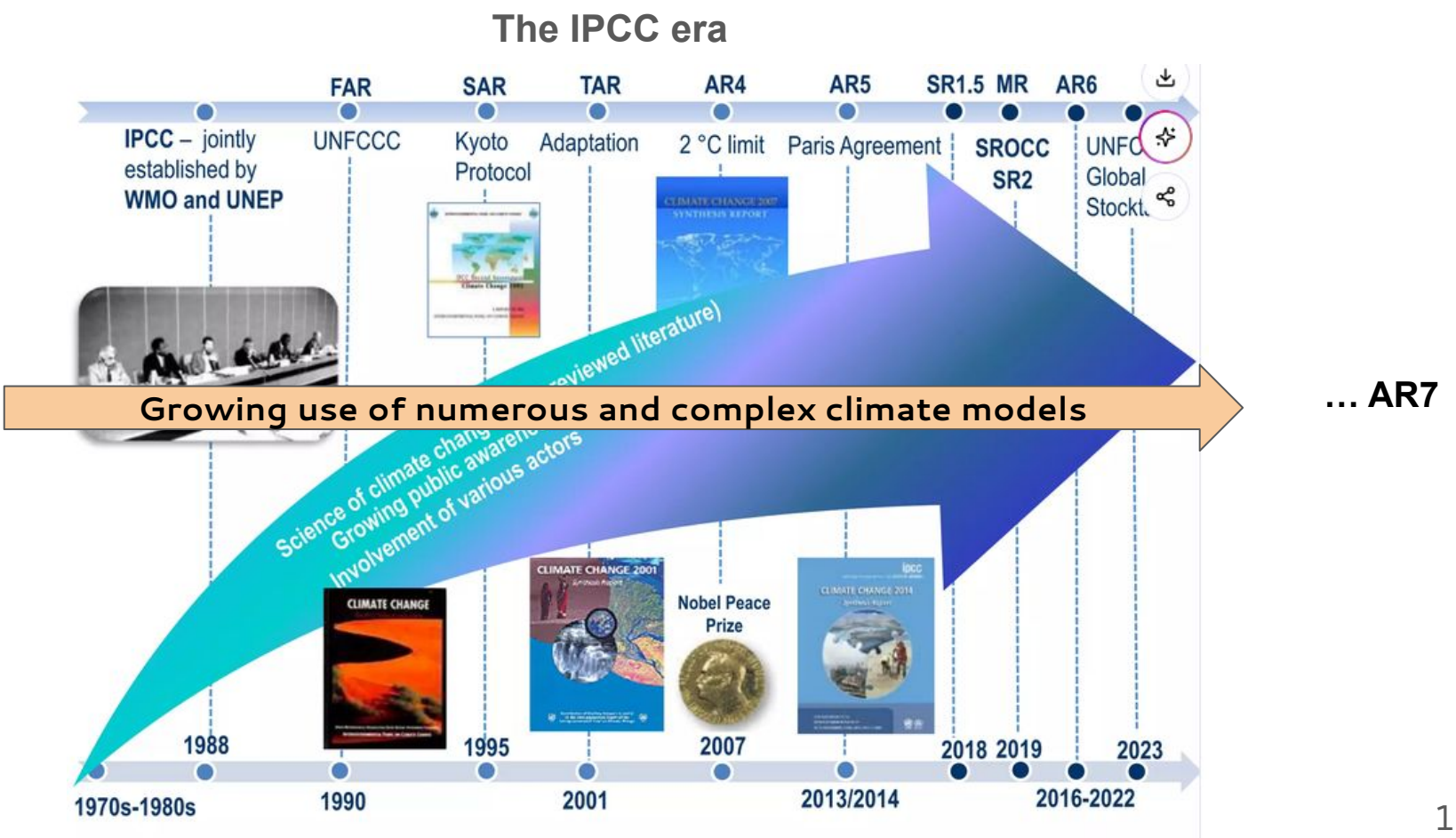
# Climate models to predict climate change

## The IPCC era

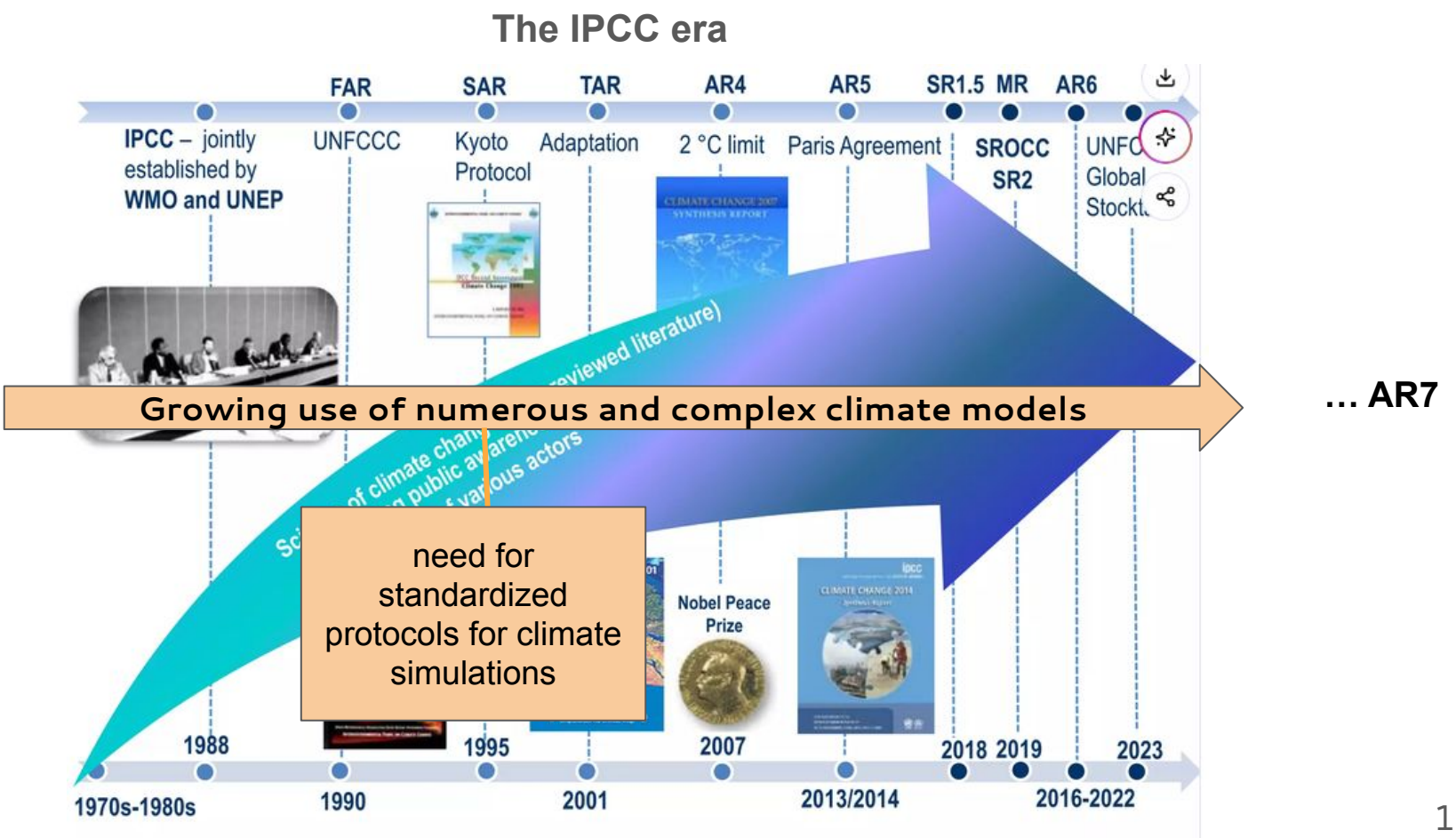



… AR7

# Climate models to predict climate change

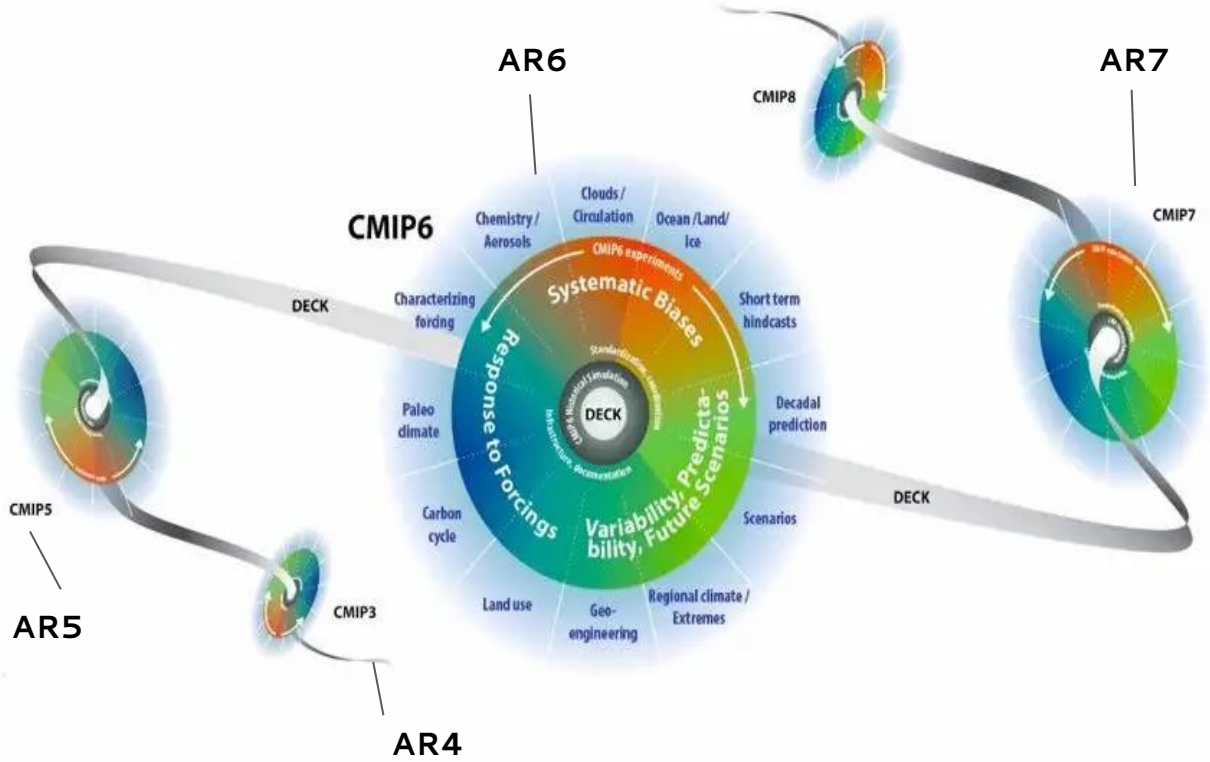


# Climate models to predict climate change



# Climate models to predict climate change

## The Coupled Model Intercomparison Projects (CMIP)



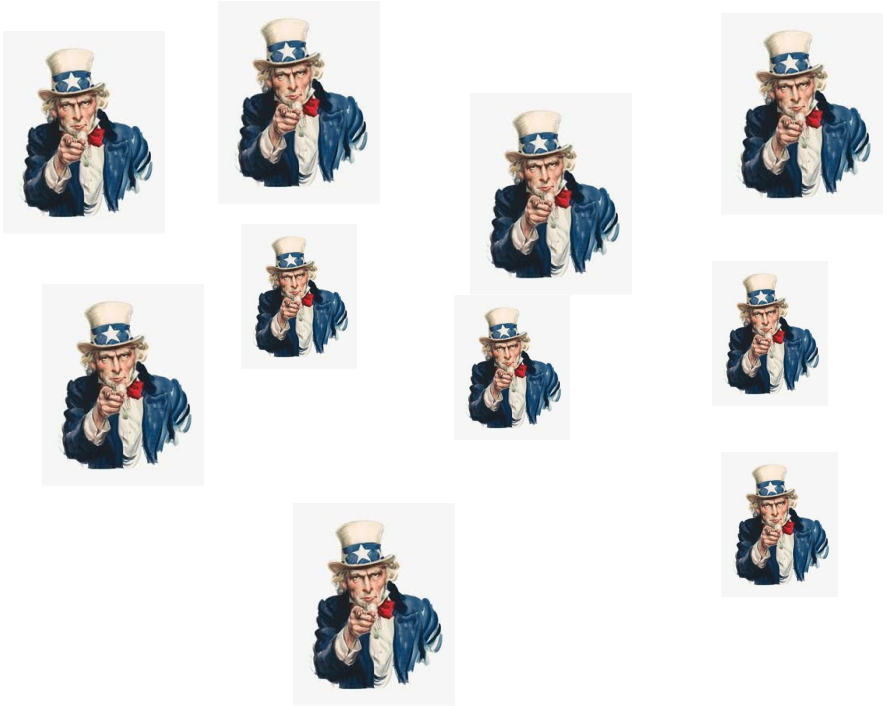

- international coordination
- standardized protocols
- open-access publications and methodology
- wider and wider use of simulations
- increase in confidence that human activity are responsible for climate change

# How to set-up a CMIP type global model configuration?



**YOU ARE A GLOBAL CLIMATE MODELER!**

# How to set-up a CMIP type global model configuration?

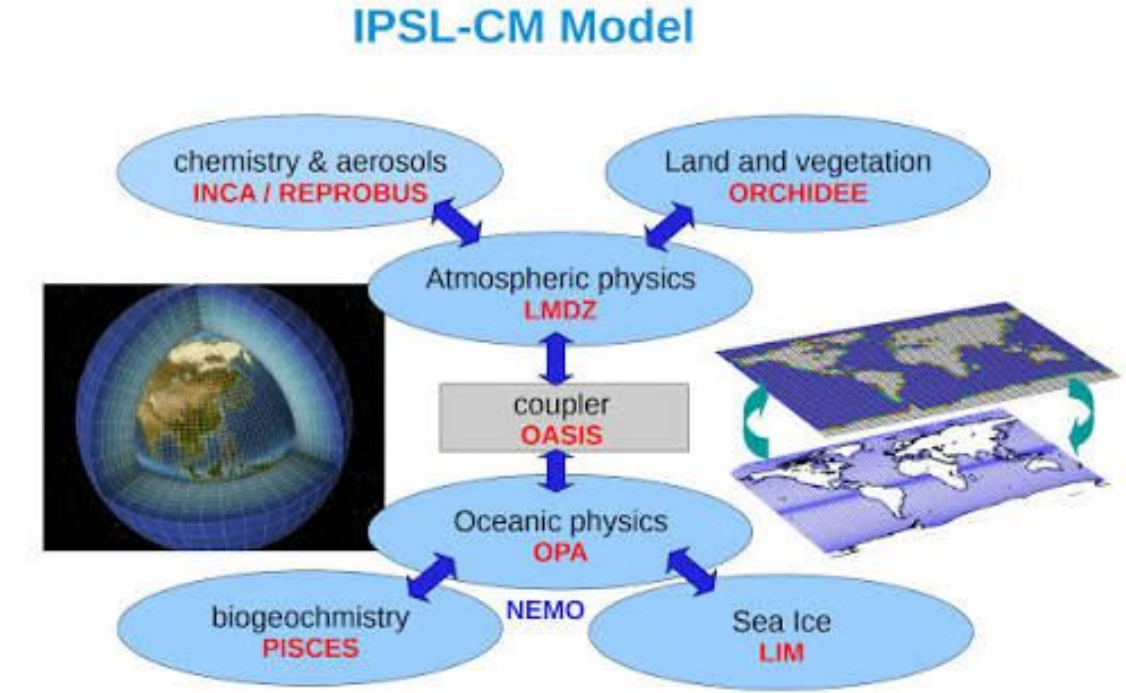


**First you are not alone, you are part of a team !**

# How to set-up a CMIP type model configuration?

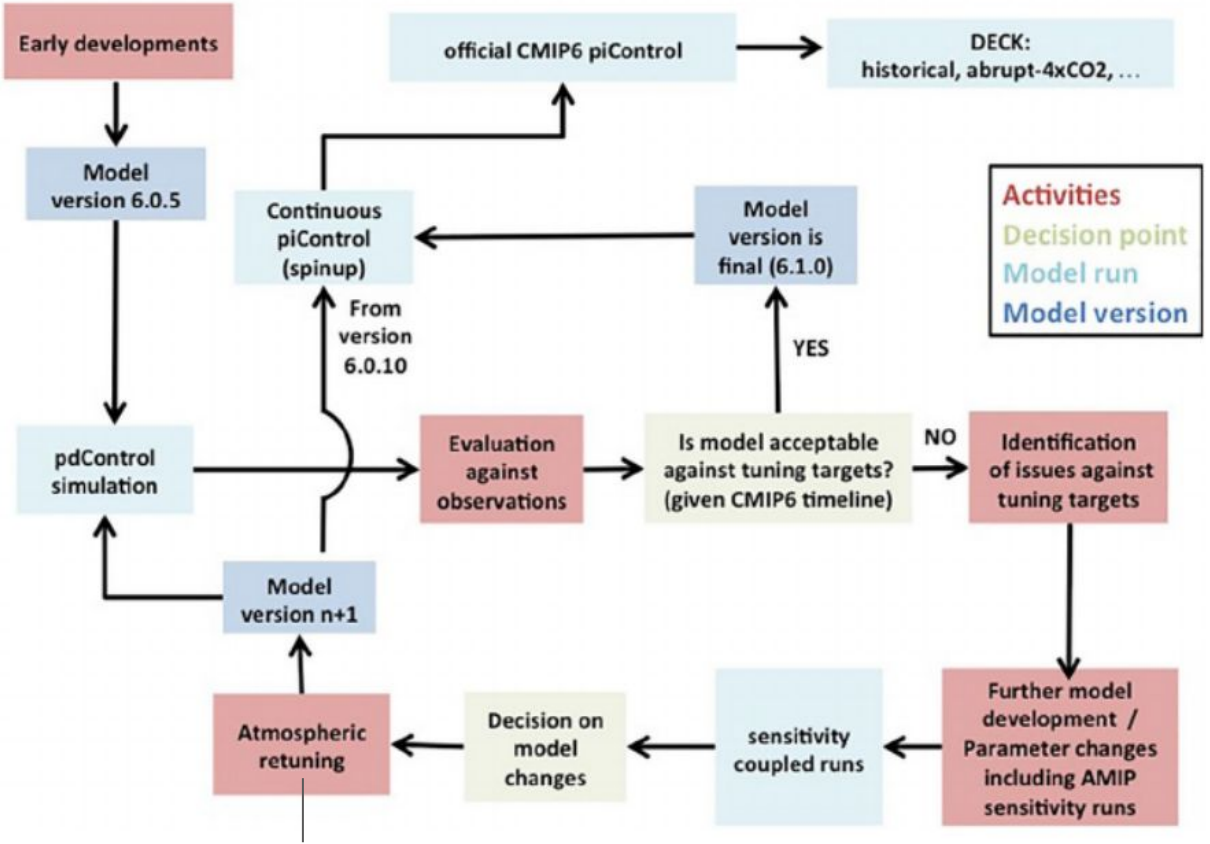
everyone improves its own component (parameterizations, tuning ...) and includes the CMIP forcing (greenhouse gases, land use ....)

Institut Pierre Simon Laplace
IPSL Climate Modelling Centre



# How to set-up a CMIP type global model configuration?

pd = present day
pi = pre-industrial

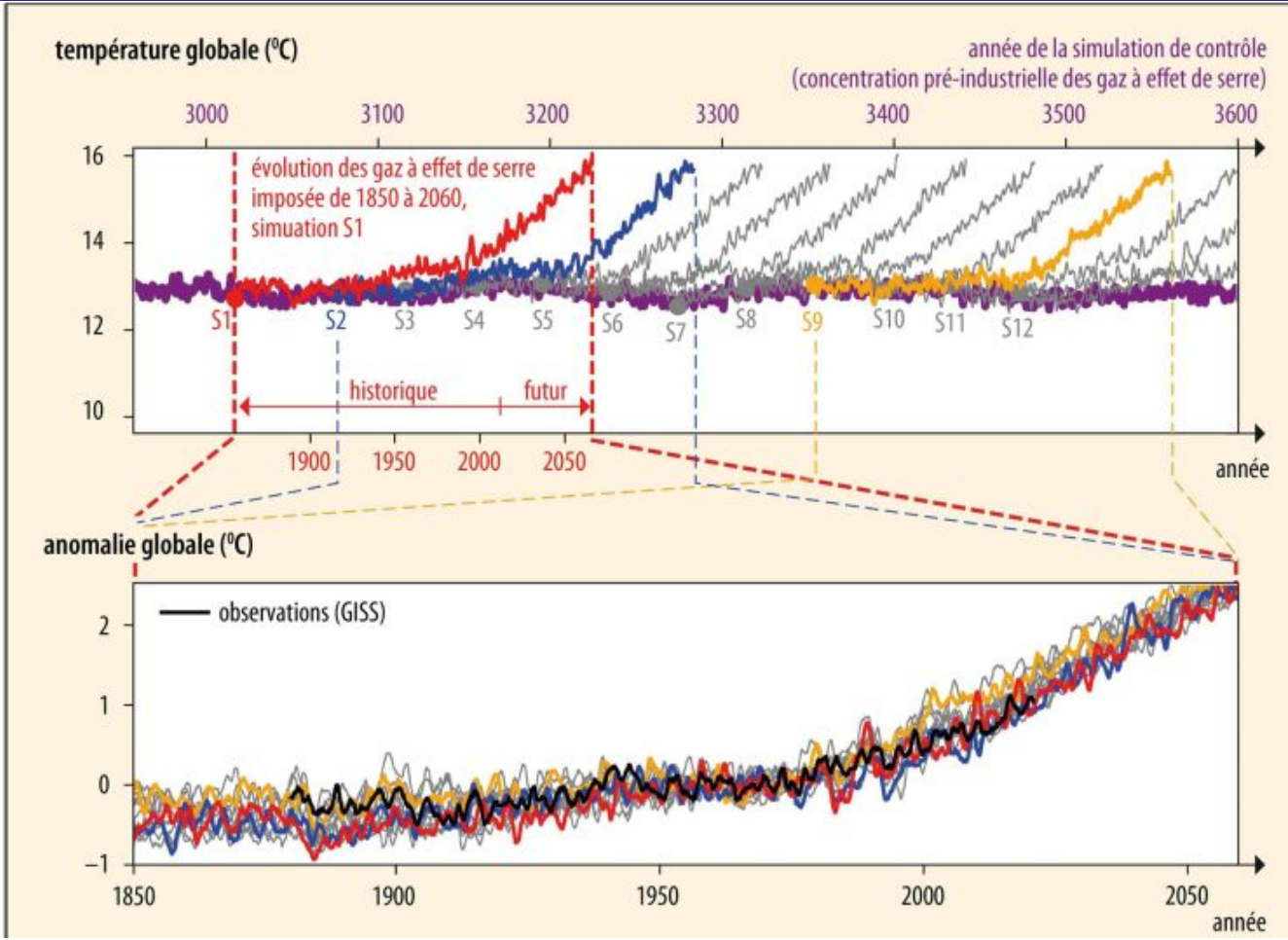



Adapted from Mignot et al. 2021

to re-adjust mean global temperature. total or minimalist

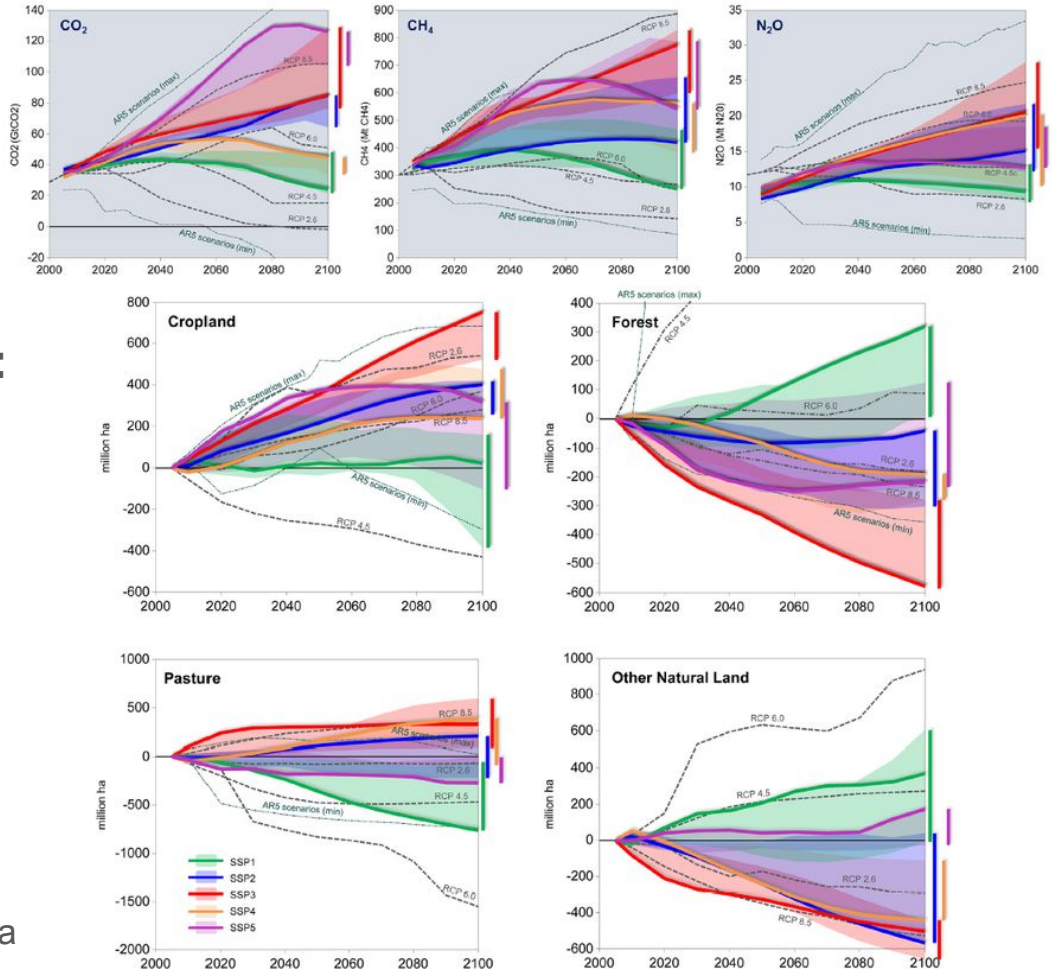
# How to set-up a CMIP type global model configuration?

Pre-industrial and historical runs



# How to set-up a CMIP type global model configuration?

Forcings for scenarios: the Shared socio-economic pathways (SSP)




https://climate-scenarios.canada.ca

# How to set-up a CMIP type global model configuration?

For the IPSL-CM6A-LR model

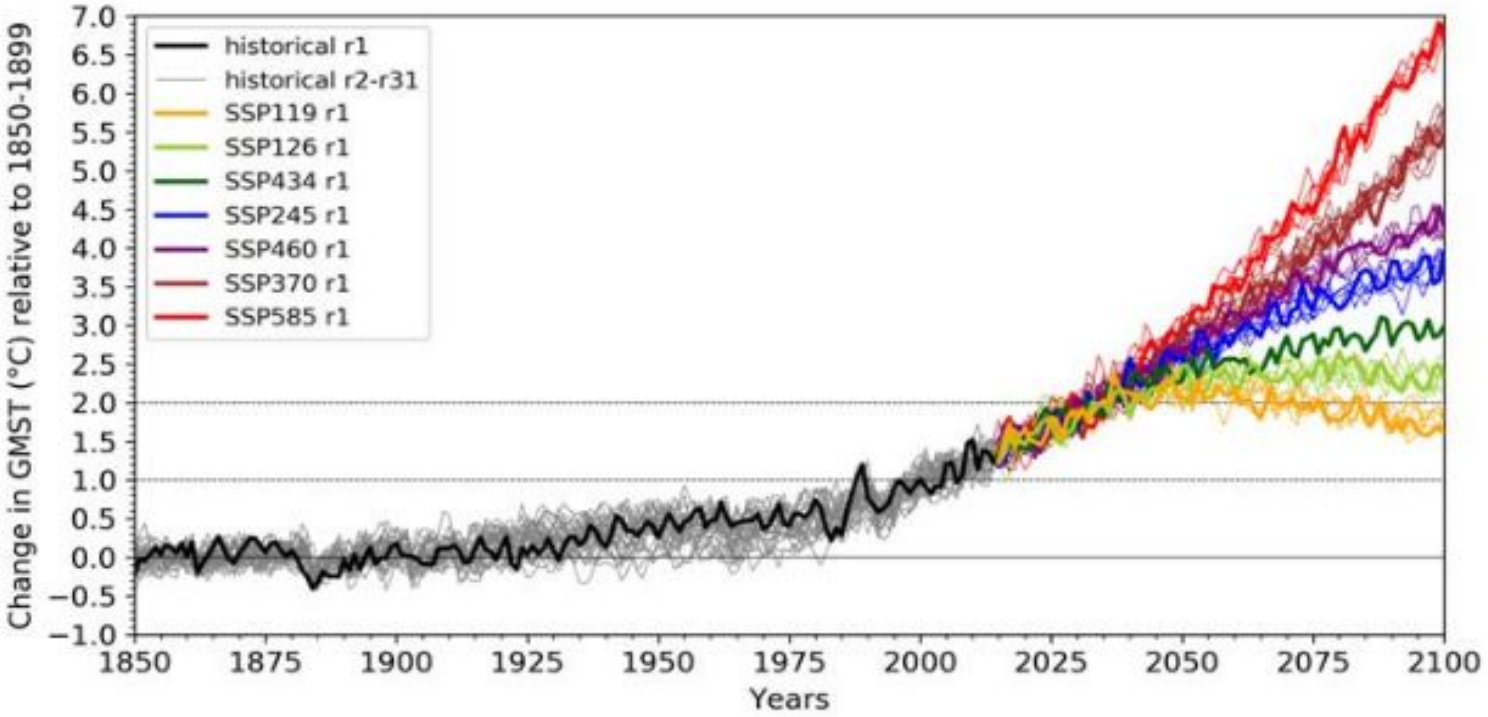
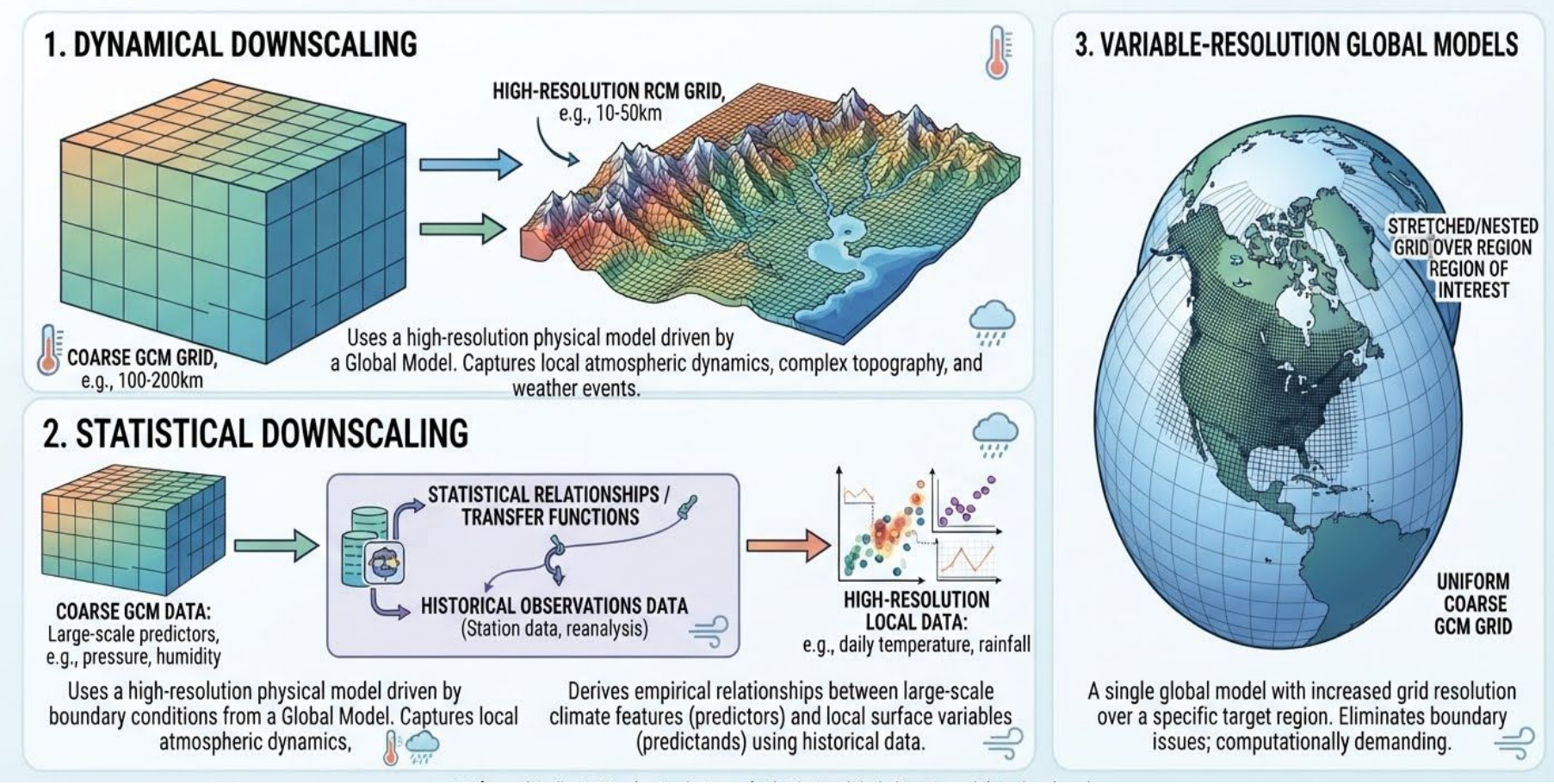



**Figure 31.** (upper panel) Change in global mean surface air temperature (GMST, in °C) relative to the 1850–1899 period in the *historical* `r1i1p1f1` member (thick black line) and the other members (thin gray lines) and scenario experiments for the `r1i1p1f1` member (thick colored lines) and other members (thin colored lines). Anomalies for 0°C,

Boucher et al. (2020)

# Regionalisation



# Future of climate modelling ?

- **Km-scale model:** granular information that might be useful at the local scale, high-resolution models might allow us to improve numerics and reduce the number of parameterizations needed ???
- **Physics augmented by parameter calibration** parameter tuning are central, even at high resolution. However, calibration techniques, while successful at tuning individual parametrizations or model components, still suffer from the curse of dimensionality in multi components global systems
- **Hybrid physics + AI:** AI approaches hold promise for rapid progress in discovering new data-driven parameterizations or to emulate existing (costly) parameterizations such as the radiative transfer or chemistry, and significantly reducing computational cost.




Bordoni et al. 2026

# Future of climate modelling ? subjective arguments

A climate model is first and foremost a **physics-based model**: a numerical representation of a system of physical equations designed to better understand a system—in this case, the climate system.

The future of climate modelling is not necessarily driven by the pursuit of more accurate climate projections, but also by **physicists' curiosity** and their noble desire to better understand the complexity of the climate system.



# Future of climate modelling ? subjective arguments

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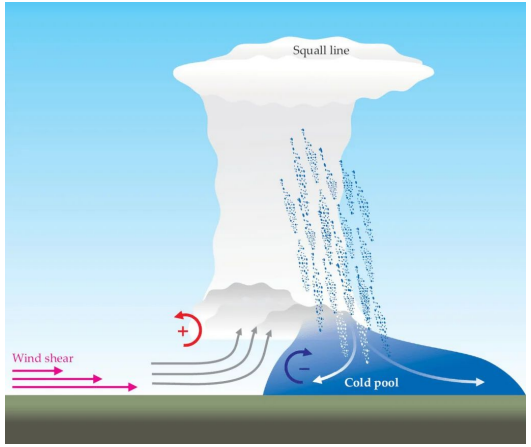
The future of climate modelling is not necessarily driven by the pursuit of more accurate climate projections, but also by **physicists' curiosity** and their noble desire to better understand the complexity of the climate system.

**The journey itself – with its successes and setbacks– can be an objective. And climate modellers can drop their bag along the way.**



# Parameterization of subgrid atmospheric motions

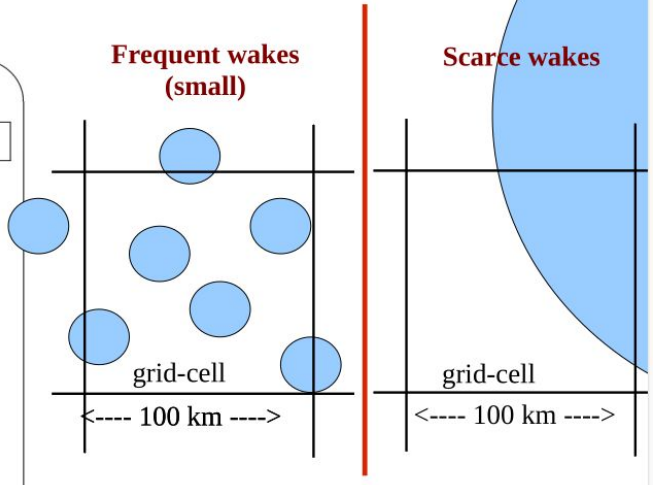
## Cold pools



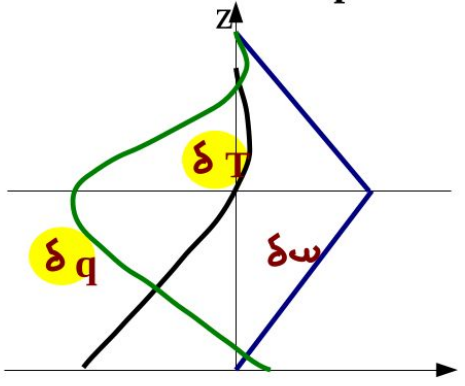

**The density current (wake) parametrization**

(Grandpeix and Lafore, JAS, 2010 ; Grandpeix et al., JAS 2010)

- Representation of a part of an infinite plane where identical cold pools (radius $r$, height $h$) are scattered with an homogeneous density $D_{\mathbf{wk}}$.
- State variables : (i) surface fraction covered by the wakes $\sigma_w = \frac{S_w}{S_t}$ ($\sigma_w = \pi r^2 D_{\mathbf{wk}}$), (ii) temperature and humidity differences (resp. $\delta\theta(p)$ and $\delta q(p)$) between wake and off-wake regions.
- Spreading speed : $C_*$ such that $C_*^2 \simeq$ WAPE (WAke Potential Energy) ; $WAPE = \int_{p_{top}}^{p_{surf}} R_d \delta T_v \frac{dp}{p}$
- Evolutions of $\delta\theta$ and $\delta q$ profiles are given by conservation equations of mass, energy and water taking into account vertical advection, turbulence and phase changes.
- Turbulence and phase change terms are assumed to be given by the deep convection scheme.
- $\delta\omega$ profile is linear between the surface and the wake top (no mass exchange through the wake boundary) ; it goes back to 0 linearly between the wake top and an arbitrary altitude (about 4000 m).

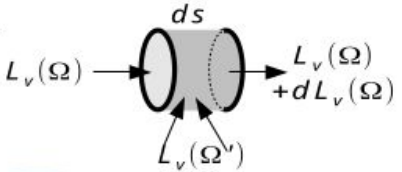



**Wake differential profiles**




*Grandpeix & Lafore, JAS, 2010*

# Parameterization of radiative transfer




**Radiative transfer : well known equations ...**
Giving the evolution of luminance along a line of sight:

$$\frac{dL_\nu(\Omega)}{ds} = -\kappa_\nu L_\nu(\Omega) + \kappa_\nu B_\nu(T) - \sigma_\nu L_\nu(\Omega) + \sigma_\nu \frac{1}{4\pi}\int_{4\pi} P(\Omega', \Omega) L_\nu(\Omega') d\Omega'$$

absorption | emission | Scattered in other directions | Scattered from other directions

**Computation of energy fluxes very costly**
- should be integrated over all frequencies ν
- should be integrated on angles
- knowing radiative properties of scatterers and absorbers is a question by itself

Computing radiation for one full scene with reference methods for the spectral integration (line-by-line) and angular (discrete ordinates, Monte-Carlo) integrations, even for a plan parallel atmosphere without clouds, may take hours of CPU hours on super computers.

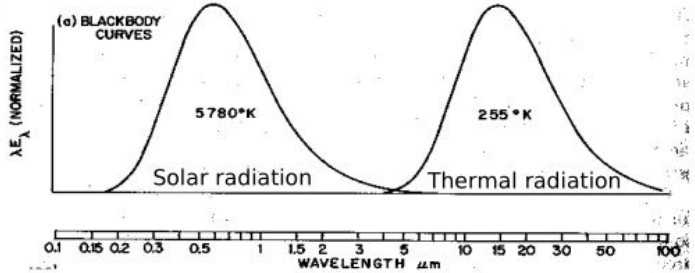
**In LMDZ : using codes developed and used at ECMWF**
3 codes avec des mots clé : **oldrad / rrtm / ecrad**

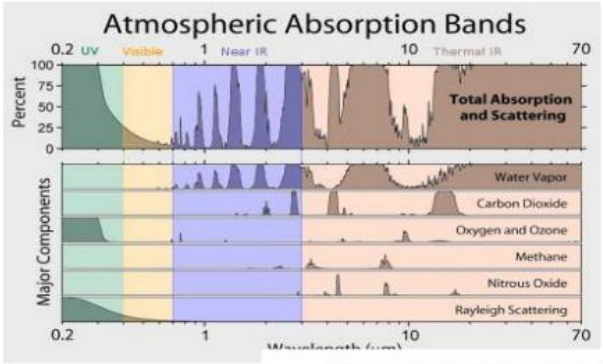
**ECrad** can be seen as a tool box with various options for :
Spectral integration : **S/RRTM or ECCKD**
Solver : **McICA, Tripleclouds or Spartacus**

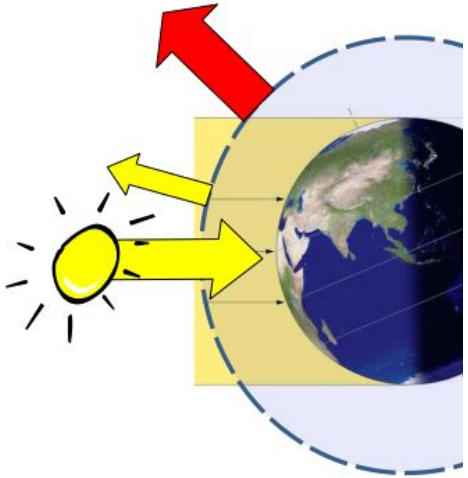
# Parameterization of radiative transfer

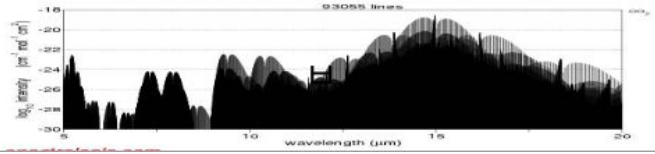
**Spectral : separating radiation between solar and thermal infrared**

Valid thanks to the linearity of the radiative transfer equation with respect to sources





# Parameterization of radiative transfer

## Approaches for spectral integration

### Emissivity / band models (code « Fouquart Morcrette, 1980)

$$\epsilon_{\Delta\nu}(z_1, z_2) = \frac{1}{\Delta\nu}\int_{\Delta\nu} \epsilon_{\nu}(z_1, z_2)\, d\nu$$

Loosing a fundamental property : $\epsilon_{\Delta\nu}(z_1, z_2) = \epsilon_{\Delta\nu}(z_1, z)\,\epsilon_{\Delta\nu}(z, z_2)$

Cost in N2 instead of N, where N is the number of layers

### K-distribution methods

Replacing the integration on $\nu$ by an integration on k.

k(P,T) differ depending on the transition considered.

| Name in .def files | SW | LW |
|---|---|---|
| oldrad | 2 bands | 6 bands |
| rrtm | 6 bands | K-distributions (RRTM) |
| ecrad | K-distributions (SRTM) ECCKD | K-distributions (RRTM) ECCKD |

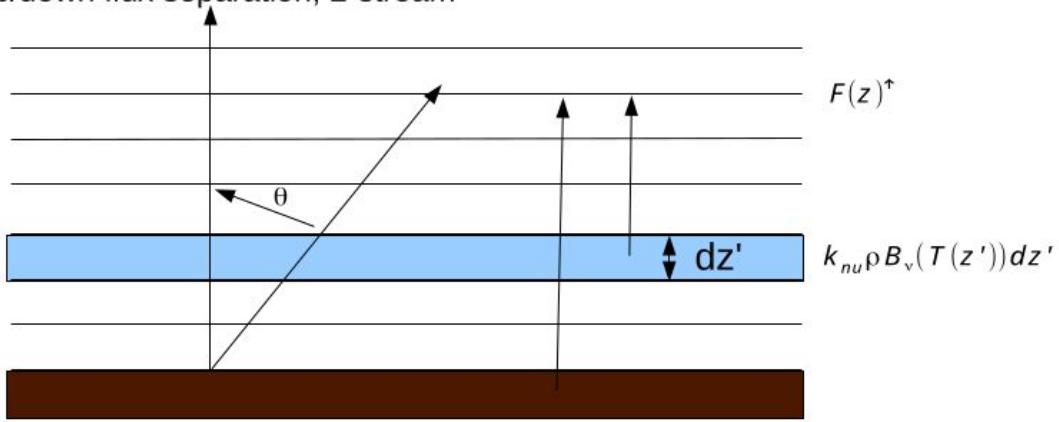
# Parameterization of radiative transfer

**Infrared, non-scattering case**

Plane parallel approximation: homogeneous semi-infinite space

Diffuse" approximation

Up/down flux separation, 2-stream




$$\frac{\partial F(z)^{\uparrow}}{\partial z} = -k_{\nu}\rho\mu F(z)^{\uparrow} + k_{\nu}\rho\mu B_{\nu}(T) \qquad \mu = \frac{1}{\cos(\theta)} = 1.66$$

$$\epsilon_{\nu}(z_1, z_2) = \exp\left[-\mu \int_{z_1}^{z_2} k_{\nu}(P,T)\rho dz\right]$$

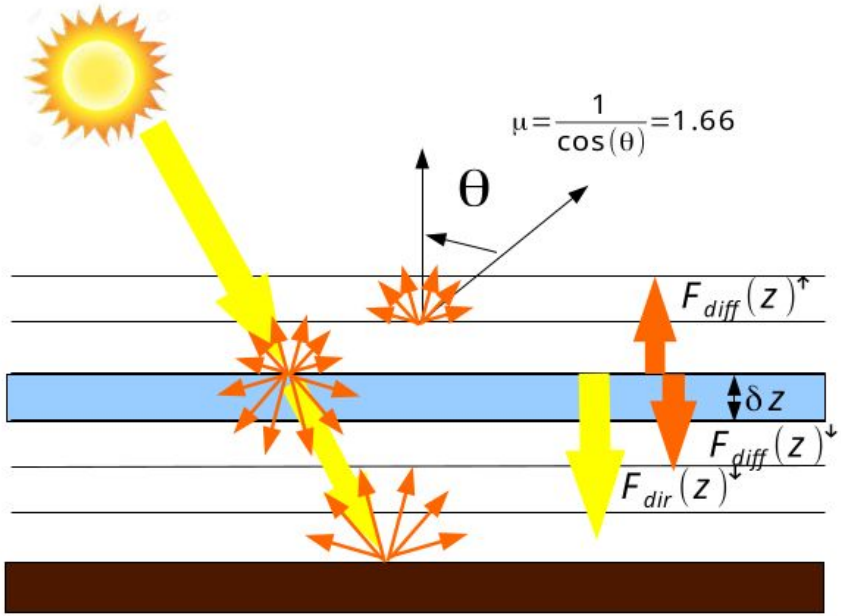
$$F(z)^{\uparrow} = B_{\nu}(T_s)\epsilon(0,z) + \int_0^z k_{nu}\rho B_{\nu}(T(z'))\epsilon(z',z)dz'$$

$$F(z)^{\uparrow} = B_{\nu}(T_s)\epsilon(0,z) + \int_0^z B_{\nu}(T(z'))\frac{\partial \epsilon(z',z)}{\partial z'}dz'$$

$$Q = \frac{\partial T}{\partial z} = \frac{1}{\rho C_p}\frac{\partial F(z)^{\uparrow}}{\partial z}$$

# Parameterization of radiative transfer

**Solar radiation : Direct radiation + 2-stream for diffuse radiation**
Plane parallel approximation: homogeneous semi-infinite space
Upward and downward photons are grouped into two streams
Delta-Eddigton approximation for scattering by strongly asymmetric phase functions




$$F^{\uparrow} = F^{\uparrow}_{diff} - F^{\downarrow}_{diff} - F^{\downarrow}_{dir}$$

$F(z)^{\uparrow}$
$F(z-\delta z)^{\uparrow}$

$$Q = \frac{F(z) - F(z-\delta z)}{C_p \rho \delta z}$$

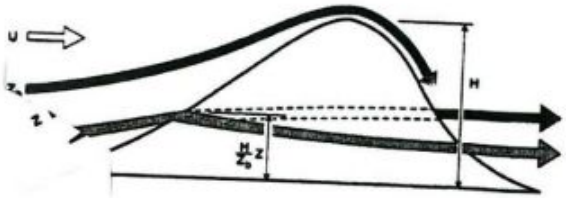
!! Column independency

One column does not see photons coming from neighbour columns

Approximation ok up to resolution ~ 10km (Di Giuseppe & Tomkins 2003)

# Parameterization of gravity wave drag

The Lott and Miller (1997) scheme treats the Subgrid Scale Dynamics controlled by the Gravity Waves



Non-dimensional height of the mountain: $H_n = NH/U$
H is the maximum height of the obstacle

- At small $H_n$ all the flow goes aver the mountain, gravity waves are forced by the vertical motion of the fluid

Tau the surface stress due to the gravity wave :

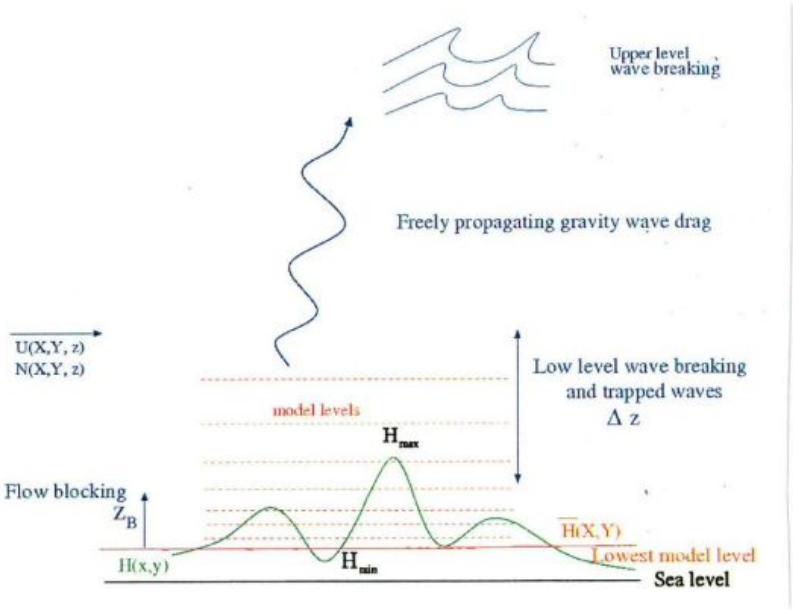
$$\tau = \rho b G B(\gamma) N U H^2$$

- At large $H_n$ the vertical motion of the fluid is limited and part of the low-level flow goes around the mountain for $z<z_b$.
The surface stress is then : $\tau = \rho C_d z_b b U^2$

# Parameterization of gravity wave drag

The scheme depends on 4 parameters $C_d$, G, $R_{ic}$ and $z_b$.

- $C_d$ and G control the amplitude of the blocked-flow drag and of the gravity-wave drag.
- $R_{ic}$ and $z_b$ control the vertical distribution of these drags.

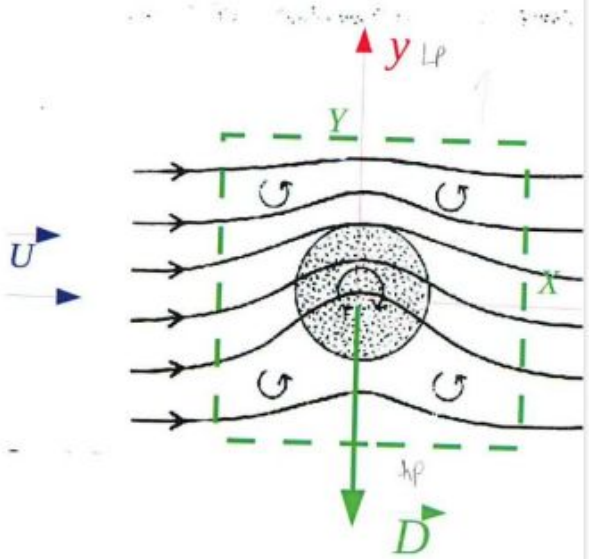


# Parameterization of gravity wave drag

**Pressure force acting on the mountain to the left due to the background pressure gradient associated with the mean flow:**

**F = MV$\rho$ U f ; MV is the mountain volume**

**The lifting of the air over the mountain is balanced by the force acting on the mountain and then results in a push to the right (*Smith 1979*).**




Between the narrow ridges of a mountain air can be blocked and separated from the large-scale flow.

A region of complex terrain acts as if it has a height larger than the actual height.

A solution could be to increase the sizes of the mountains

In lift-noro the mean orography is kept and the missing forces are applied.

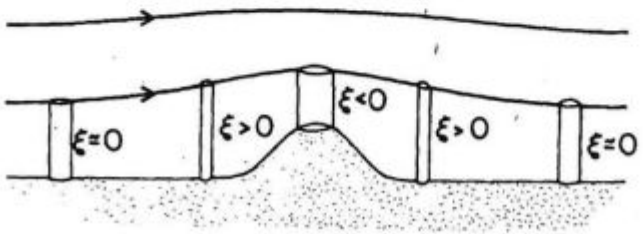
# Parameterization of gravity wave drag

Conservation of potential vorticity for an adiabatic motion:

$$PV = \frac{1}{\rho}(f + \xi_r)\frac{d\theta}{dz}$$

If the motion to the South or North is large enough, one can't consider that $f$ is constant.

**The mountain triggers a steady Rossby wave.**



# Parameterization of gravity wave drag

Brewer–Dobson middle–atmosphere circulation

