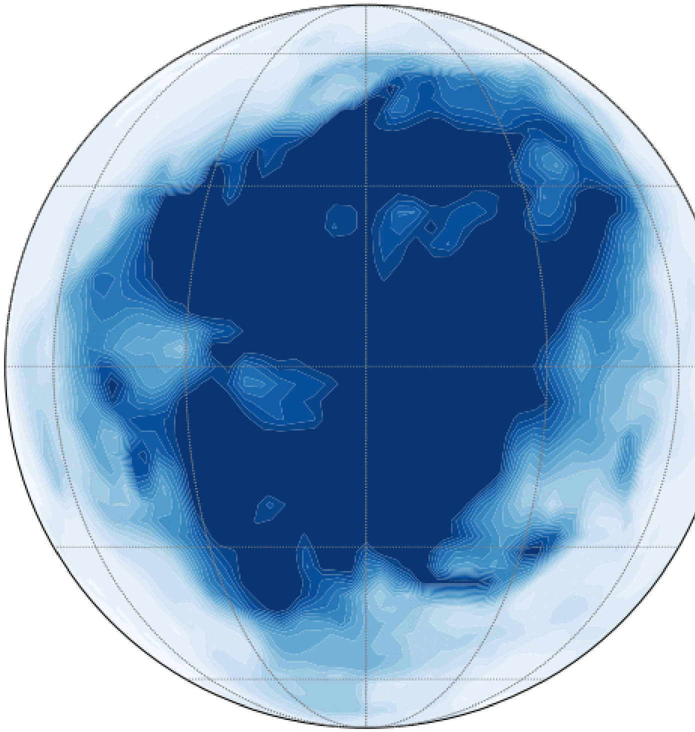
Numerical modelling of planetary atmospheres and climates



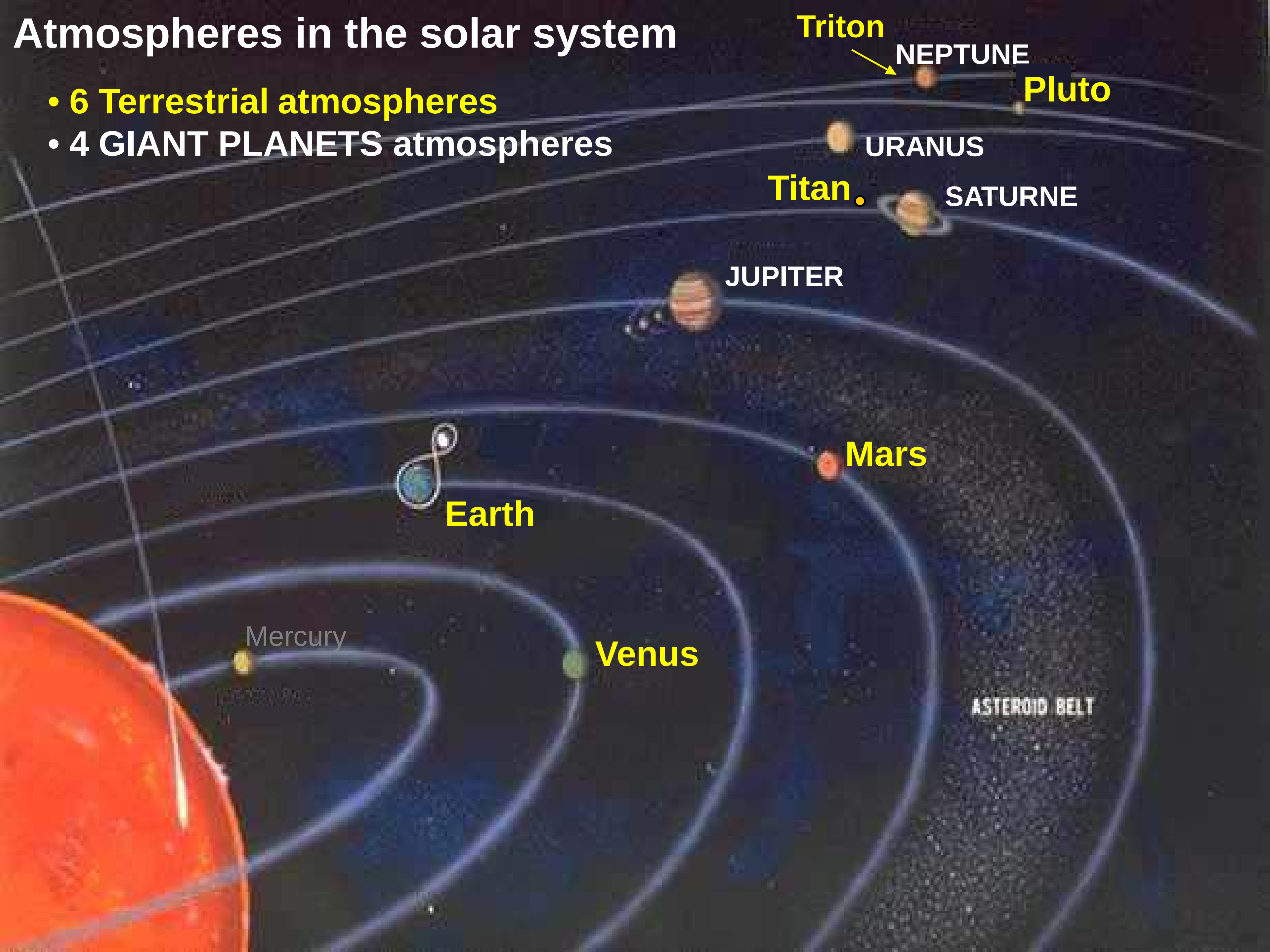
Modeled Cloud pattern on a tidally locked
planet around a M dwarf star
LMD GCM. J. Leconte

François Forget,
Ehouarn Millour, Aymeric Spiga,
Sébastien Lebonnois and the LMD GCMs
team.

CNRS, Institut Pierre Simon Laplace,
Laboratoire de Météorologie Dynamique, Paris

Atmospheres in the solar system

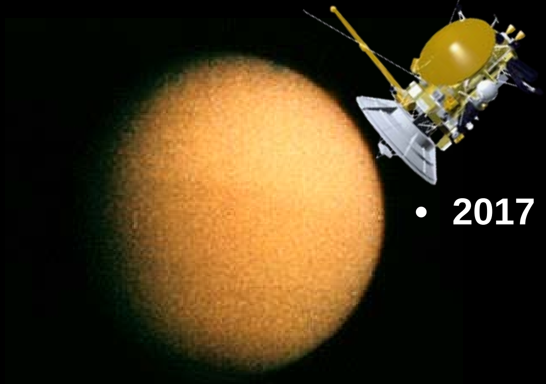
- 6 Terrestrial atmospheres
- 4 GIANT PLANETS atmospheres



VENUS: <Ts> > 450˚C
Ps = 90 bars
Distance to Sun=0.82 AU

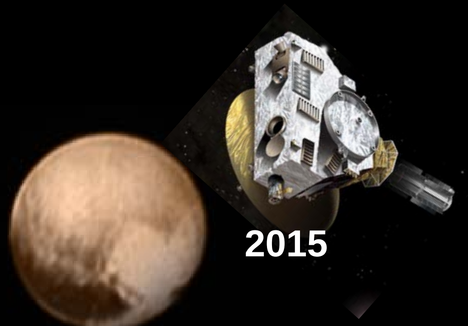
EARTH: <Ts> ~ 15˚C
Ps=1 bar
Distance to sun=1. AU

MARS: <Ts> < -70˚C
Ps = 0.006 bar
Distance to sun=1.52AU



TITAN: <Ts> ~ -180˚C
Ps = 1.5 bars
Distance to Sun=9.53 AU

TRITON: <Ts> ~ -235˚C
Ps = ~2 Pa
Distance to Sun=30 AU

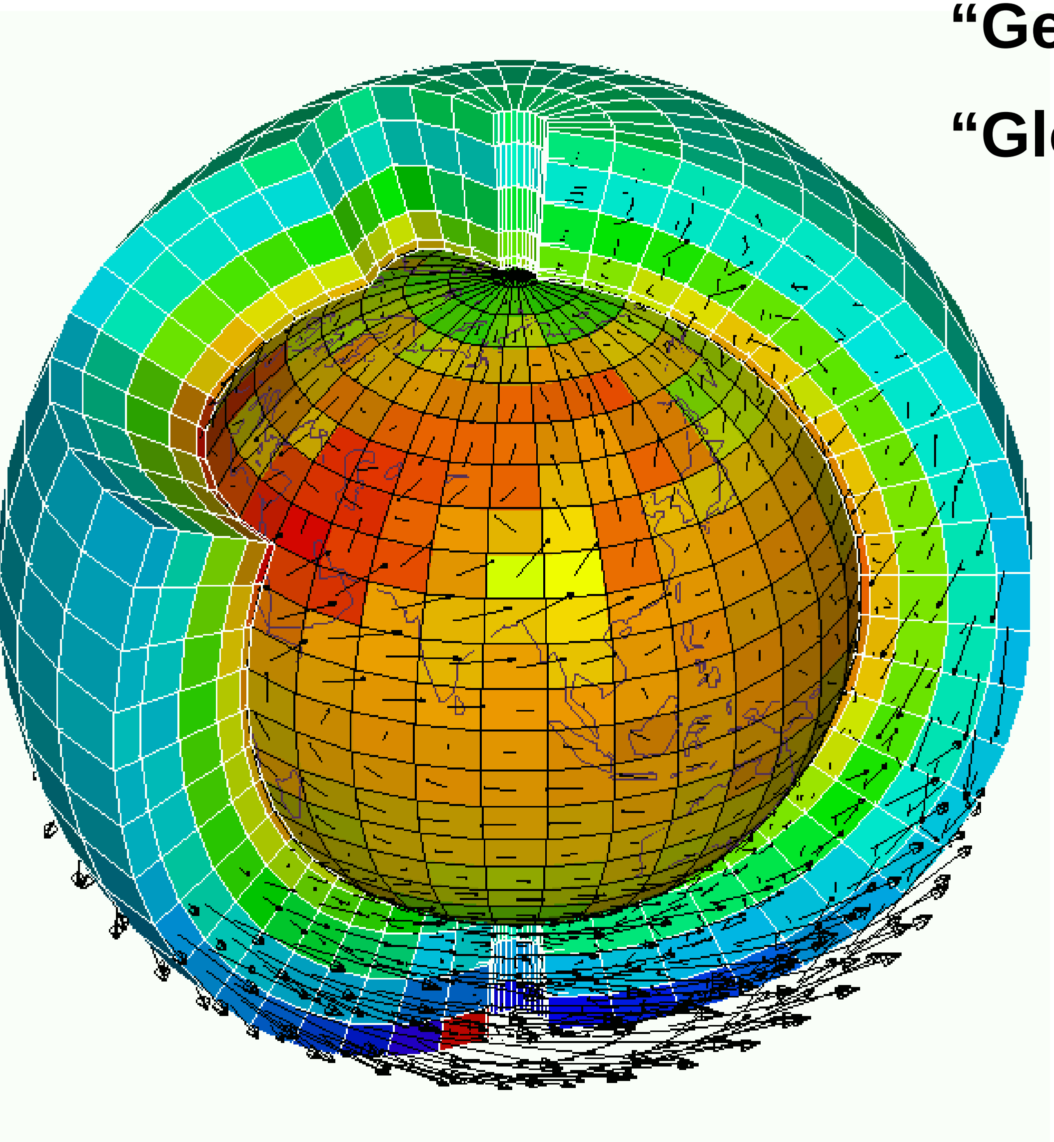


PLUTO: <Ts> ~ -230˚C
Ps = ~1 Pa
Distance to Sun=30-50 AU

GCM

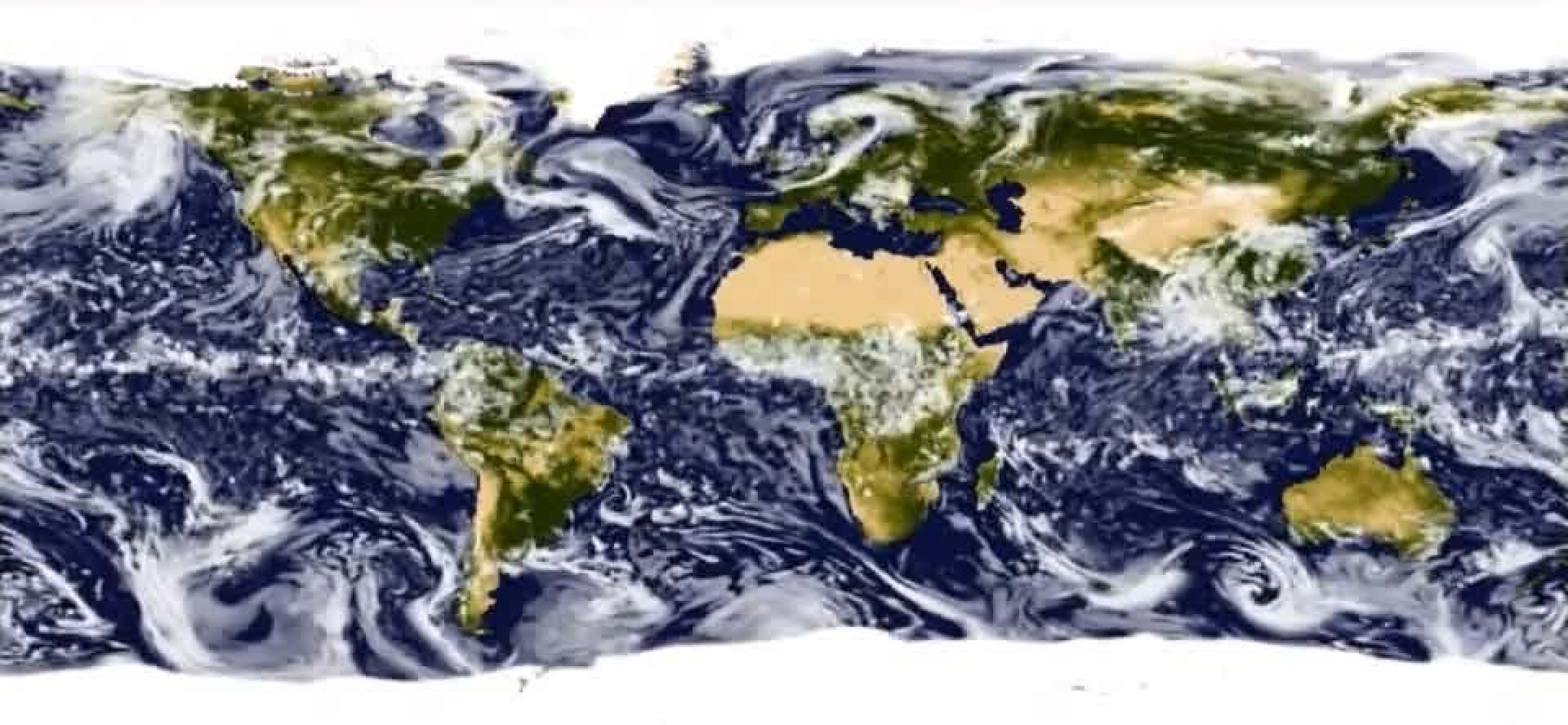
“General Circulation Model”

“Global Climate Model”

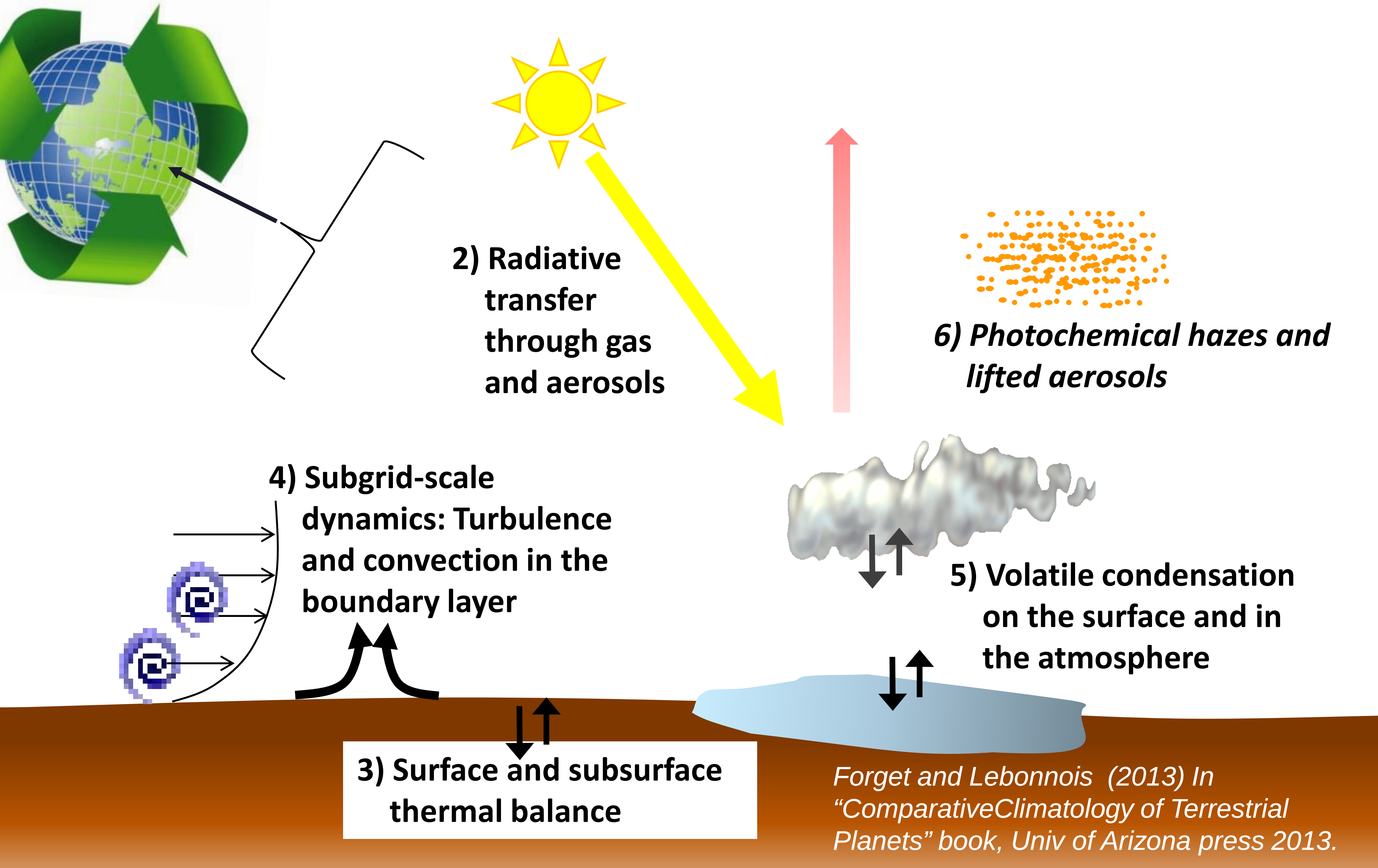


How to build a full Global Climate Simulator ?

Community Earth System Model (CESM), NCAR (Boulder)



How to build a full Global Climate Simulator ?



1) Dynamical Core to compute large scale atmospheric motions and transport

2) Radiative transfer through gas and aerosols

6) Photochemical hazes and lifted aerosols

4) Subgrid-scale dynamics: Turbulence and convection in the boundary layer

5) Volatile condensation on the surface and in the atmosphere

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Forget and Lebonnois (2013) In “ComparativeClimatology of Terrestrial Planets” book, Univ of Arizona press 2013.

How to build a full Global Climate Simulator ?

Dynamical core: solving the simplified Navier Stokes equation on a rotating sphere

Minimum version:

Zonal ***u***
Meridional ***v***
Wind components

Pressure gradient

Coriolis
f = 2 • sin•

Friction ***F***

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + F_x,$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + F_y$$

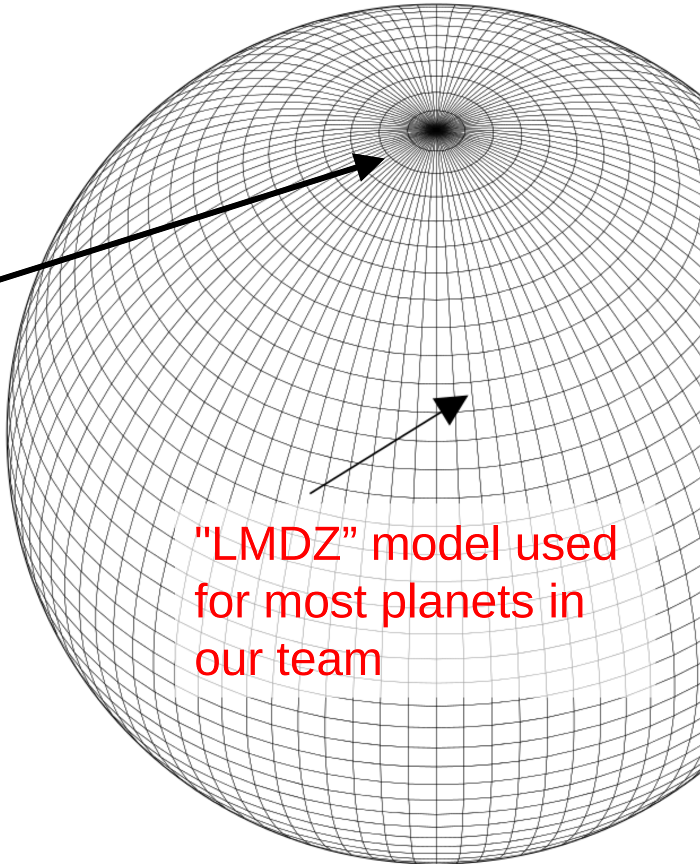
Solving the equations of motions in the "Dynamical Cores". How to descritize the sphere ?

Historical solutions:

1) **Spherical harmonics based methods "spectral model"** (dominated in GCMs for decades)
   - ⇒ Problem : **difficult to parallelize because it requires non-local communication**

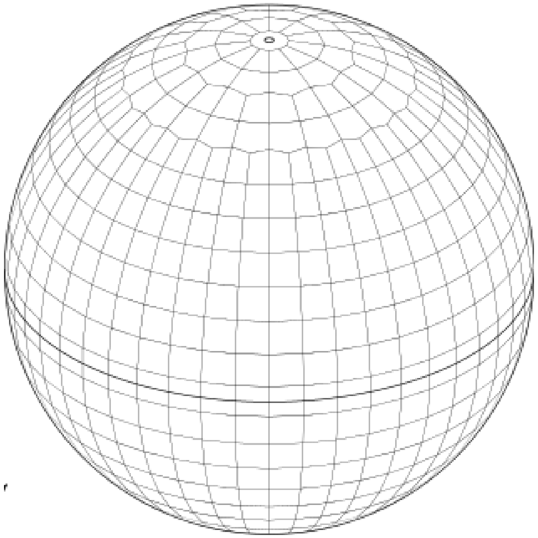
2) **Finite differences/Finite volume methods ("Grid point model")** on a Latitude-Longitude Grid

- Easy to code, to plot
- BUT: Convergence of meridians at the pole
  - ⇒ Polar regions are special regions
  - ⇒ Requires "polar filters" to avoid infinite resolution and very small time steps (CFL criteria)
  - ⇒ **Not easy to parallelize because of non-local communication**

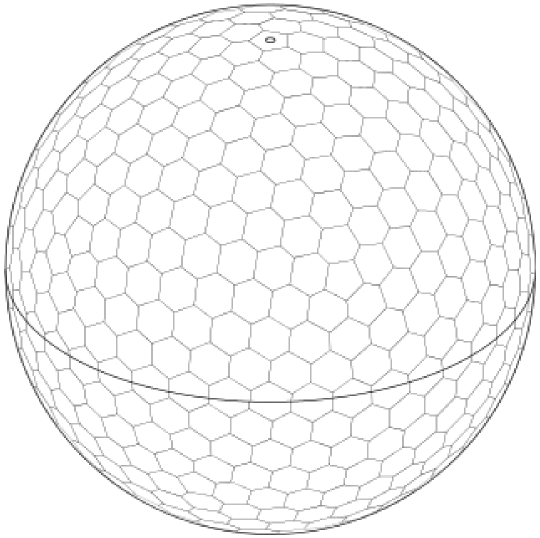


"LMDZ" model used for most planets in our team

New horizontal grid to avoid singularities at the poles and for parallel scaling:



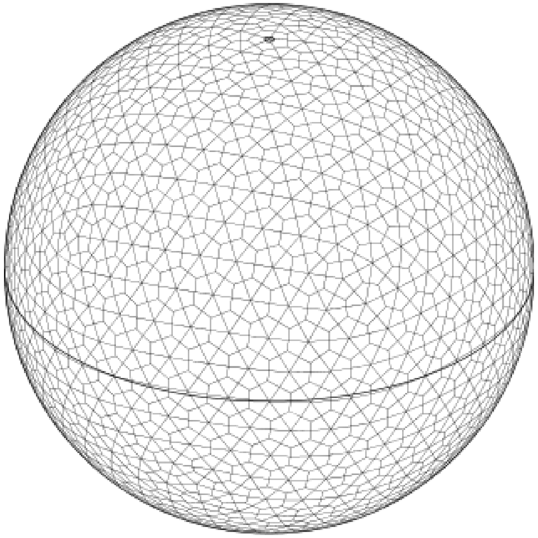
skipped lat-lon



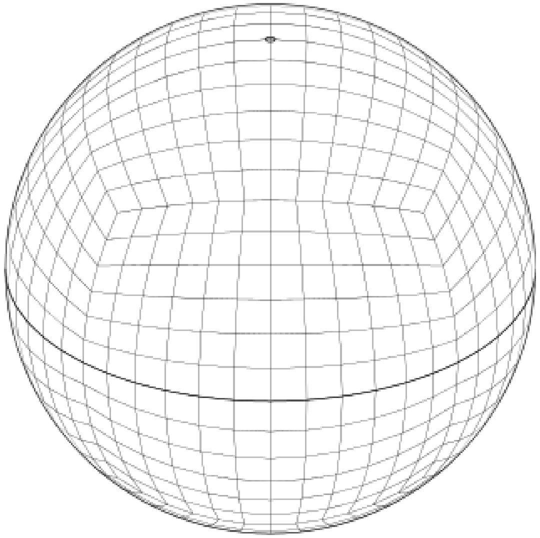
hexagonal-icosahedral

New "Dynamico" model to be used for our planetary models (see next talk By Aymeric Spiga)

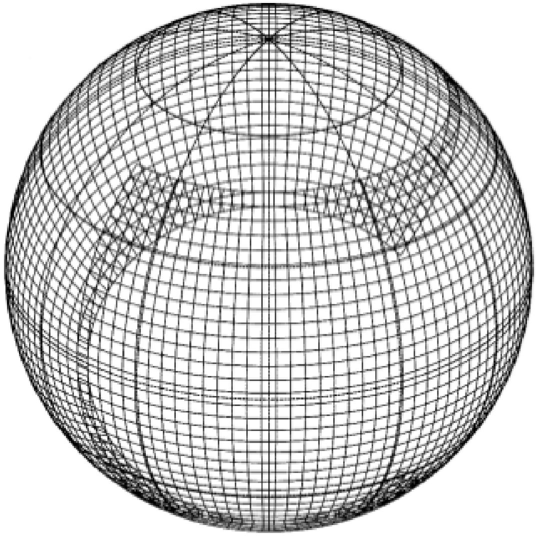
triangular icosahedral



kites

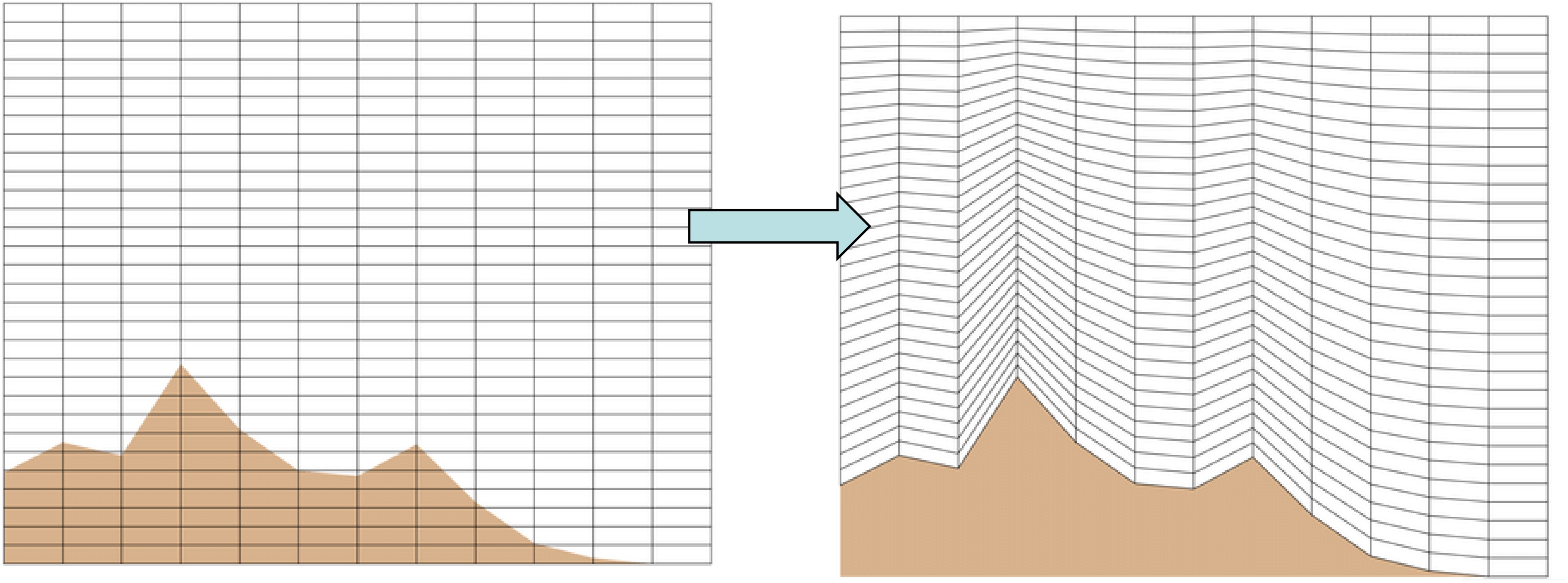


cubed sphere



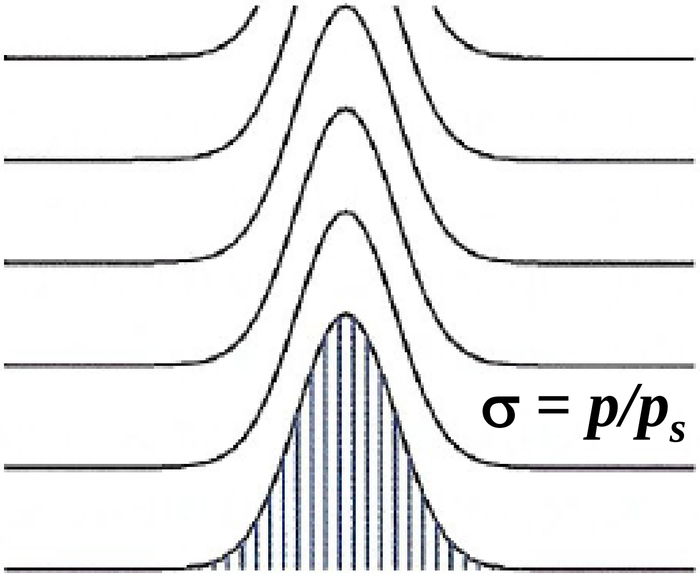
Yin-Yang

Vertical discretization: “terrain following coordinates”

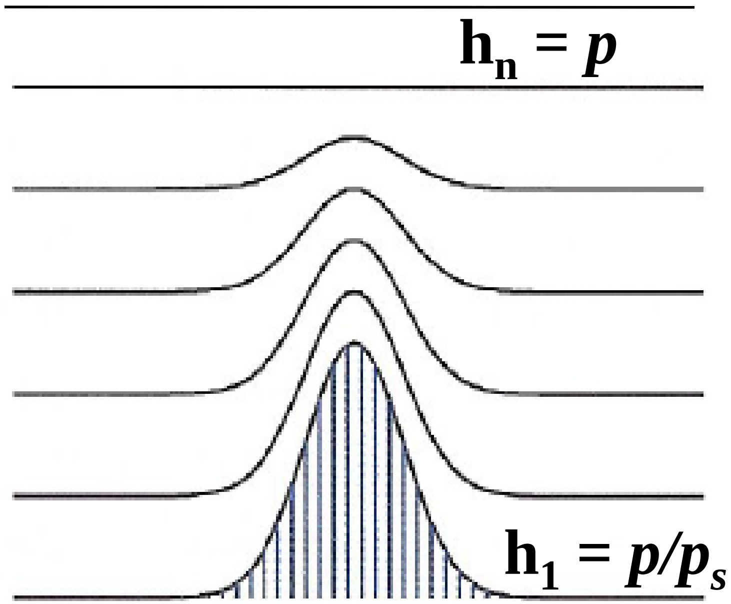


Vertical discretization: “terrain following coordinates”

Sigma coordinates

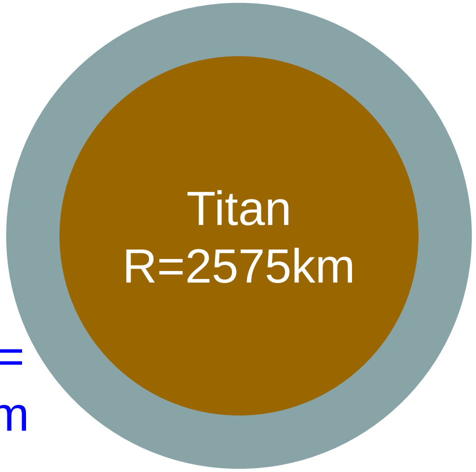


Hybrid coordinates



Can we use Earth dynamical core on other planets ?

- Dynamical core: simplification made for the Earth valid in most cases, with a few exceptions:
  - Assumption that air specific heat Cp is constant : not valid on Venus *(Lebonnois et al. 2010)*
  - Assumption that air Molecular mass is constant : not valid in Mars polar night *(Forget et al. 2005)*
  - “Thin layer approximation” : may not be valid on Titan *(Hirtzig et al. 2010, Tort et al. 2014)*



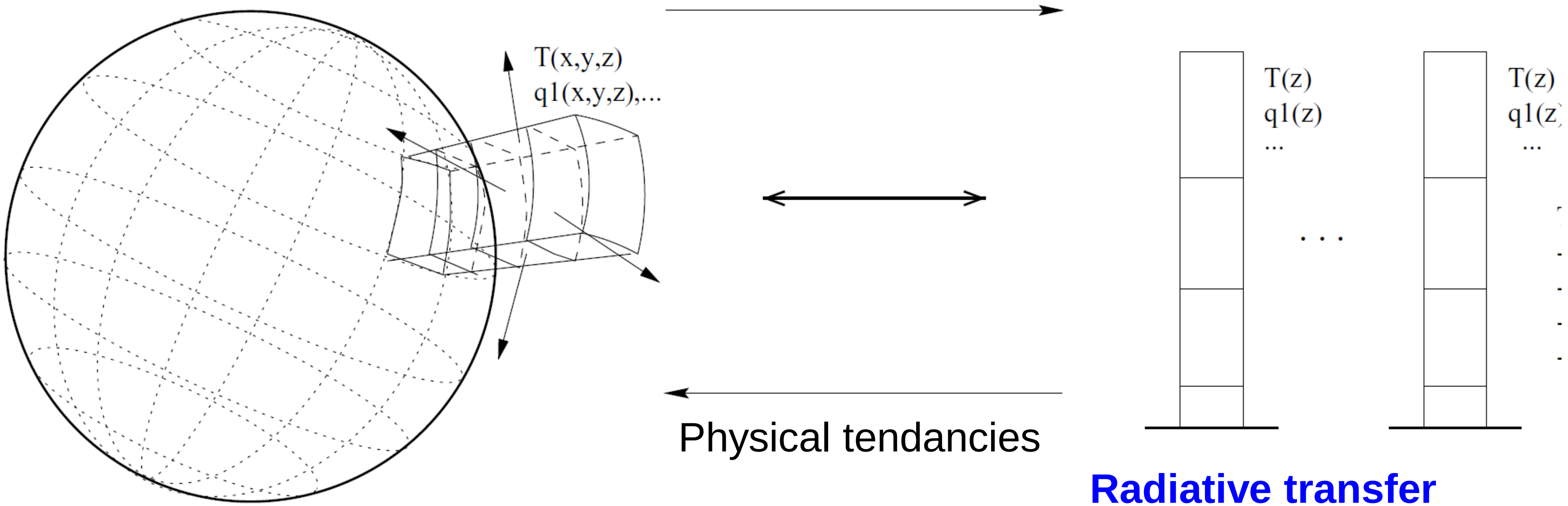
- atm= 600km

Code architecture : separation Dynamics/Physics

Dynamics

Physics

Dynamical fields



Physical tendancies

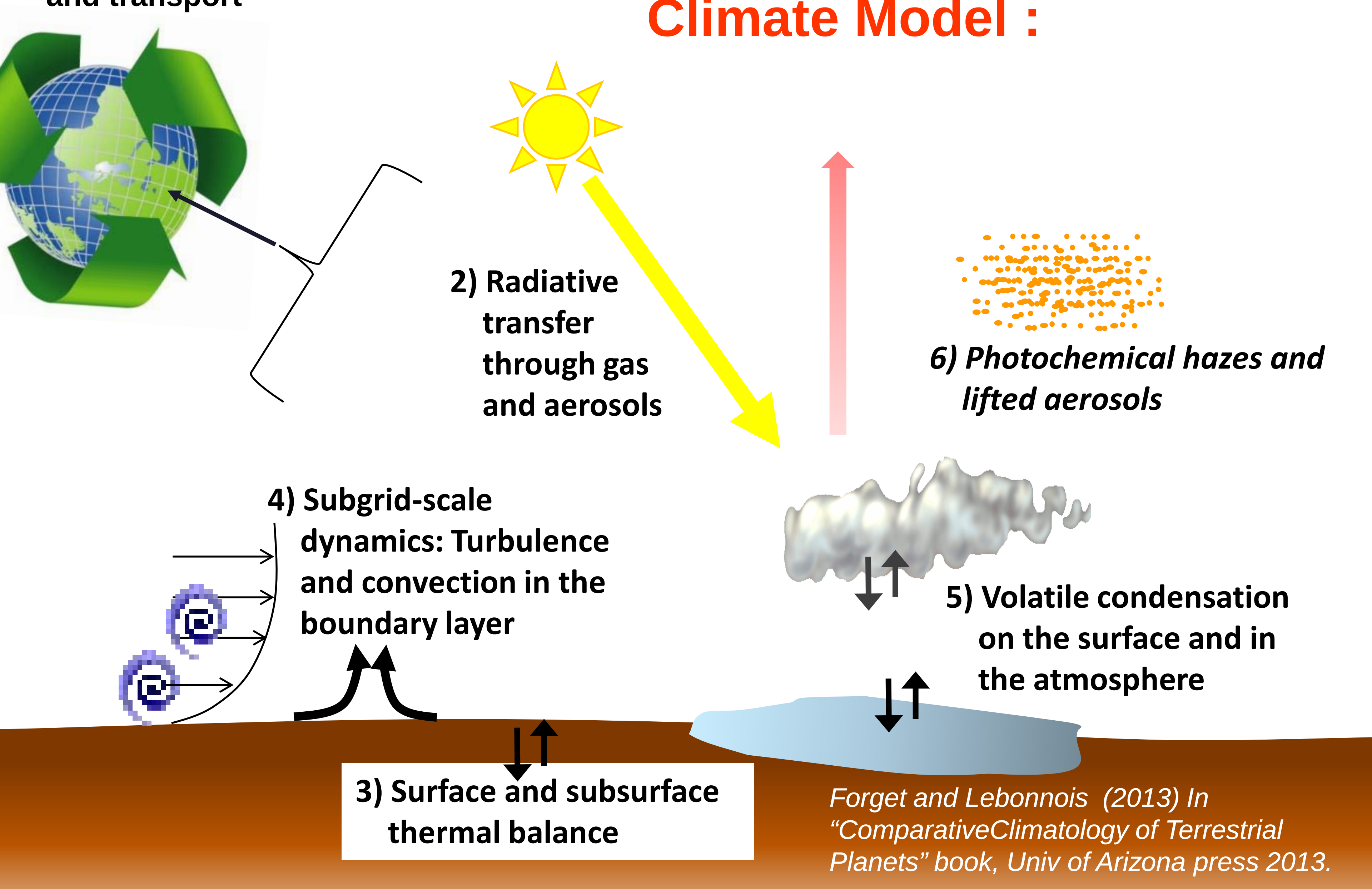
To compute large scale atmospheric motions & transport

Timestep driven by CFL criterion (e.g. ~2 mn with 200 km resolution)

Radiative transfer
Turbulence
Phase changes & clouds
Etc.

Timestep can be significantly longer (e.g. 15-30 mn)

Components of a Global Climate Model :



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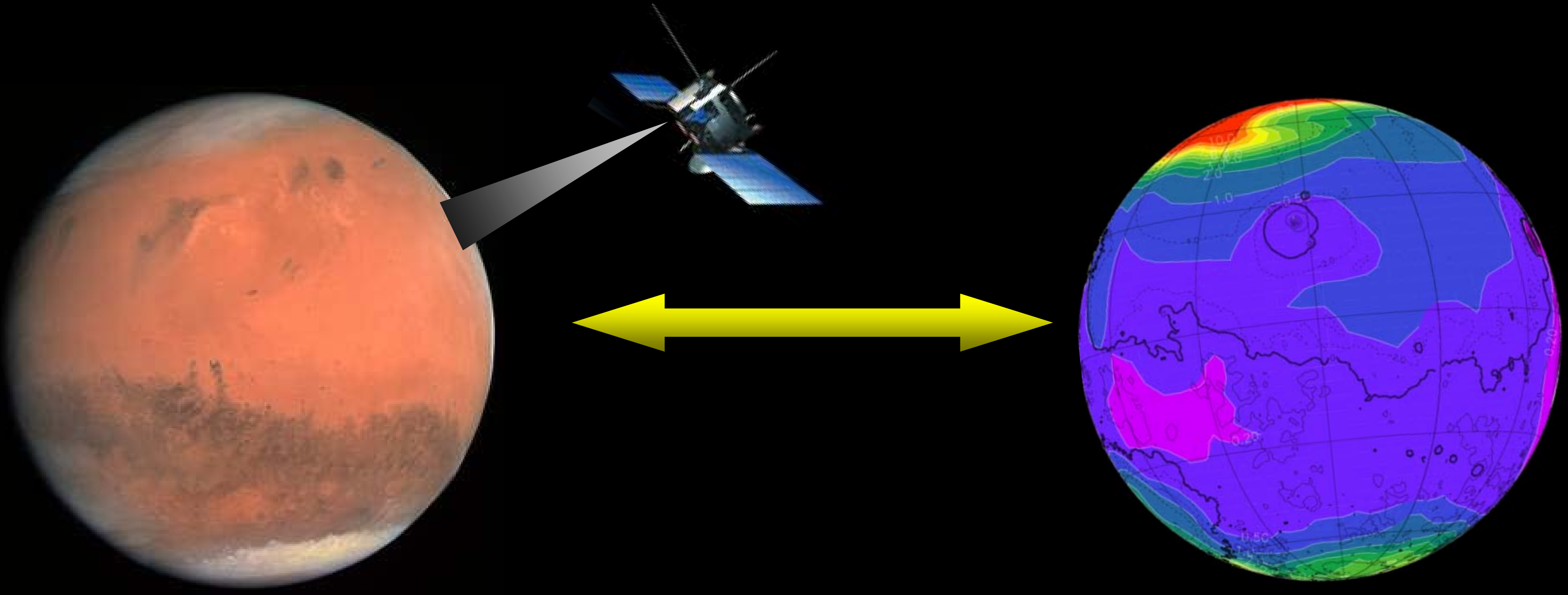
Ambitious Global Climate models : Creating “virtual” planets behaving like the real ones, on the basis of universal equations



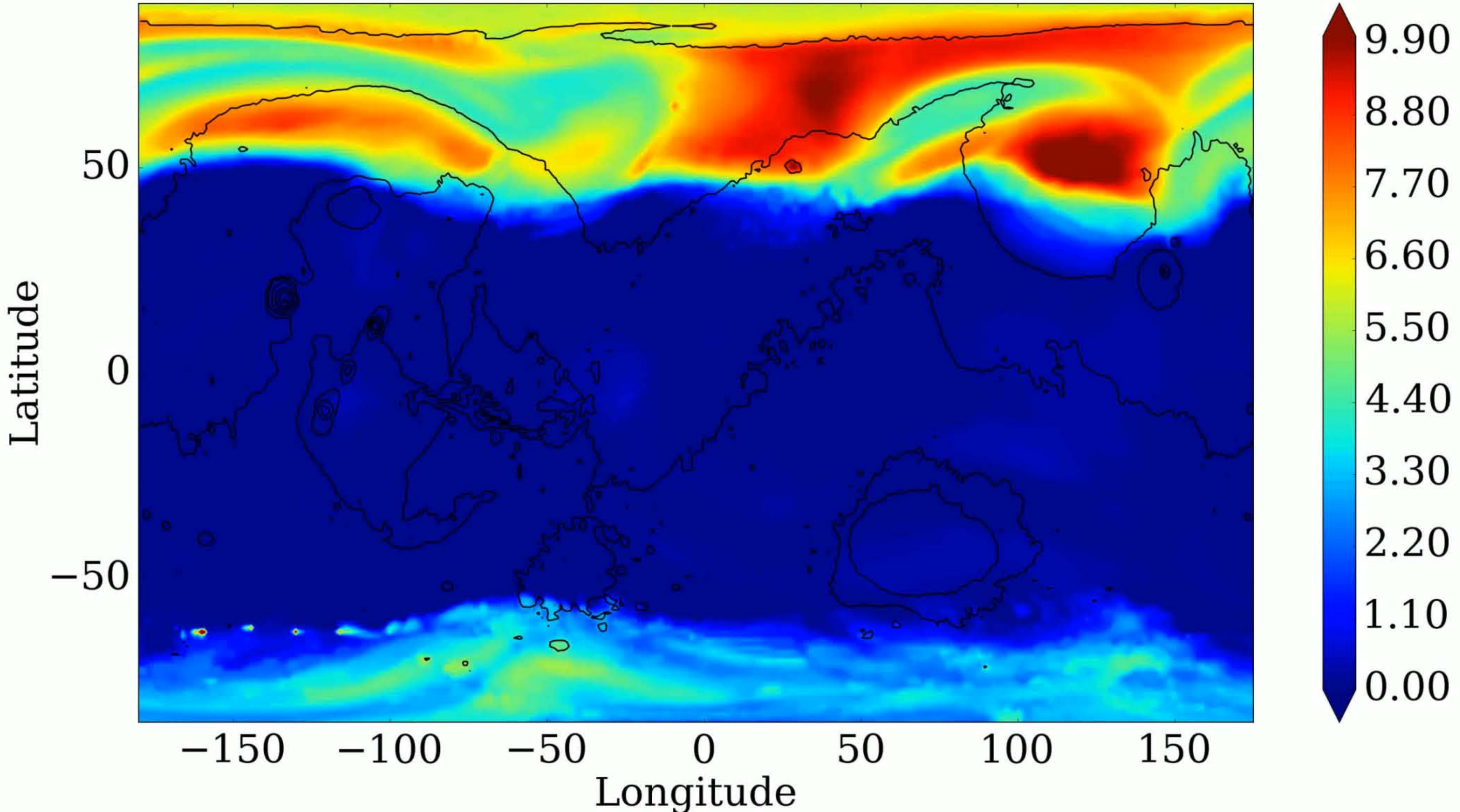
Observations

Reality

Models

Mars Global Climate Modelling
Example: H2O ice clouds (pr-µm) in fall

1°x1° LMD GCM Ls=210°



Climate Models in the solar system: What have we learned?

Lesson # 1: By many measures: GCMs work

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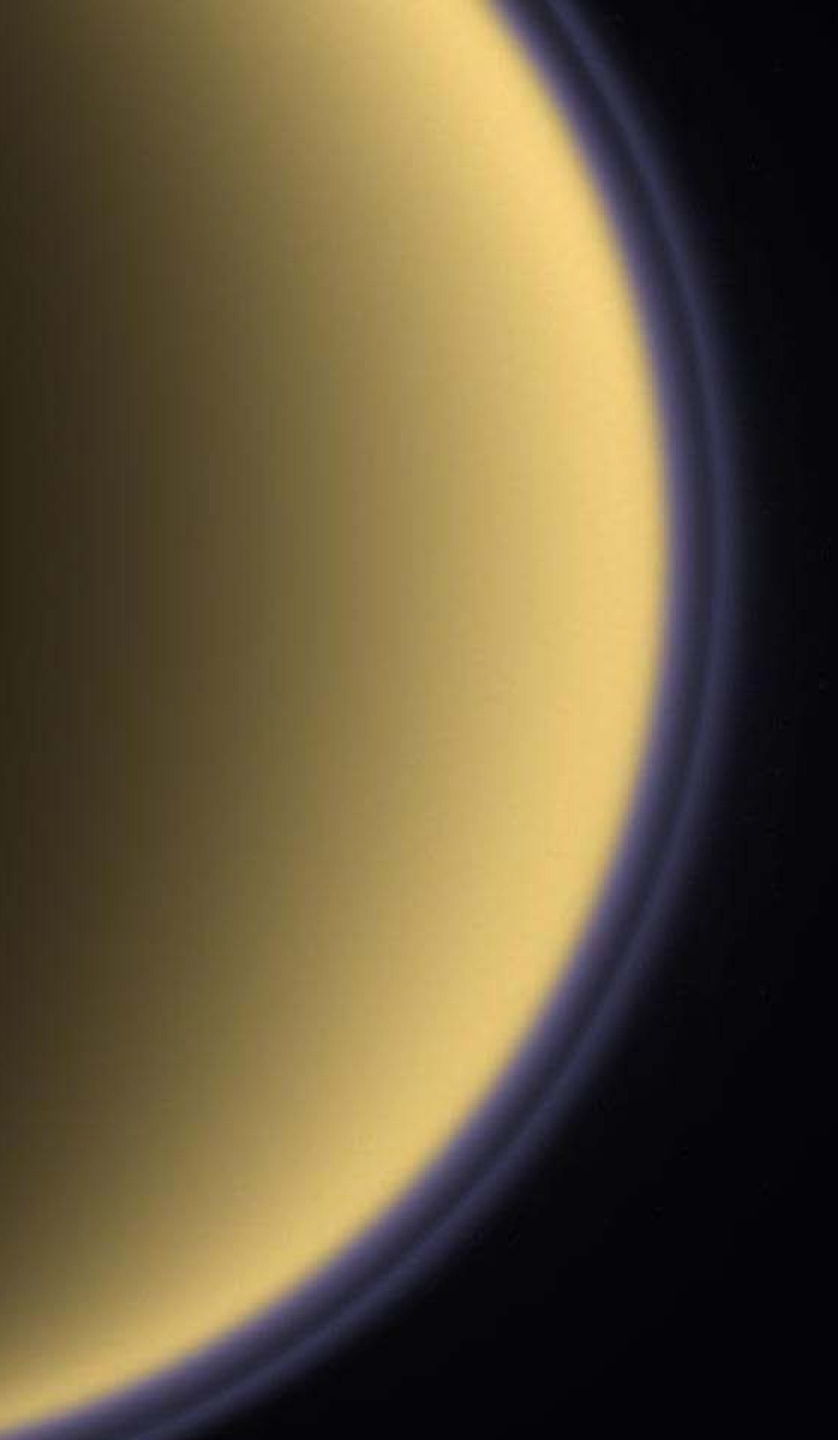
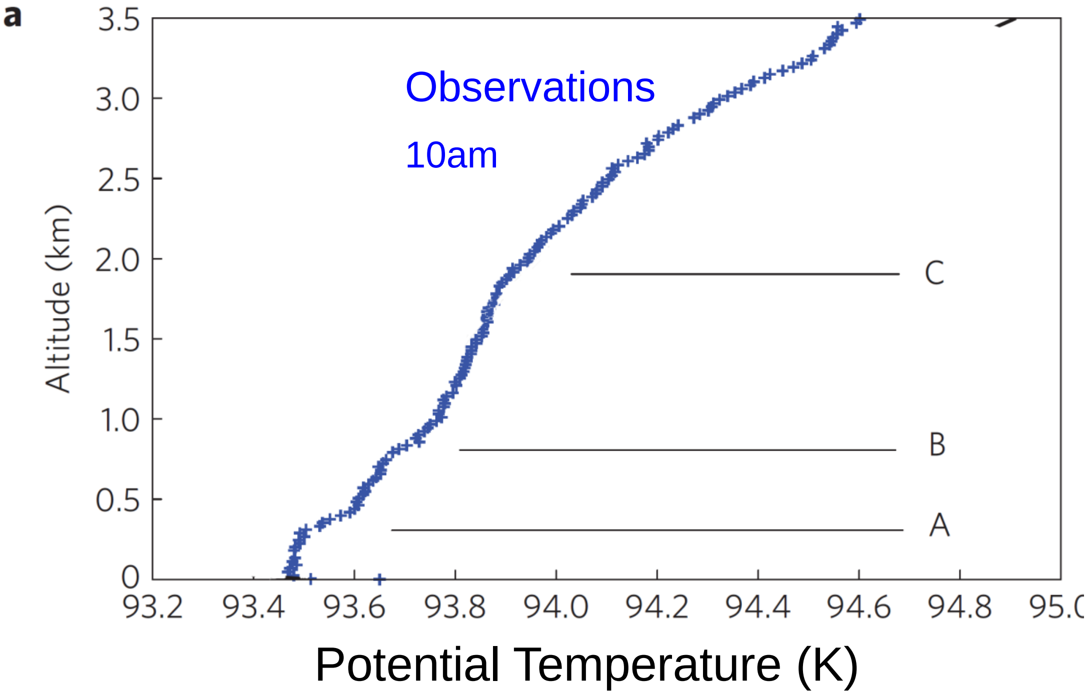
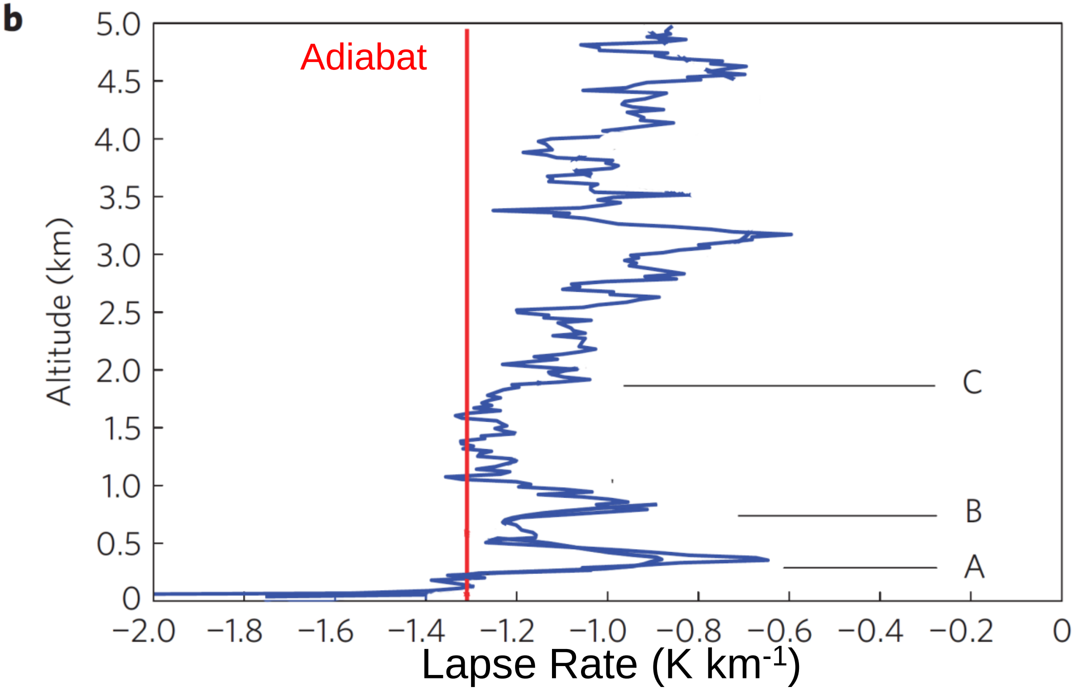


Titan

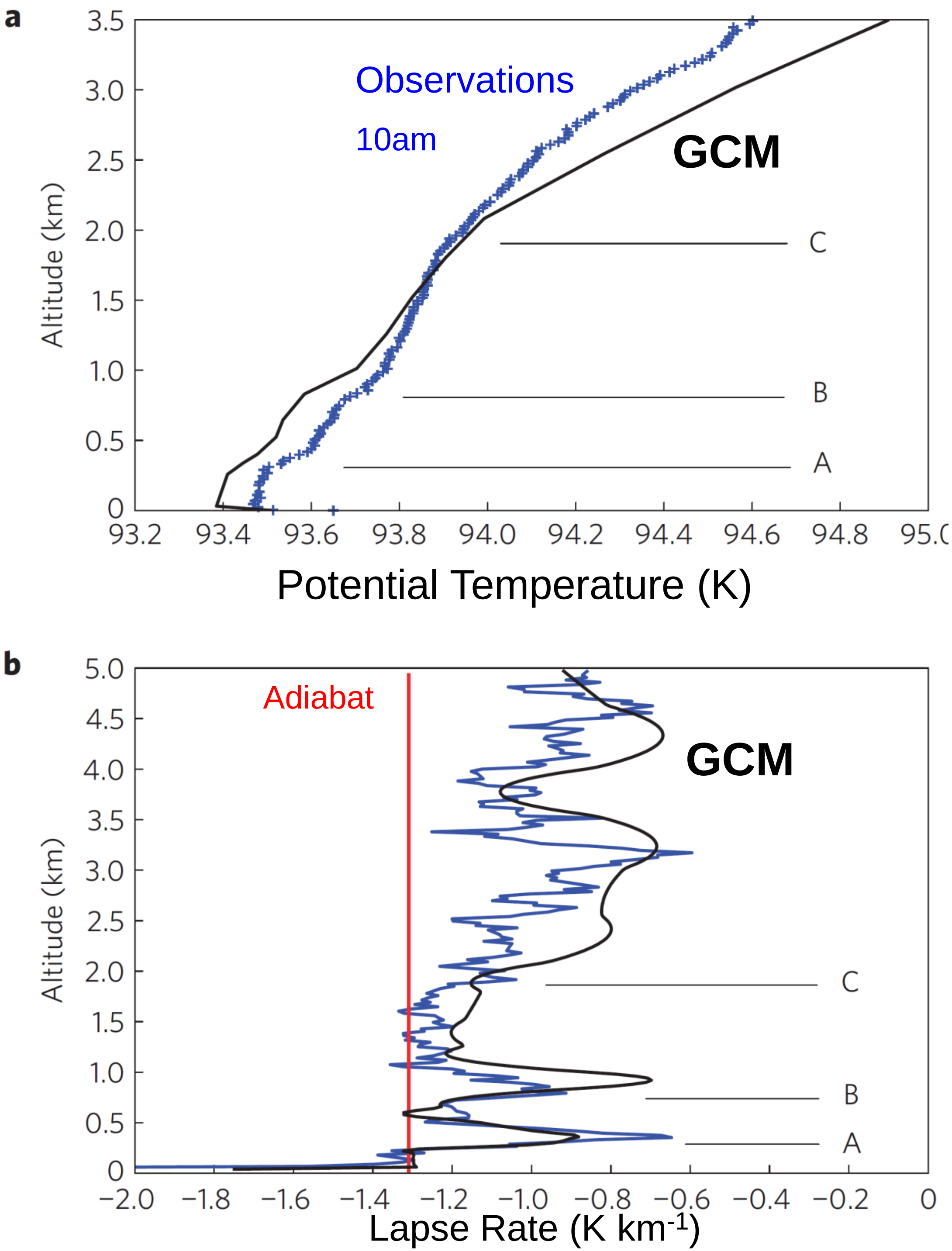
Titan LMD-IPSL Global Climate Model

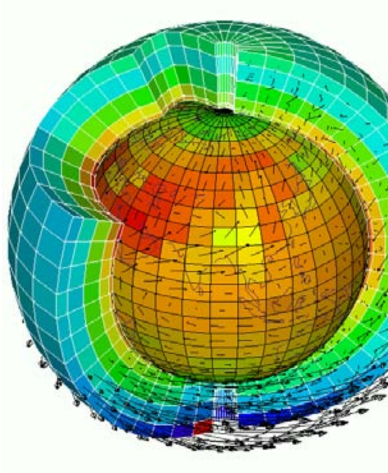
Hourdin et al. 1995, 2004 Lebonnois et al., 2003, 2013, Rannou et al. 2002, 2004, 2006





Charnay and Lebonnois 2012





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2. **Insufficient representation of physical processes** notably due to:
    - **Unresolved subgrid scale process** *(e.g. clouds on the Earth, Gravity waves on Venus, Mars “Rocket dust storms”)*

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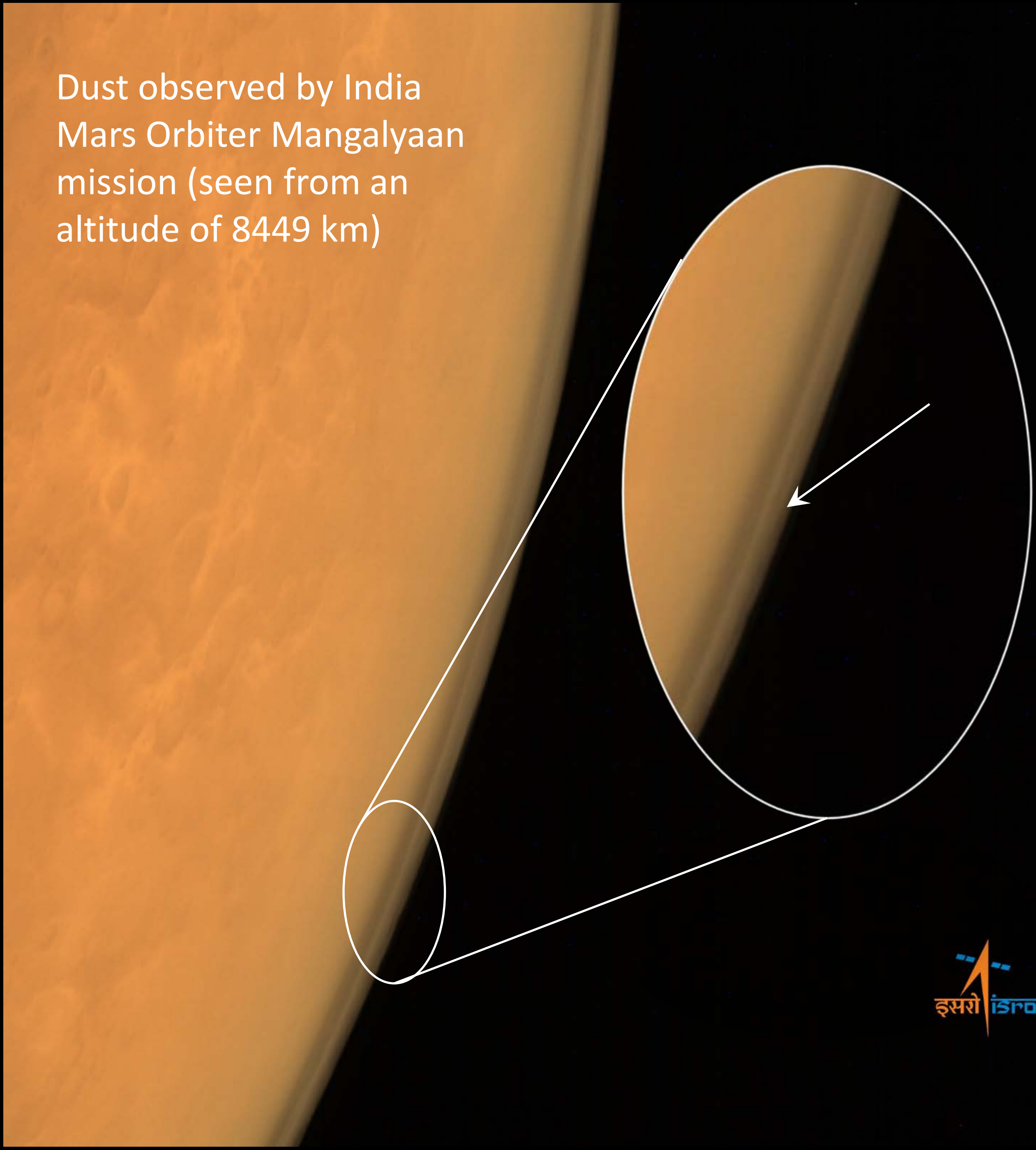
Tempêtes de poussières sur Mars

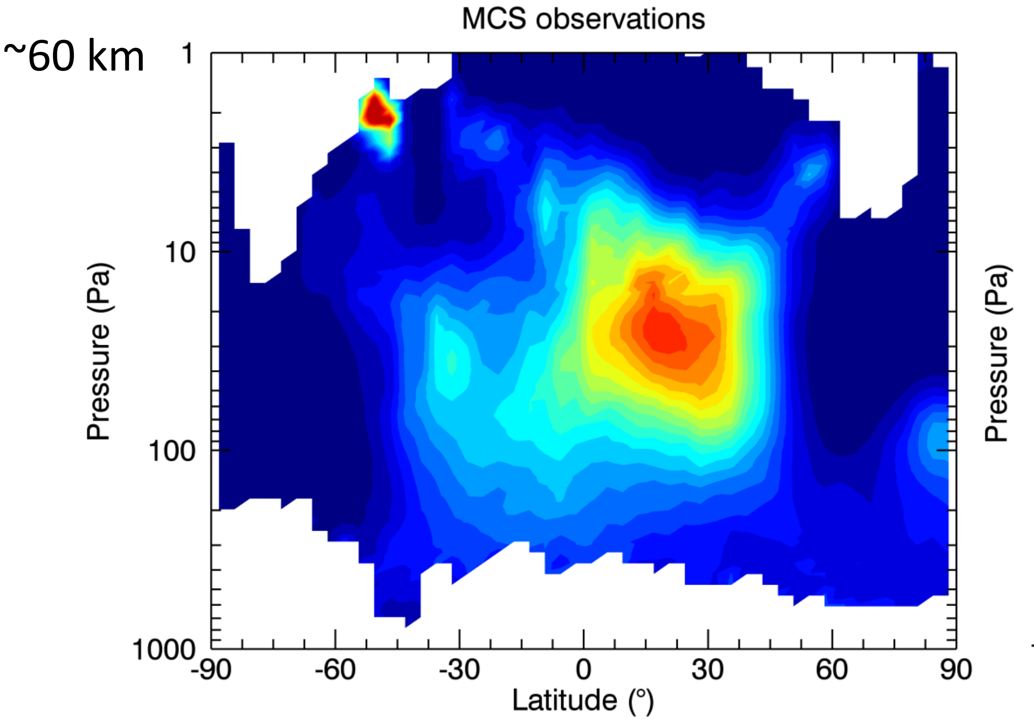
The enigmatic detached dust layers



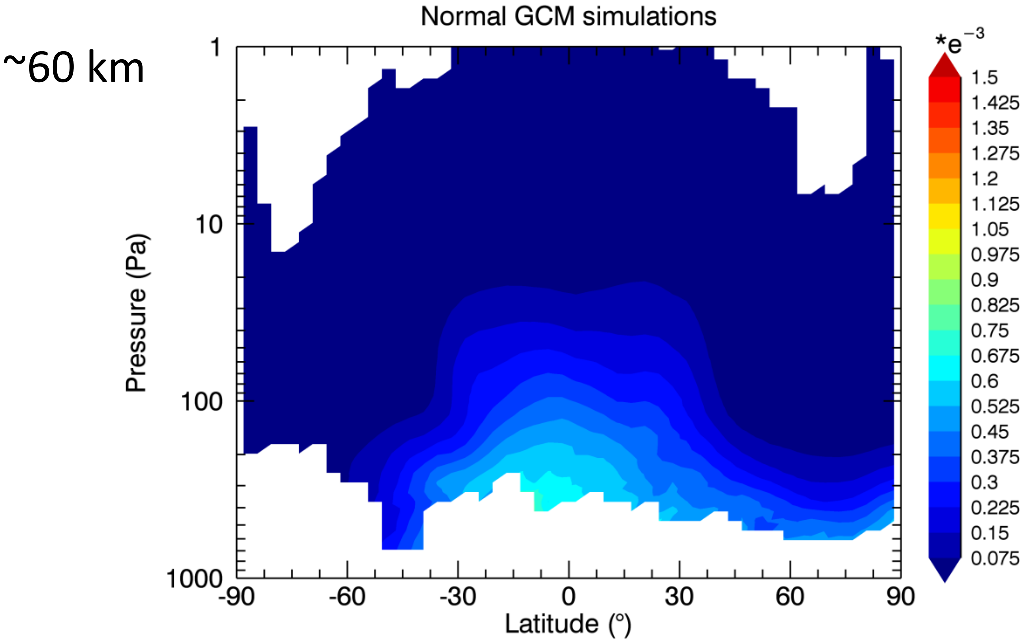
Dust observed by India Mars Orbiter Mangalyaan mission (seen from an altitude of 8449 km)

Zonally averaged night-time density-scaled dust opacity at MY29 from Ls=145˚-150˚

MCS observations



GCM simulations



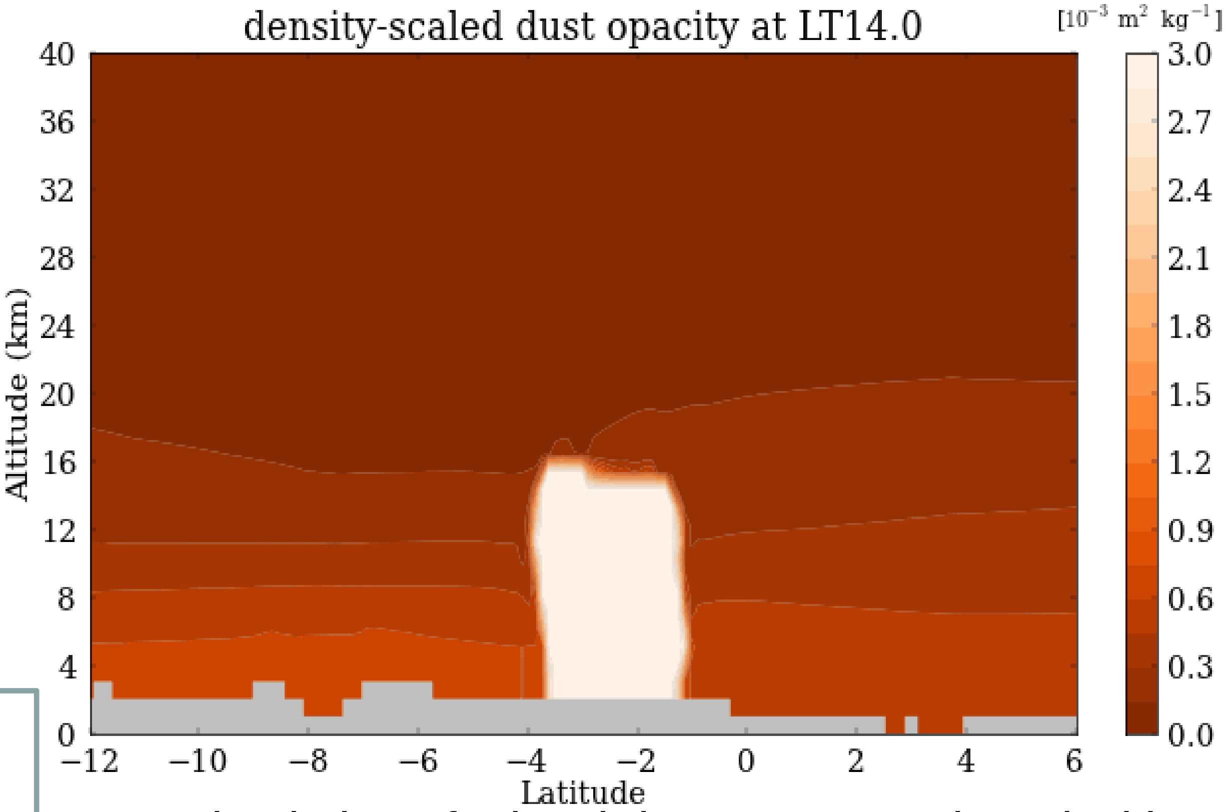
Wang et al. 2015

Detached layers spontaneously form in Mesoscale models

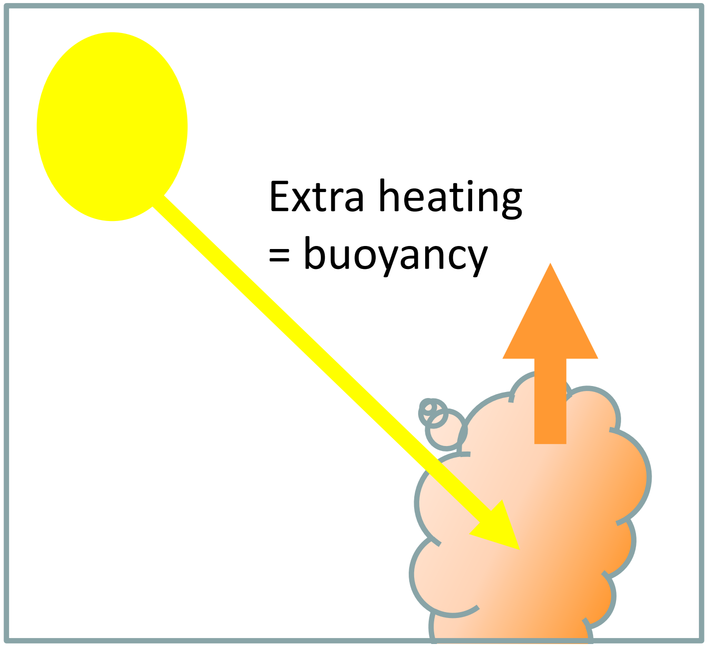
(resolution < 10 km)

and not in Global Climate Models

(Resolution > 100 km)

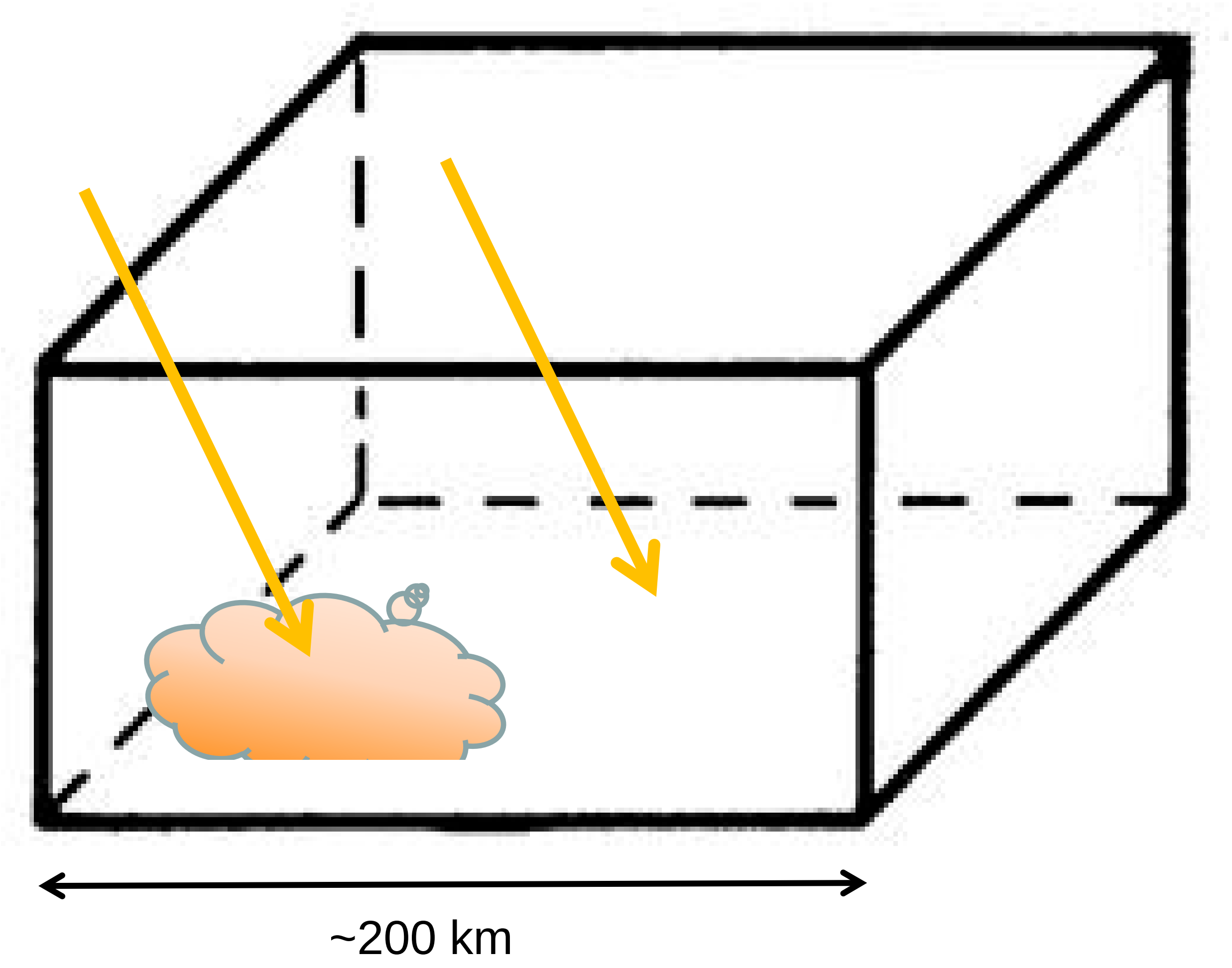


Simulation of a local dust storm monitored with the LMD Martian ***Mesoscale Model*** *(Spiga et al, 2013)*



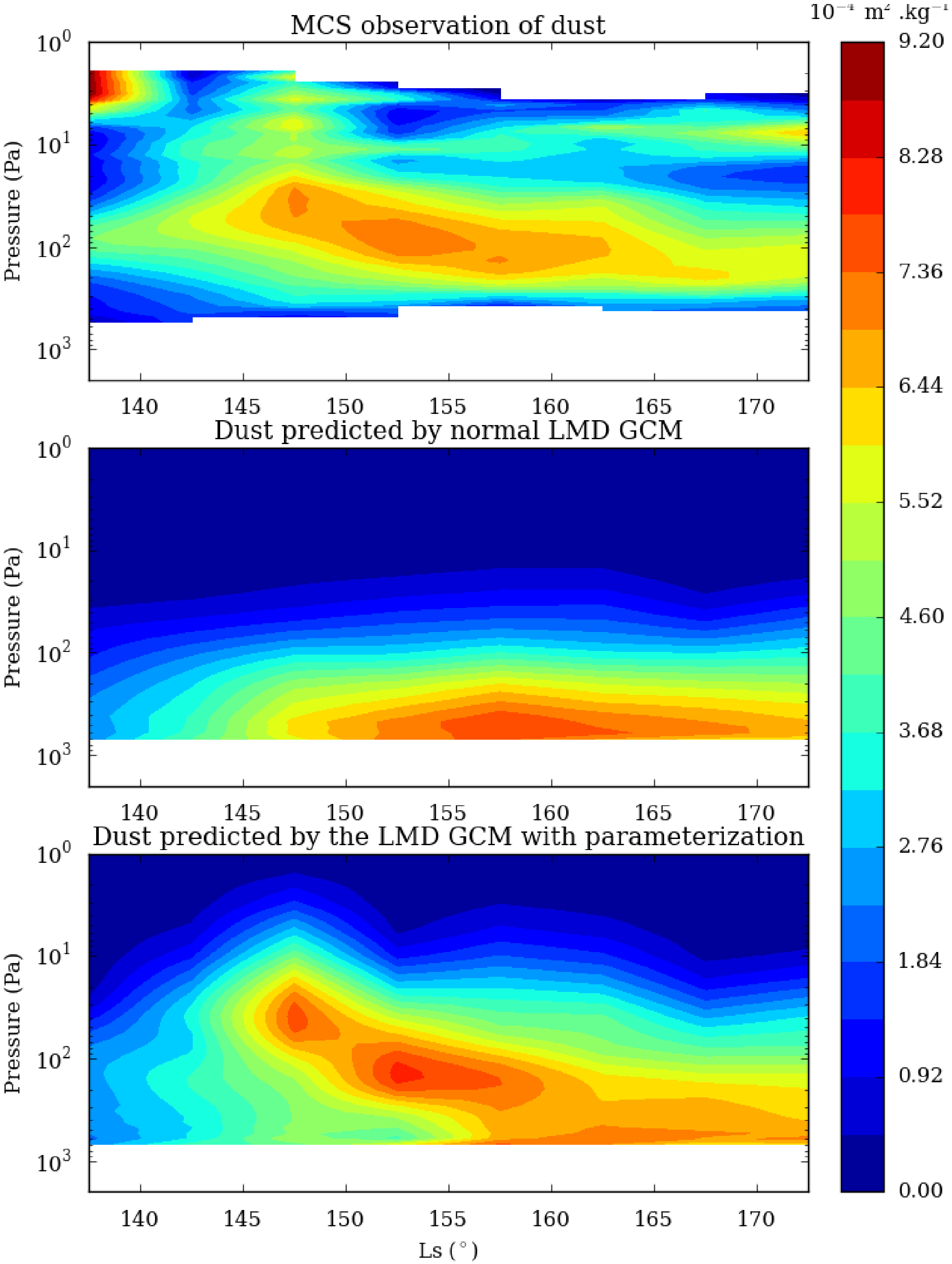
Extra heating = buoyancy

In a GCM: Parametrization of Rocket dust storms = Introducing sub-grid scale dust storm on Mars



Wang et al. (2018)

Equatorial dust , Ls=135° -180°
Zonal mean -10° < lat < 10°



MCS observations

Regular GCM

GCM with subgrid-scale dust storm parametrization

Wang et al. (2018)

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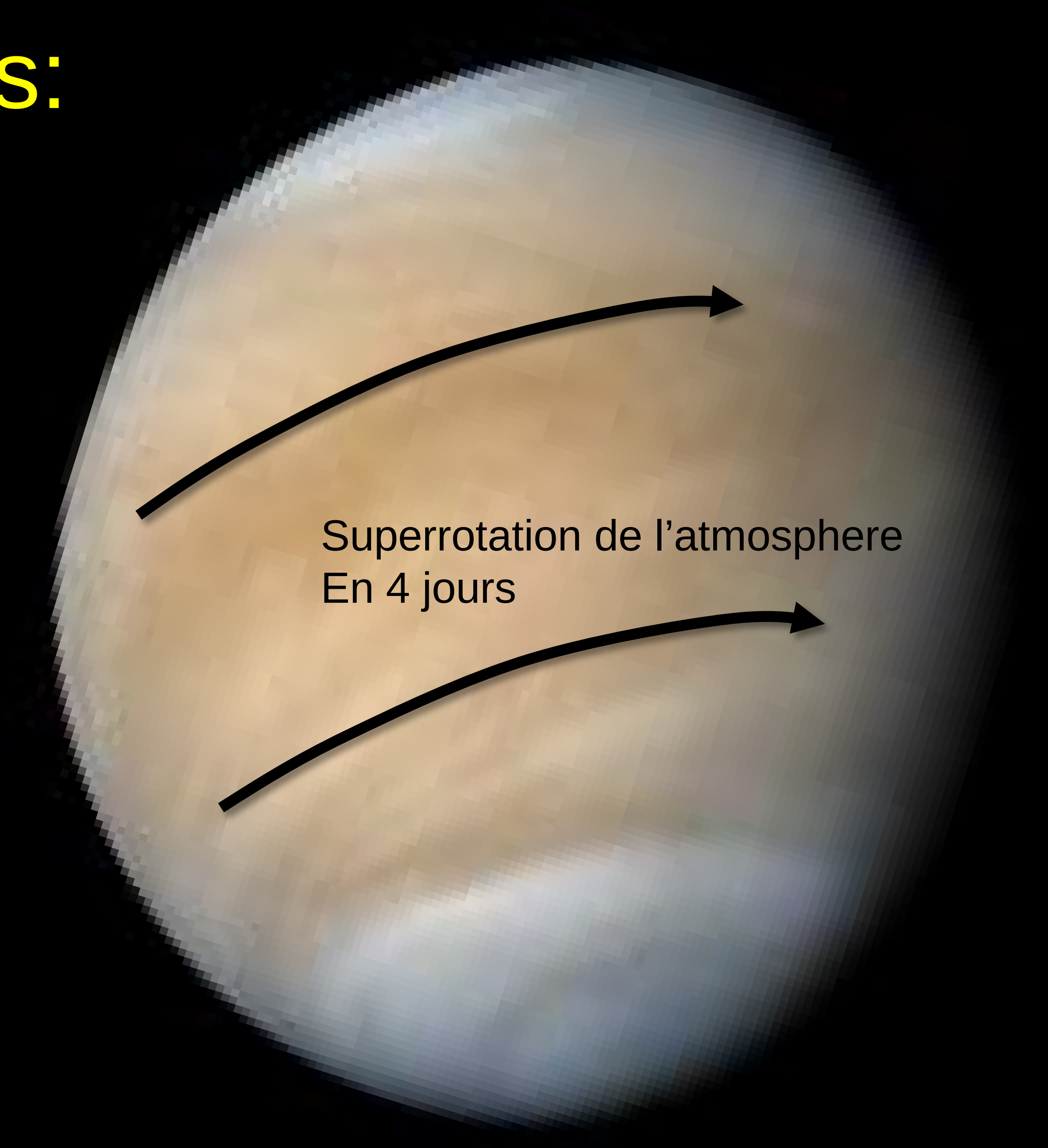
2. Insufficient representation of physical processes notably due to:
   - **Unresolved subgrid scale process** *(e.g. clouds on the Earth, Gravity waves on Venus, Mars "Rocket dust storms")*
   - **Positive feedbacks and unstability** *(e.g. sea ice and land ice albedo feedback on the Earth) :* need to tune models or explore sensitivity
   - **Non linear behaviour and threshold effect** *(e.g. dust storms on Mars)*
3. Long time scale & difficult choice of initial states *(e.g. Pluto ices)*
4. Weak Forcing : when the evolution of the system depends on a subtle balance between modeled process rather than direct forcing *(e.g. Venus circulation)*

Forget and Lebonnois (2013) In "Comparative Climatology of Terrestrial Planets" book, Univ of Arizona press 2013.

Venus:



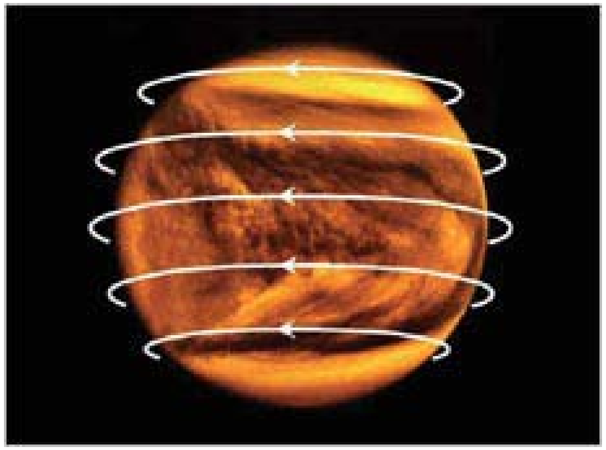
Superrotation de l’atmosphere
En 4 jours

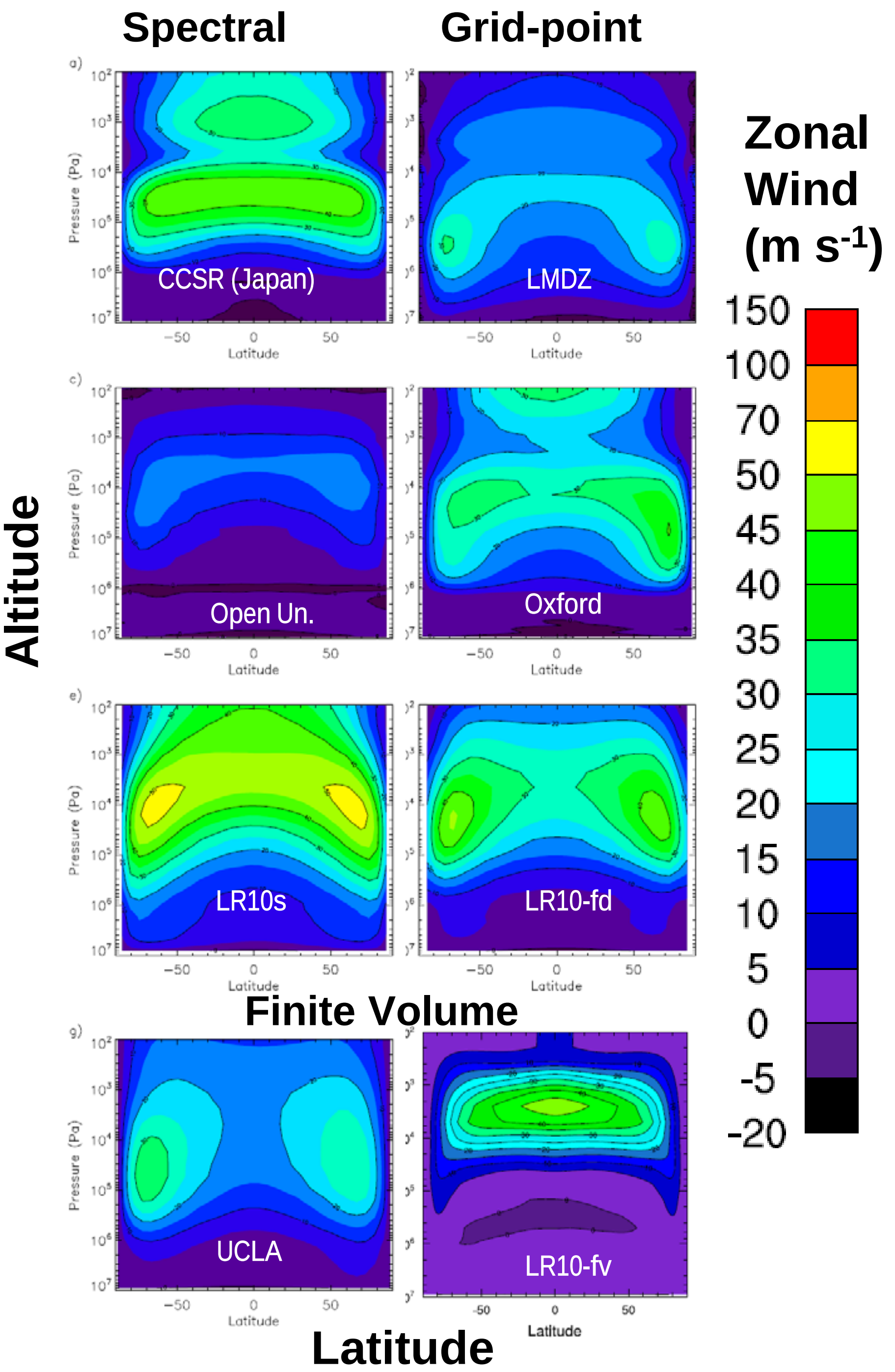
Période de rotation: 243 jours terrestres

Mean zonal wind field predicted by several GCM dynamical core with « Venus like » forcing

(All GCMs share the same solar forcing and boundary layer sheme)

Lebonnois et al. (2011)





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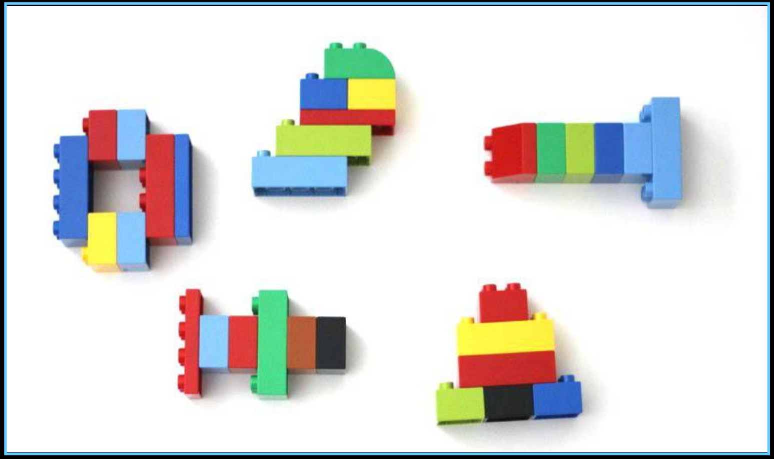
Lesson # 2: Why and when GCMs fail

Lesson # 3 Climate model components can be applied without major changes to most terrestrial planets.



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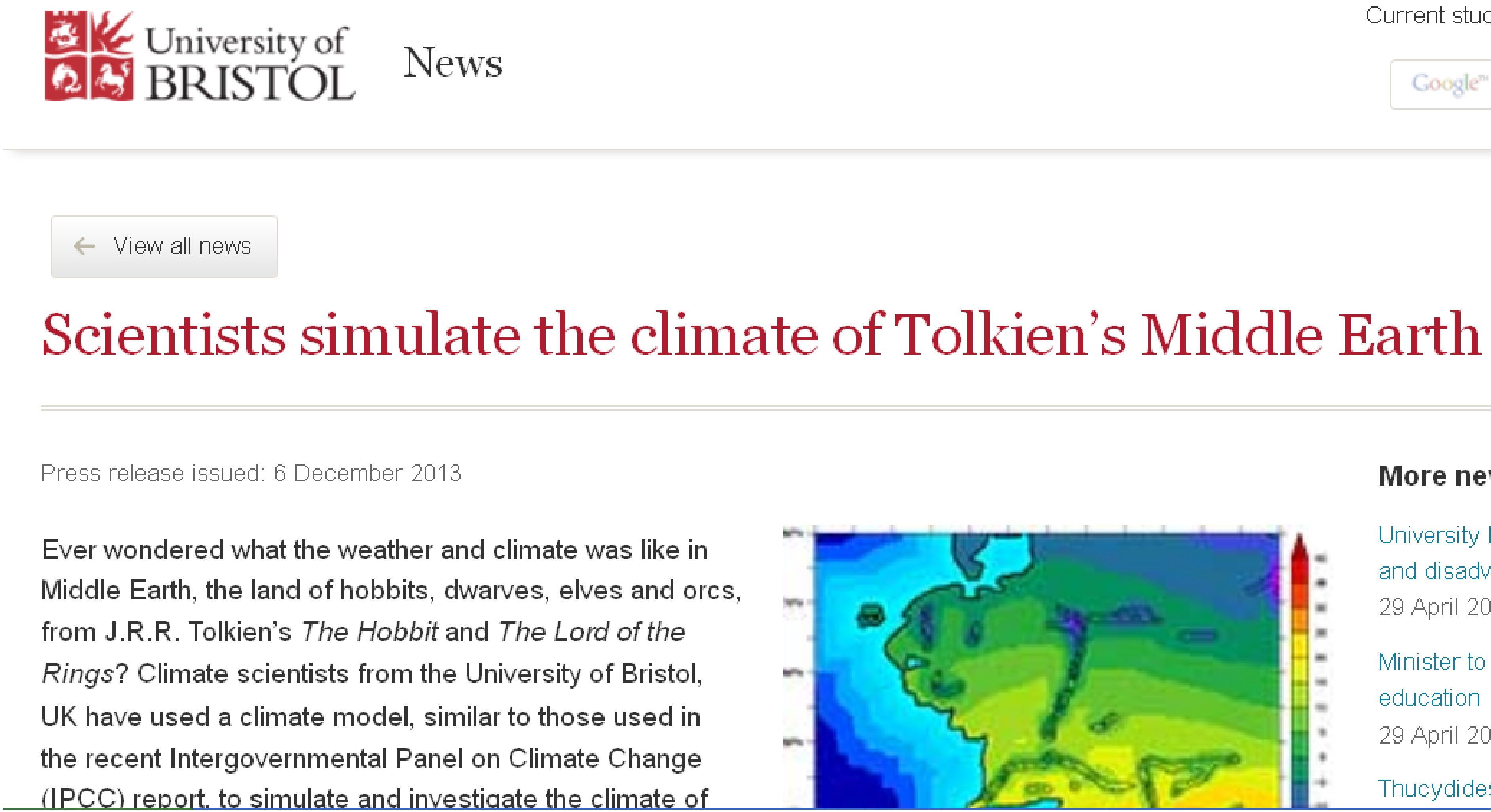


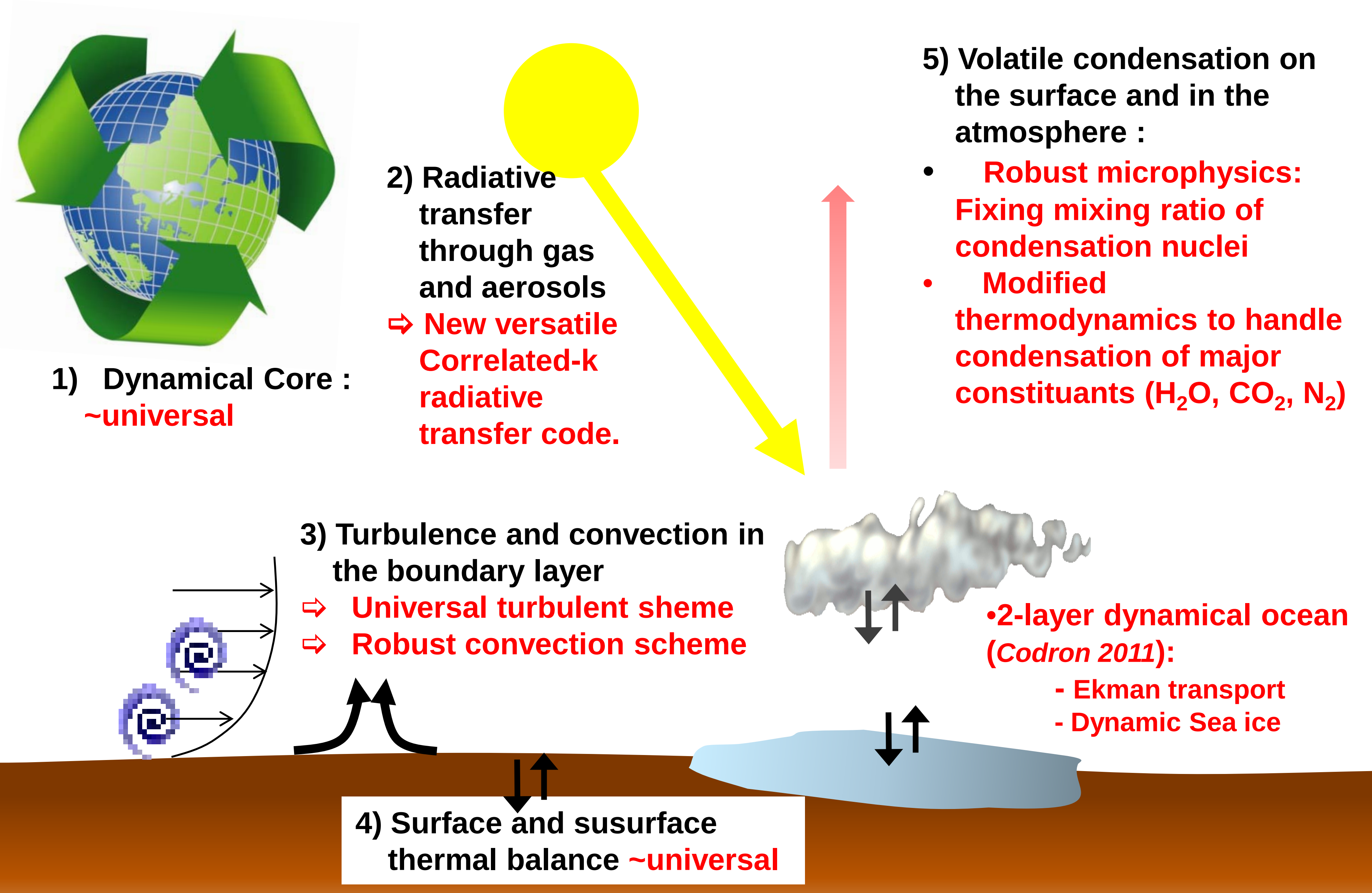
Scientists simulate the climate of Tolkien's Middle Earth

Press release issued: 6 December 2013

Ever wondered what the weather and climate was like in Middle Earth, the land of hobbits, dwarves, elves and orcs, from J.R.R. Tolkien's *The Hobbit* and *The Lord of the Rings*? Climate scientists from the University of Bristol, UK have used a climate model, similar to those used in the recent Intergovernmental Panel on Climate Change (IPCC) report, to simulate and investigate the climate of

One Model to simulate them all

LMD 3D "generic" Global climate model designed to simulate any atmosphere on any terrestrial planet around any star.



1) **Dynamical Core :** ~universal

2) **Radiative transfer through gas and aerosols**
⇨ New versatile Correlated-k radiative transfer code.

5) **Volatile condensation on the surface and in the atmosphere :**

- Robust microphysics: Fixing mixing ratio of condensation nuclei
- Modified thermodynamics to handle condensation of major constituants (H_2O, CO_2, N_2)

3) **Turbulence and convection in the boundary layer**
⇨ Universal turbulent sheme
⇨ Robust convection scheme

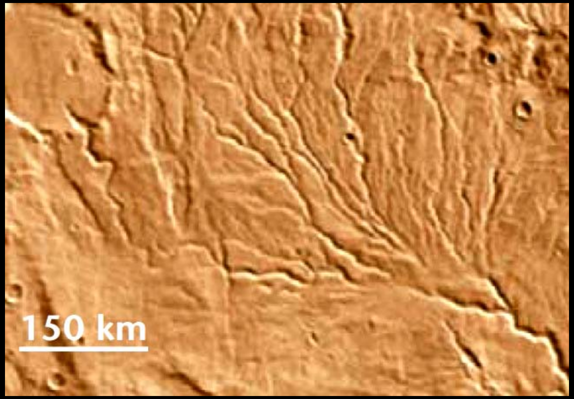
•2-layer dynamical ocean (*Codron 2011*):
- Ekman transport
- Dynamic Sea ice

4) **Surface and susurface thermal balance** ~universal

A “Generic” LMD GCM for all terrestrial atmospheres:

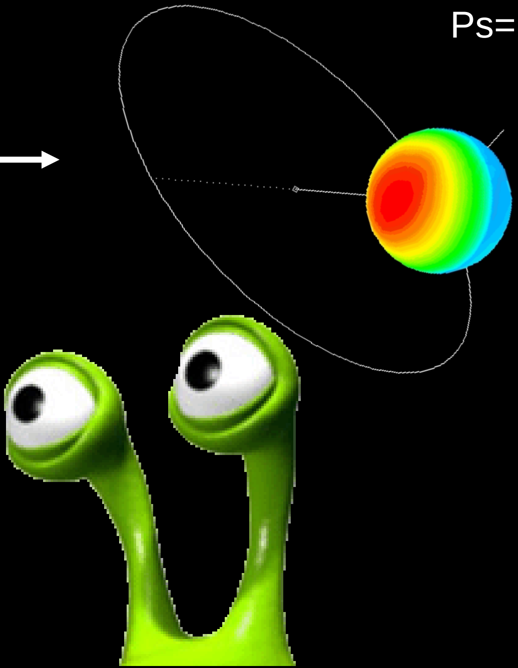
Why simulate planets where no observations are available ?

- **To Model ancient climates to understand geological records**
  - Early Earth and the “faint young sun paradox” *(Charnay et al. 2013, 2017)*
  - Early Mars *(Forget et al. 2013, Wordsworth et al. 2013, 2015, Kerber et al 2014, Bouley et al. 2016, Turbet et al. 2017)*
  - Ancient Titan *(Charnay et al. 2014)*



- **To simulate planets around other star to design future telescopic measurements**
  - Exoplanet Thermal phase curves (*Selsis et al. 2011, Turbet et al. 2016, Samuel et al., 2014, etc…)*
  - Spectra simulations *(Charnay et al. 2016), Turbet et al. 2016)*

View at 8.67 µm
Ps= 1bar



- **To adress key scientific questions regarding habitability:**
  - Define the habitable zone: runaway greenhouse effect (*Leconte et al. 2011, 2014), *Glaciation *(Turbet et al. 2017)*
  - What is the probability of habitable planet in the galaxy ?
  - Study specific cases: Gliese 581d, Trappist 1, Proxima b, etc.

Terrestrial atmospheres to Model

Amount of observations available to constrain & test GCMs

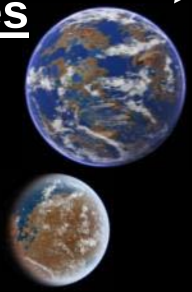
Paleoclimates

Past Earth

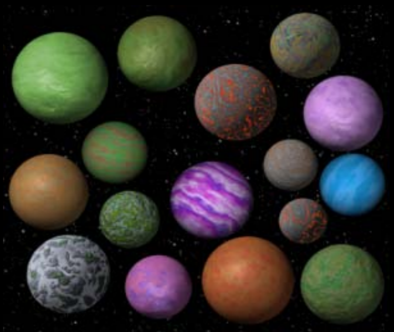
Past Mars

Past Titan…

Past Venus…



Exoplanets



Terrestrial atmospheres to Model

Amount of observations available to constrain & test GCMs

Specific challenge when lots of data are available

Paleoclimates

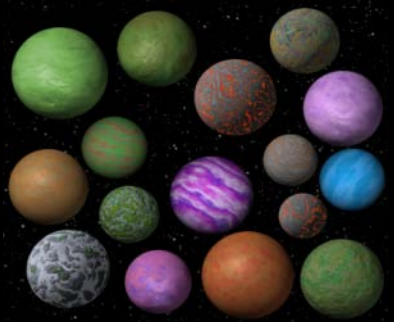
Past Earth

Past Mars

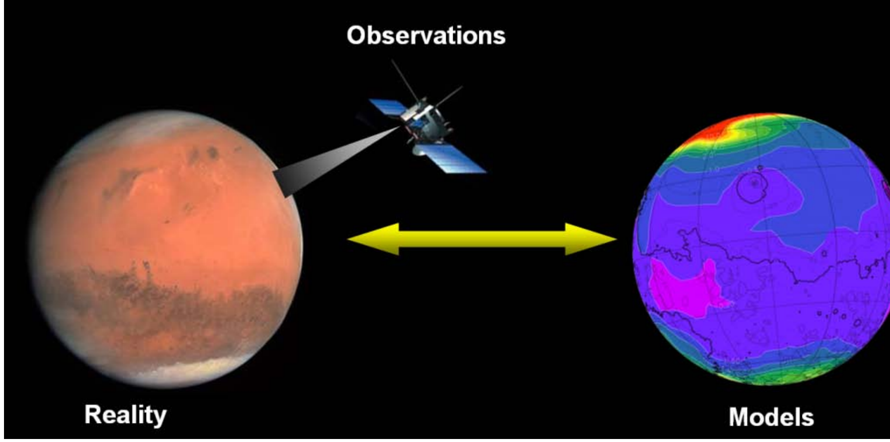
Past Titan…

Past Venus…

Exoplanets



When lots of data are available: The challenge of "Tuning" Global Climate Model



- Even the best, physically-based models, remain sensitive to parameters which cannot be estimated theoretically. Choosing these parameters to optimize the model-observations is a challenge: how to define a method ? risk of driving the model in the wrong regime ?
- In principle minimization of a cost function:

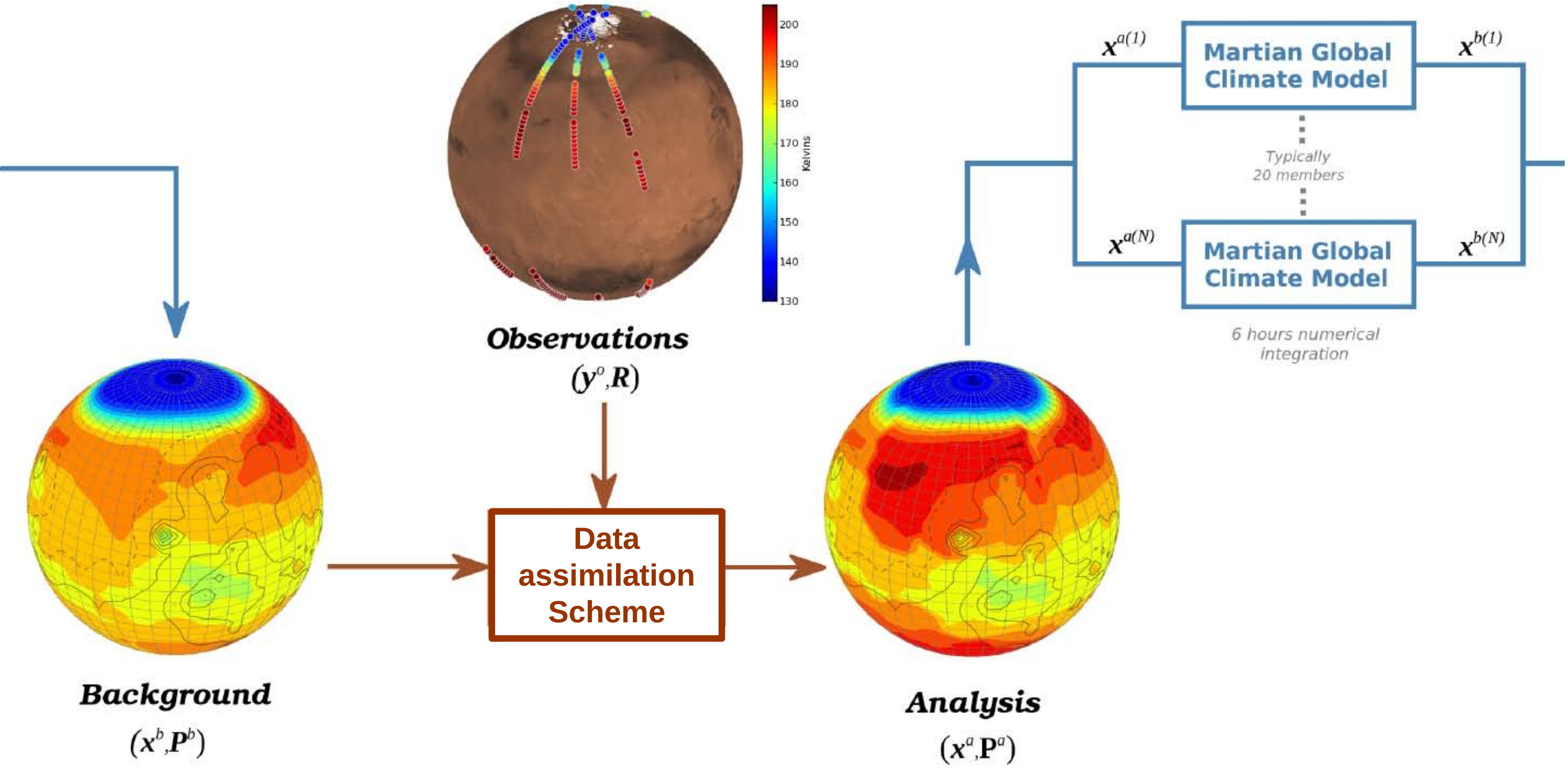
$$C(p_1, p_2, \ldots) = \sum_{1}^{N} w_i \|\phi_i - \phi_i^{obs}\|$$

p chosen in a range given by theory orbservations…

⇨ *The choices of model parameters and the exploration of model sensitivity should evolve from being an inhouse hidden tinkering to become a scientific, open process* (Hourdin et al., "The art and Science of Climate Model Tuning", BAMS, 2017)

- .

When lots of data are available:
As on Earth : Meteorological Data assimilation



Observations

(y^o, R)

Background

(x^b, P^b)

Data assimilation Scheme

Analysis

(x^a, P^a)

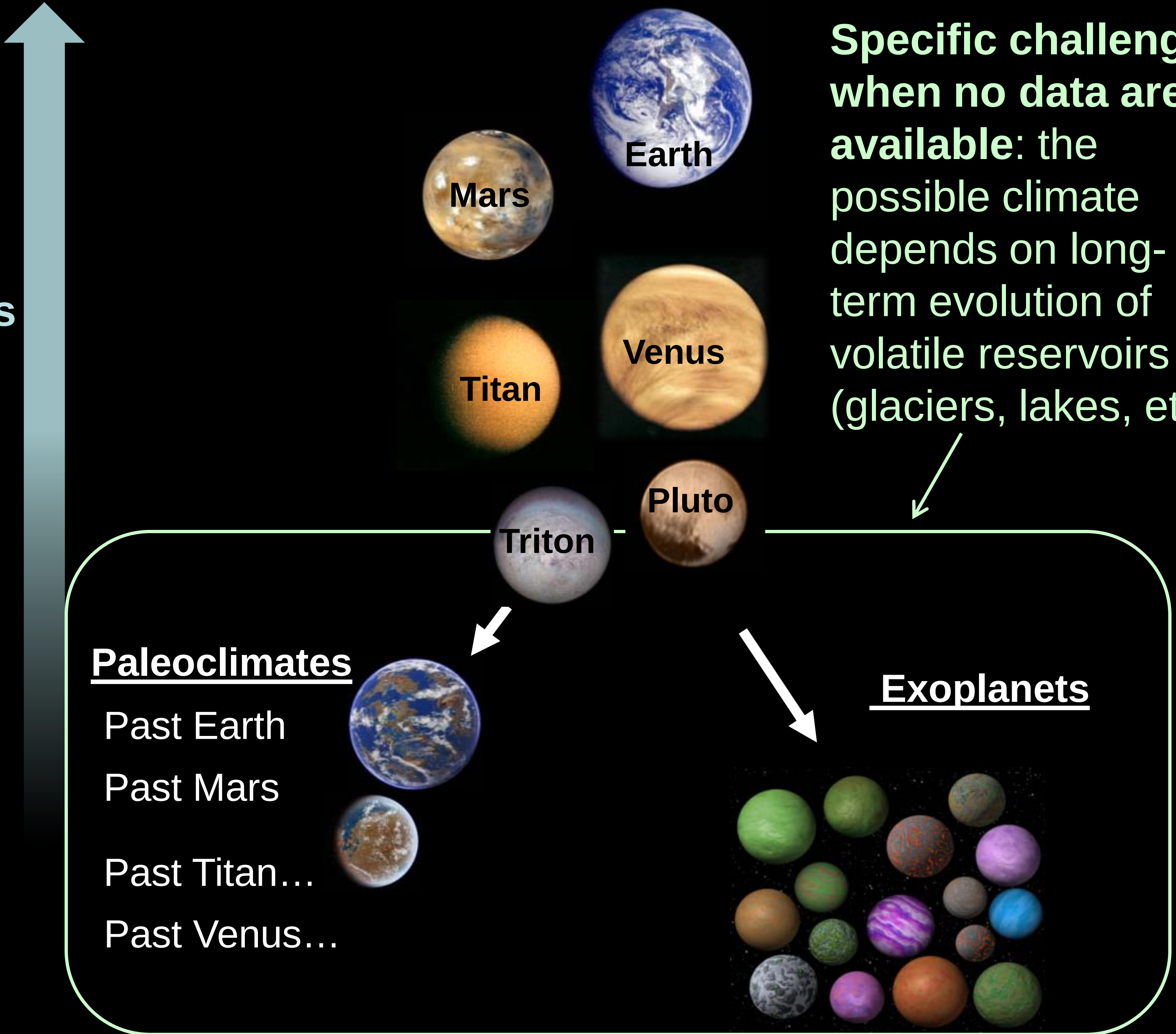
$x^{a(1)}$ **Martian Global Climate Model** $x^{b(1)}$

Typically 20 members

$x^{a(N)}$ **Martian Global Climate Model** $x^{b(N)}$

6 hours numerical integration

Terrestrial atmospheres to Model



Amount of observations available to constrain & test GCMs

Specific challenge when no data are available: the possible climate depends on long-term evolution of volatile reservoirs (glaciers, lakes, etc.)

Paleoclimates

Past Earth

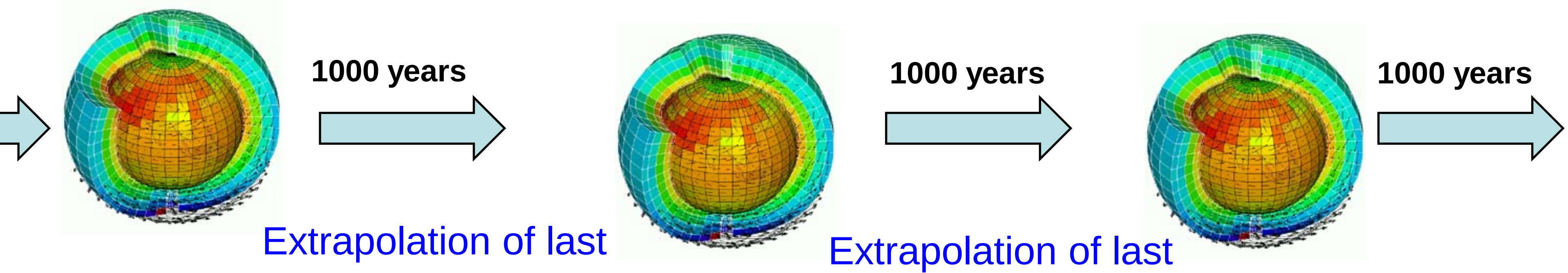
Past Mars

Past Titan…

Past Venus…

Exoplanets

Performing climate simulations over géological timescale



5 years simulations
⇒ *converged H_2O cycle : precipitation /evaporation*

1000 years

Extrapolation of last years annual mean tendancies ⇒ evolution of glaciers & lakes

5 years simulations
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5 years simulations
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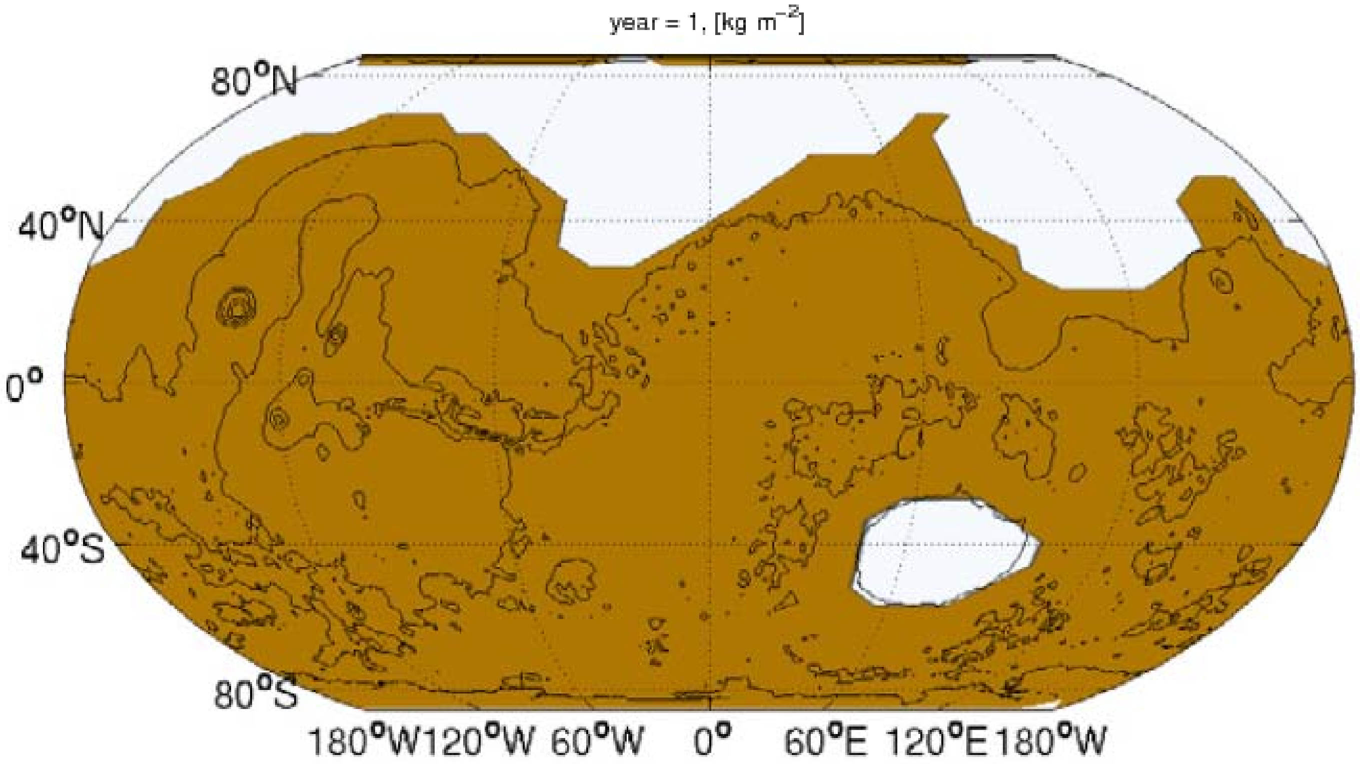
Example on Mars 3 billions years ago: the ice migrate to the highlands

Ps=0.5 bar
Obliquity=45°

Initially : Northern polar cap and frozen ocean



Wordsworth et al. 2013, 2015

Example on Mars 3 billions years ago: the ice migrate to the highlands

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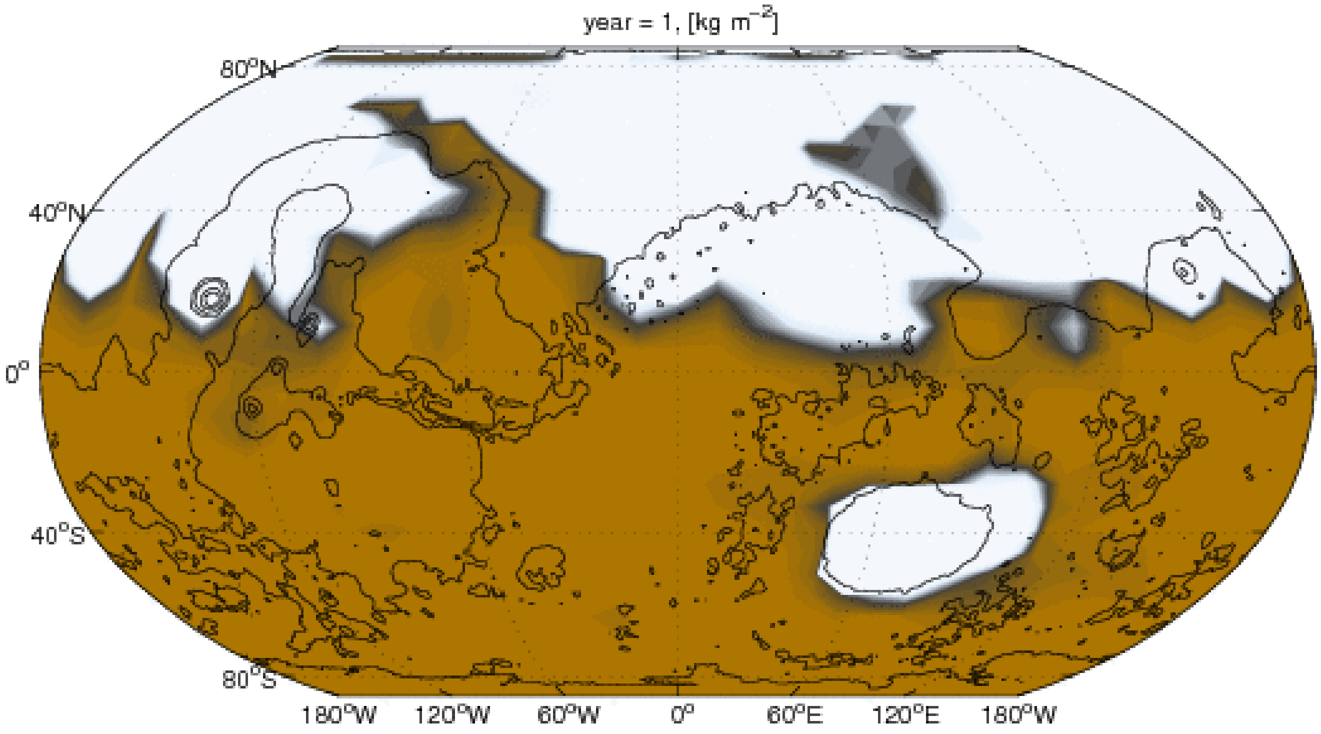
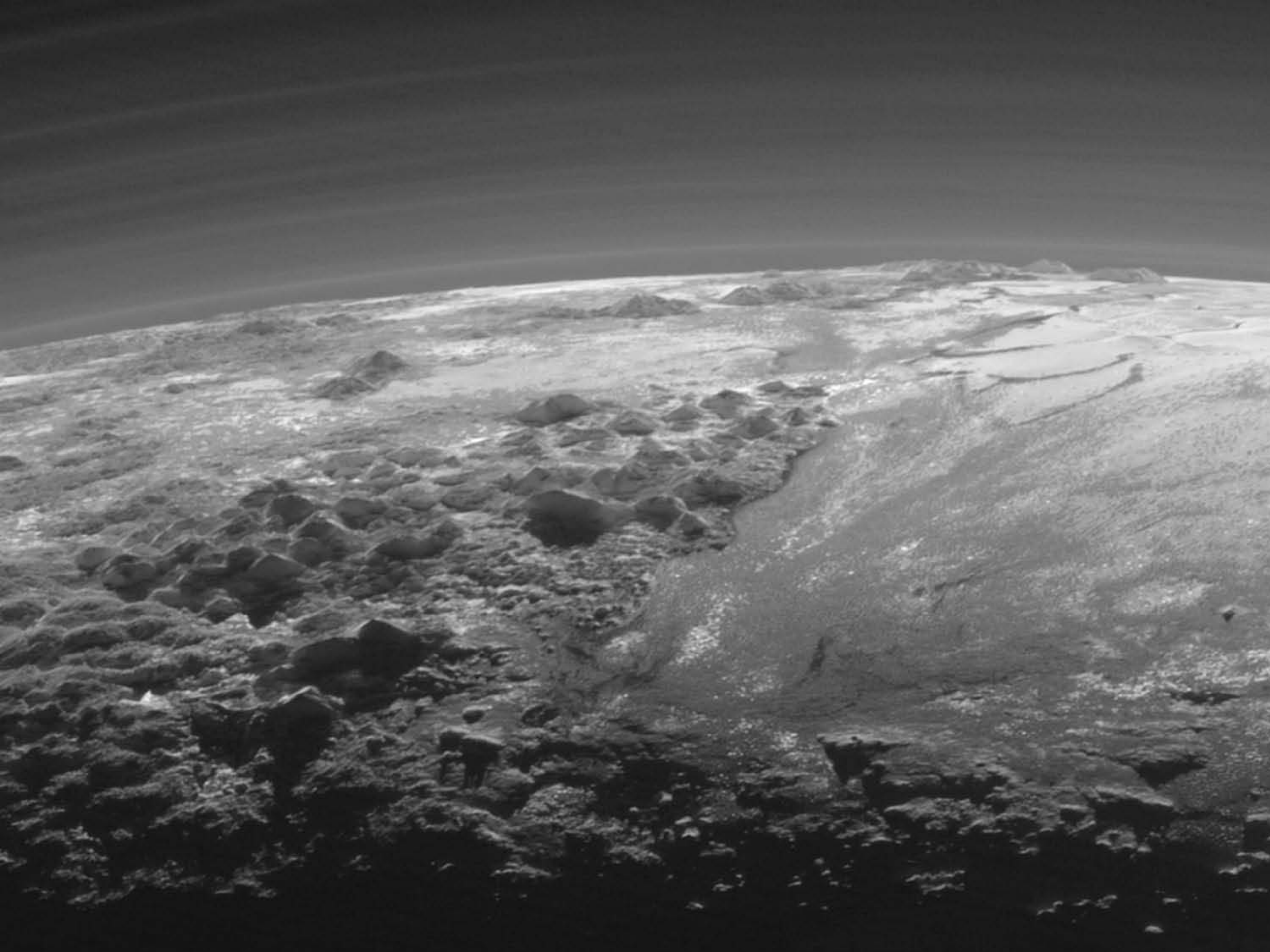


Wordsworth et al. 2013, 2015

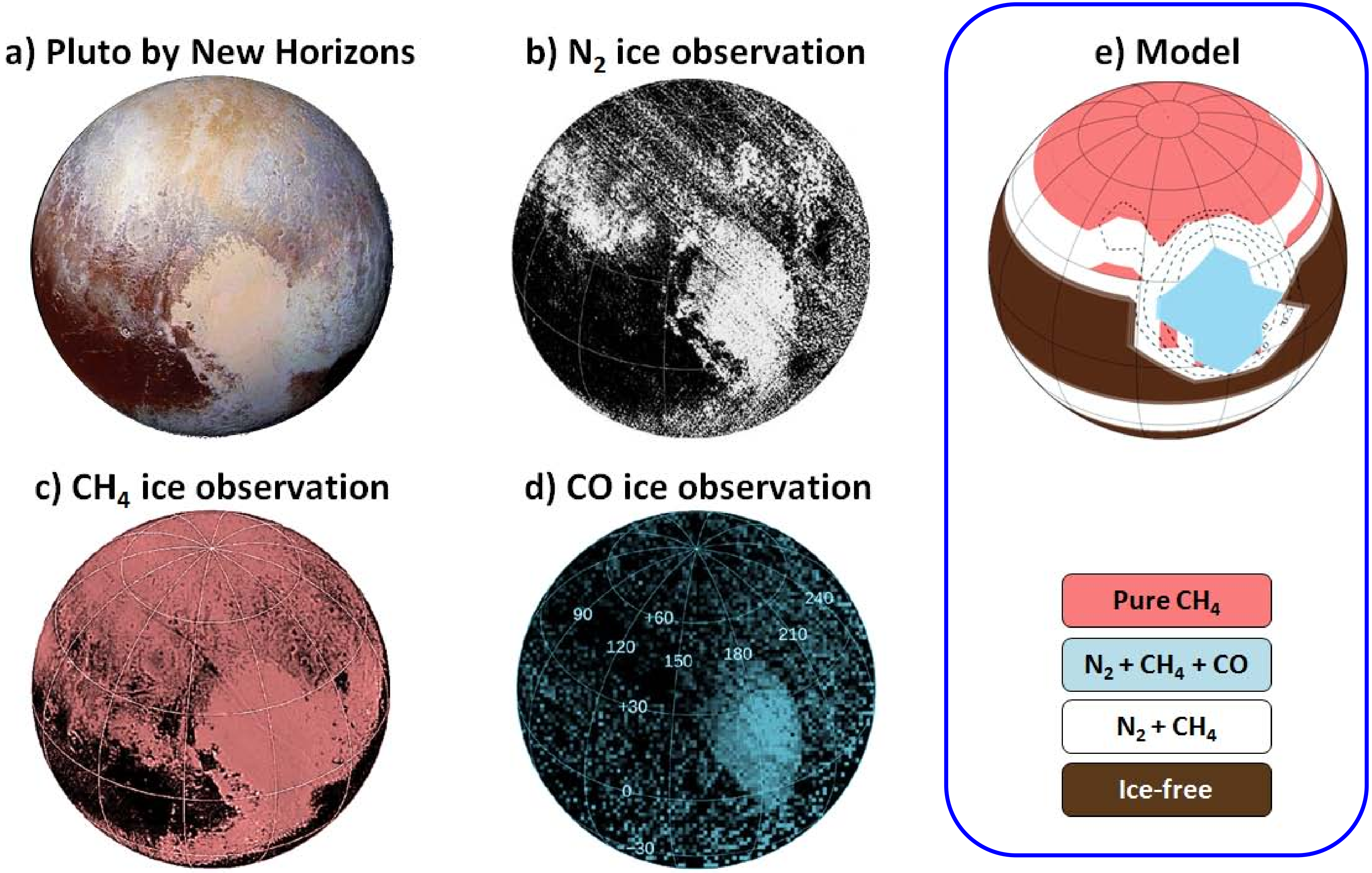
Pluton

Pluton révélée par la sonde « New Horizons » le 14 juillet 2015



Pluton en 2015

(Bertrand and Forget, Nature 2016)



a) Pluto by New Horizons

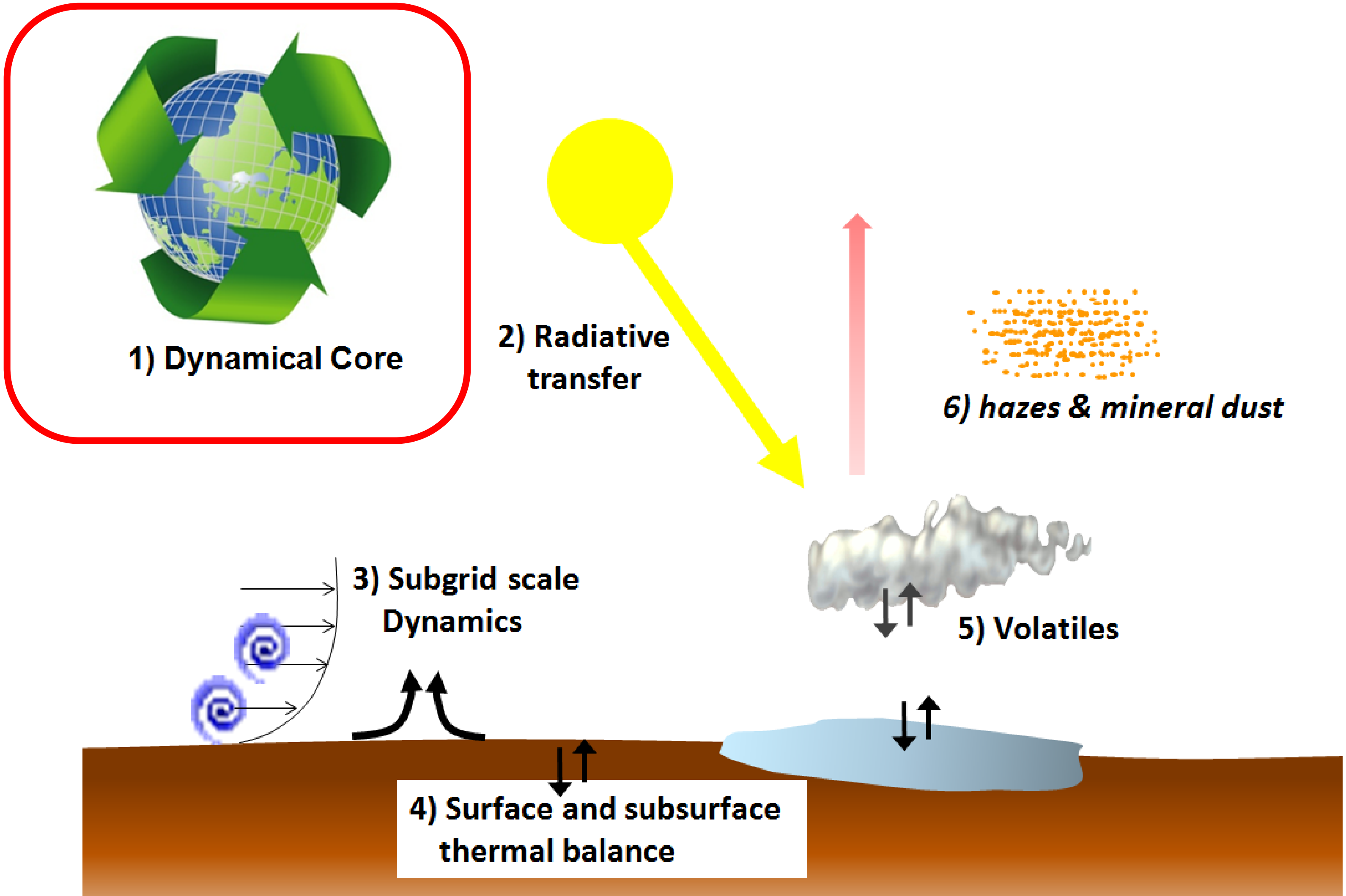
b) N_2 ice observation

c) CH_4 ice observation

d) CO ice observation

e) Model

How to improve Planetary Global Climate Models in the future ?



1) Dynamical Core

2) Radiative transfer

6) *hazes & mineral dust*

3) Subgrid scale Dynamics

5) Volatiles

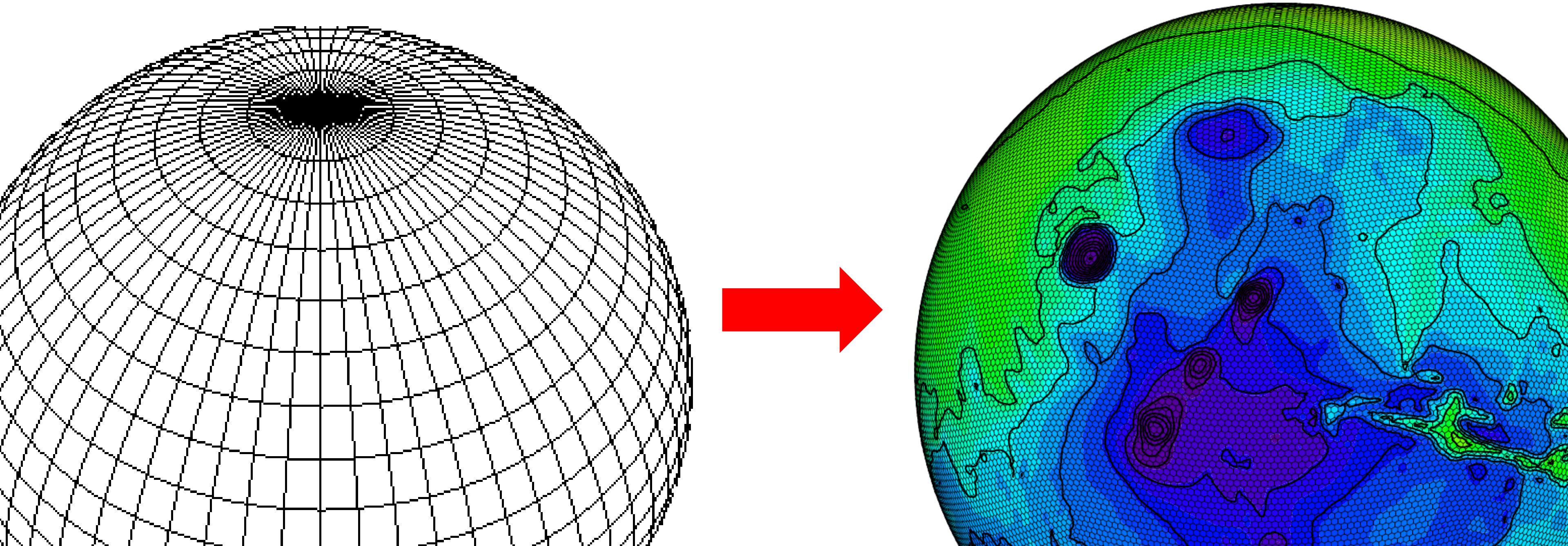
4) Surface and subsurface thermal balance

High resolution and new generation Dynamical Cores

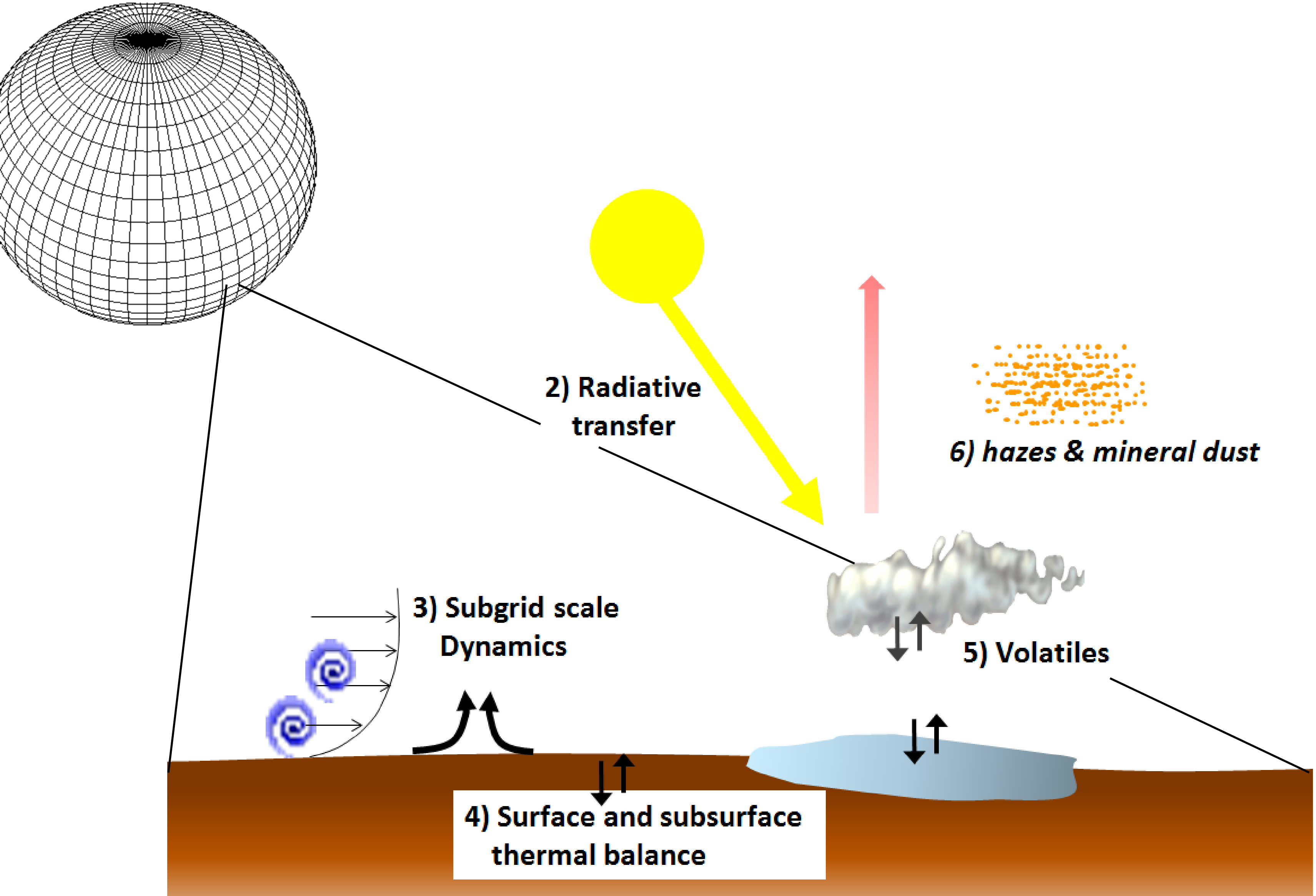
- Very high resolution is now possible with **Massively parallel computing**
  ➩ requires **new generation dynamical cores**

➩ **High resolution** (mesoscale-like ~50 km): Better representation of topography(circulation, waves, clouds), filamentation of tracers, waves,etc.

➩ **Super high resolution ?** (~1 km) Could resolve convection, all gravity waves: « cloud resolving models » ?



Improving the physics parameterizations



2) Radiative transfer

6) *hazes & mineral dust*

3) Subgrid scale Dynamics

5) Volatiles

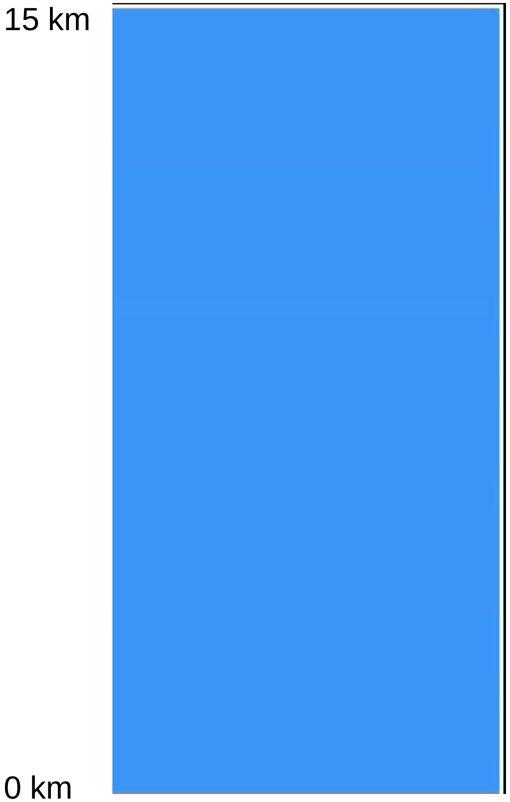
4) Surface and subsurface thermal balance

Improving the physics parameterizations

- Improved parameterizations should go toward **more** fundamental physical principles, **less** tunable parameters.
  - ⇨ Development of GCM parameterizations could be based on dedicated, yet universal, physical models *(e.g. cloud microphysics, convection, cloud convection model, etc…)*

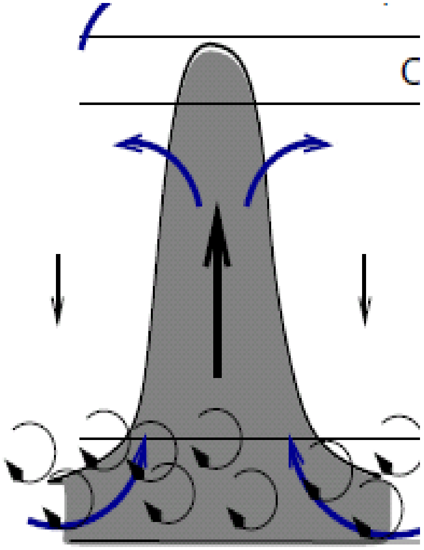
Example: parametrization of Martian convection using a microscale (res~ 20 m) LES model *(Colaitis et al. 2014)*

LES simulation of vertical wind

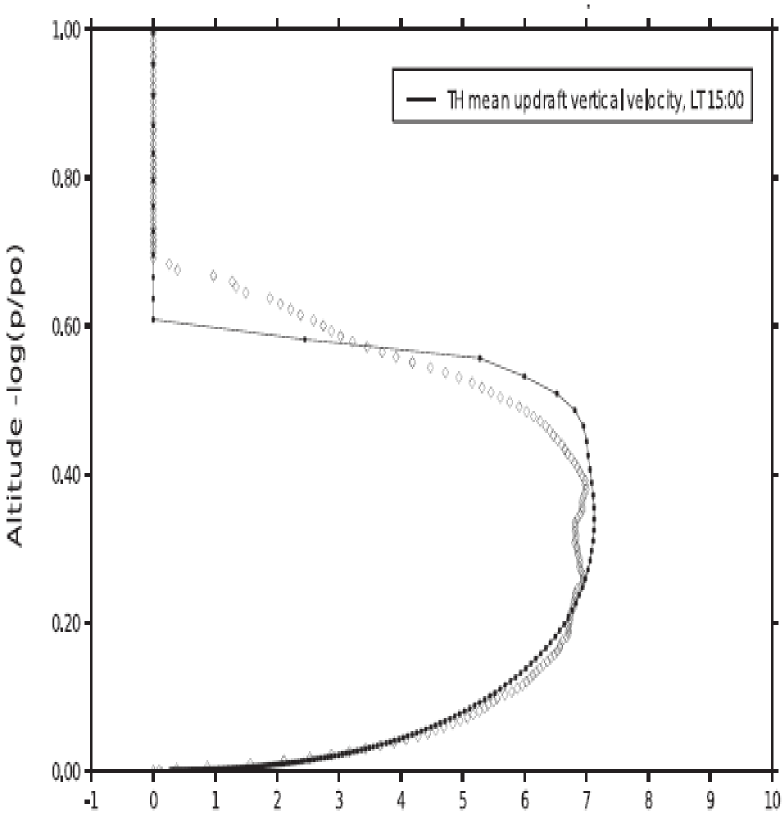


Vertical wind

Physically-based, 3 columns simple Mass flux scheme for GCM tuned with LES



Mean convective updraft wind in LES and GCM scheme



Mean velocity of updrafts (m/s)

Improving the physics parameterizations

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  - ⇨ Development of GCM parameterizations could be based on dedicated physical models *(e.g. cloud microphysics, convection, cloud convection model, etc…)*
- Find New concept of parametrizations ? Recent example: introduction of stochastic events to better represent reality

  (e.g. Lott and Guez 2013)

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 8897–8909, doi:10.1002/jgrd.50705, 2013

A stochastic parameterization of the gravity waves due to convection and its impact on the equatorial stratosphere

F. Lott[1] and L. Guez[1]

Received 27 March 2013; revised 22 July 2013; accepted 2 August 2013; published 26 August 2013.

[1] A formalism is proposed to parameterize the gravity waves due to convection in general circulation models with a stratosphere. It is based on a stochastic approach, where a large ensemble of monochromatic gravity waves is built up by launching a few waves at each time step, and by adding the effect of these waves, to that of the waves launched before, during the same day. The frequency and horizontal wave numbers of each wave are chosen randomly with fixed probability distribution, but the wave amplitude is directly related to precipitation, which is converted into heating rate. Linear theory is then used to predict the gravity wave generated by the heating rate. Off-line tests are carried out using reanalysis and global precipitation data. These tests demonstrate that the scheme launches gravity wave momentum fluxes that are much more erratic in amplitude than when uniform sources are considered. Consequently, the scheme tends to produce momentum flux deposition at lower levels than for the case when uniform sources are considered. We verify that the parameterization, when included in a general circulation model with vertical resolution in the stratosphere $\delta z \approx 500$m, is able to produce a quasi-biennial oscillation, without being detrimental to other aspects of the model climatology, like the semiannual oscillation and the behavior of the extratropics.

Citation: Lott, F., and L. Guez (2013), A stochastic parameterization of the gravity waves due to convection and its impact on the equatorial stratosphere, *J. Geophys. Res. Atmos.*, *118*, 8897–8909, doi:10.1002/jgrd.50705.

1. Introduction

[2] The parameterization of gravity waves (GWs) is itical to the proper representation of the circulations of the middle atmosphere in general

nonorographic GWs is as important as that of the orographic ones [*Dunkerton*, 1982].

[3] In the equatorial regions, it is also well established that the nonorographic GWs are a substantial driver of the quasi-biennial oscillation QBO, *Lindzen and Holton* [1968], plementing the forcing from the synoptic and plane- at GCMs can resolve explicitly

Improving the physics parameterizations

- Improved parameterizations should go toward **more** fundamental physical principles, **less** tunable parameters.
  - ⇨ Development of GCM parameterizations could be based on dedicated physical models *(e.g. cloud microphysics, convection, cloud convection model, etc…)*
- Find New concept of parametrizations ? Recent example: introduction of stochastic events to better represent reality

  (e.g. Lott and Guez 2013)
- Improving "The Art and Science of Climate Model Tuning" *(Hourdin et al., BAMS 2017)*

- To be continued
- Thank you…