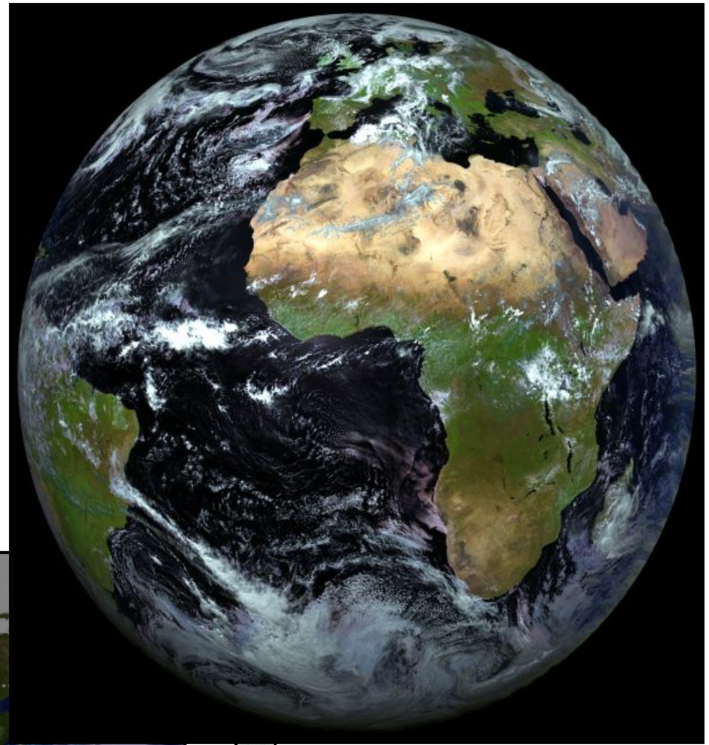
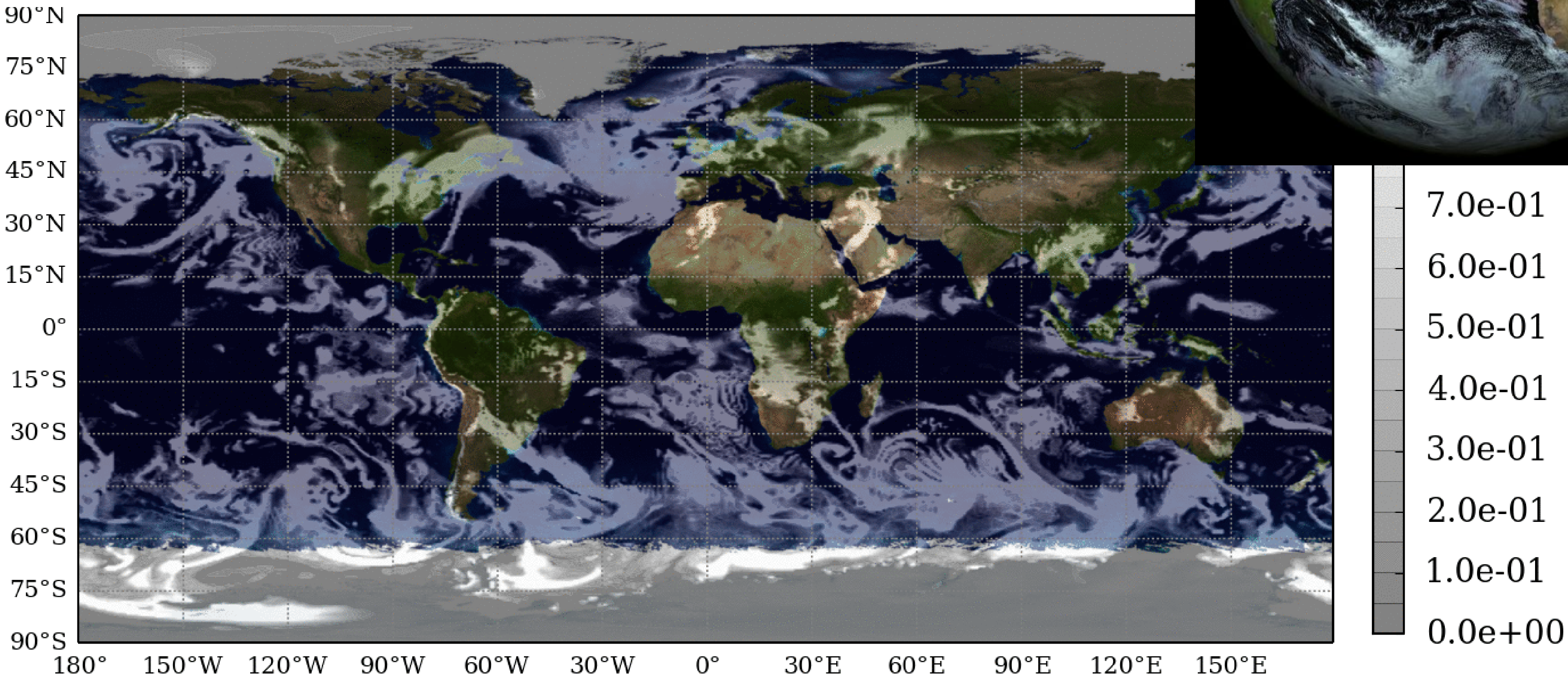
LMDZ training course, 2026, January

Meteosat observation of clouds



Low clouds simulated with LMDZ with
a global 50km resolution grid
January

Lancer l'animation



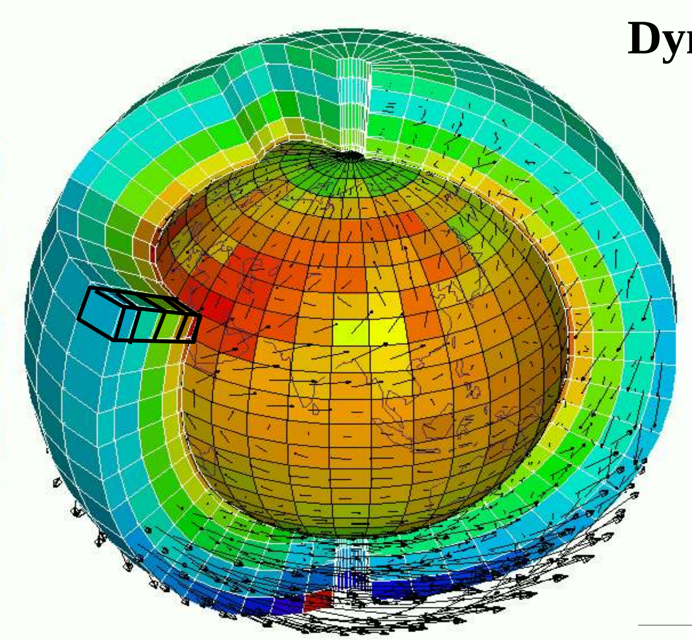
Introduction

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**)

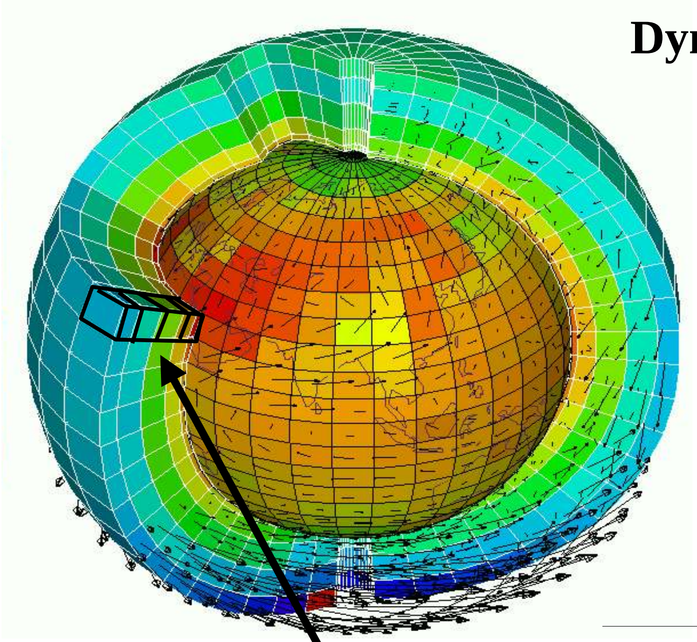
From physics to numerics :

→ 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

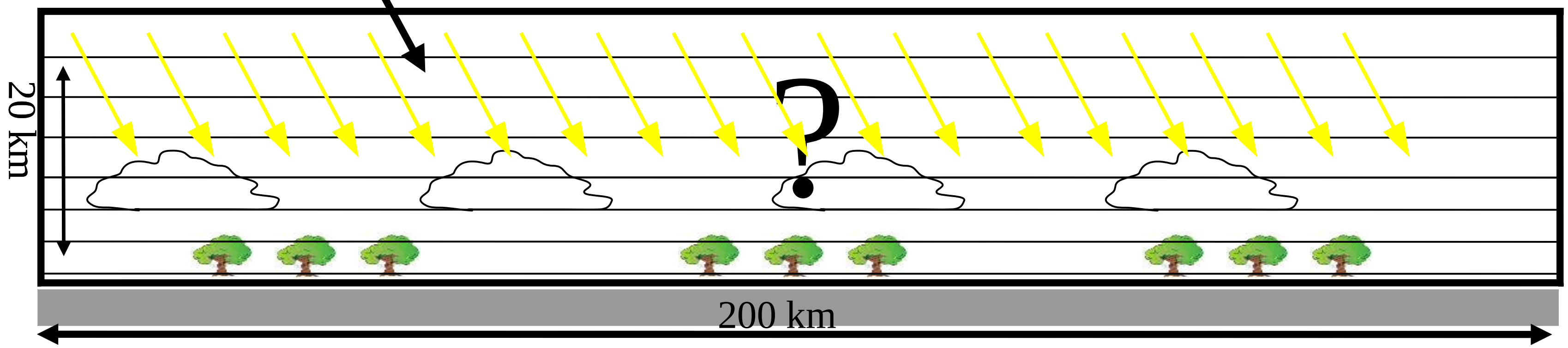
  $D\theta / Dt = Q / Cp \; (p0/p)^{\kappa}$

- Momentum conservation

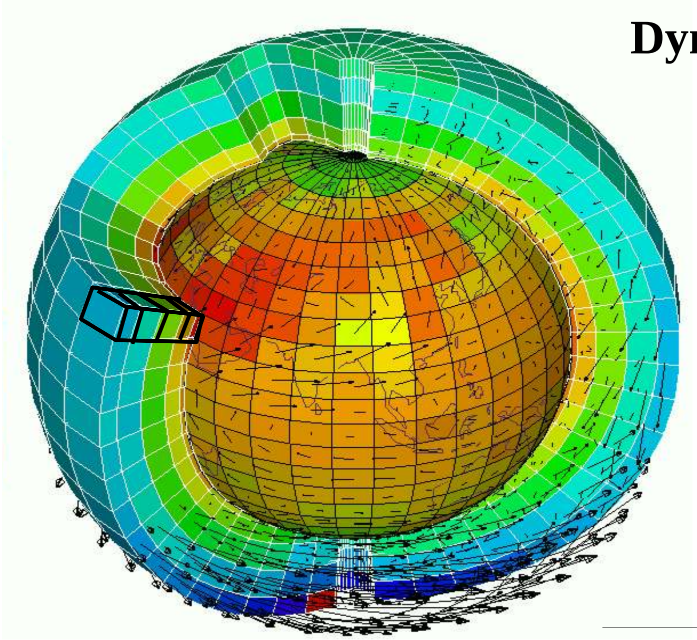
  $D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}p} - \underline{g} + 2\,\underline{\Omega} \wedge \underline{U} = \underline{F}$

- Secondary components conservation

  $Dq/Dt = Sq$



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

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

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

Parameterizations : principles




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

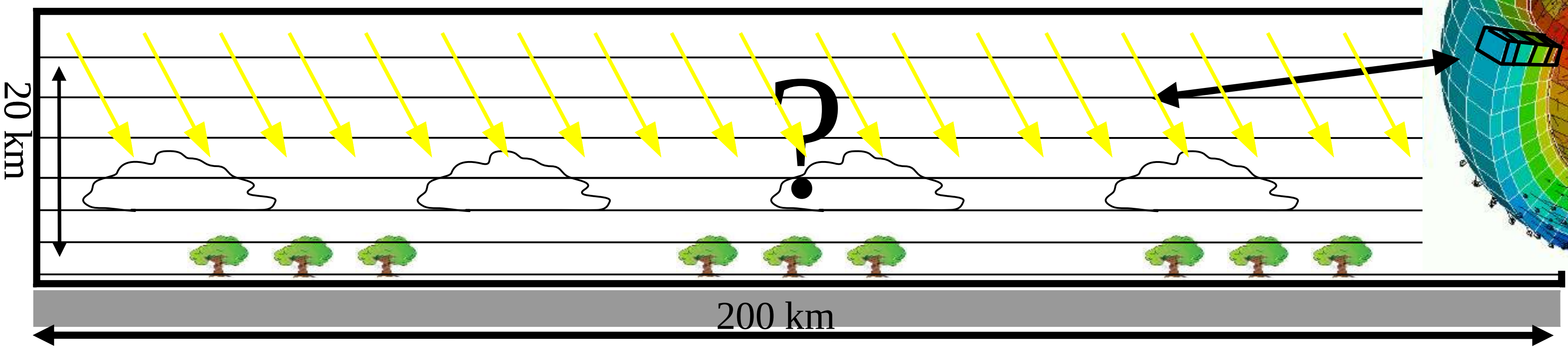
- **Based on a description of the approximate collective behavior** of processes

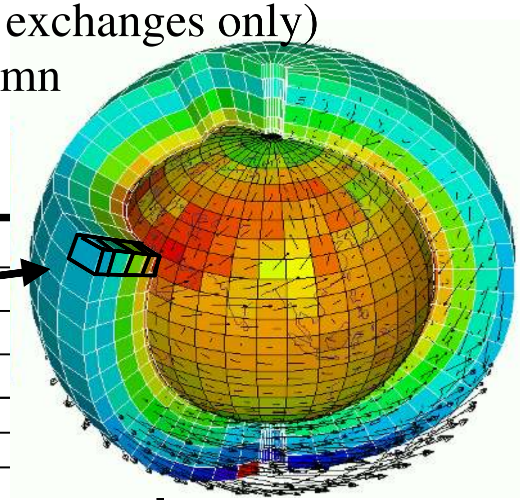
- Involve additional **parameterization internal variables** (cloud characteristics, standard deviation of the sub-grid scale distribution of a variable, …)

- 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 » …





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, Flexibility/Multi-configuration, post-processing

Dynamcial core

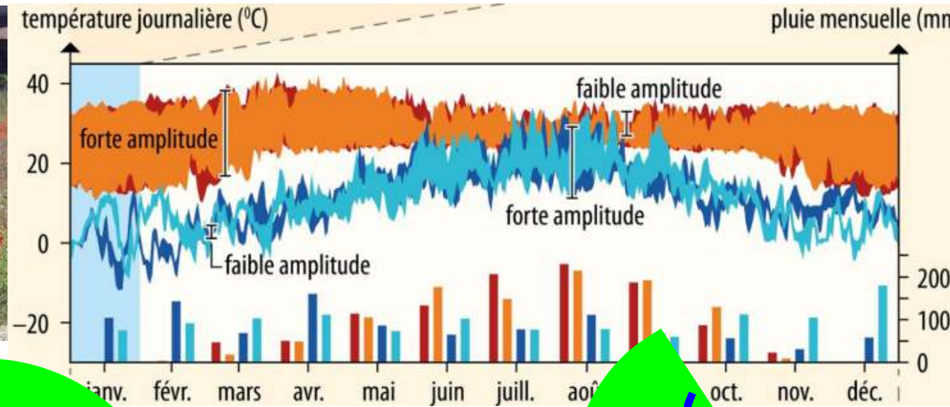
parameterizations

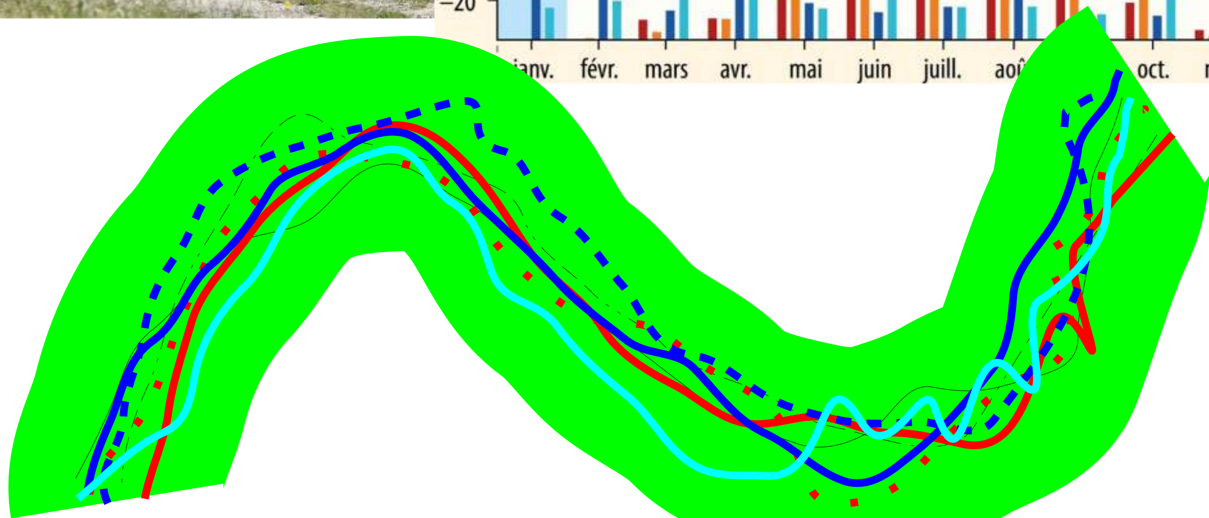
Dynamical core :
Well established equations. Work on approximations, numerics, HPC

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

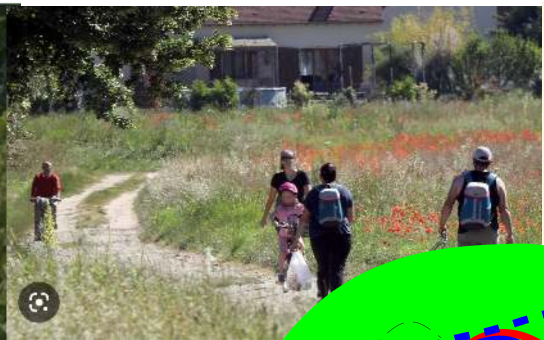
General comments :
- Modeling concerns all the layers. Lot of expertises required and shared.
- Be aware of the layer in which you are working, or at which transition between layers.
- Do not forget that your goal is to explain things in the first layer
- A large expertise and field of research shared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

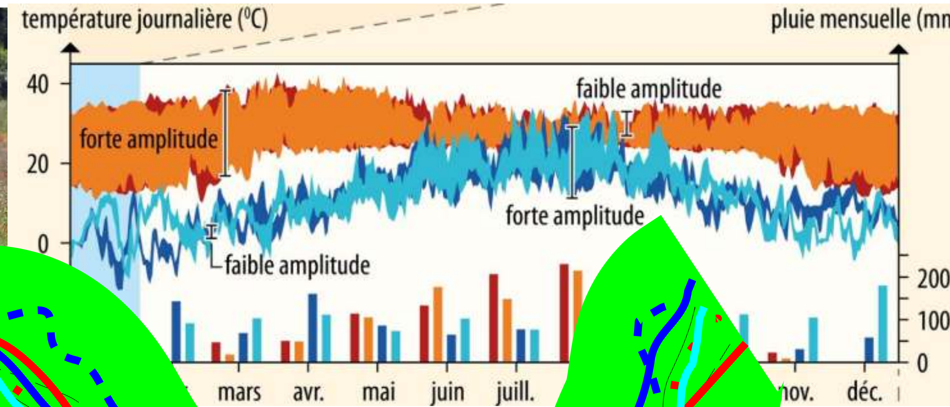
	Climate modeling	Numerical Weather Forecast
Models	Identical (more couplings)	Identical (higher resolution)
Initial state	any	“**analysis**” obtained form an “assimilation” of observations within a model.
Simulation length	decades to centuries	15 days (Seasonal forecast in between)
Prediction	statistical (ex : mean temperature, internal variability of precipitation, heat waves) Strange attractor = climate	deterministic (the weather tomorrow at a given location)

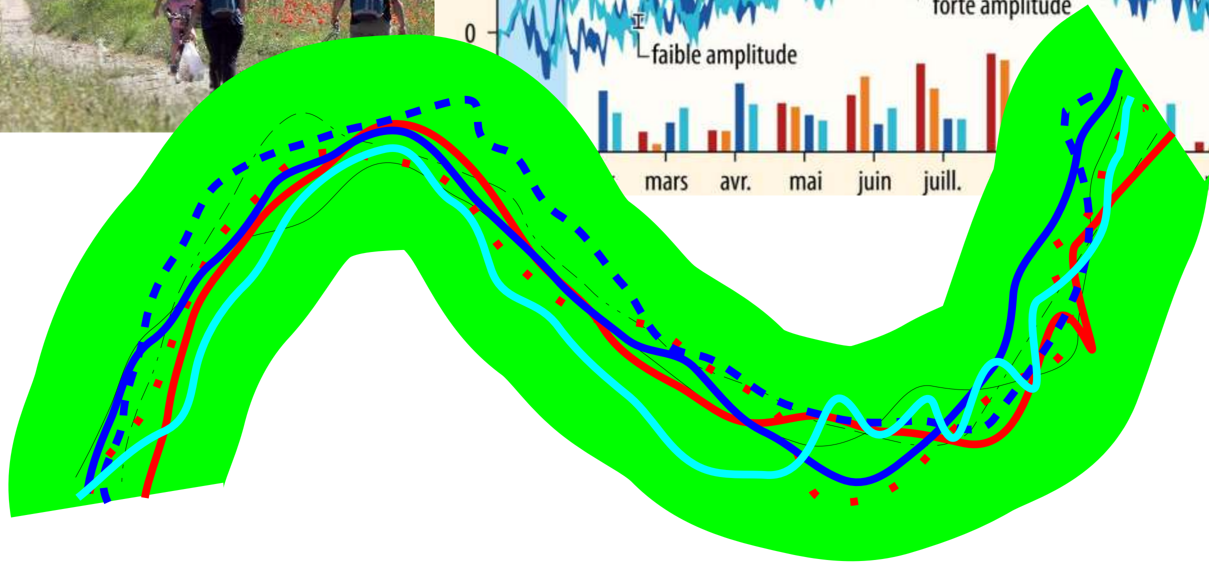




	Climate modeling	Numerical Weather Forecast
Models	Identical (more couplings)	Identical (higher resolution)
Initial state	any	"**analysis**" obtained form an "assimilation" of observations within a model.
Simulation length	decades to centuries	15 days (Seasonal forecast in between)
Prediction	statistical (ex : mean temperature, internal variability of precipitation, heat waves) Strange attractor = climate	deterministic (the weather tomorrow at a given location)







I. LMDZ : a general circulation model

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

2. 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 (Coupled Model Intercomparison Project) 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

2019 : Labélisation outil national « Institut national des sciences de l’Univers » , Insu

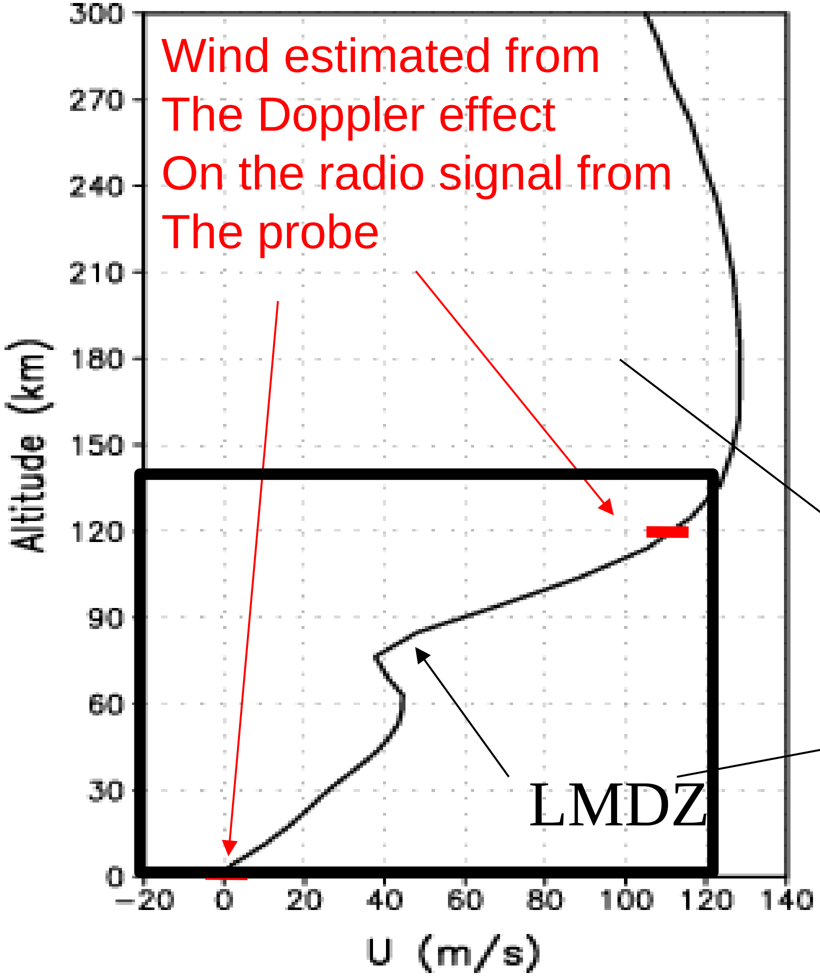
2020 : reference publications

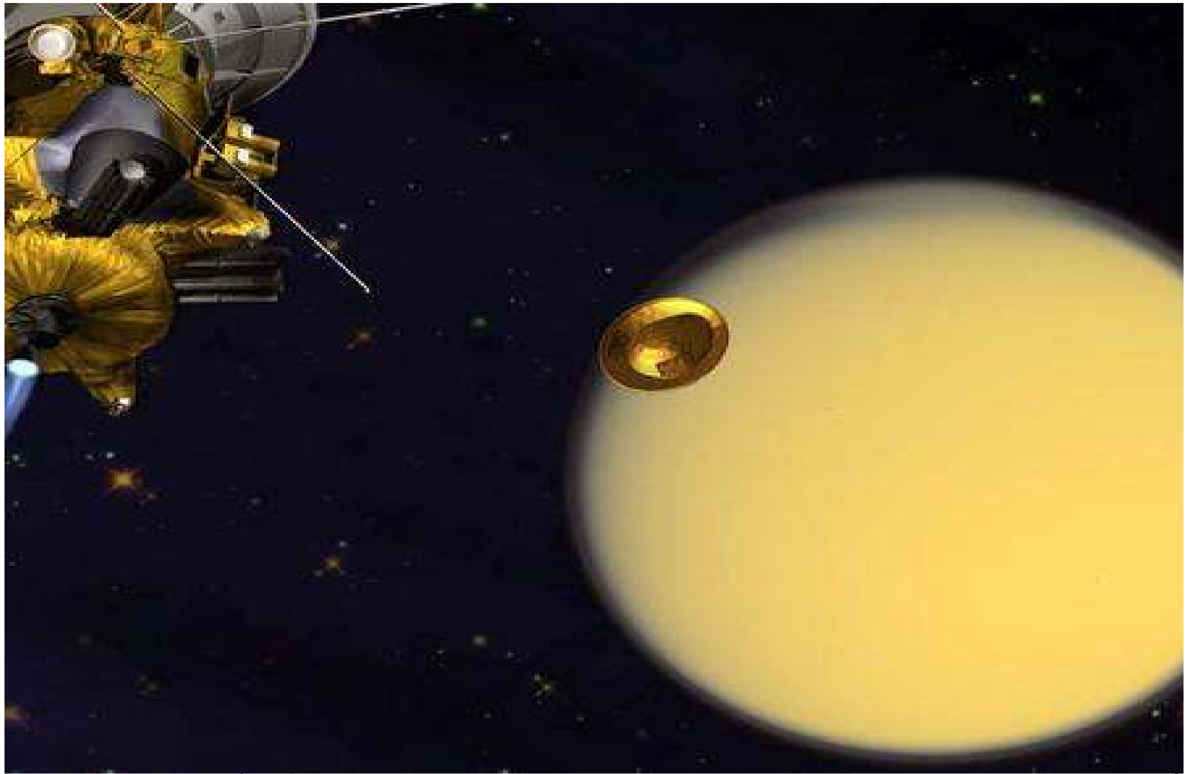
2024 : LAM version

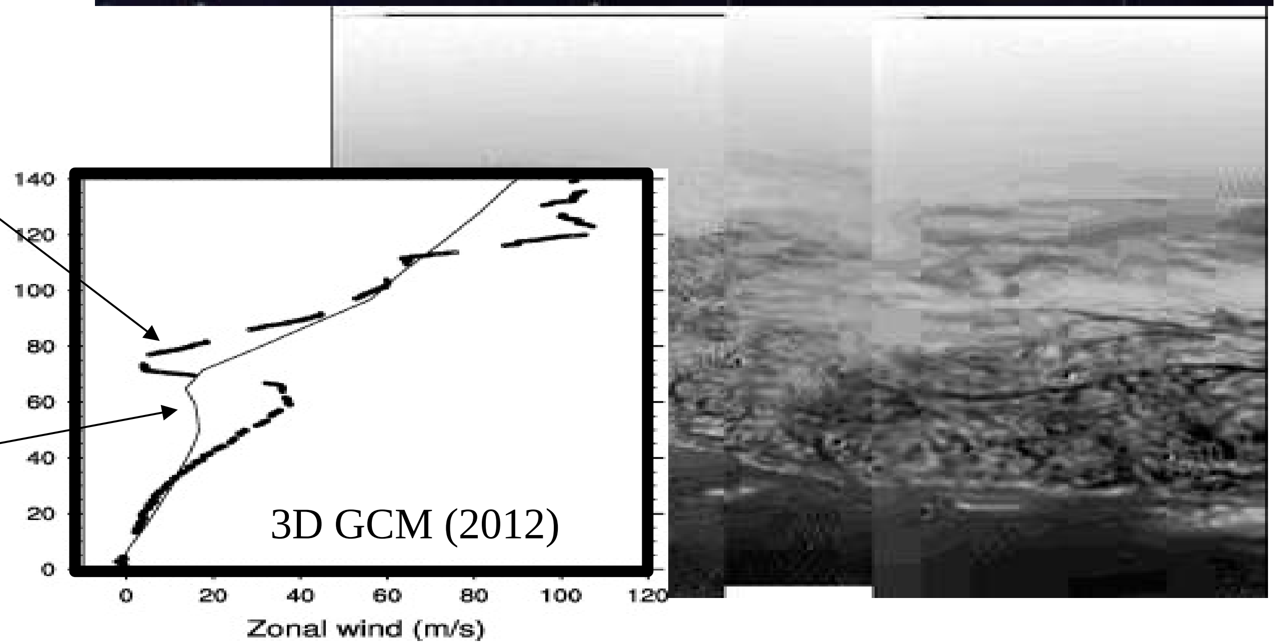
2. LMDZ

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

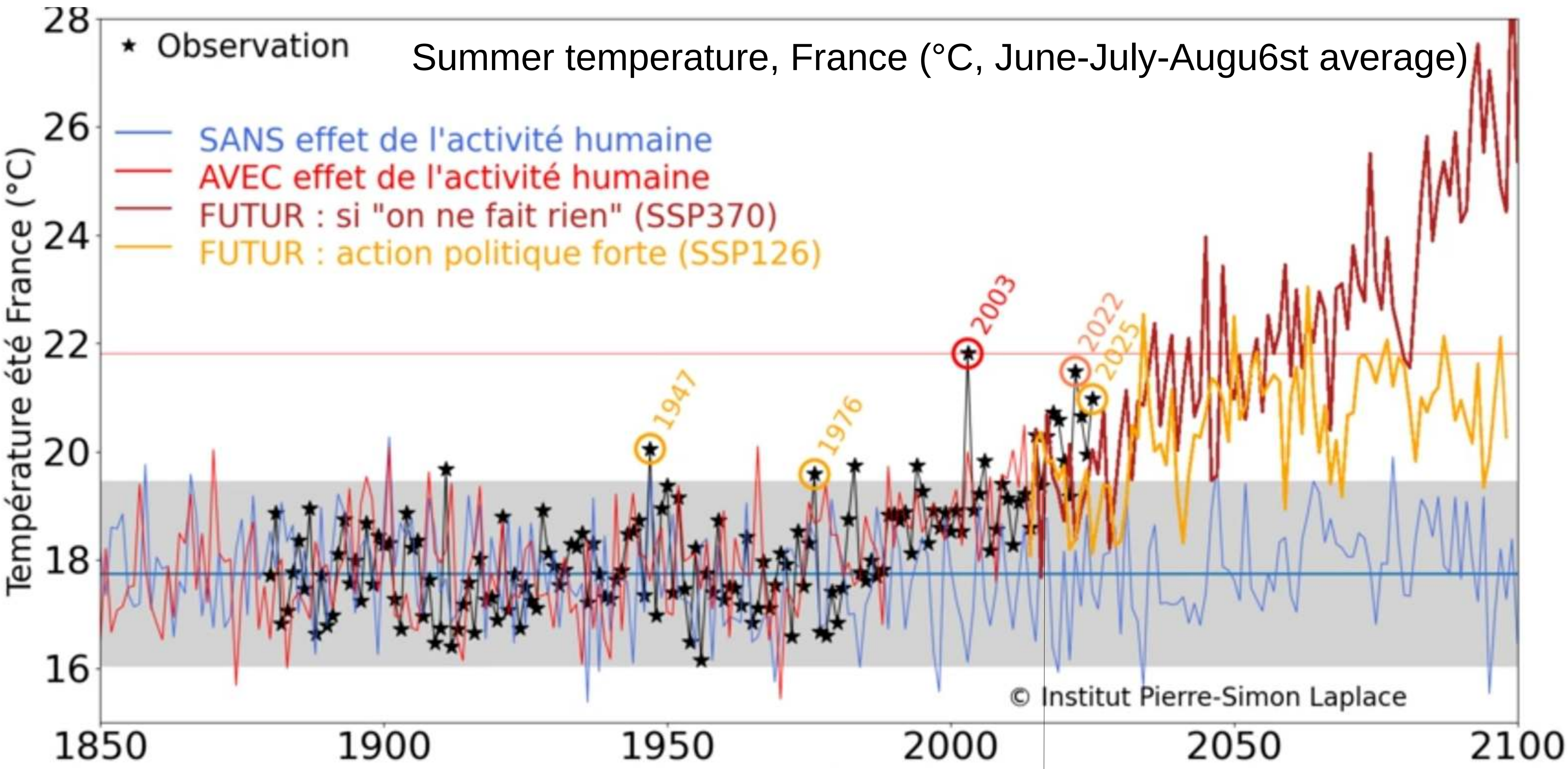






2. LMDZ

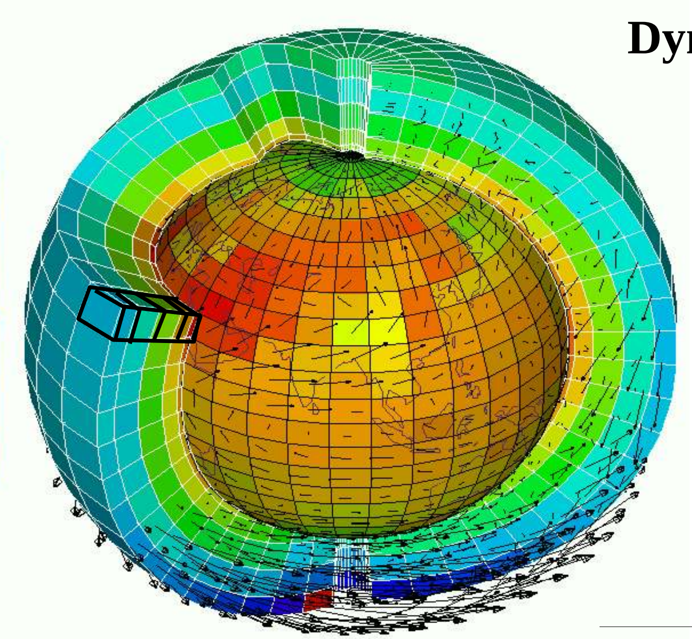
Atmospheric component of the IPSL climate model :
Coupled to ocean, continental surface, chemistry
The terrestrial version is used in particular for climate change projections
Reference versions for the Coupled Model Intercomparison Projects (CMIP)



Reconstruction **Projection**

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

2. LMDZ



Dynamical core : primitive equations discretized on the sphere

- Mass conservation

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

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

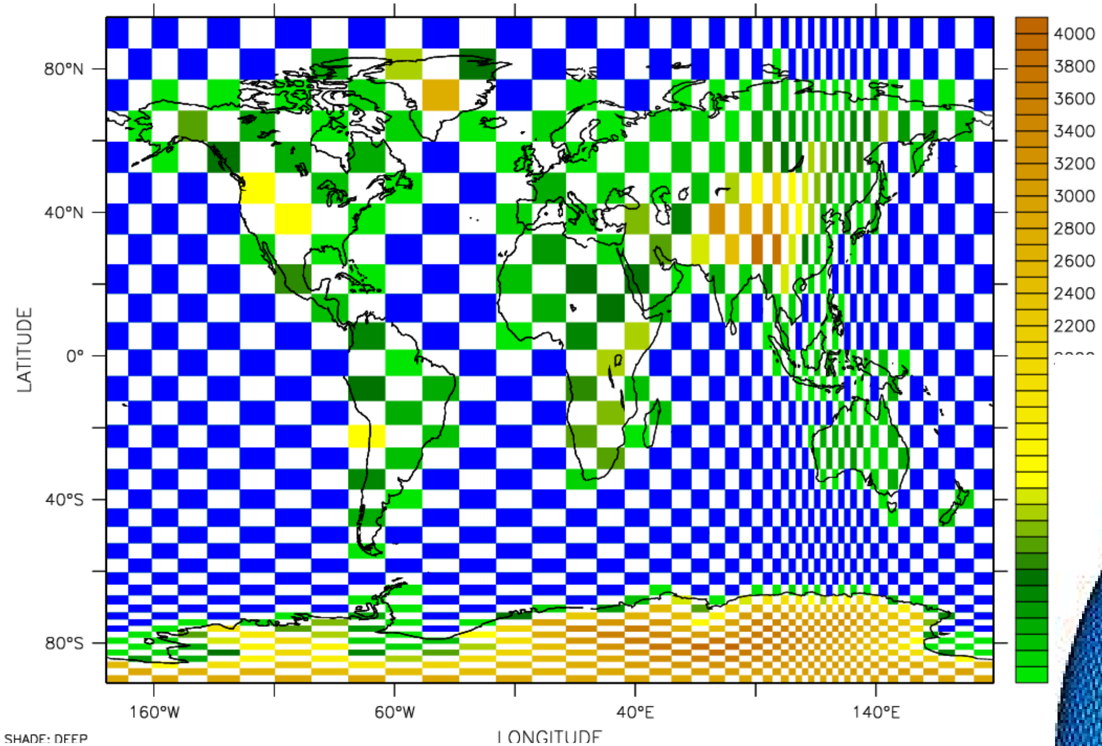
  $D\underline{U}/Dt + (1/\rho) \, \underline{\mathrm{grad}p} - \underline{g} + 2 \, \underline{\Omega} \wedge \underline{U} = \underline{F}$
- Secondary components conservation

  $Dq/Dt = Sq$

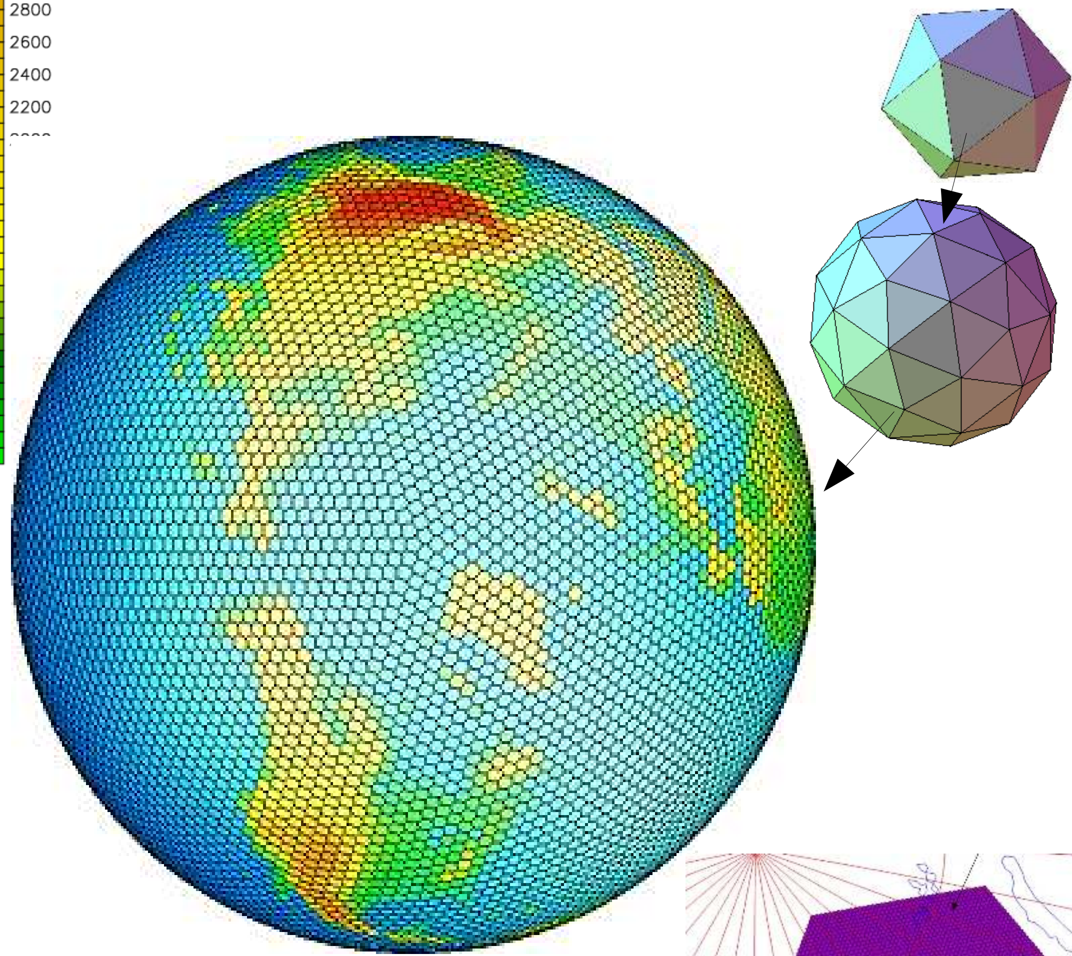
LMDZ dynamical core :

→ Grid point approach
→ Zoom capability (« Z » of « LMDZ »)
→ Finite difference and 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)

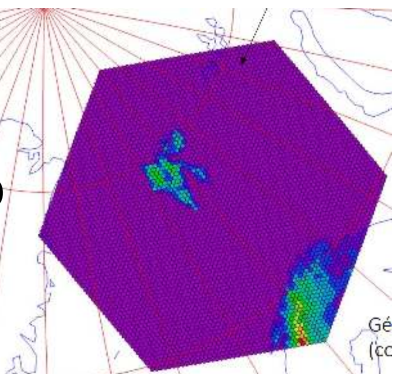
3 dynamical cores now available



LMDZ original longitude-latitude grid :
with **zoom** capability
(Sadourny and Levan, 1984)



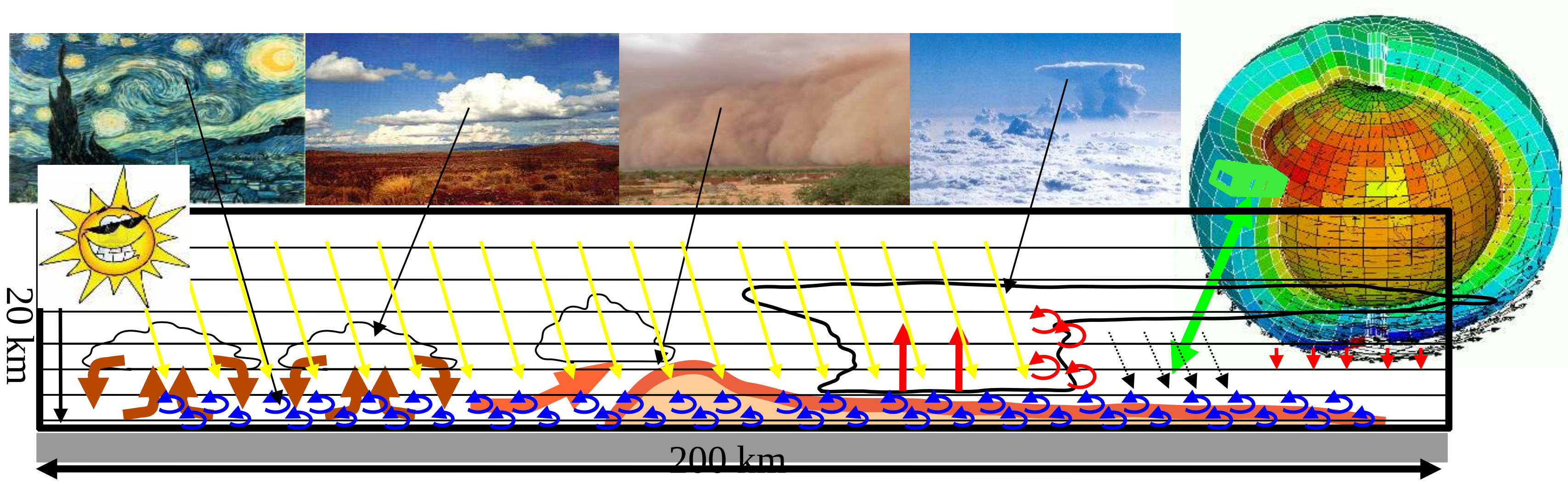
New dynamical core Dynamico
hexagonal grid cells
based on an icosahedron
(Dubos, Meurdesoif et al. 2016)



Limited area (LAM) version of Dynamico
based on hexagonal grid cells
(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

2. LMDZ

Publications concerning the LMDZ « New Physics »

Near surface turbulence :

→ E. Vignon, Hourdin, F., Genthon, Van de Wiel, Bas J. H., C., Gallée, Madeleine, J.-B. And Gallée Hubert., Modeling the Dynamics of the Atmospheric Boundary Layer Over the Antarctic Plateau With a General Circulation Model , https://doi.org/10.1002/2017MS001184, **2018**

→ E. Vignon, Hourdin, F., Genthon, C., Gallée, H. Bazille, E., Lefebvre, M.-P., Madeleine, J.-B. And Van de Wiel, Bas J. H., Antarctic boundary layer parametrization in a generalcirculation model: 1-D simulations facing summerobservations at Dome C, James, **2017**, https://doi.org/10.1002/2017JD026802

Boundary layer convection and clouds :

→ Hourdin, F., Williamson, D., Rio, C., Couvreux, F., Roehrig, E., Villefranque, N., Musat, I., Fairhead, L., Diallo, F. B. and Volodina, V., Process-based climate model development harnessing machine learning: II. model calibration from single column to global, James, vol. 13, no. 6, 2021. doi:10.1029/2020MS002225.

→ Couvreux, F., F. Hourdin, and C. Rio, **2010**, Resolved Versus Parametrized Boundary-Layer Plumes. Part I: A Parametrization-Oriented Conditional Sampling in Large-Eddy Simulations, Boundary-layer Meteorol., 134, 441–458, 2010.

→ Grandpeix, J., and J. Lafore, **2010**, A Density Current Parameterization Coupled with Emanuel's Convection Scheme. Part I: The Models, Journal of Atmospheric Sciences, 67, 881–897, 2010.

→ Hourdin, F., F. Couvreux, and L. Menut, **2002**, Parameterisation of the dry convective boundary layer based on a mass flux representation of thermals, J. Atmos. Sci., 59, 1105–1123, 2002.

→ Hourdin, F., Arnaud J., Rio C., Couvreux F., Sandu I., Lefebvre M.-P., Brient F., and Idelkadi A., Unified Parameterization of Convective Boundary LayerTransport and Clouds With the Thermal Plume Model, James, **2019**, https://doi.org/10.1029/2019MS001666

→ Hourdin, F and Rio, C, Jam A., Traore A.-K. and Musat , I., Convective boundary layer control of the sea surfacetemperature in the tropics, Journal of Advances in Modeling Earth Systems, 12, https://doi.org/10.1029/2019MS001988

→ Rio, C., and F. Hourdin, 2008, A thermal plume model for the convective boundary layer : Representation of cumulus clouds, J. Atmos. Sci., 65, 407–425, **2008**.

→ Rio, C., F. Hourdin, F. Couvreux, and A. Jam, **2010**, Resolved Versus Parametrized Boundary-Layer Plumes. Part II: Continuous Formulations of Mixing Rates for Mass-Flux Schemes, Boundary-layer Meteorol., 135, 469–483, 2010.

→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.**

→ J. Jouhaud, J.-L. Dufresne, J.-B. Madeleine, N. Villefranque, and A. Jam, Accounting for Vertical Subgrid-Scale Heterogeneity inLow-Level Cloud Fraction Parameterizations, James, **2018**, 10.1029/2018MS001379

→ Locatelli, R., P. Bousquet, F. Hourdin, M. Saunois, A. Cozic, F. Couvreux, J.-Y. Grandpeix, M.-P. Lefebvre, C. Rio, P. Bergamaschi, S. D. Chambers, U. Karstens, V. Kazan, S. van der Laan, H. A. J. Meijer, J. Moncrieff, M. Ramonet, H. A. Scheeren, C. Schlosser, M. Schmidt, A. Vermeulen, and A. G. Williams, , **2015,** Atmospheric transport and chemistry of trace gases in LMDz5B: evaluation and implications for inverse modelling doi:10.5194/gmd-8-129-2015

Deep Convection, wake and coupling with boundary layer :

→ Hourdin, F., I. Musat, S. Bony, P. Braconnot, F. Codron, J.-L. Dufresne, L. Fairhead, M.-A. Filiberti, P. Friedlingstein, J.-Y. Grandpeix, G. Krinner, P. Levan, Z.-X. Li, and F. Lott, 2006, The LMDZ4 general circulation model: climate performance and sensitivity to parametrized physics with emphasis on tropical convection, Climate Dynamics, 27, 787–813, 2006.

→ Grandpeix, J. Y., V. Phillips, and R. Tailleux, 2004, Improved mixing representation in Emanuel's convection scheme, Q. J. R. Meteorol. Soc., 130, 3207–3222, 2004.

→ Grandpeix, J., J. Lafore **2010**, A Density Current Parameterization Coupled with Emanuel's Convection Scheme. Part I Journal of Atmospheric Sciences, 67, 898–922, 2010.

→ Grandpeix, J., J. Lafore, and F. Cheruy, 2010, A Density Current Parameterization Coupled with Emanuel's Convection Scheme. Part II: 1D Simulations, Journal of Atmospheric Sciences, 67, 898–922, **2010**.

→ Rio, C., F. Hourdin, J. Grandpeix, and J. Lafore, 2009, Shifting the diurnal cycle of parameterized deep convection over land, Geophys. Res. Lett., 36, 7809–+, **2009**.

→ Rio, C., J.-Y. Grandpeix, F. Hourdin, F. Guichard, F. Couvreux, J.-P. Lafore, A. Fridlind, A. Mrowiec, R. Roehrig, N. Rochetin, M.-P. Lefebvre, and A. Idelkadi, 2013, Control of deep convection by sub-cloud lifting processes: the ALP closure in the LMDZ5B general circulation model, Clim. Dyn., 40, 2271–2292, **2013.**

→ N Rochetin, JY Grandpeix, C Rio, F Couvreux, Deep convection triggering by boundary layer thermals. Part II: Stochastic triggering parameterization for the LMDZ GCM.Jas 71 (2), 515-538

→ N Rochetin, F Couvreux, JY Grandpeix, C Rio, Deep convection triggering by boundary layer thermals. Part I: LES analysis and stochastic triggering formulation Jas 71 (2), 496-514

2. LMDZ

Publication of reference configurations :

→ Rémy Bonnet, Didier Swingedouw, Guillaume Gastineau, Olivier Boucher, Julie Dehayes, Frédéric Hourdin, Juliette Mignot, Jérôme servonnat, Adriana Sima Increased risk of near term global warming due to a
recent AMOC weakening, Nature, https://doi.org/10.1038/s41467-021-26370-0

→ Rémy Bonnet, Olivier Boucher, Julie Dehayes, Guillaume Gastineau, Frédéric Hourdin, Juliette Mignot, Jérôme servonnat, Didier Swingedouw The Presentation and Evaluation of the IPSL-CM6A-LR Ensemble of Extended Historical Simulations, James, vol. 13, no. 9, 2021. doi:10.1029/2021MS002565.

→Mignot, J., Hourdin, F., Deshayes, J., Boucher, O., Gastineau, G., Musat, I., Vancoppenolle, M., Servonnat, J., Caubel, A., Chéruy, C., Denvil , S., Dufresne, J.-L., Ethé, C., Fairhead, L., Foujols, M.-A., Grandpeix, J.-Y., Levavasseur, L., Marti, O., Menary, M., Rio, C. and Rousset, C. The tuning strategy of IPSL-CM6A-LR, James, vol. 13, no. 5, 2021. doi:10.1029/2020MS002340.

→ Hourdin, F., J.-Y. Grandpeix, C. Rio, S. Bony, A. Jam, F. Cheruy, N. Rochetin, L. Fairhead, A. Idelkadi, I. Musat, J.-L. Dufresne, A. Lahellec, M.-P. Lefebvre, and R. Roehrig, 2013b, **LMDZ5B: the atmospheric component of the IPSL climate model with revisited parameterizations for clouds and convection**, Clim. Dyn., 40, 2193–2222, 2013b.

→ Hourdin, F., C. Rio, J.-Y. Grandpeix, J.-B. Madeleine, F. Cheruy, N. Rochetin, A. Jam, I. Musat, A. Idelkadi, L. Fairhead, M.-A. Foujols, L. Mellul, A. Traore, J.-L. Dufresne, O. Boucher, M.-P. Lefebvre, E. Millour, E. Vignon, J. Jouhaud, B. Diallo, F. Lott, G. Gastineau, A. Caubel, Y. Meurdesoif, and J. Ghattas, **LMDZ6A: the atmospheric component of the IPSL climate model with improved and better tuned physics**, James, http://dx.doi.org/10.1029/2019MS001892

→ Madeleine, Jean-Baptiste, Frédéric Hourdin, Jean-Yves Grandpeix, Catherine Rio, Jean-Louis Dufresne, Dimitra Konsta, Ionela Musat, Abderrahmane Idelkadi, Laurent Fairhead, Ehouarn Millour, Marie-Pierre Lefebvre, Lidia Mellul, Frédérique Cheruy, Olivier Boucher, Etienne Vignon, Nicolas Rochetin, Florentin Lemonnier, Ludovic Touzé-Peiffer and Marine Bonazzola, **Improved representation of clouds in the LMDZ6A Global Climate Model**, James, 10.1029/2020MS002046

→ Cheruy, F., A. Ducharne, F. Hourdin, I. Musat, E. Vignon, G. Gastineau, V. Bastrikov, N. Vuichard, B. Diallo, J.-L. Dufresne, J. Ghattas, J.-Y. Grandpeix, L. Idelkadi, A. Mellul, F. Maignan, M. Menegoz, C. Ottlé, P. Peylin, F. Wang, and Z. Yanfeng,
Improved near surface continental climate in IPSL-696 CM6A-LR by combined evolutions of atmospheric and land surface physics, James, doi:10.1029/2019MS002005

→ *F. B. Diallo 1 , F. Hourdin 1 , C. Rio 2 , A.-K. Traore 1 , L. Mellul 1 , F. Guichard 2 and L. Kergoat 3,*
The surface energy budget computed at the grid-scale of aclimate model challenged by station data in West Africa, *James,*
https://doi.org/10.1002/2017MS001081*, 2017*

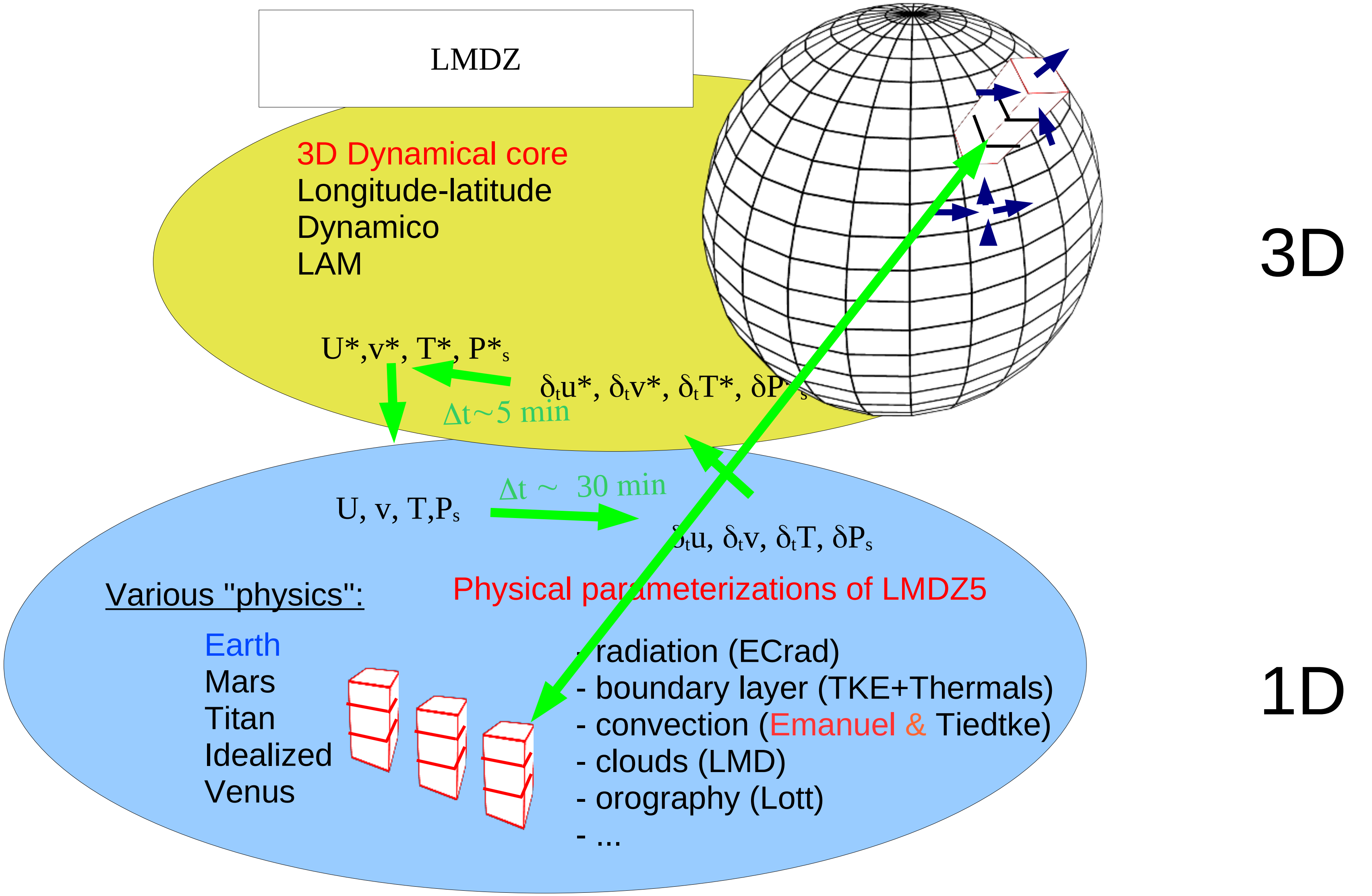
→ Boucher, O., J. Servonnat, A. L. Albright, O. Aumont, Y. Balkanski, V. Bastrikov, S. Bekki, R. Bonnet, S. Bony, L. Bopp, P. Braconnot, P. Brockmann, P. Cadule, A. Caubel, F. Cheruy, A. Cozic, D. Cugnet, F. Dandrea, P. Davini, C. de Lavergne, S. Denvil, J. Deshayes, M. Devilliers, A. Ducharne, J. Dufresne, E. Dupont, C. Éthé, L. Fairhead, L. Falletti, M.-A. Foujols, S. Gardoll, G. Gastineau, J. Ghattas, J.-Y. Grandpeix, B. Guenet, L. Guez, E. Guilyardi, M. Guimberteau, D. Hauglustaine, F. Hourdin, A. Idelkadi, S. Joussaume, M. Kageyama, M. Khodri, G. Krinner, N. Lebas, G. Levavasseur, C. Lévy, L. Li, F. Lott, T. Lurton, S. Luyssaert, G. Madec, J.-B. Madeleine, F. Maignan, M. Marchand, O. Marti, L. Mellul, Y. Meurdesoif, J. Mignot, . Ionela, C. Ottlé, P. Peylin, Y. Planton, J. Polcher, C. Rio, C. Rousset, P. Sepulchre, A. Sima, D. Swingedouw, R. Thiéblemont, A. Traoré, M. Vancoppenolle, J. Vial, J. Vialard, N. Viovy, and N. Vuichar,**Presentation and evaluation of the IPSL-CM6A-LR climate model,**

→ Frédéric Hourdin, Daniel Williamson, Catherine Rio, Fleur Couvreux, Romain Roehrig, Najda Villefranque, Ionela Musat, Laurent Fairhead, F. Binta Diallo, Victoria Volodina, **Process-based climate model development harnessing machine learning: II. model calibration from single column to global,** Accepté par James

→ Gastineau, G., Lott, F., Mignot, J., Hourdin, F., Alleviation of an Arctic Sea Ice Bias in a Coupled Model Through Modications in the Subgrid ScaleOrographic Parameterization, James, https://doi.org/10.1029/2020MS002111

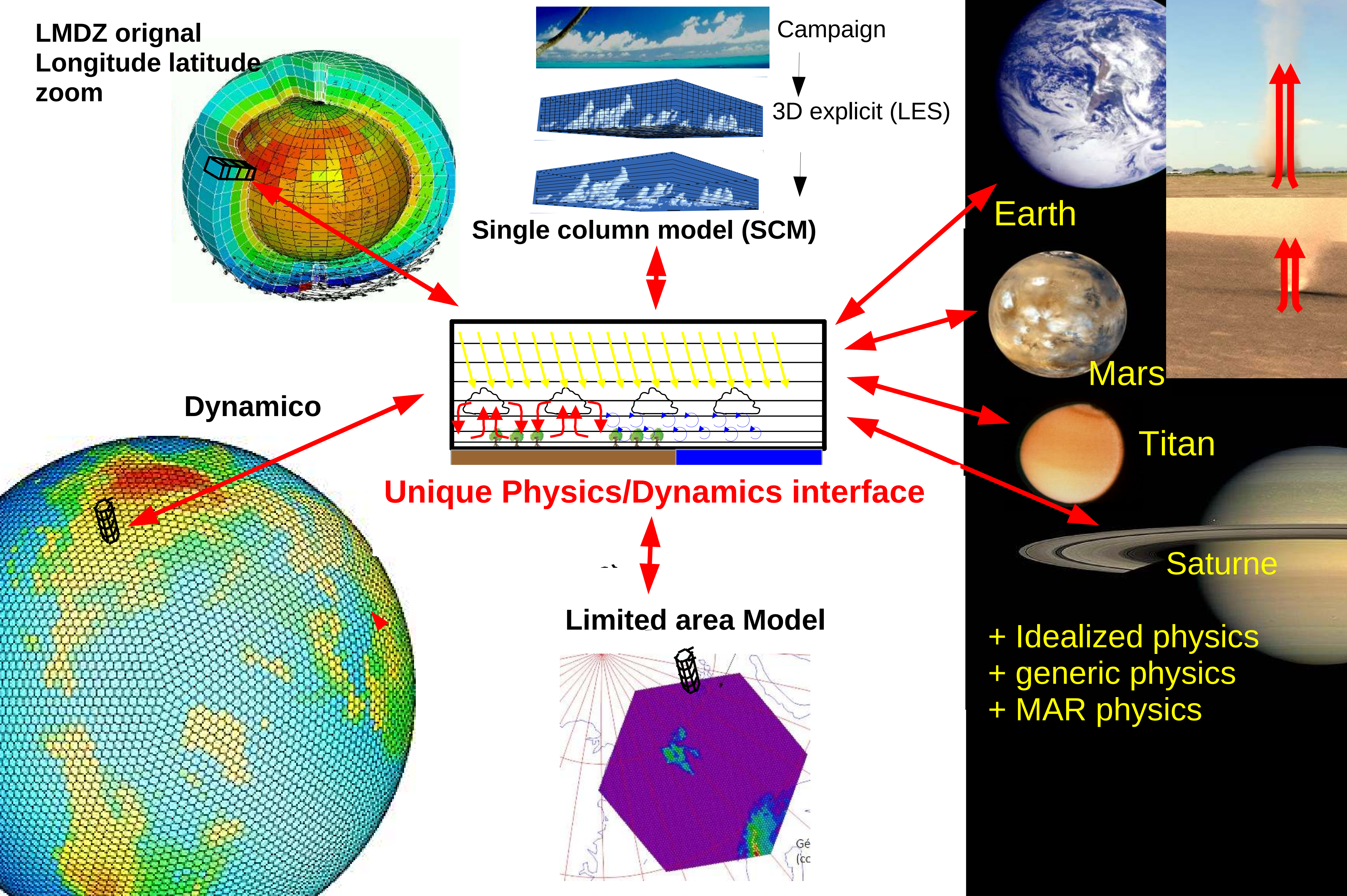
I. LMDZ : a general circulation model
    1. General Circulation Models
    2. LMDZ
    3. Splitting/coupling and modularity

3. Splitting / coupling and modularity

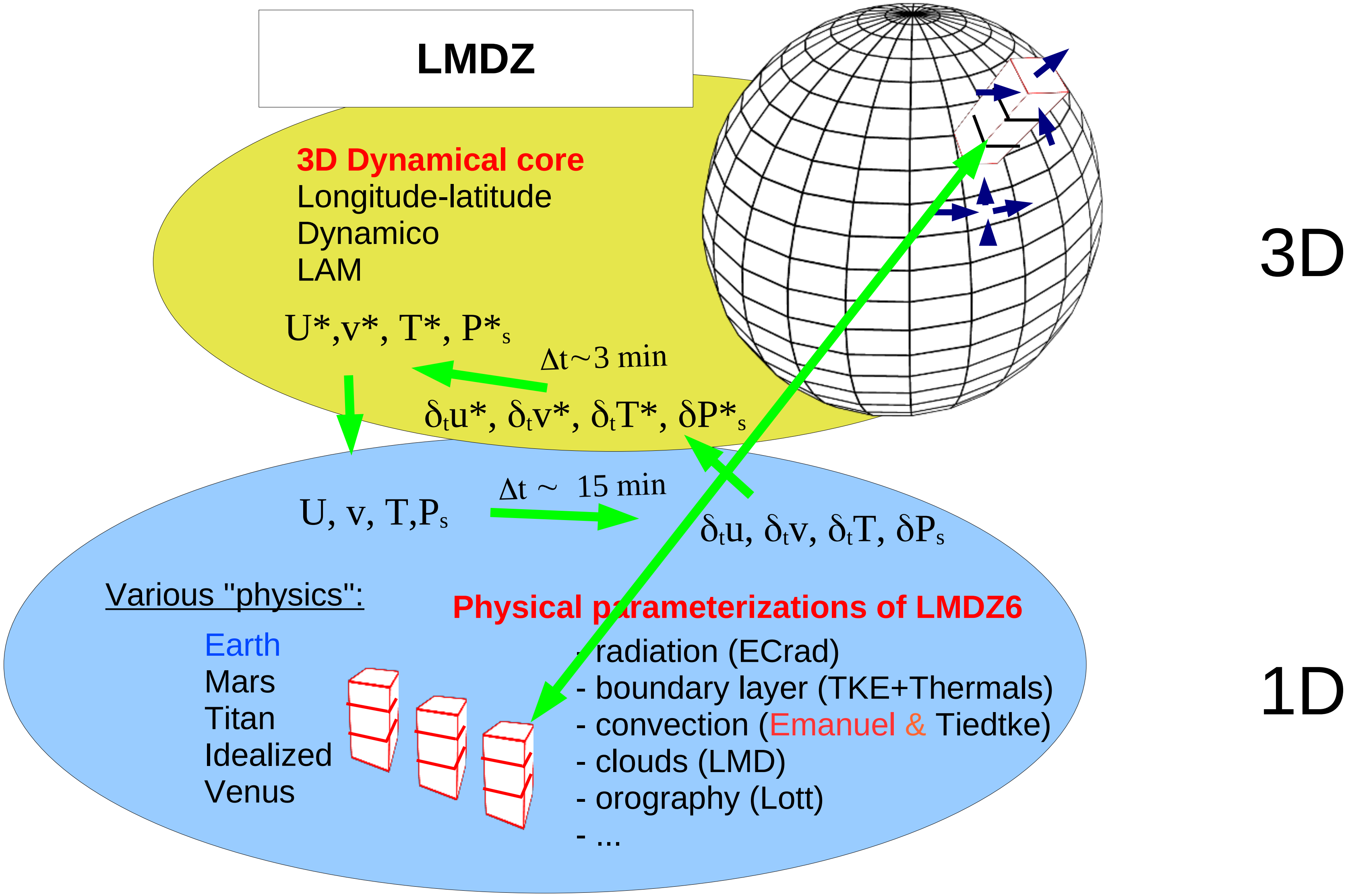


Using the 1D nature of the parameterizations to clearly separate two worlds
Helps a lot for parameterization development and test

3. Splitting / coupling and modularity

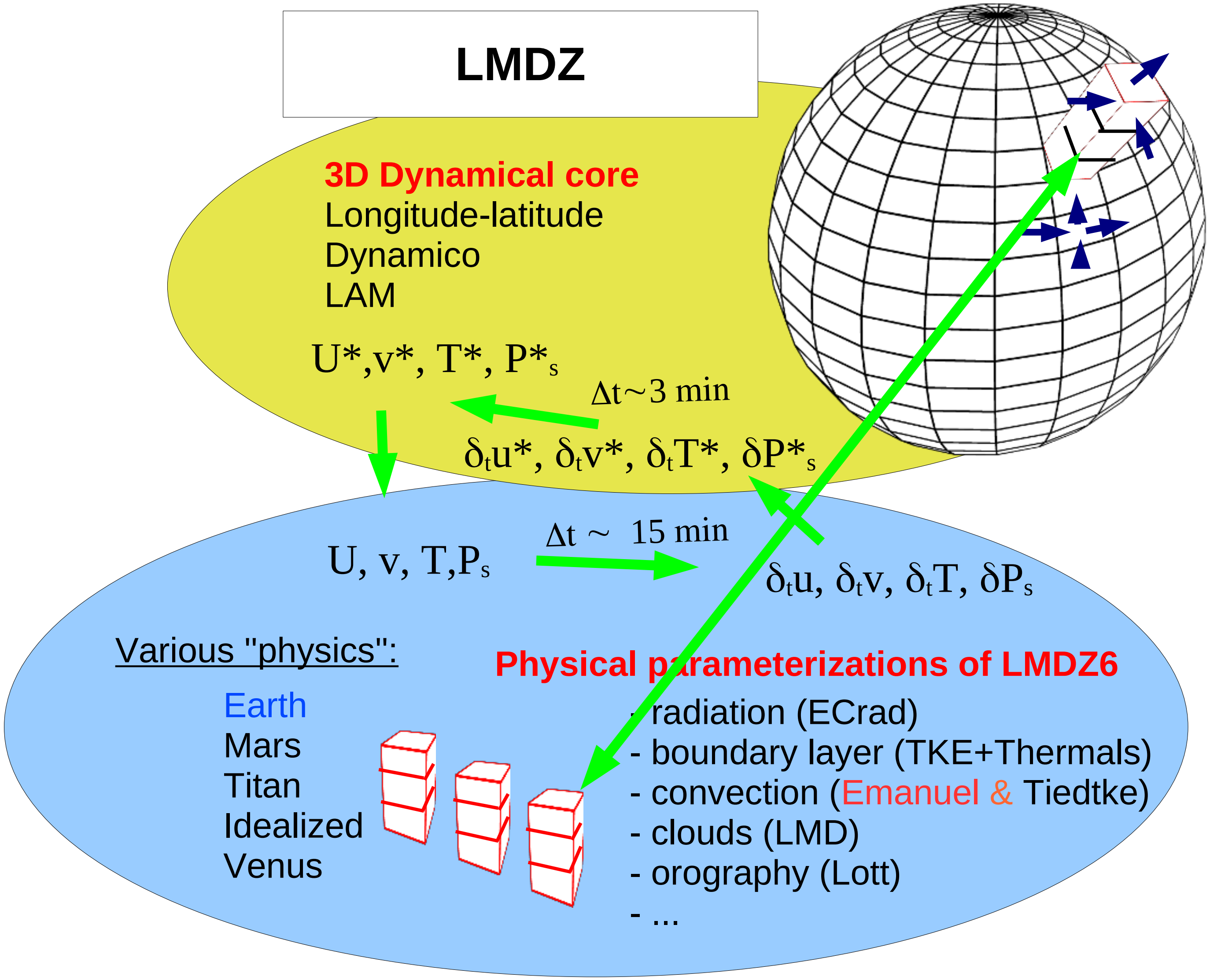


3. Splitting / coupling and modularity

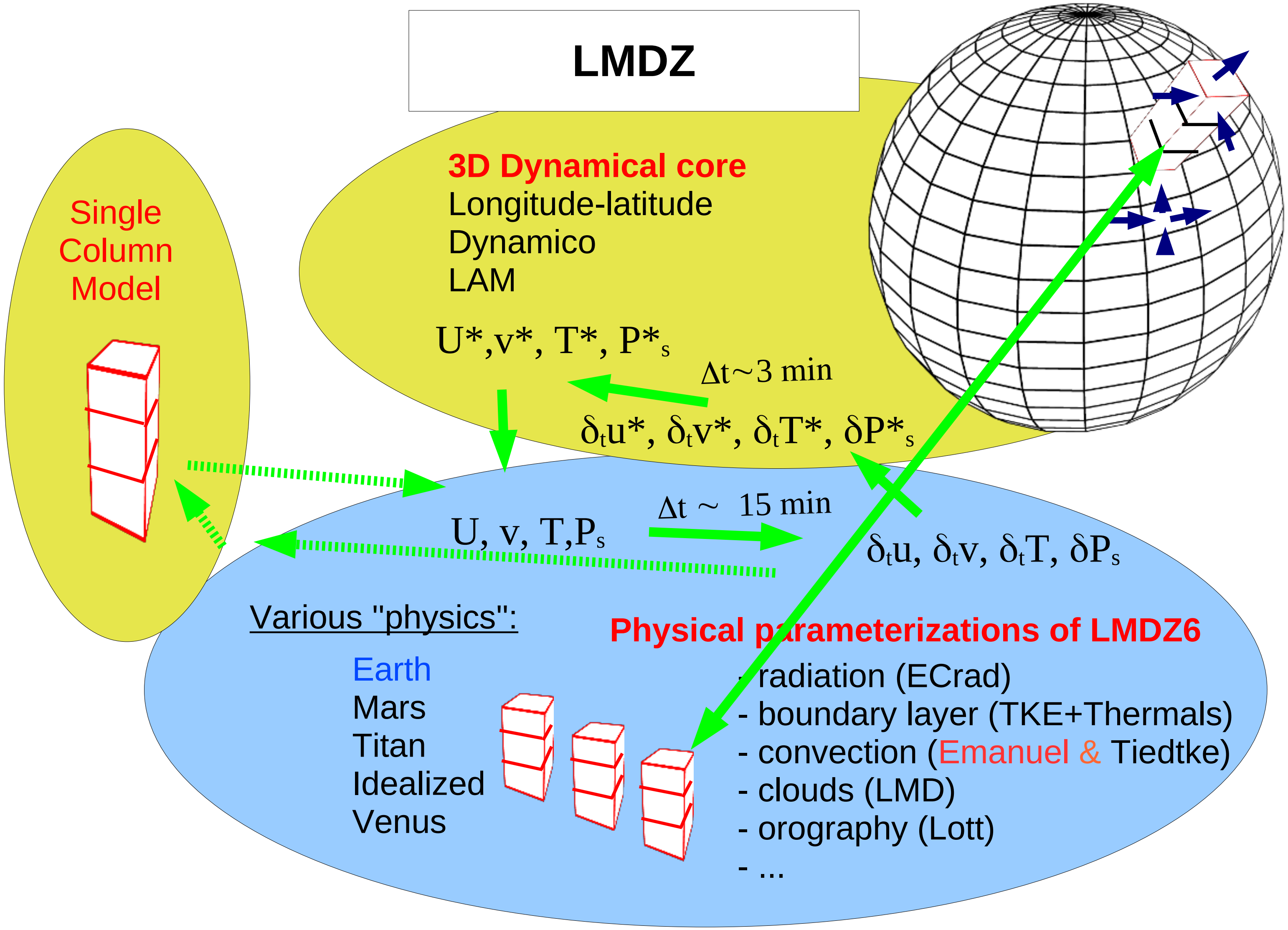


Using the 1D nature of the parameterizations to clearly separate two worlds
Helps a lot for parameterization development and test

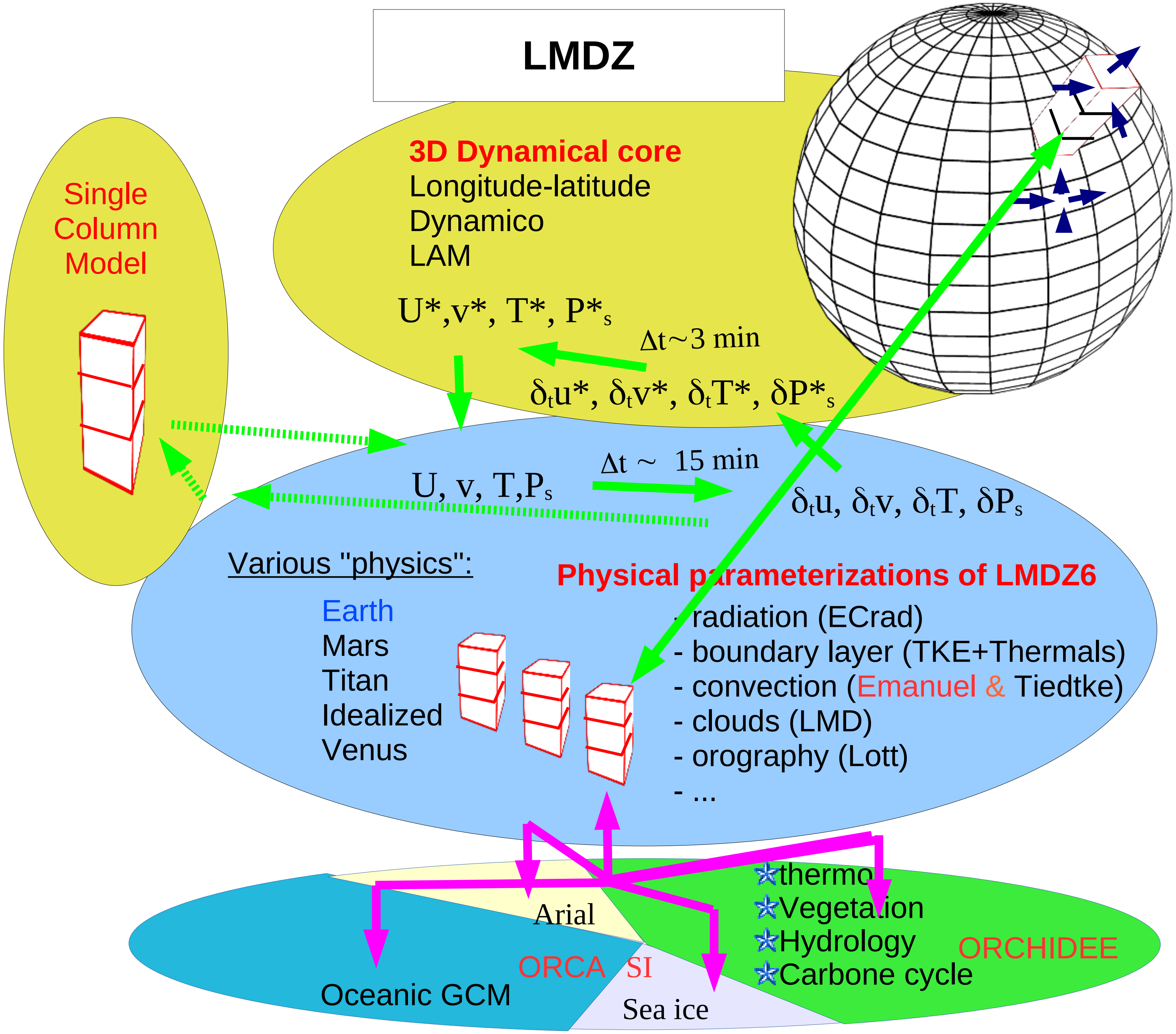
3. Splitting / coupling and modularity



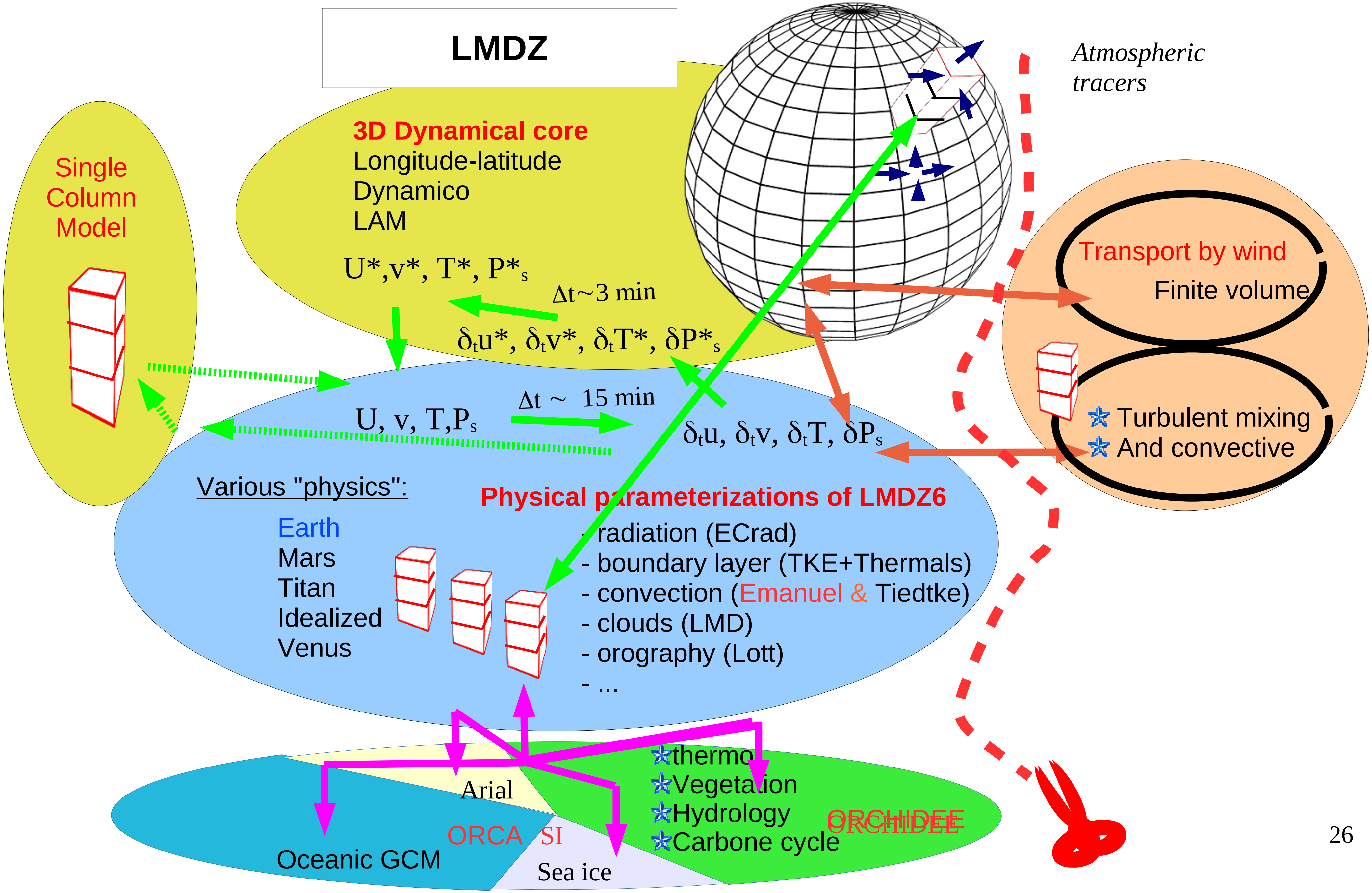
3. Splitting / coupling and modularity



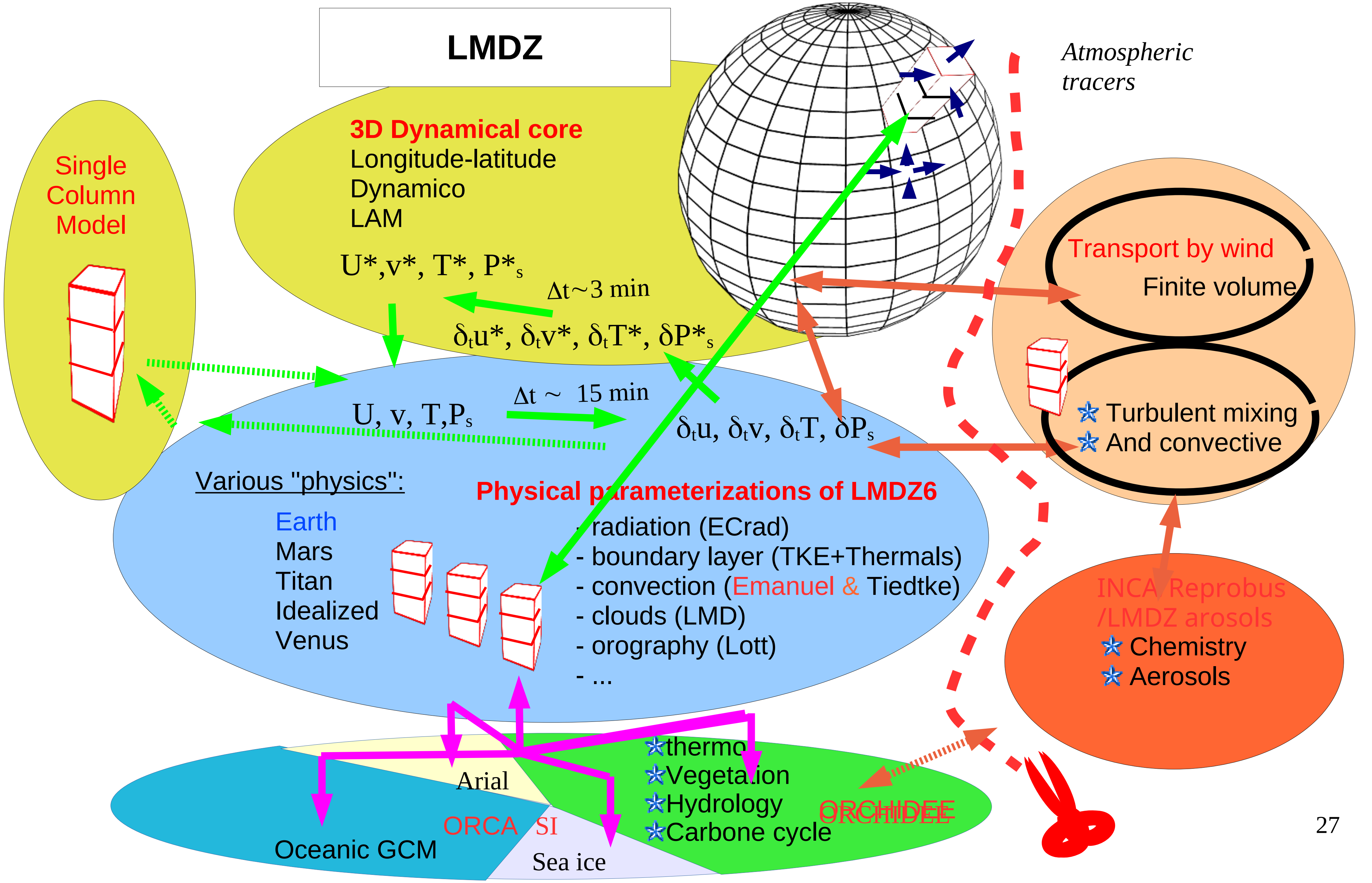
3. Splitting / coupling and modularity



3. Splitting / coupling and modularity



3. Splitting / coupling and modularity



LMDZ to summarize

1. Made of 2 well distinct parts :
Dynamical core, 3D AND physical parameterizations, N x 1D

2. Coupling with chemistry, 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 global with longitude latitude with zoom (longitude and latitude)
3D global icosahedral grid (Dynamico) with zoom (Schmidt transformation)
3D regional
Nudging (eg. by meteorological reanalysis)
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