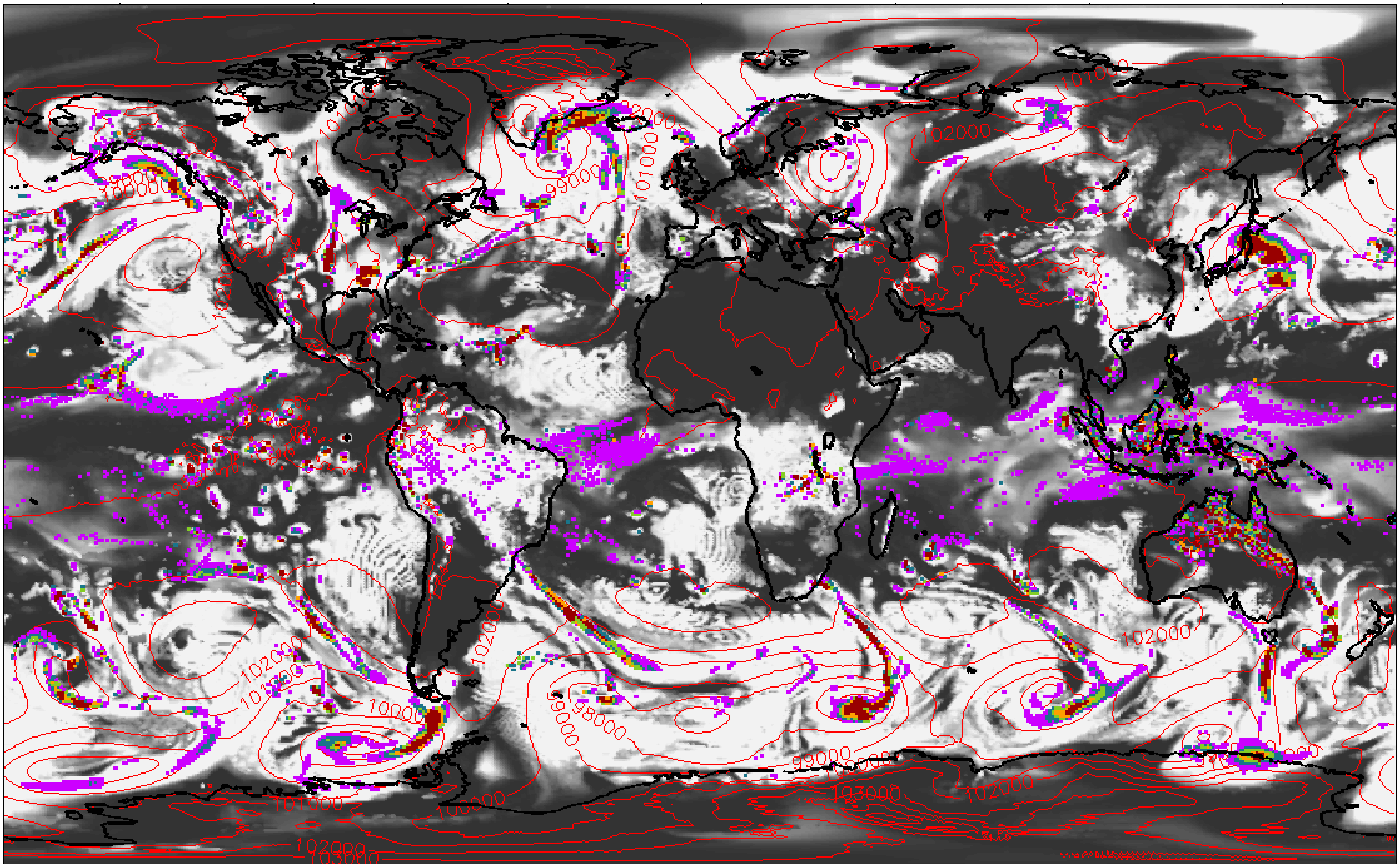
Snapshot of a 50km resolution global simulation with LMDZ
Clouds (grey shading) + rainfall (color) and sea level pressure (red contours)



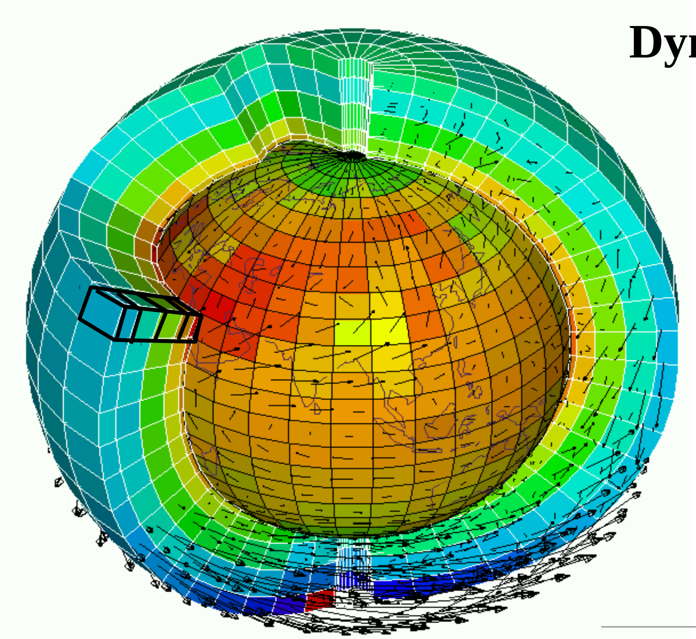
Introduction

Frédéric Hourdin

LMDZ : a general circulation model

1. **General Circulation Models**
2. **LMDZ**
3. **Splitting/coupling and modularity**

1. General Circulation Models



Dynamical core : primitive equations discretized on the sphere

- Mass conservation

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

  $D\theta \, / Dt = 0$
- Momentum conservation

  $D\underline{U}/Dt + (1/\rho) \, \underline{\mathrm{grad}p} - \underline{g} + 2 \, \underline{\Omega} \wedge \underline{U} = 0$
- Secondary components conservation

  $Dq/Dt = 0$

Primitive equations of meteorology

→ Thin layer approximation

→ Hydrostatic approximation (**valid down to 10-20 km**)

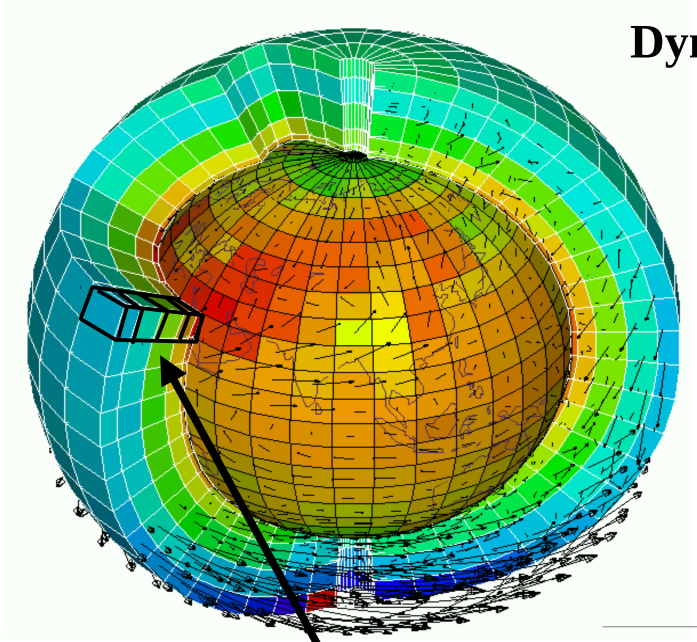
From physics to numerics :

→ Grid point or spectral models

→ Explicit resolution down to 20-300 km depending of the configuration

→ Numerical conservation of important quantities (mass, water, enstrophy ...).

1. General Circulation Models



Dynamical core : primitive equations discretized on the sphere

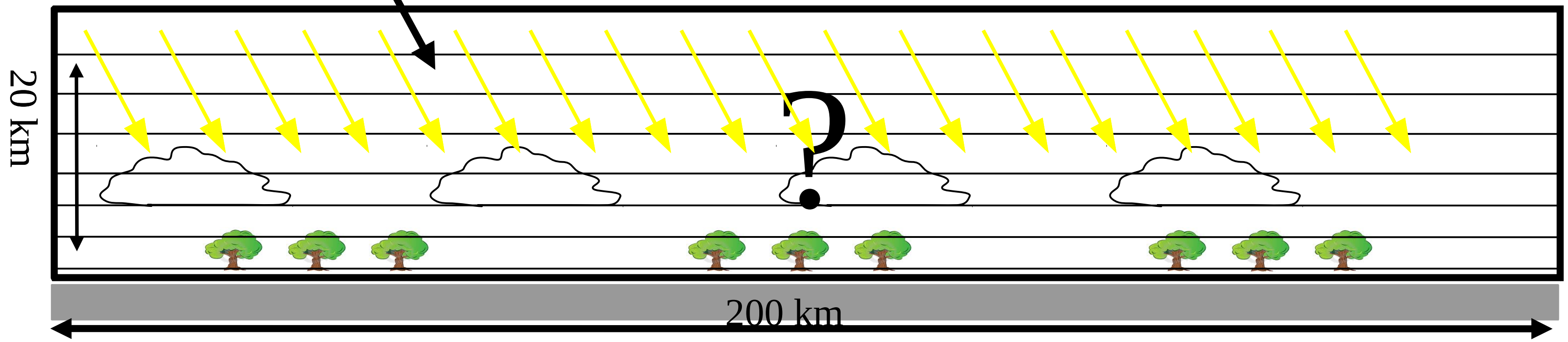
- Mass conservation

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

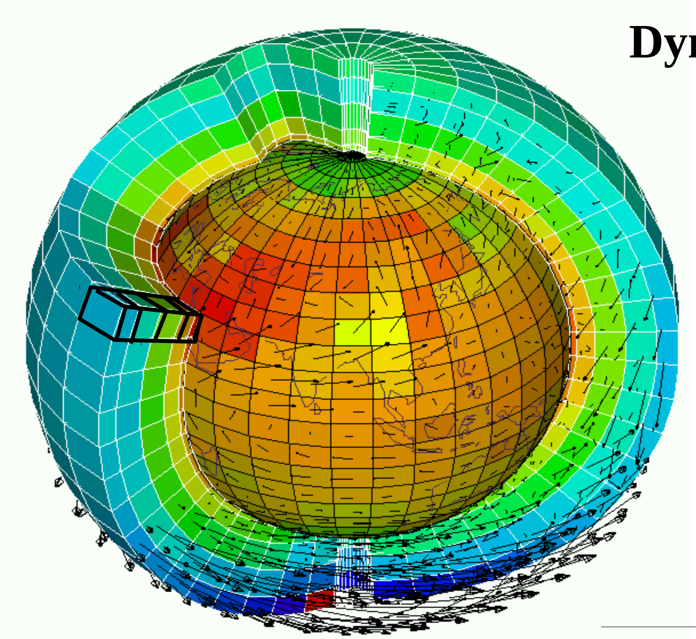
  $D\theta\ / Dt = Q / Cp\ (p_0/p)^{\kappa}$
- Momentum conservation

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

  $Dq/Dt\ = Sq$



1. General Circulation Models



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- 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)**

- *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)**

Parameterizations : principles

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

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

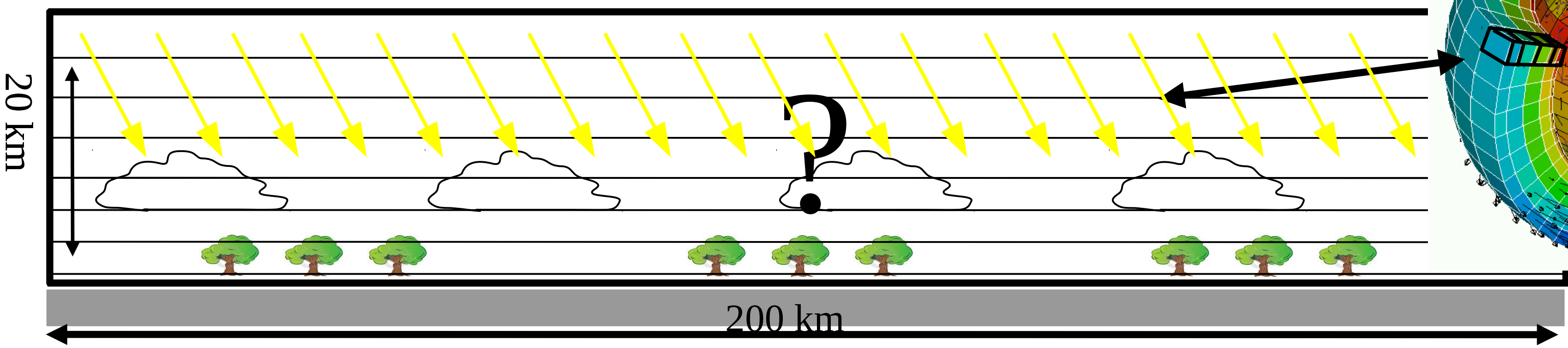
- Involve additional **parameterization internal variables** (cloud characteristics, standard deviation of the sub-grid scale distribution of a variable, …)

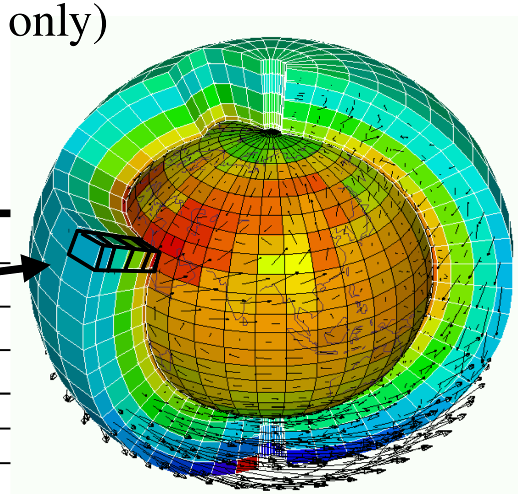
- Derive **equations** relating internal variables to the state variables

  $\underline{U}$, θ, q at time t → **internal variables** → $\underline{F}$, Q, Sq → $\underline{U}$, θ, q at t+δt

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

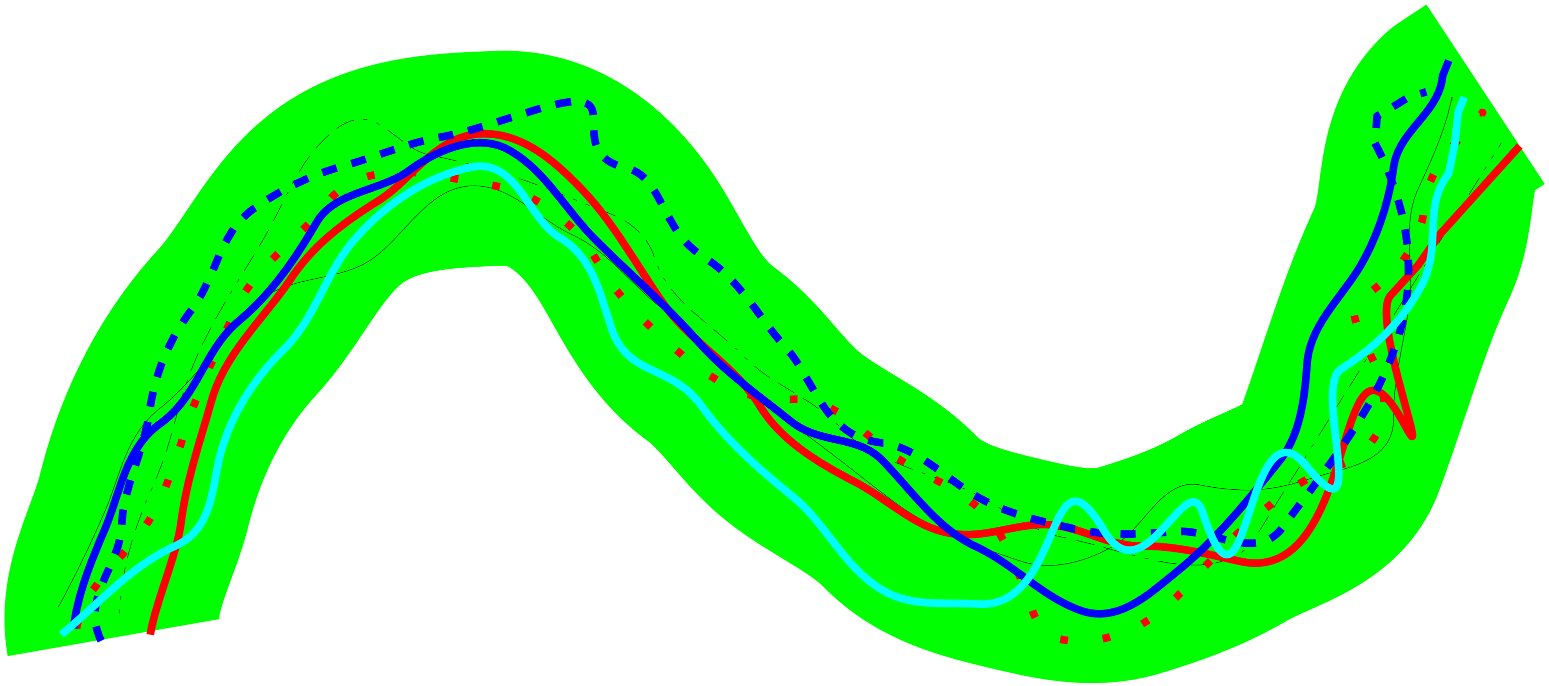
Inside an « atmospheric column » ...





Used for both climate modeling and numerical weather forecast

- **Models** : identical.
- **Duration** : several decades or centuries / 15 days (seasonal forecast in between)
- **Initial state** : any (existence of an attractor : the climate) / “analysis” obtained through an assimilation procedure of observations into the model.
- **Forecast** : statistical (ex : inter-annual variability, intensity of storms ...) / deterministic (the weather of tomorrow).



1. General Circulation Models

In the world of numerical models

Before computers

Appearances :
Meteorology, climate, atmospheric composition

Theories :
Fluid mechanics, Gas/radiation interaction, Thermodynamics, Chemistry

Mathematics
Primitive equations, Thermodynamical laws, Radiative transfer equations

Numerics
Grid point discretization, spectral methods, Finite volume and finite differences
conservation, robustness and efficiency, rather than accuracy

Computers
Fortran / Linux, High Performance Computing, Modularity, Flexibility / Multi-configuration

Dynamcial core

parameterizations

Dynamical core :
Well established equations. Work on approximations, numerics, HPC

Parameterizations :
Based on combinations of theories, heuristic approaches, and conservation laws.
Many ways possible. Strong diversity across models

General comments :
- Modeling concerns all the layers. Lot of expertises required and shared.
- Be aware of the layer in which you are working, or at which transition between layers.
- Do not forget that your goal is to explain things in the first layer

I. LMDZ : a general circulation model

1. General Circulation Models
2. **LMDZ**
3. Splitting/coupling and modularity

LMDZ – a brief history

Pioneers : years 60-70. Robert Sadourny and Phu Le Van (Sadourny, 1975)

The LMD5/LMD6 model : 90-95 (Laval, 1981)

1985 : Rewriting of the dynamical core : modularity and **Z**oom (the previous version had been written over punch cards with a very small RAM memory)

1990 : versions for Mars, Titan, and a generic 20-parameter version

1992 : decision to develop the terrestrial model on the basis of this new dynamical core, by adapting the physical package of LMD5/6 → LMD**Z**

1995-1999 : transport of trace species

2005 : First participation to CMIP exercise with LMDZ

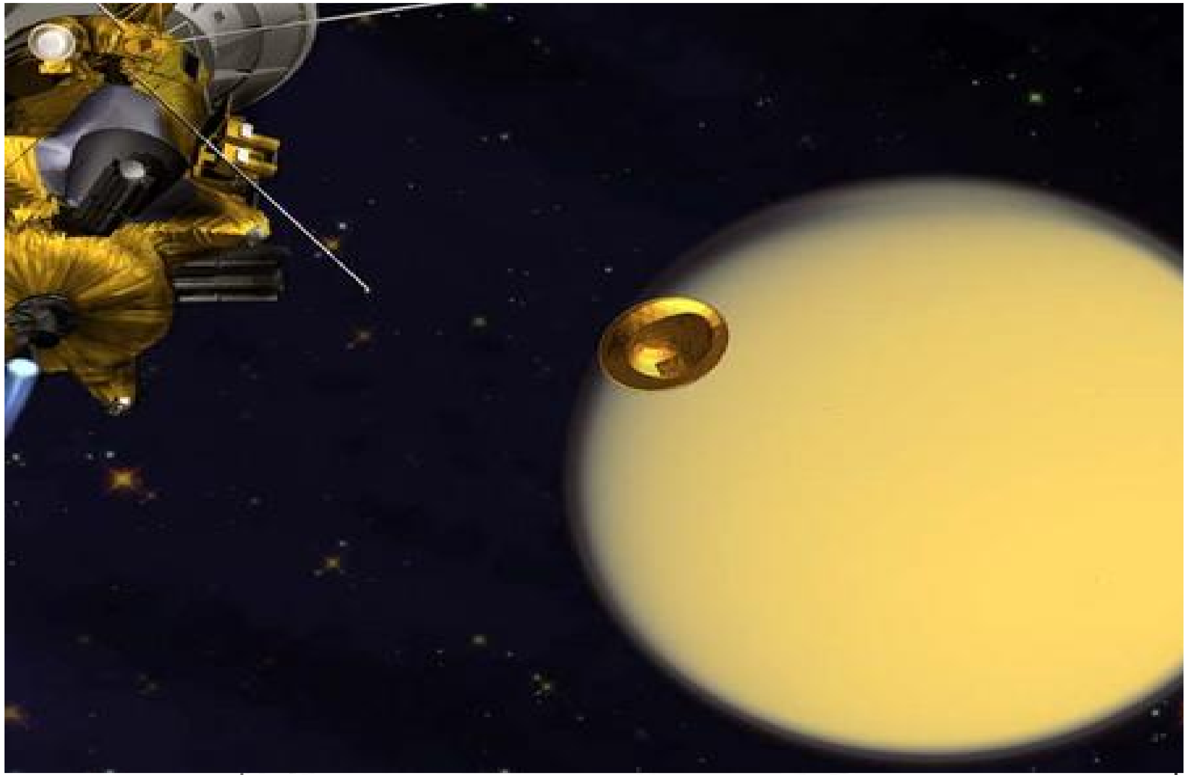
2007 : rising organization around LMDZ (web, regular meetings,Svn, training, …)

2011 : “New Physics” version (result of a 10-year research) and participation to CMIP5

2017 : new dynamical core Dynamico

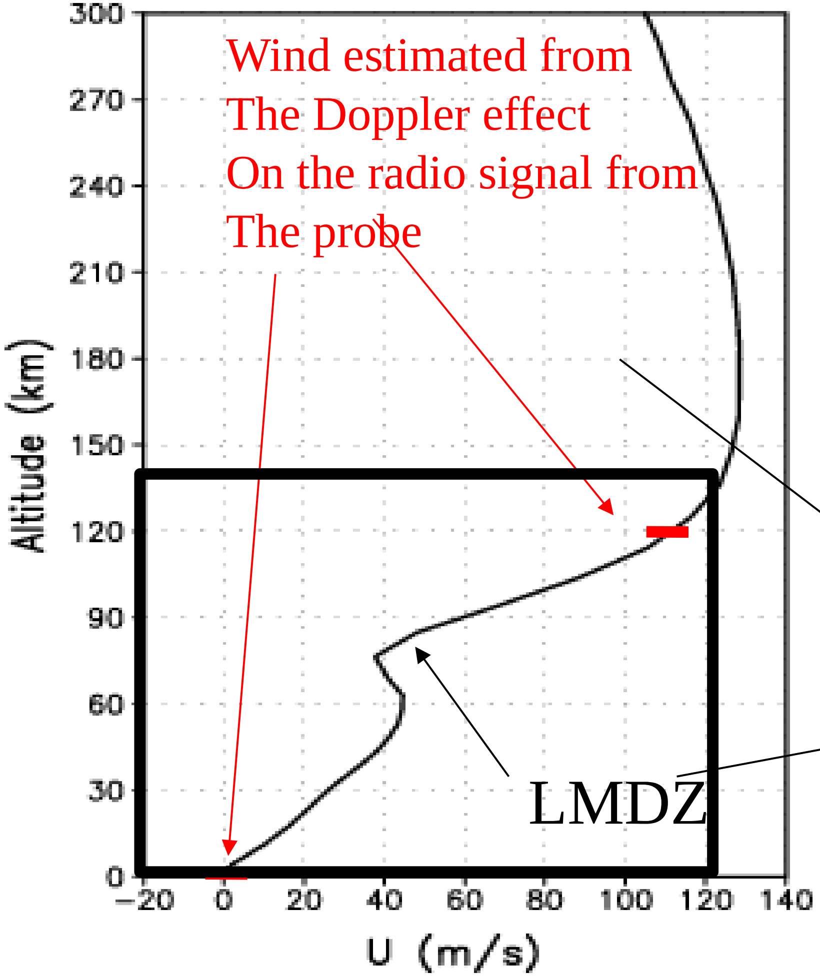
2017 : CMIP6 version

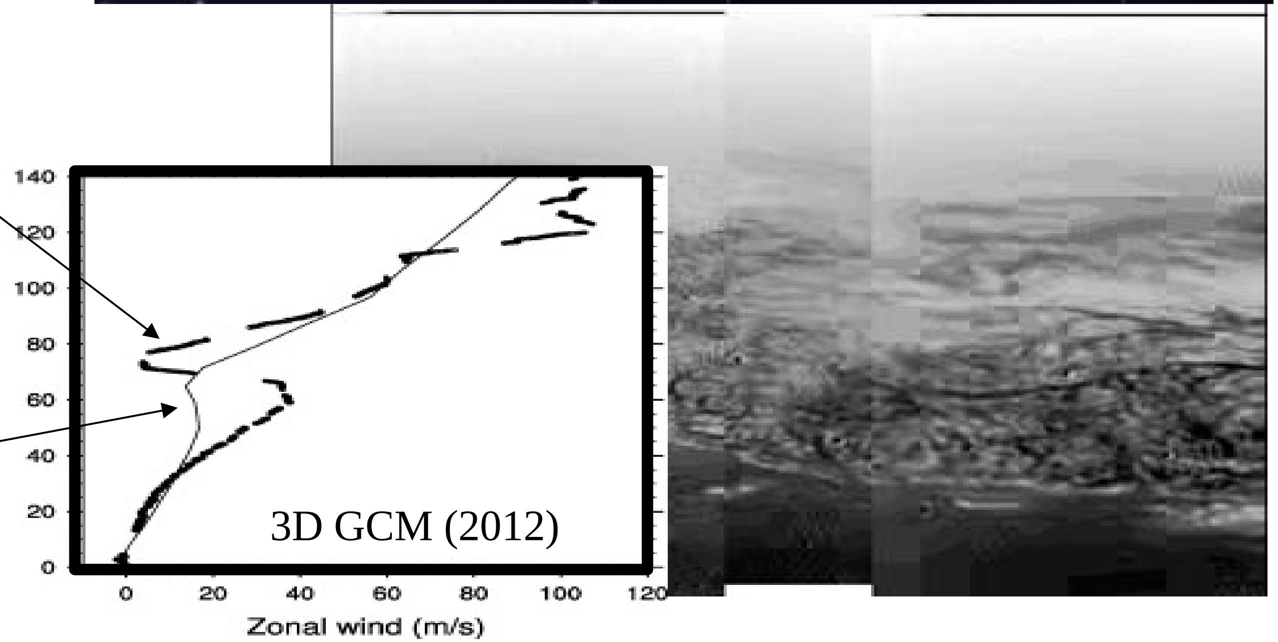
2. LMDZ



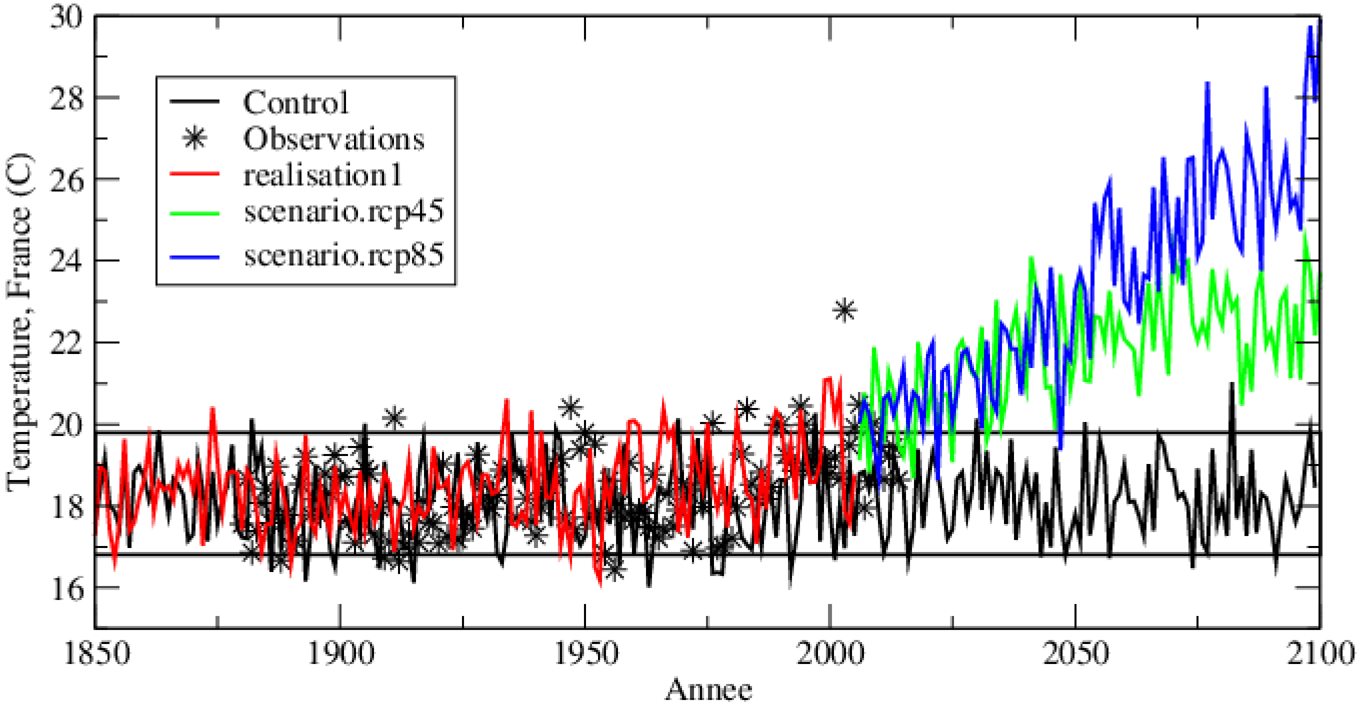
Planetary atmospheres
Mars, Titan, Venus, Triton, ...

Prediction of Titan atmospheric super-rotation with the LMDZ Titan GCM (1995, 2005)
An a posteriori comparison with
The Huygens entry profile



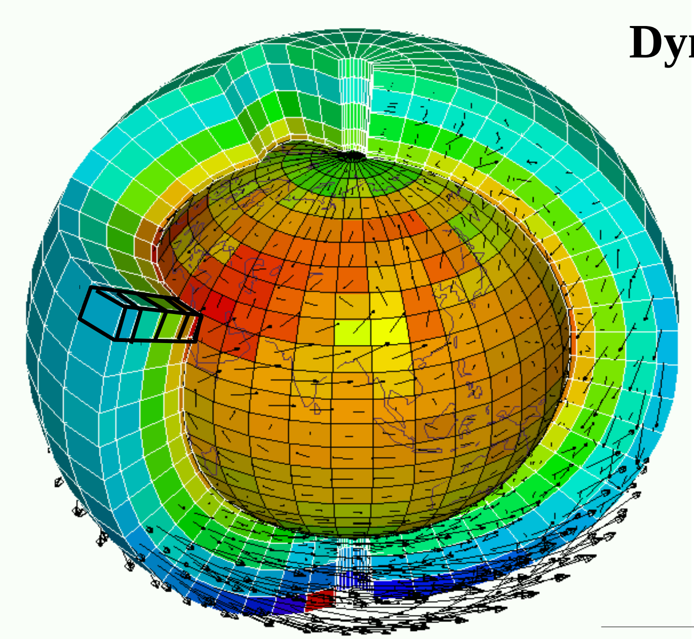


Atmospheric component of the IPSL climate model :
Coupled to ocean, continental surface, chemistry
The terrestrial version is used in particular for climate change projections
Reference versions for the Coupled Model Intercomparison Projects (CMIP)
Each ~ 7 years



Also used for :
Regional climate
Process studies / rôle of cloud processes in climate and climate change
Tracer transport / chemistry / aerosols
Transport inversion

2. LMDZ



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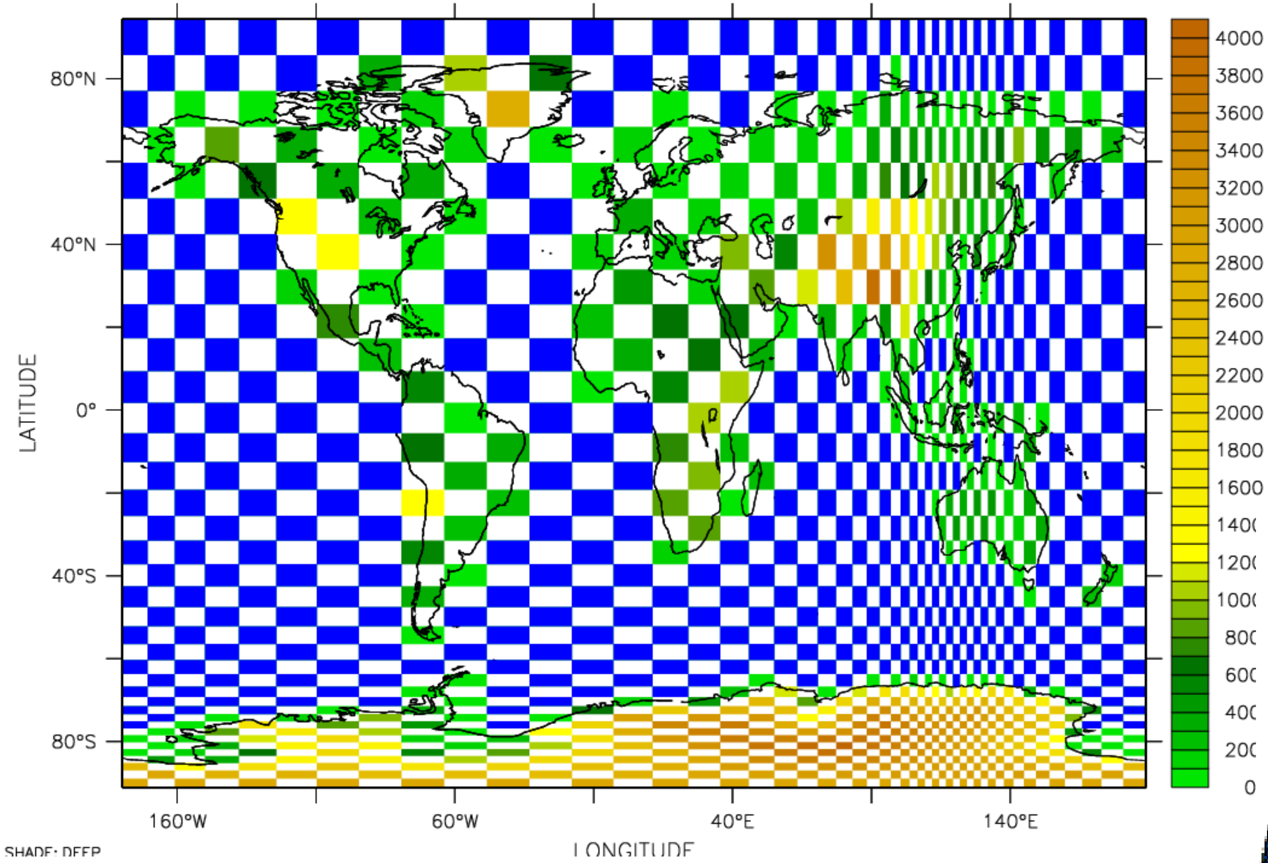
- Secondary components conservation

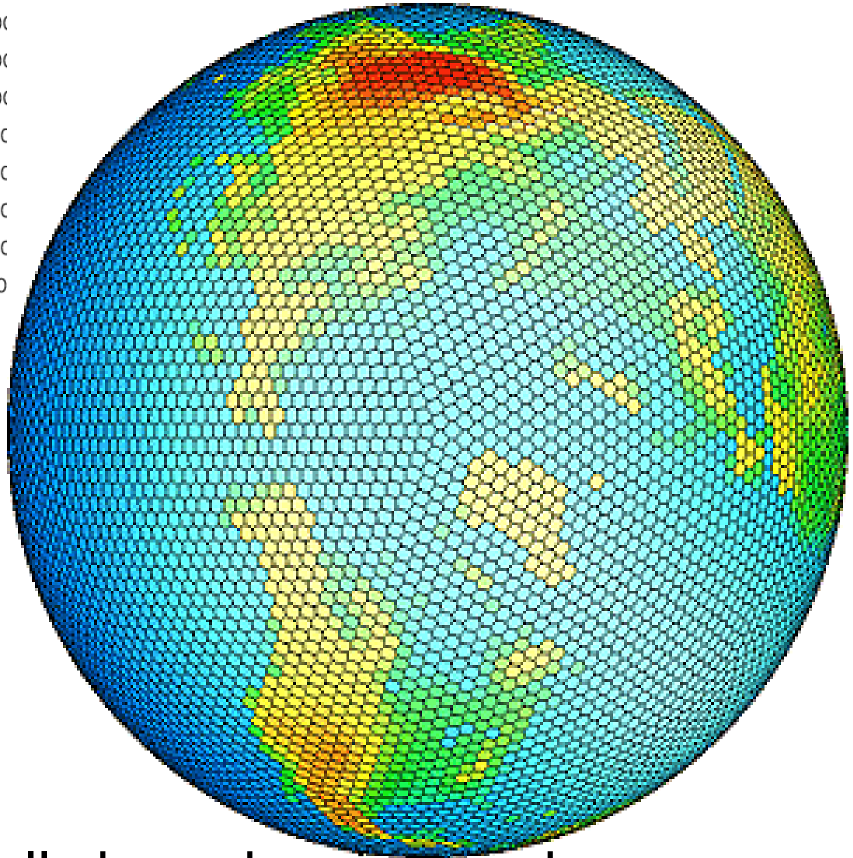
  $Dq/Dt = Sq$

The LMDZ dynamical core :

→ Global longitude-latitude grid
→ Zoom capability (« Z » of « LMDZ »)
→ Finite difference / finite volume numerical schemes
→ Conservation of air mass, enstrophy, partly angular momentum and energy
→ Positive/monotonic/conservative Van Leer schemes for tracer advection
→ Horizontal dissipation (stability + scale interaction) : iterated Laplacian
→ Sponge layer (dumping winds and wave in the upper layers)



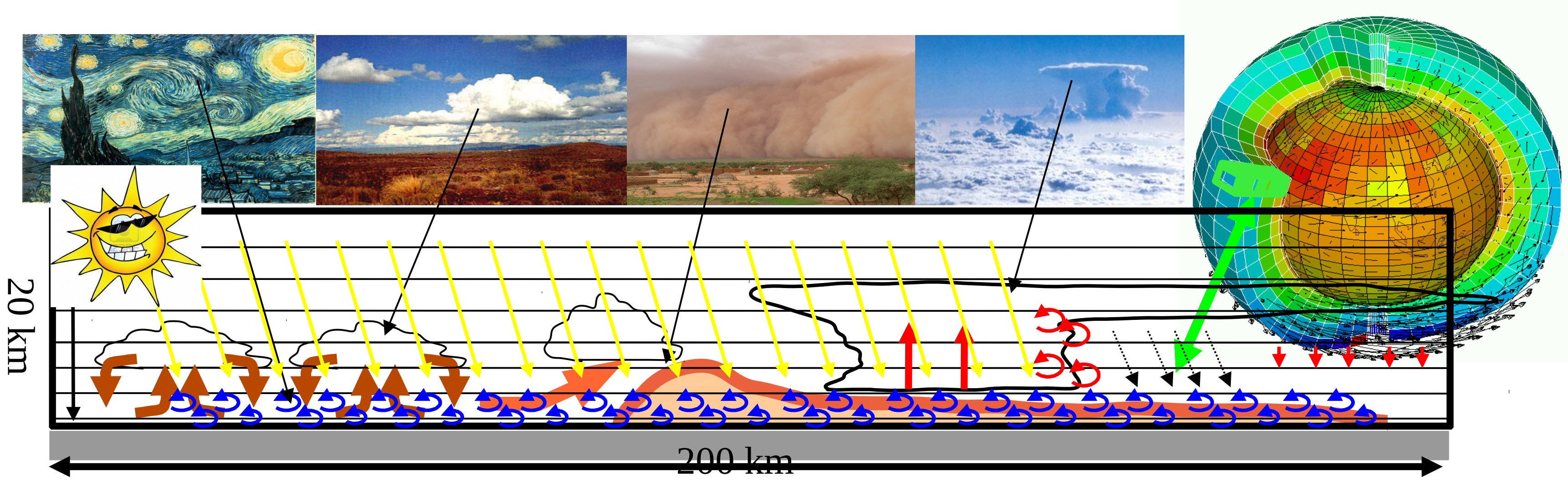
LMDZ current grid :
Longitude-latitude
with zoom capability
(Sadourny and Levan, 1984)



Coming soon :
New dynamical core based on hexagonal grid cells based on icosaedron
(Dubos, Meurdesoif et al. 2016)

2. LMDZ

Earth : development of a **« New Physics »** version (15-year team work)
New framework for model development and evaluation
Splitting in 3 scales for vertical transport
turbulence / organized structure of the boundary layer / deep convection



→ **Boundary layer small scale turbulence treated as « turbulent diffusion »**
→ **Organized structures of the convective boundary layer parameterized with a single « thermal plume » and associated cumulus clouds**
→ **Deep convection , mass flux scheme, buoyancy sorting ...**
→ **Cold pools**
→ **Radiative transfer**

+ micro-physics
+ effect of subgrid-scale horography
+ non orographic gravity waves

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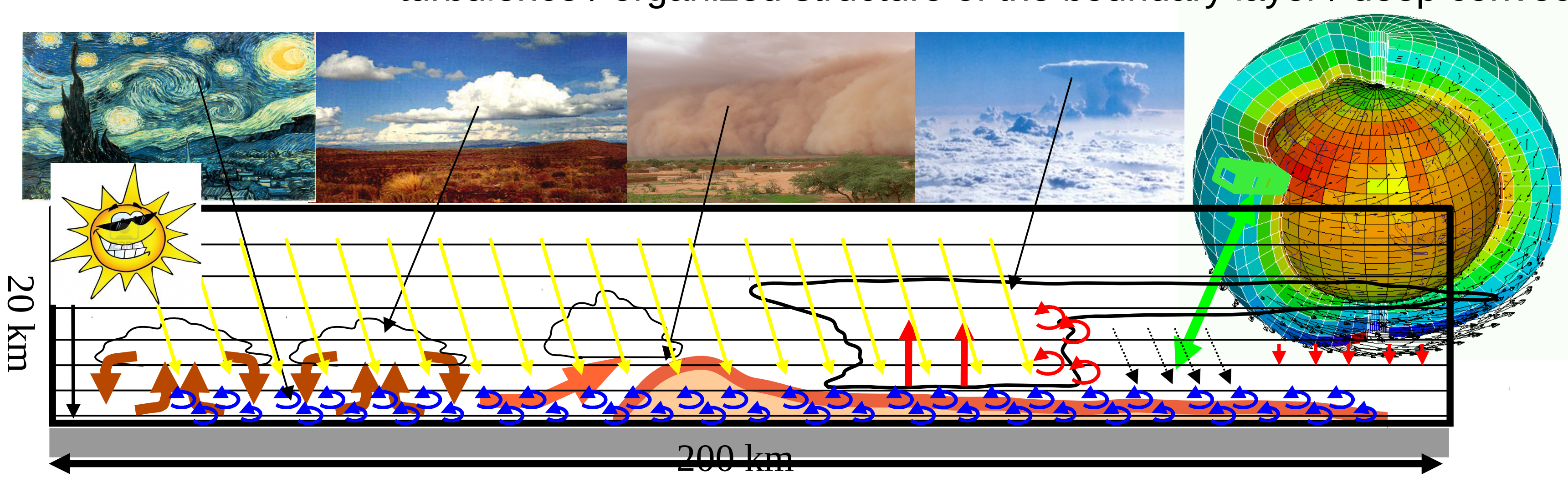

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→Jam, A., F. Hourdin, Rio C., and F. Couvreux, Resolved versus parameterized Boundary Layer Plumes: III Derivation of a statistical scheme for cumulus cloudsR, Clim. Dyn., accepted for publication Resolved Versus Parametrized Boundary-Layer Plumes. Part III: Derivation of a Statistical Scheme for Cumulus Clouds, Boundary-layer Meteorol., 147, 421–441, **2013.**
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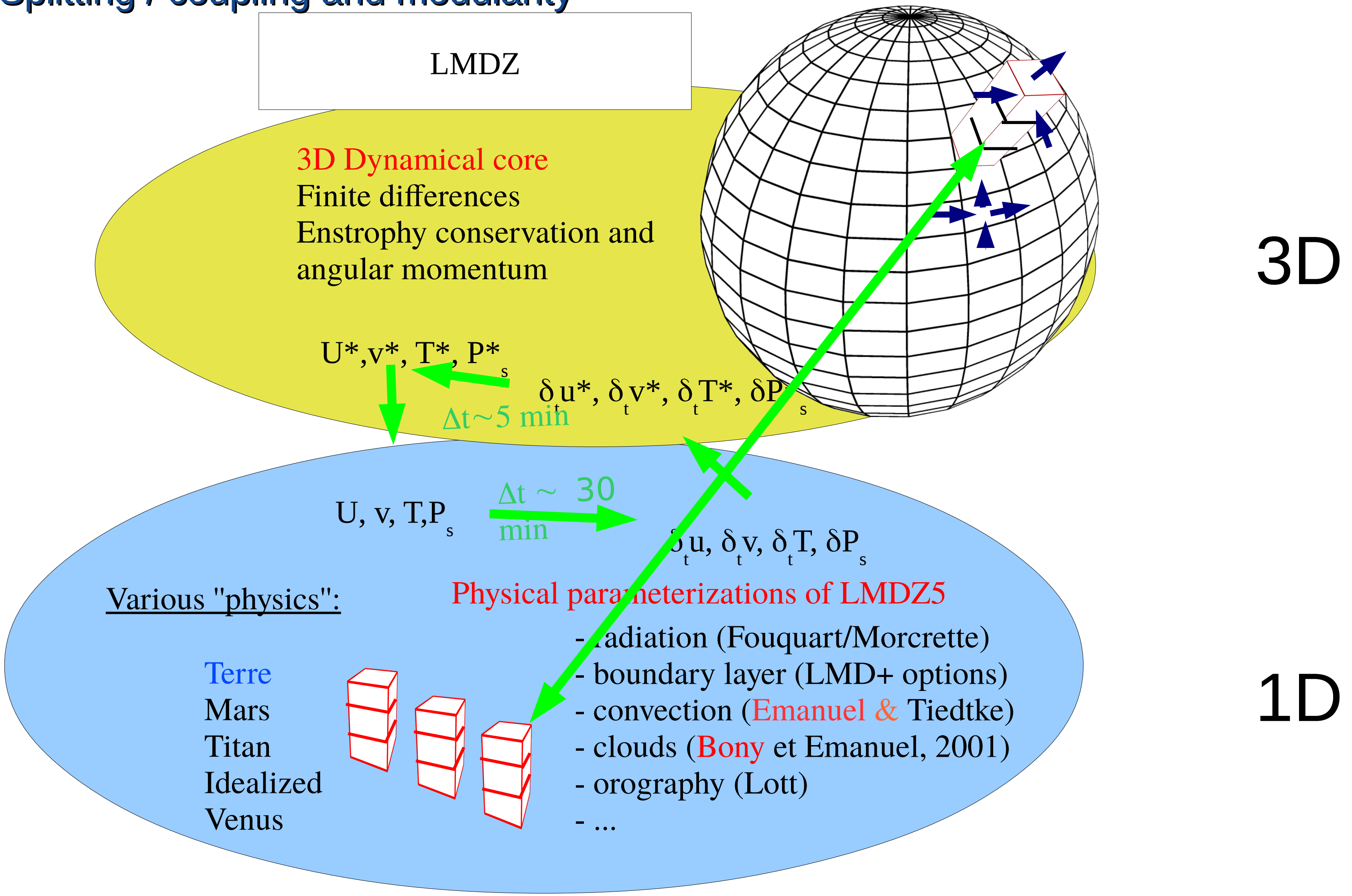
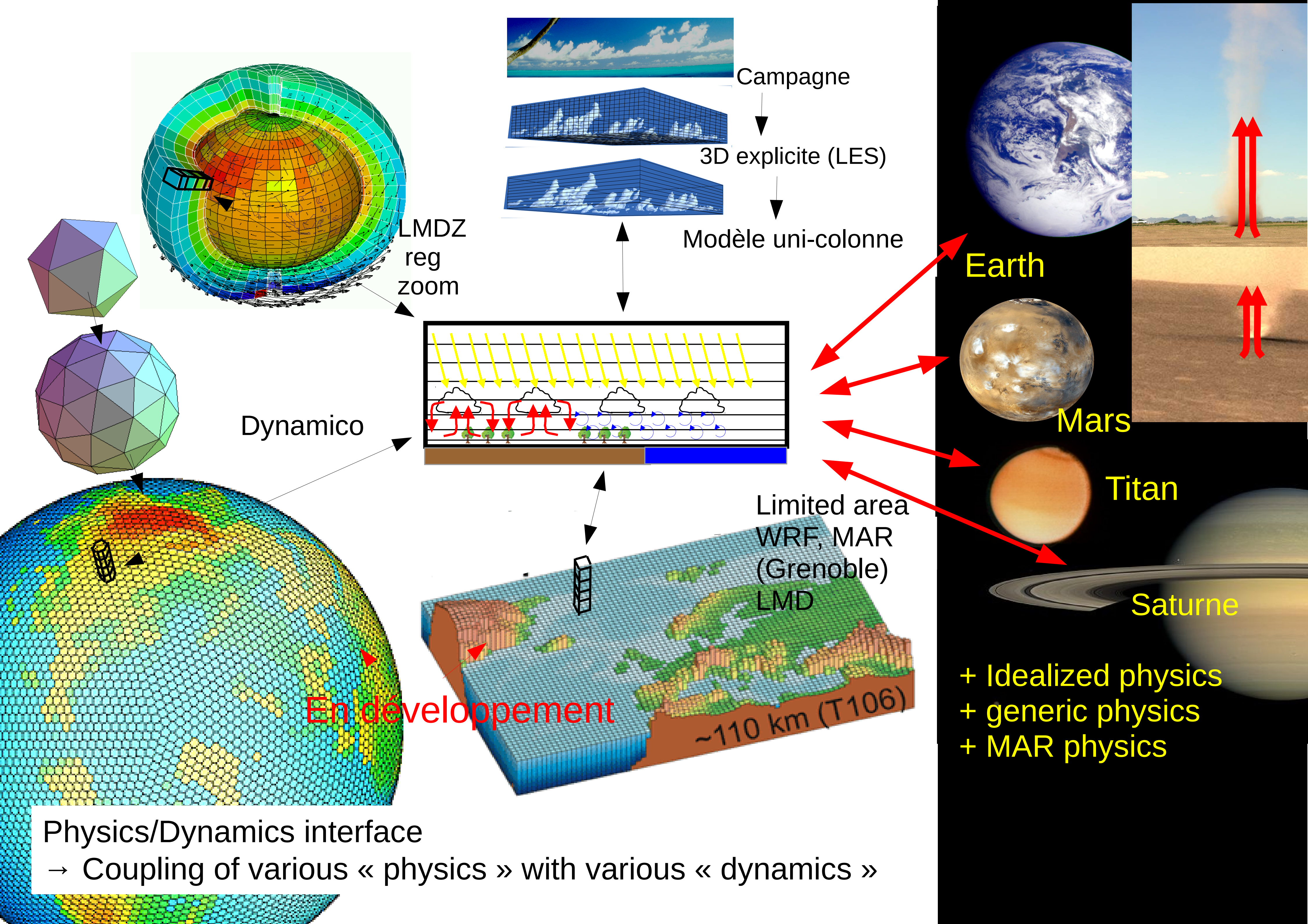
I. LMDZ : a general circulation model

1. General Circulation Models
2. LMDZ
3. **Splitting/coupling and modularity**

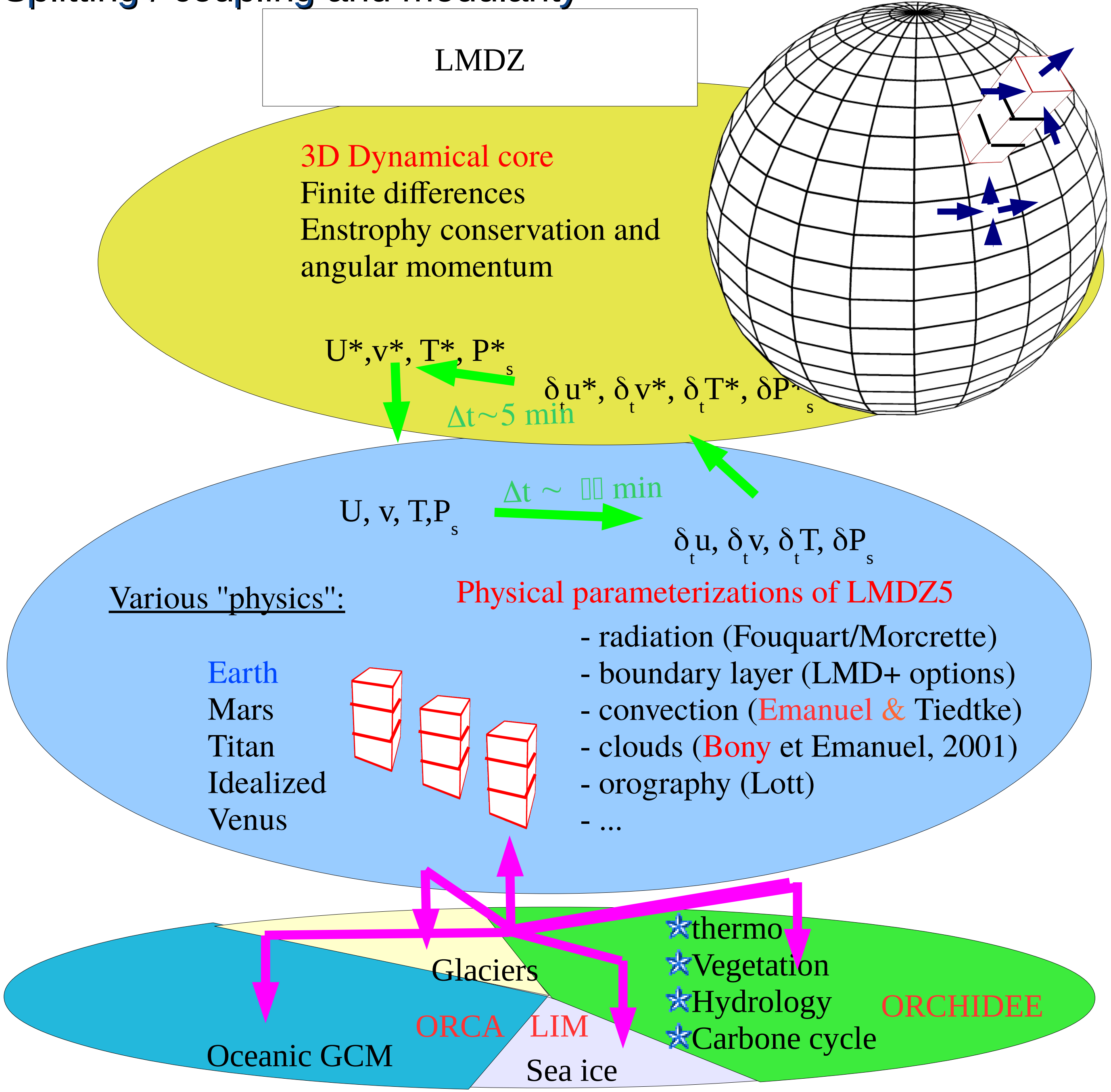
3. Splitting / coupling and modularity



Using the 1D nature of the parameterizations to clearly separate two worlds
Helps a lot for parameterization development and test


Campagne
3D explicite (LES)
Modèle uni-colonne
LMDZ
reg
zoom
Dynamico
Limited area
WRF, MAR
(Grenoble)
LMD
~110 km (T106)
En développement
Earth
Mars
Titan
Saturne
+ Idealized physics
+ generic physics
+ MAR physics
Physics/Dynamics interface
→ Coupling of various « physics » with various « dynamics »

3. Splitting / coupling and modularity



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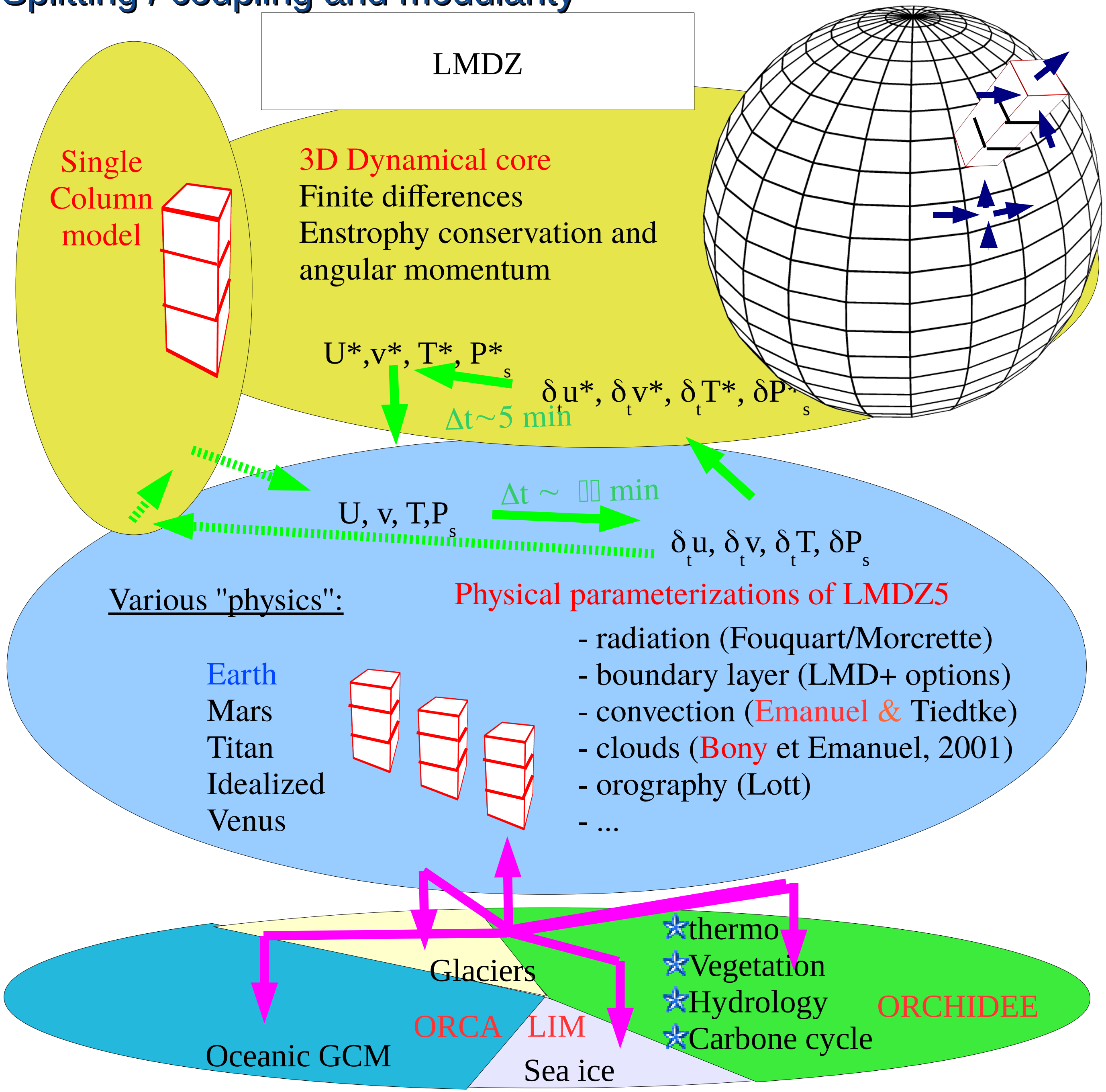

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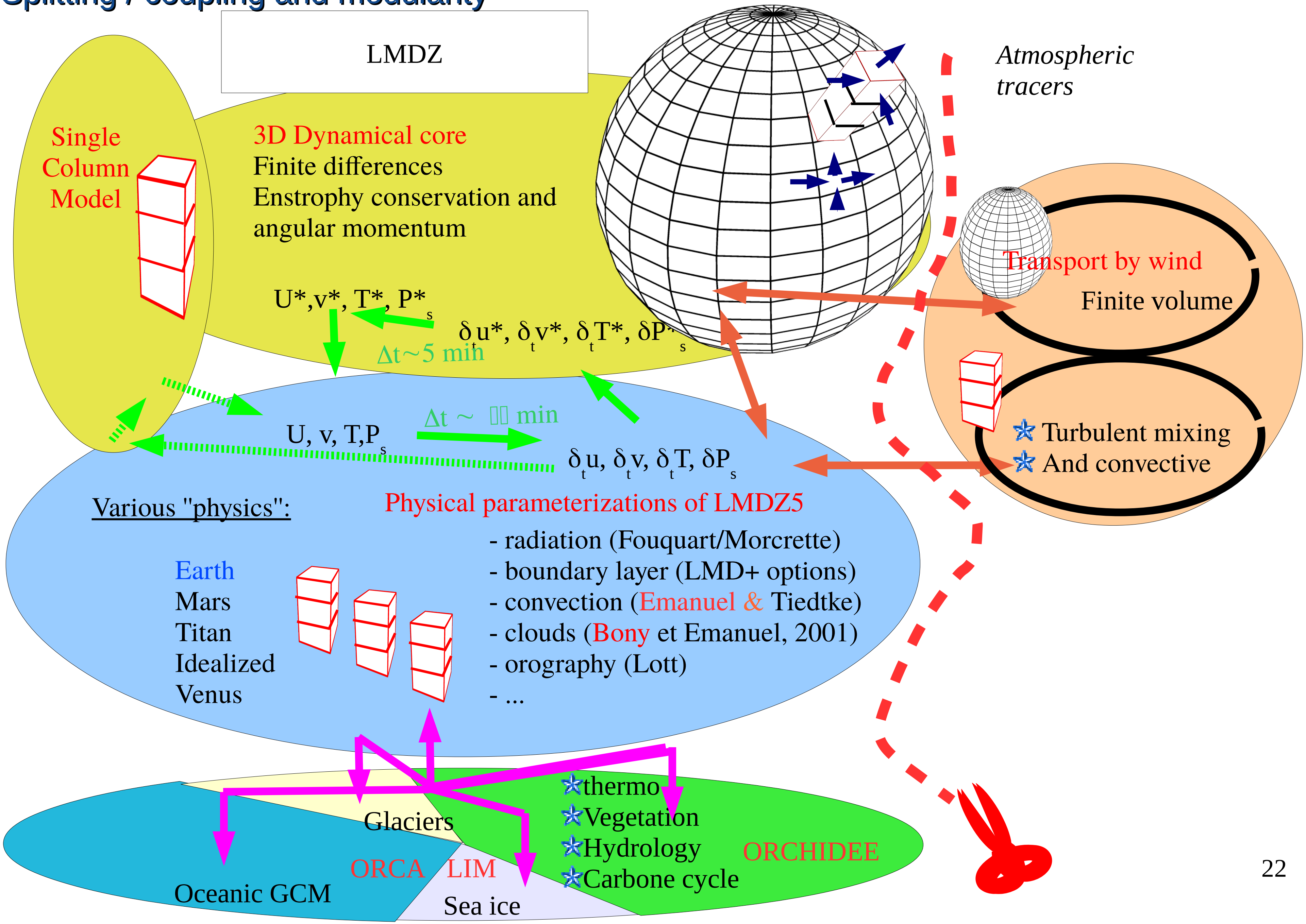

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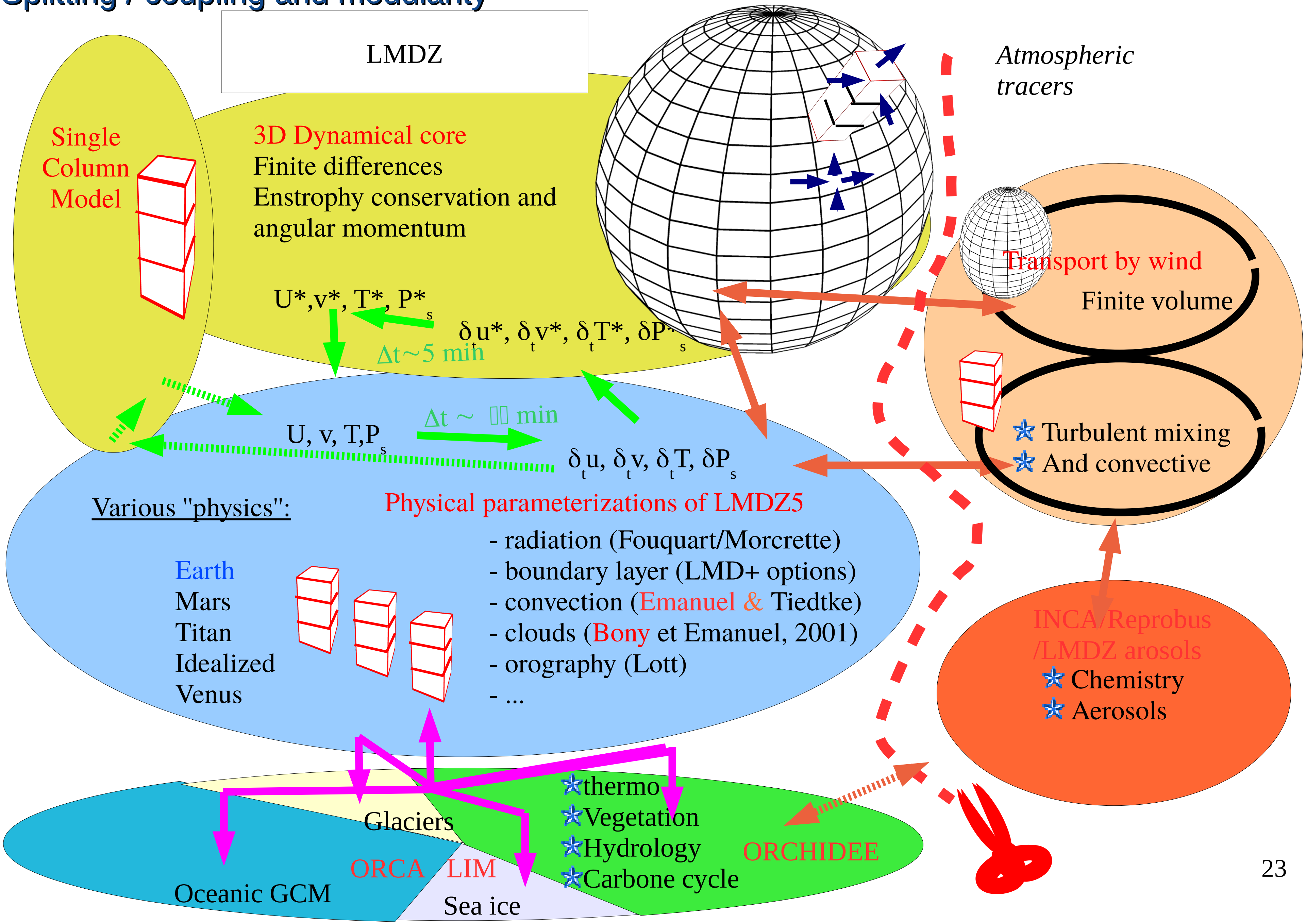

LMDZ to summarize

1. Made of 2 well distinct parts :
   A/ dynamical core, 3D.
   B/ physical parameterizations, N x 1D

2. Coupling with ocean and continental surfaces in the physics

3. Coupled to chemistry through large scale transport (dynamics) and physical parameterizations (physics)

4. Various configurations :
   1D (« physics » alone)
   3D with nudging (by meteorological reanalysis)
   3D with zoom
   Off line for tracers (not maintained in current versions), direct & backward

5. Flexible tool
   Used on computer centers in HPC mode
   Easy to install on personal computers for research
   All the configurations available in the same model version
   Switching from one configuration to another through « .def » ascii files