On the diversity of terrestrial planets

Which climate and atmospheres can we expect ?

François Forget and Jeremy Leconte

(+ S. Lebonnois, R. Wordsworth, A. Spiga, B. Charnay, E. Millour, F. Codron, F. Montmessin, F.Lefevre, S.R. Lewis, P. Read, M.A. Lopez-Valverde, F. Gonzalez-Galindo, P. Rannou and many others)

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Why speculate ?

- We need to prepare future observations and adress key theoretical science questions (*e.g. probability of habitable planets in the galaxy*)
- **For ECHO**
  - Prepare observations of super Earths
  - Assess what Echo will teach us on the question of habitability, origins, etc…

Key parameters controlling the climate on a terrestrial planet:

- **Stellar insolation**
- **Atmospheric composition** and surface volatile inventory
- **Rotation** (rate and obliquity)

Climate system

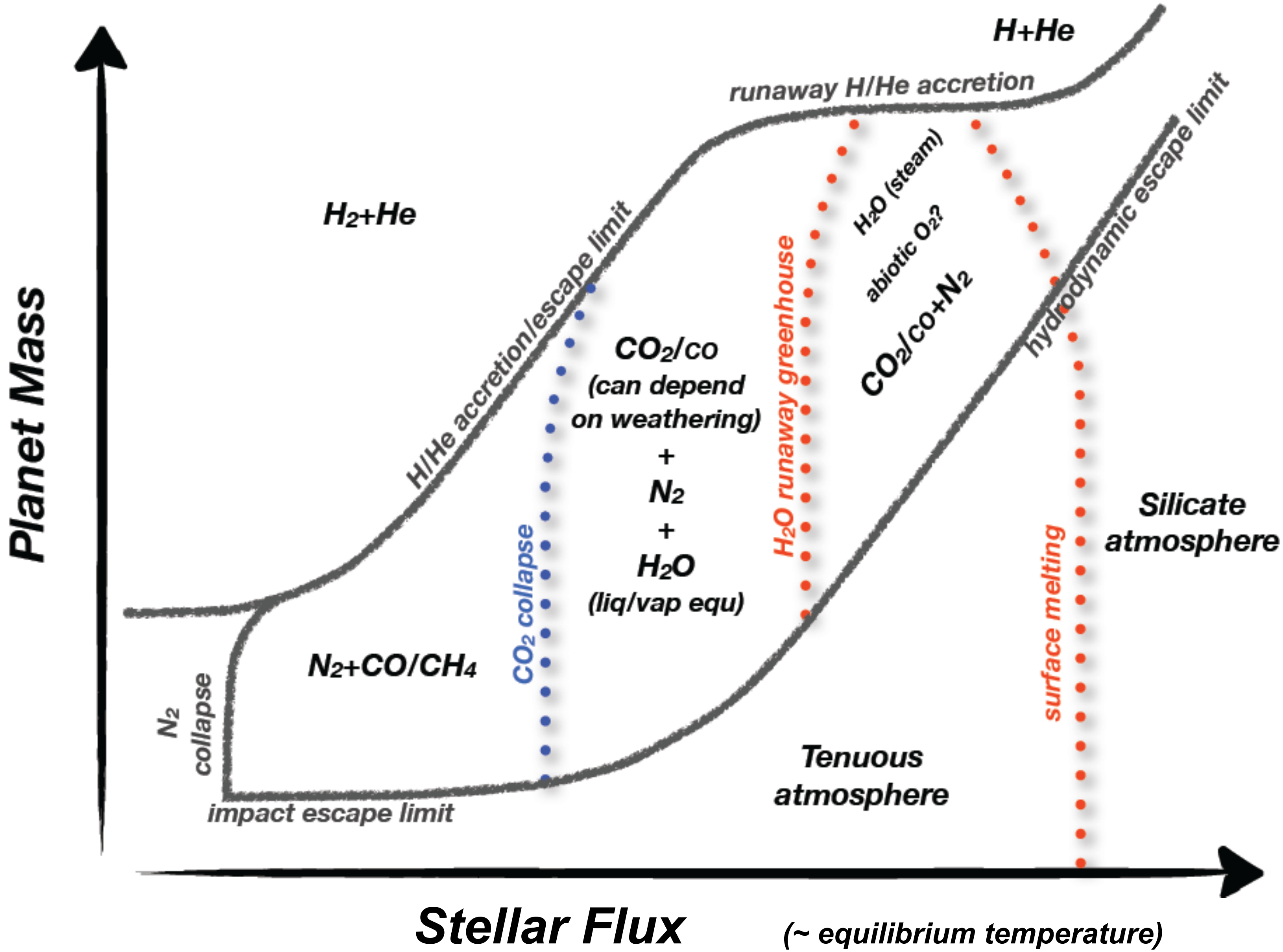
(Which can be modeled to predict the actual environment)

Atmospheric composition and surface volatile inventory ?

- Our experience in the solar system is not sufficient.
- The nature of terrestrial atmospheres depends on complex processes difficult to model:
  - Planetary formation and origins of volatiles
  - Atmospheric escape
  - Geochemistry (degassing and interaction with surface)
  - Long term photochemistry …

⇨ **But let's speculate**

Expected dominant species in an terrestrial planet atmospheres (abiotic)



Forget and Leconte, PTRSA, 2013 submitted / Echo Yellow Book tech. Note (Leconte et al.)

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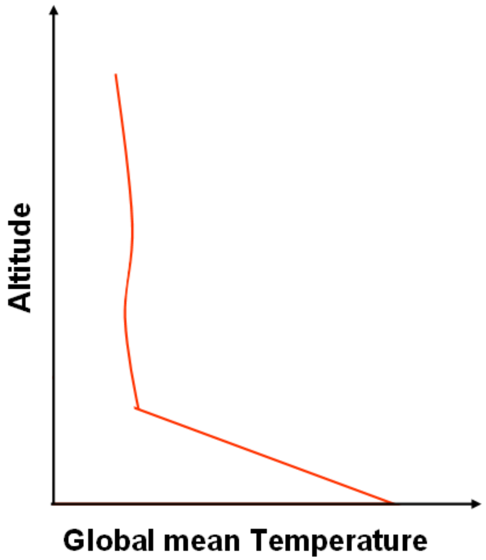
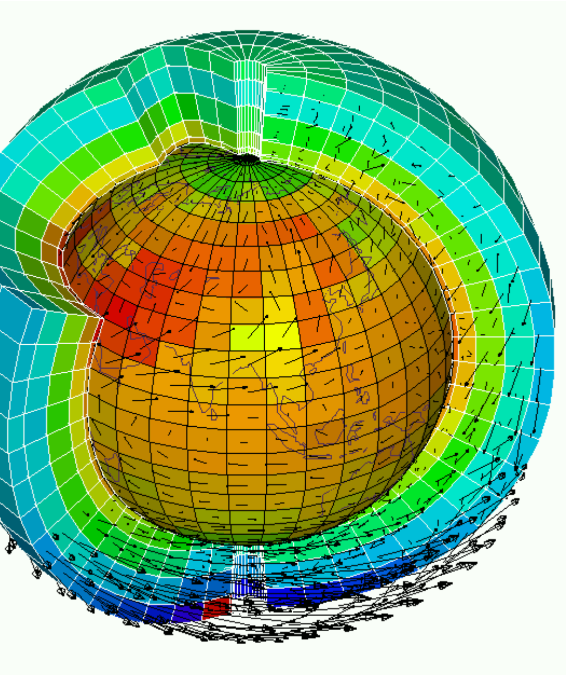
A hierarchy of models for planetary climatology





1. 1D global radiative convective models

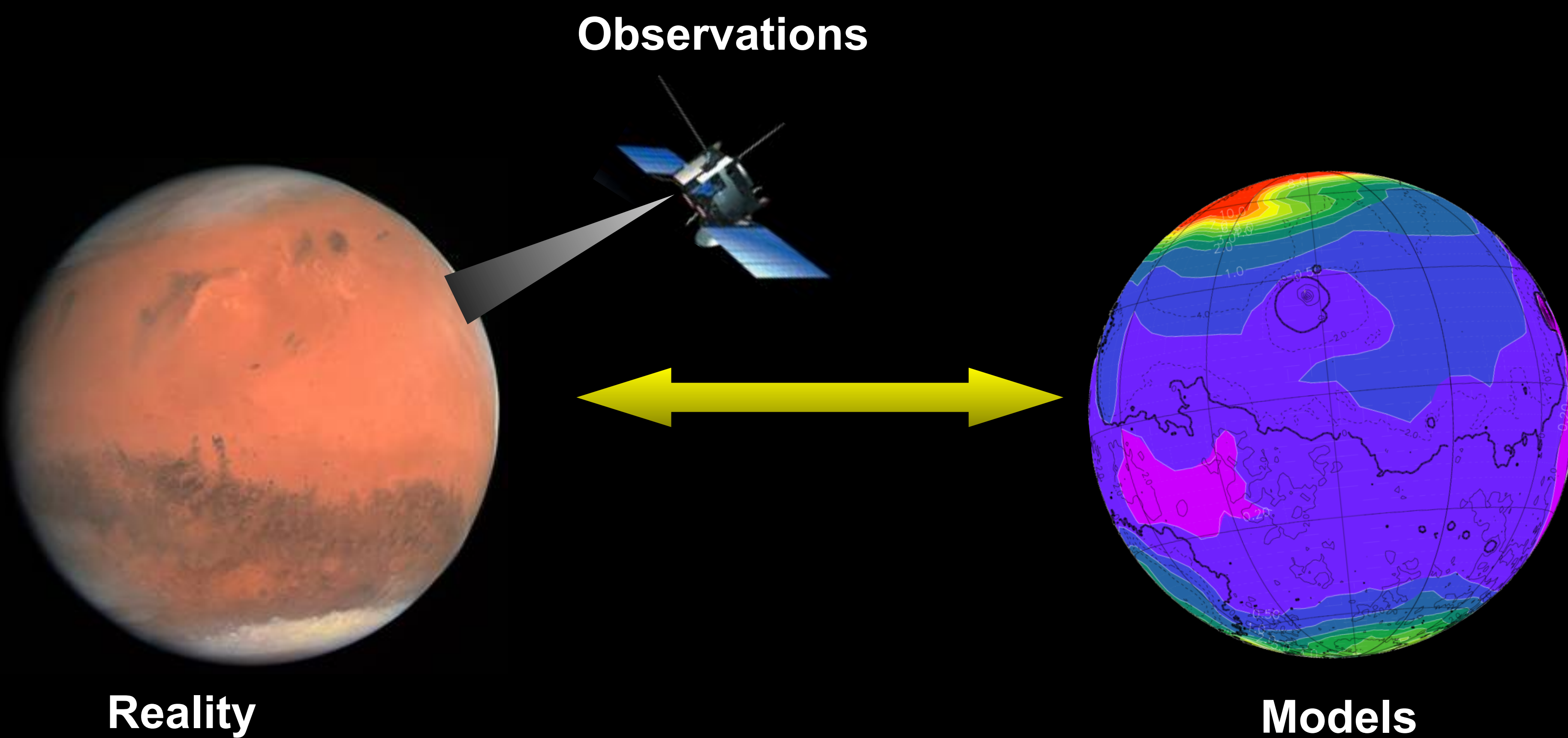
⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone *(e.g. Kasting et al. 1993)*

2. 2D Energy balance models…

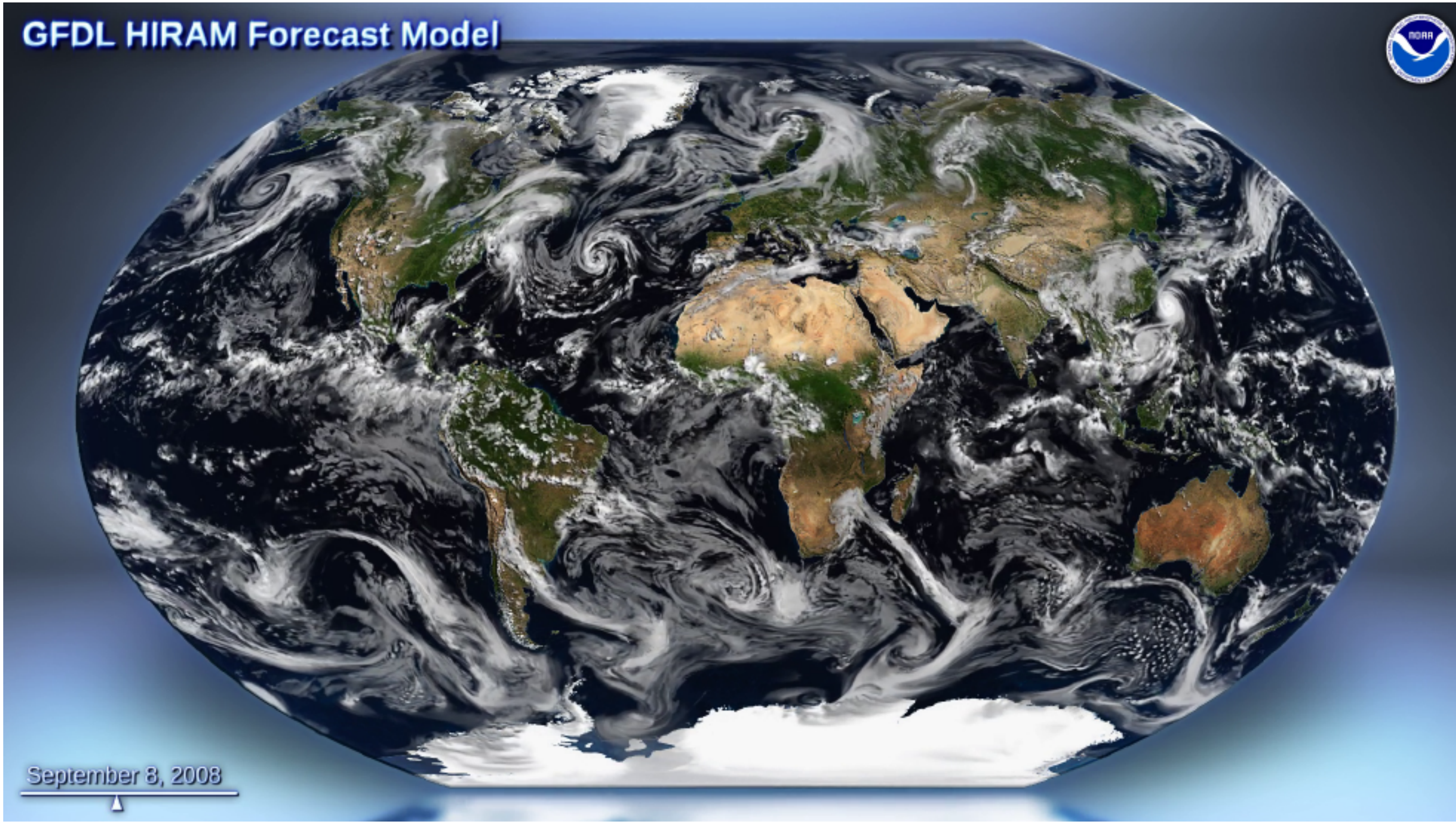
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime (*see Read 2011, Showman et al. 2013, etc)*

4. Full Global Climate Models aiming at building “virtual” planets.

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



How to build a full Global Climate Model :



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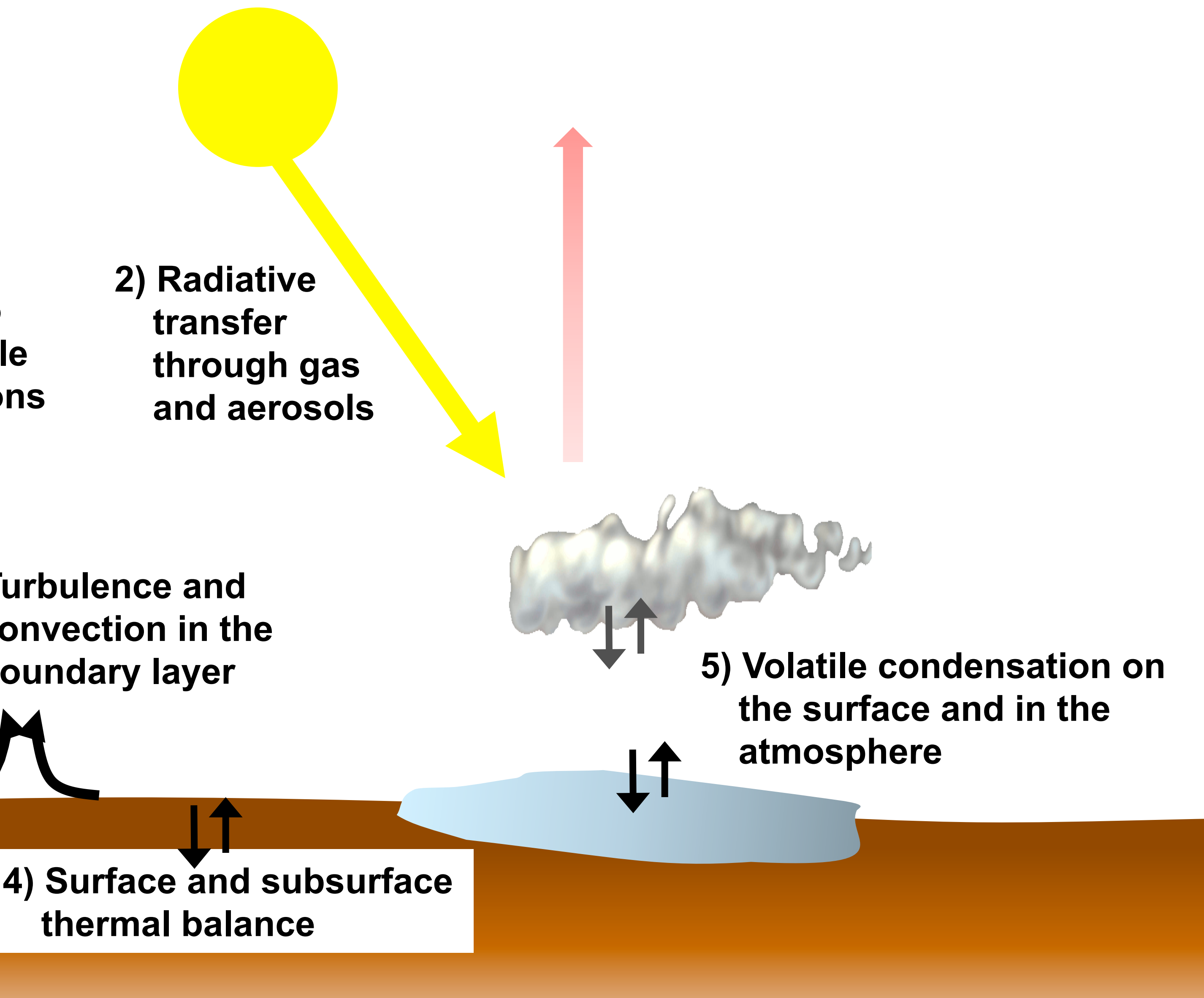


IN THE SOLAR SYSTEM:

VENUS

~2 GCMs

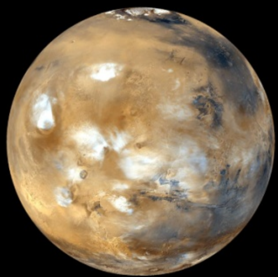
Coupling dynamic & radiative transfer (LMD, Ashima)

EARTH

Many GCM teams

Applications:

- **Weather forecast**
- **Assimilation and climatology**
- **Climate projections**
- **Paleoclimates**
- **chemistry**
- **Biosphere / hydrosphere cryosphere / oceans coupling**
- **Many other applications**



MARS

Several GCMs

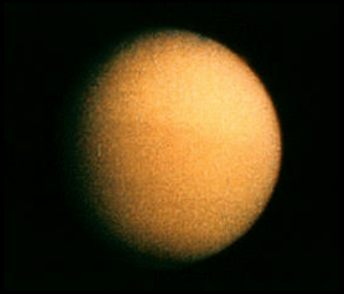
(NASA Ames, GFDL, LMD, AOPP, MPS, Ashima Research Japan, York U., Japan, etc…)

Coupled cycles:

- **CO_2 cycle**
- **dust cycle**
- **water cycle**
- **Photochemistry**
- **thermosphere and ionosphere**
- **isotopes cycles**
- **etc…**

Applications:

Dynamics, assimilation; paleoclimates, etc…



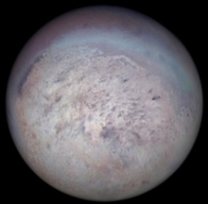
TITAN

~a few GCMs

(LMD, Univ. of Chicago, Caltech, Köln…)

Coupled cycles:

- **Aerosols**
- **Photochemistry**
- **Clouds**



TRITON

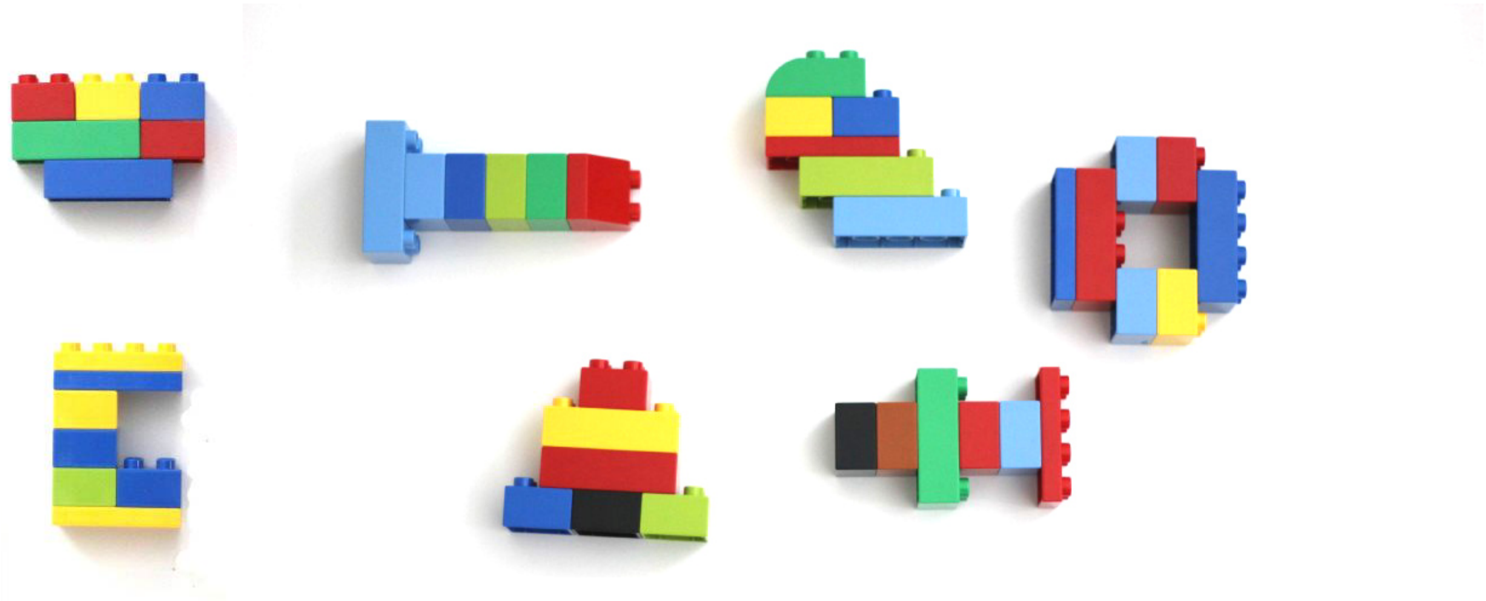
GCM s (LMD, MIT)

PLUTO

GCMS (LMD, MIT)

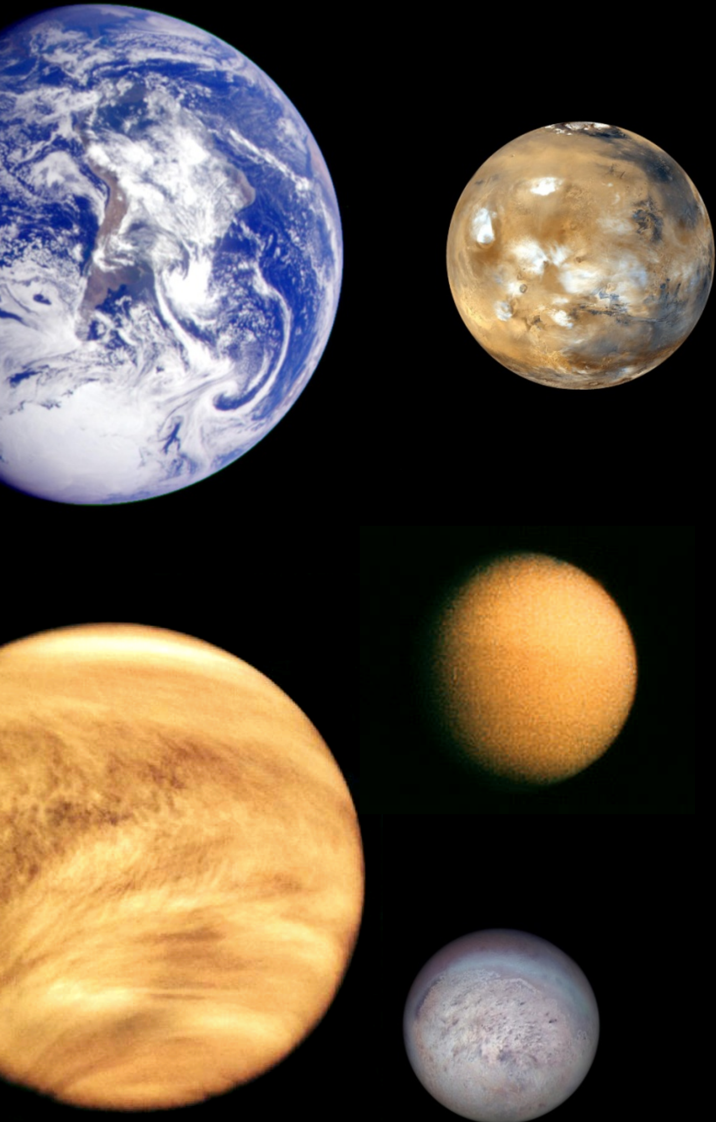
What we have learned from solar system GCMs

- **Lesson # 1 To first order**: GCMs work
  - A few equations can build « planet simulators » with a realistic, complex behaviour and strong prediction capacities
- **Lesson # 2 The model components that make a climate model can be applied without major changes to most terrestrial planets.**



What we have learned from solar system GCMs:

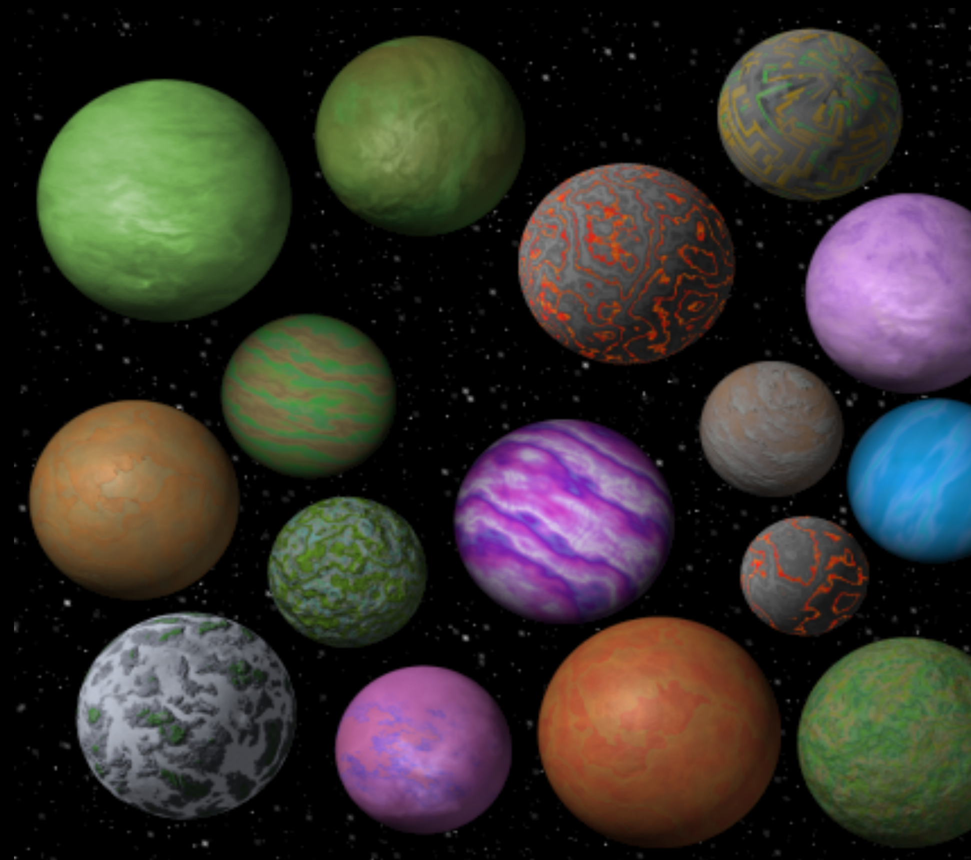
- **Lesson # 1: By many measures: GCMs work**
  - A few equations can build « planet simulators » with a realistic, complex behaviour and strong prediction capacities
- **Lesson # 2: GCM components are valid on various planets without major changes.**
- **Lesson # 3: Sometime GCMs fail: When and why GCMs have not been able to predict the observations accurately?**
  - **Missing physical processes** (*e.g. radiative effects of Martian clouds*; *subsurface water ice affecting CO2 ice mass budget on Mars)*
  - ⇨ Complex subgrid scale process and poorly known physics *(e.g. clouds on the Earth, Gravity waves on Venus)*
  - **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)*
  - **Weak Forcing** : when the evolution of the system depends on a subtle balance between modeled process rather than direct forcing *(e.g. Venus circulation)*



The science of simulating the unobservable:

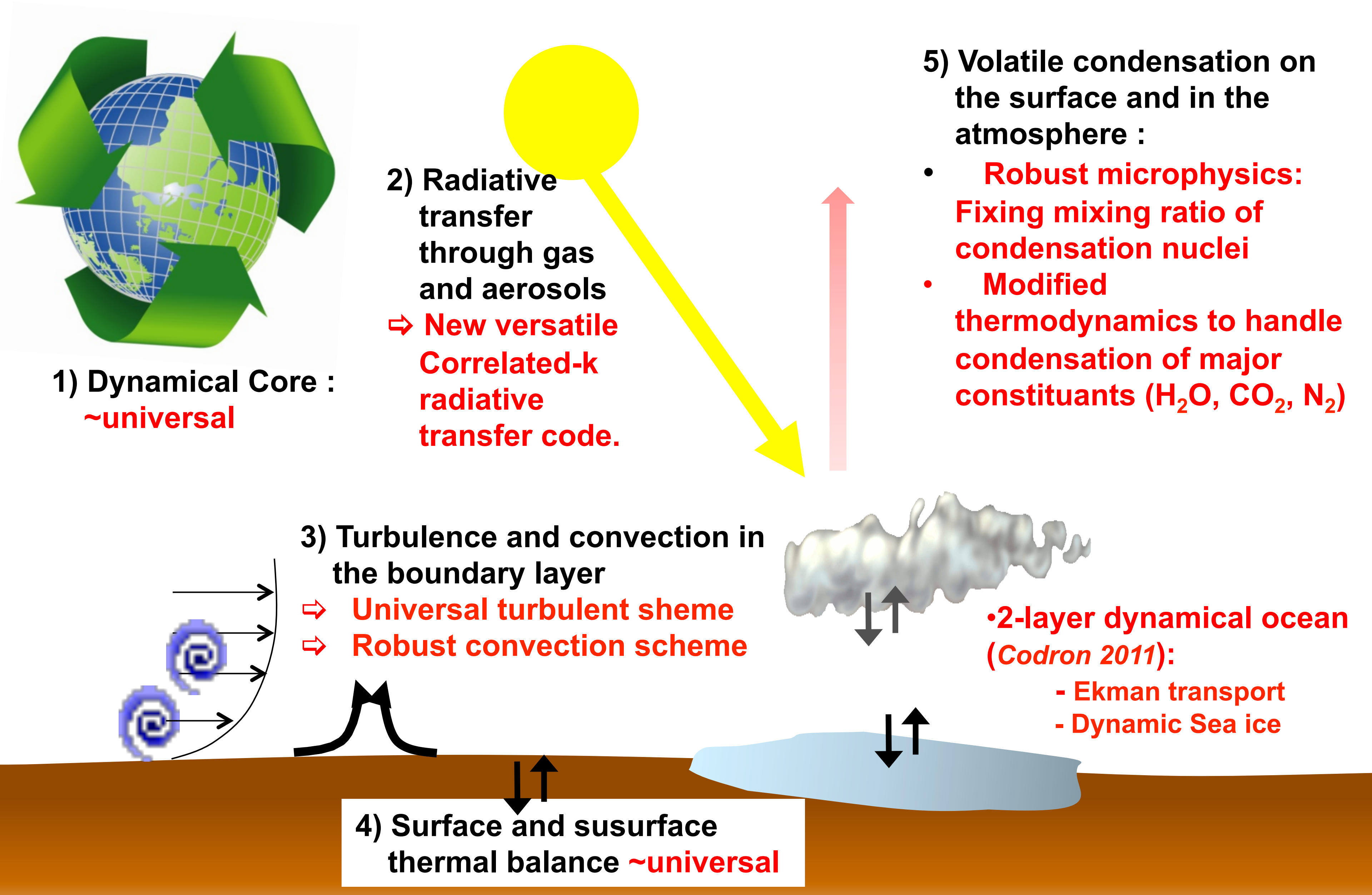
From planet GCMs to extrasolar planets

(or past atmospheres).

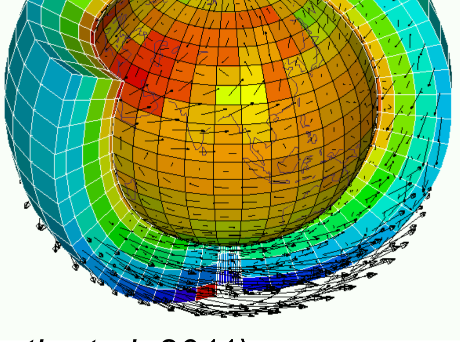


A 3D ''generic'' Global climate model (LMDZ Generic)

designed to simulate any atmosphere on any terrestrial planet around any star.



Recent applications of the LMD ‘‘generic’’ Global climate model:



❑ Cold terrestrial climates:

• Climate on cold tidally locked super-Earth: Gliese 581d *(Wordsworth et al. 2011)*

• Modelling the early Mars Climate *(Forget et al. 2013, Wordsworth et al. 2013)*

• 3D simulations of the Archean Earth « Faint young sun paradox » *(Charnay et al. 2013)*

❑ Warm and Hot Climate **(see next talk by Jeremy leconte):**

• 3D simulations of the runaway greenhouse effect

• climate moist bistability and habitability on warm super Earth (e.g. Gl 581 c and HD85512 b) *(Leconte et al. 2013)*

• An Ocean on early Venus ?

• Very hot super-earths like CoRot 7b *(Samuel et al. 2013)*

❑ Observation Simulations:

• Modelling Thermal phase curves of nontransiting terrestrial exoplanets (*Selsis,Wordsworth and Forget 2011)*

• CoRoT-7b as seen by JWST (*Samuel et al. 2013)*

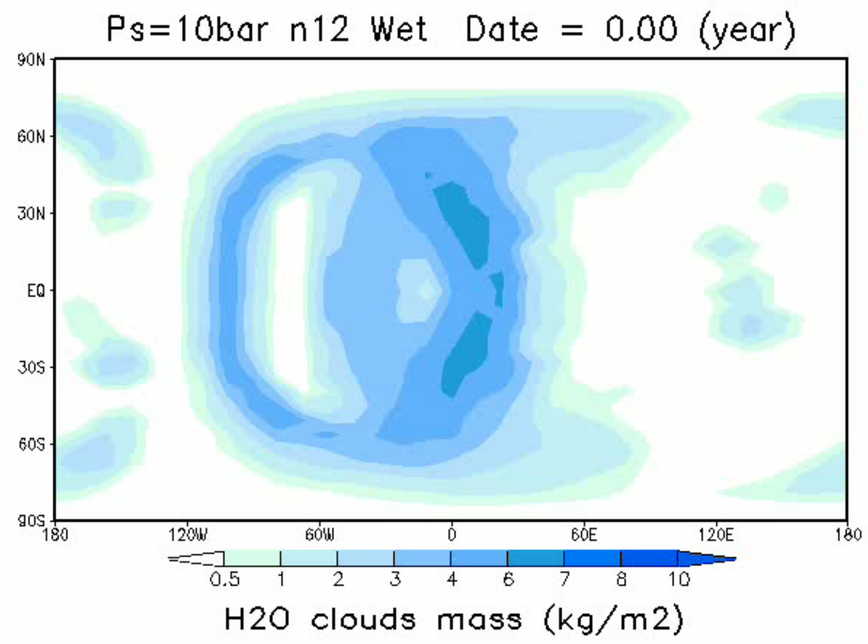
❑ An ongoing project : Modelling giant planet atmosphere

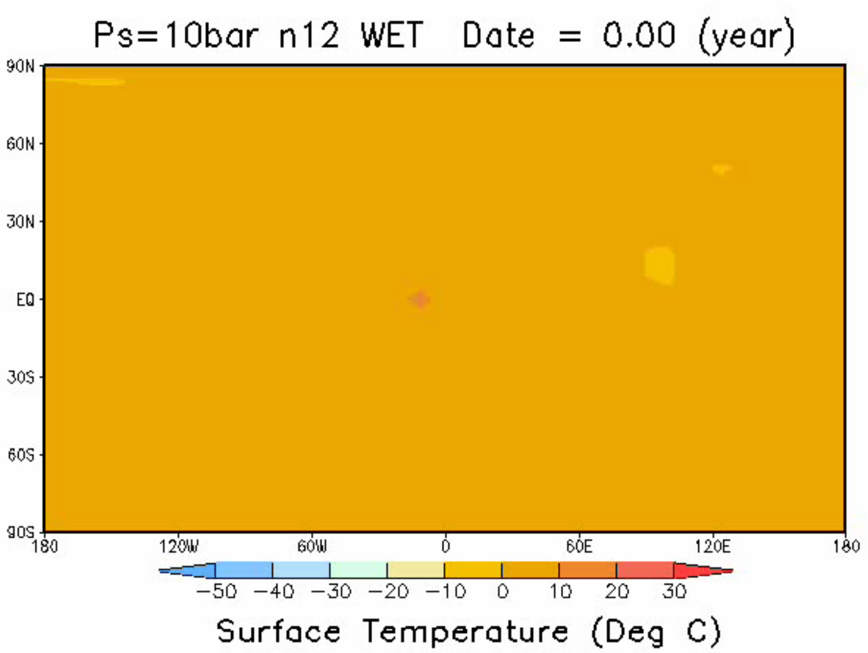
• Saturne stratosphere (A. Spiga)

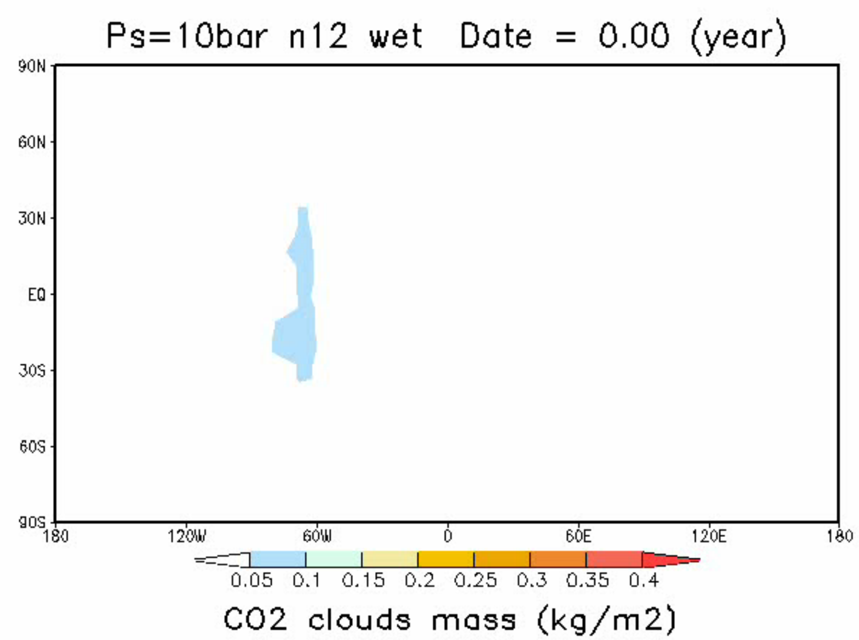
A simulation of cold tidally locked super-Earth: Gliese 581d

(Wordsworth et al. 2011)

(assuming an ocean planet with 10 bars of CO2)







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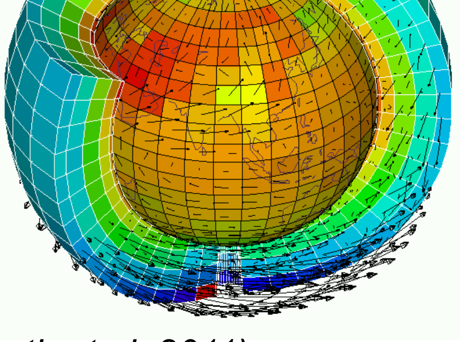

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Some Conclusions

- Assuming atmosphere/ocean compositions, Global Climate Models are fit to address scientic questions related to extrasolar planets:
  - Limits of habitability and frequency of habitable worlds
  - Climate on specific planets (assuming a specific atmosphere)
  - ⇨ Preparation of observations
- *However, whatever the quality of the model, heavy study of model sensitivity to parameters will always be necessary.*
- The key scientific problem remains our understanding of the zoology of atmospheric composition, controlled by even more complex processes (planetary formation, atmospheric escape, geochemistry, etc.)

⇨ We need observations of atmospheres, even from outside the Habitable zone.

⇨ **ECHO !!**