Can Global Climate Models Simulate All Terrestrial Planets in the Solar System and Beyond ?

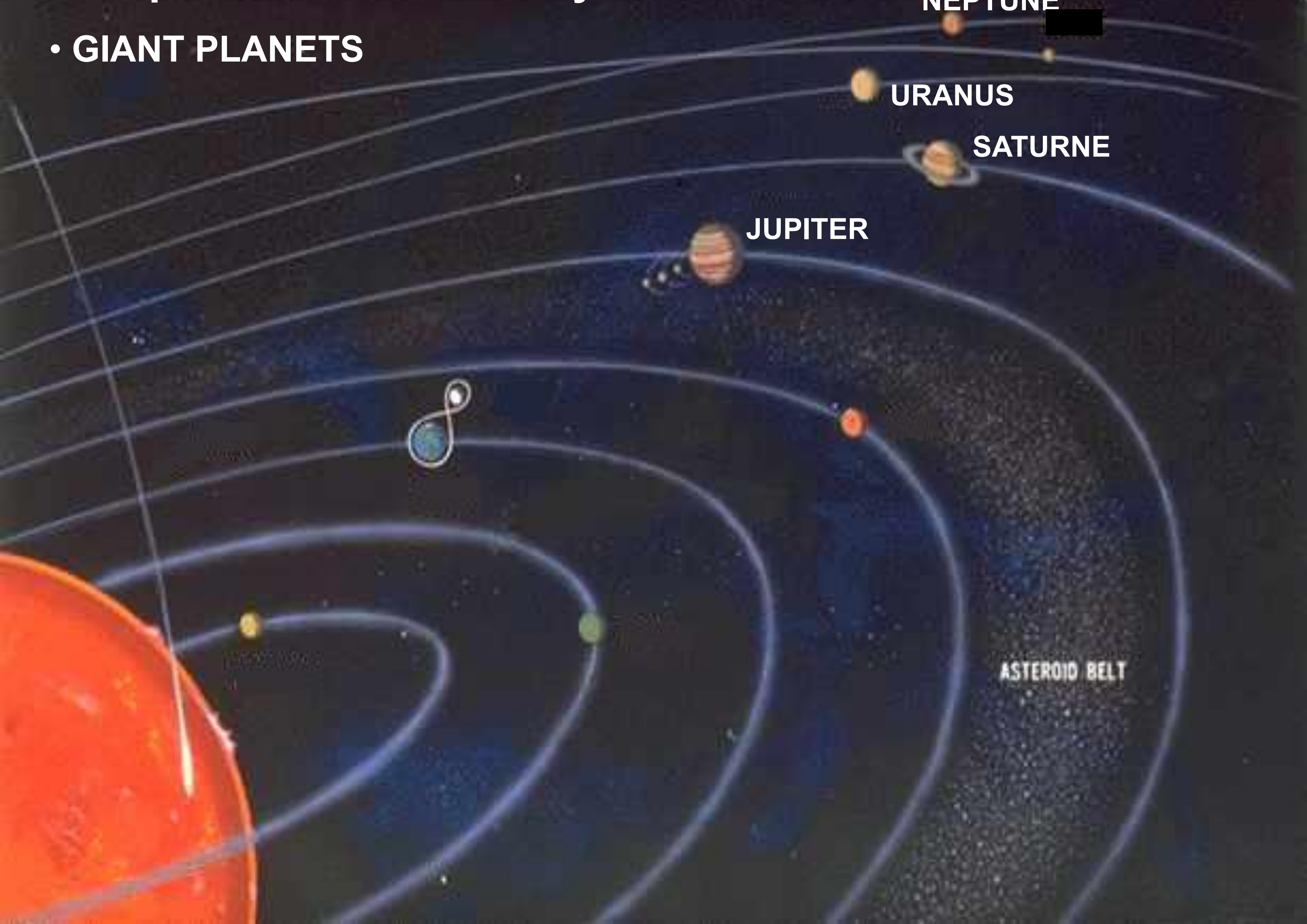
François Forget

(+ , J.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)

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

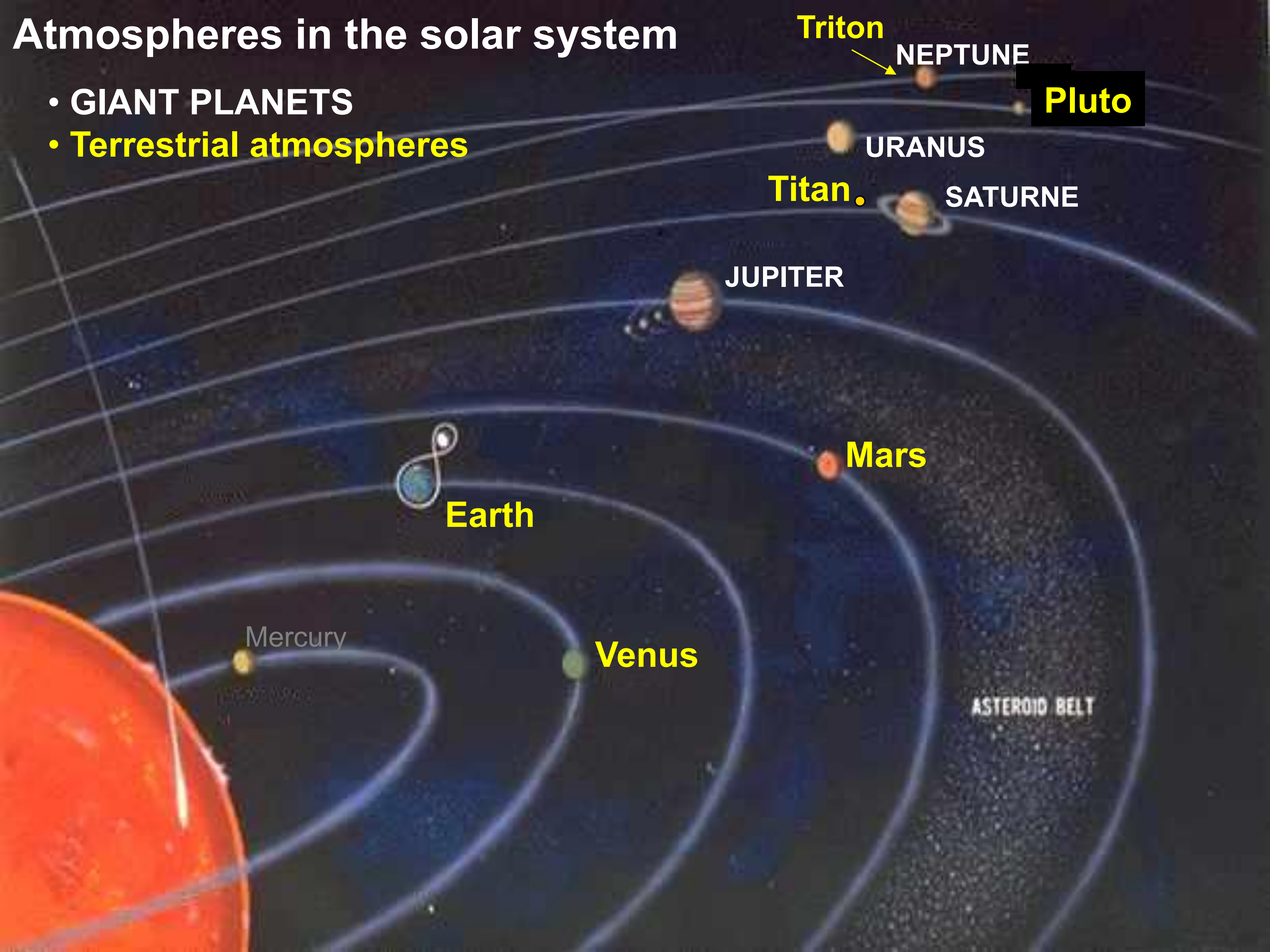
Atmospheres in the solar system

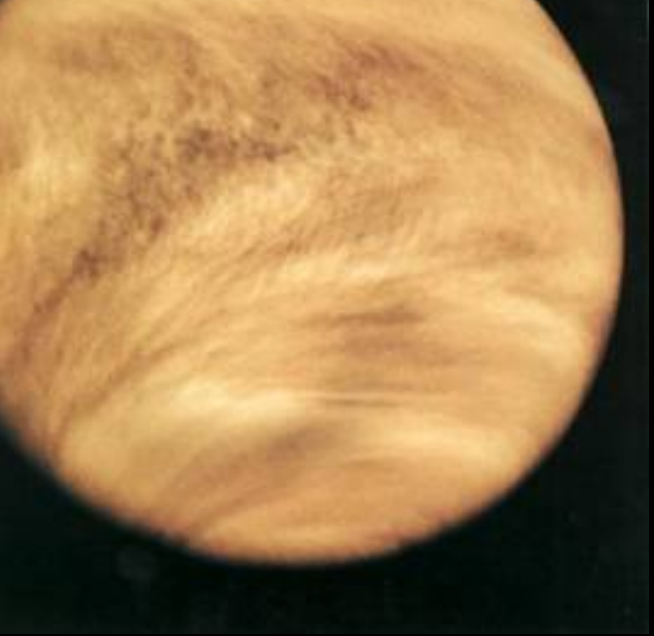
- GIANT PLANETS



Atmospheres in the solar system

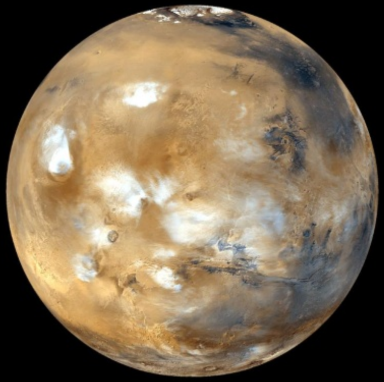
- GIANT PLANETS
- Terrestrial atmospheres



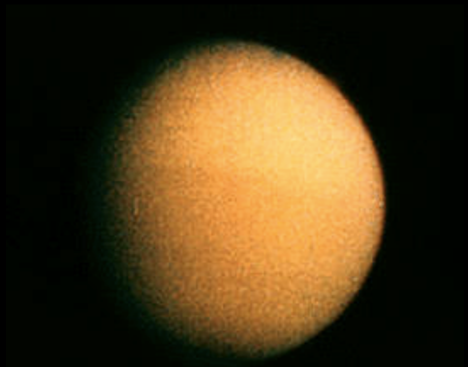


VENUS: <Ts> > 450°C
Ps = 90 bars
Distance to Sun=0.82 AU

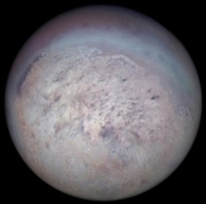
EARTH: <Ts> ~ 15°C
Ps=1 bar
Distance to sun=1. AU



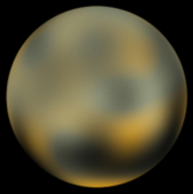
MARS: <Ts> < -70°C
Ps = 0.006 bar
Distance to sun=1.52AU



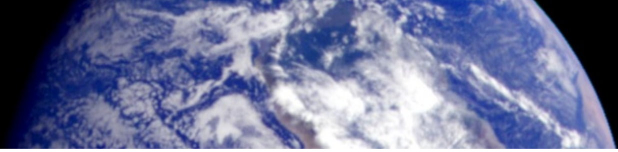
TITAN: <Ts> ~ -180°C
Ps = 1.5 bars
Distance to Sun=9.53 AU

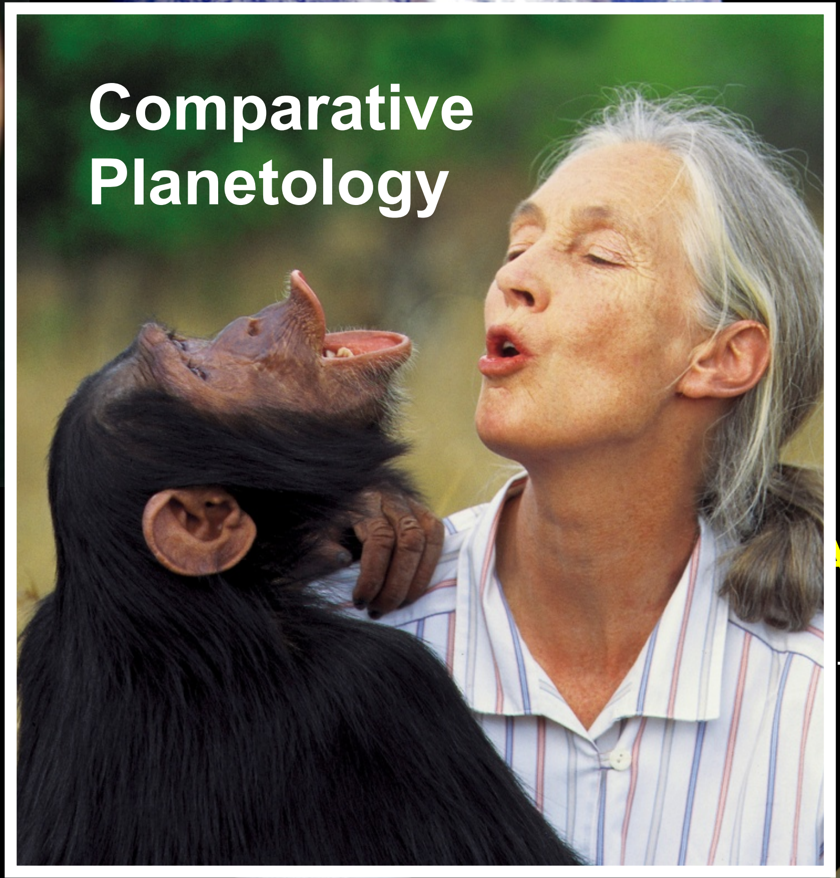


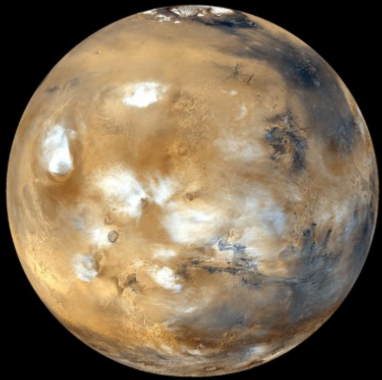
TRITON: <Ts> ~ -235°C
Ps = ~2 Pa
Distance to Sun=30 AU



PLUTO: <Ts> ~ -230°C
Ps = ~2 -5 Pa
Distance to Sun=39.5 AU







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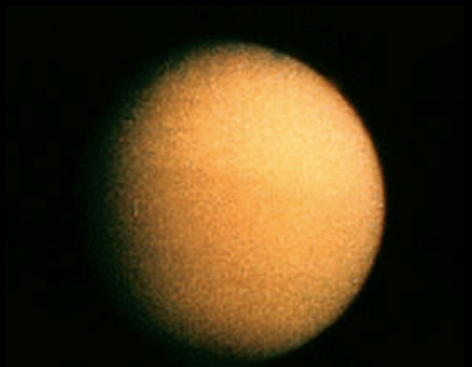

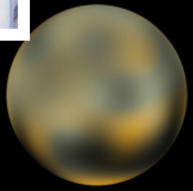

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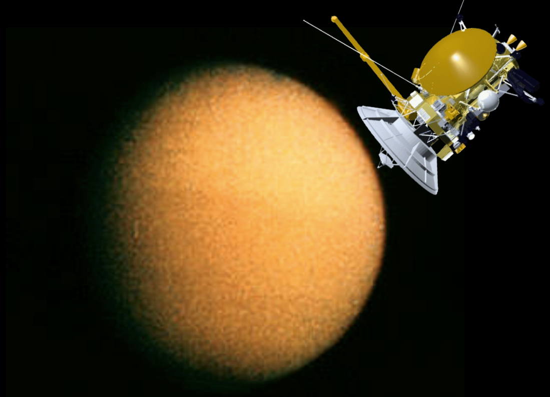

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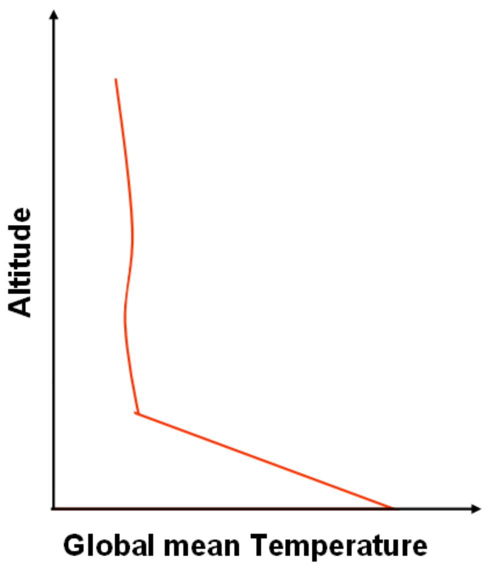
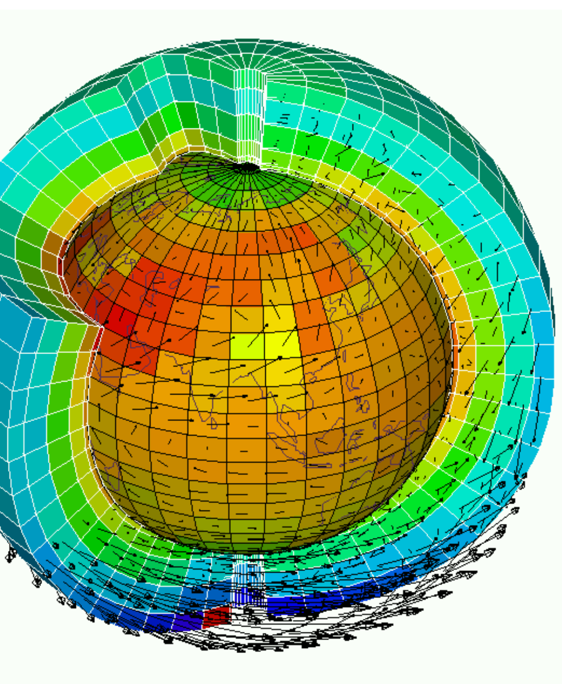
A hierarchy of models for comparative climatology





1. 1D global radiative convective models

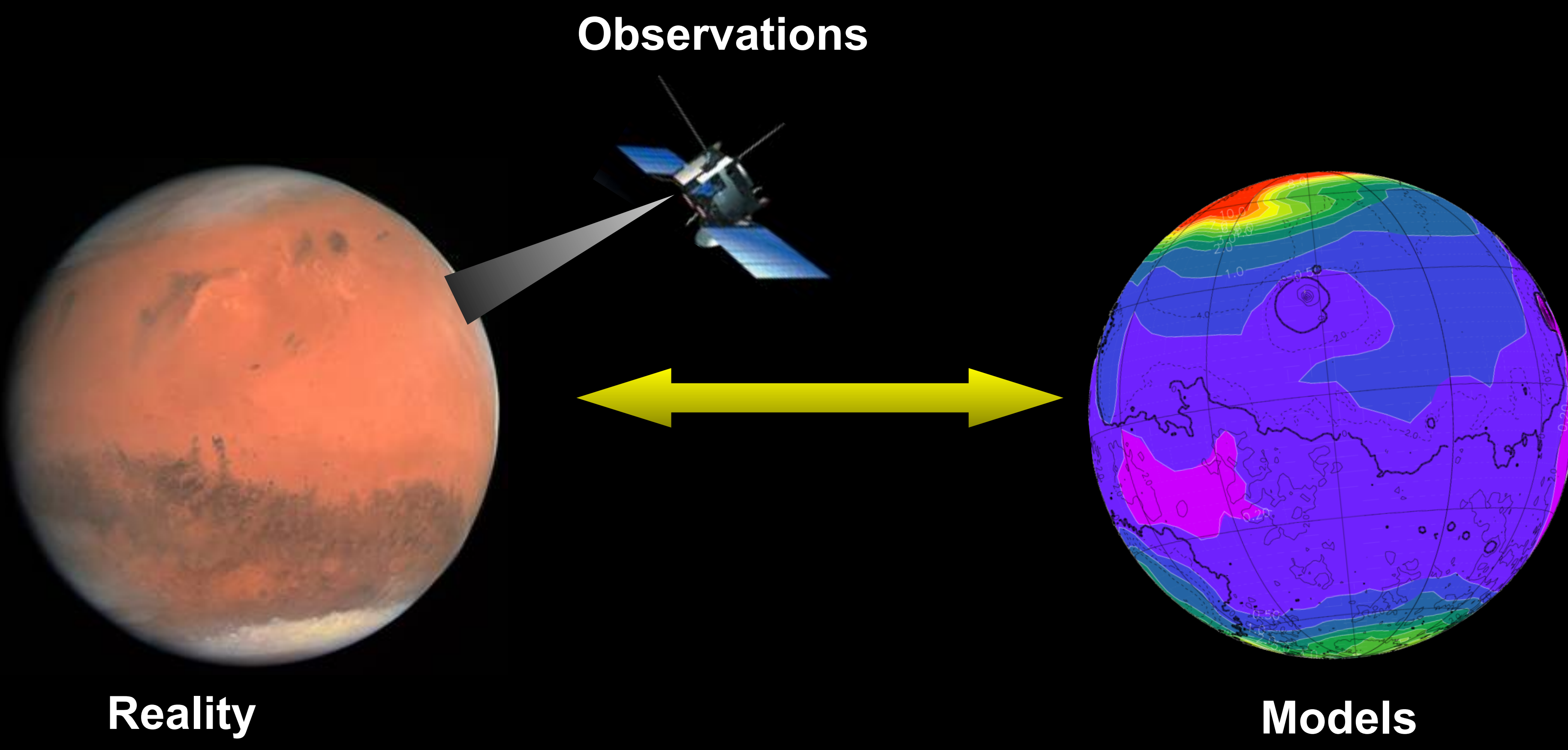
⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone *(e.g. Kasting et al. 1993)*

2. 2D Energy balance models…

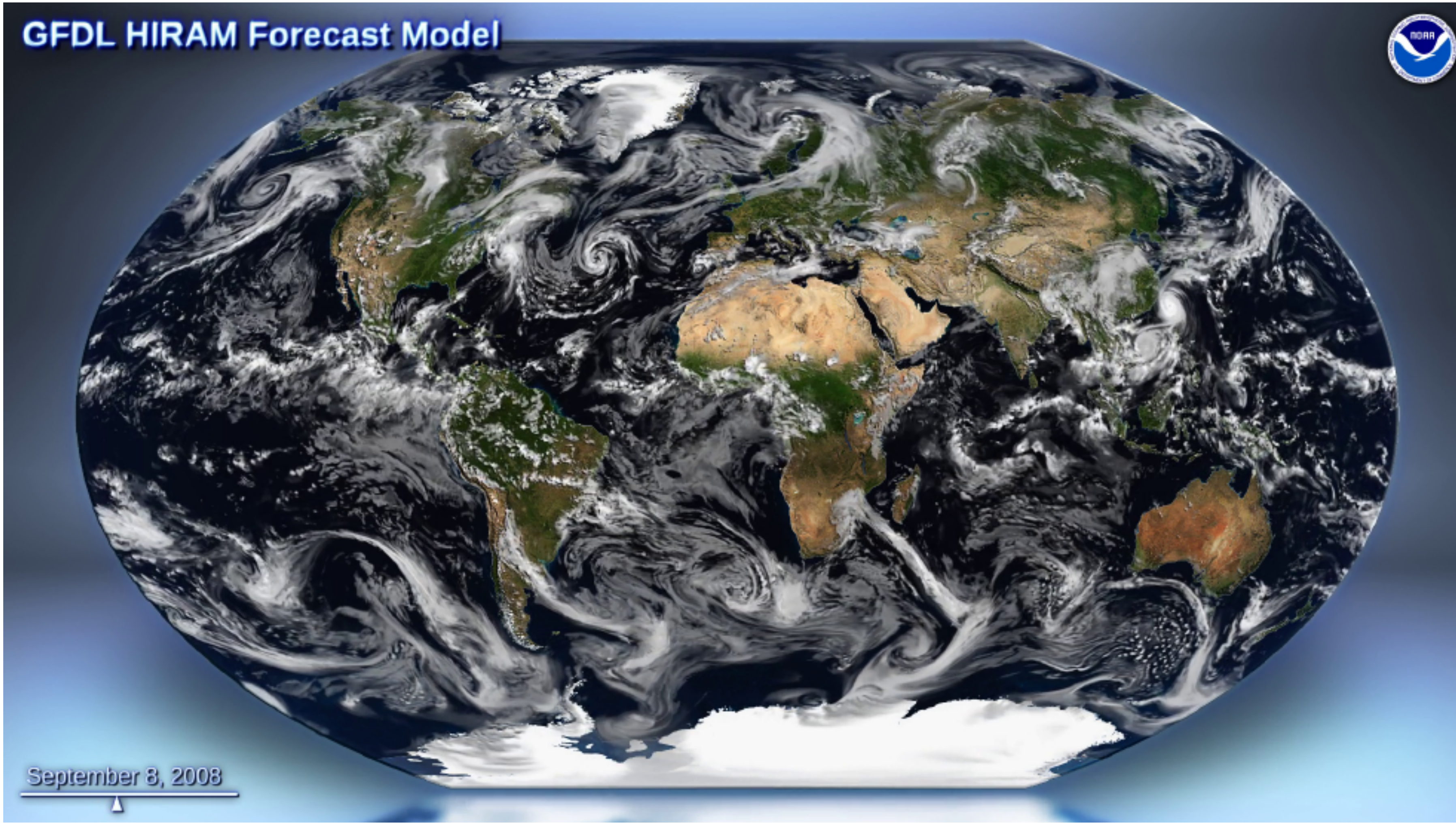
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime (*e.g. many talks during this week !)*

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 Global Climate Model :



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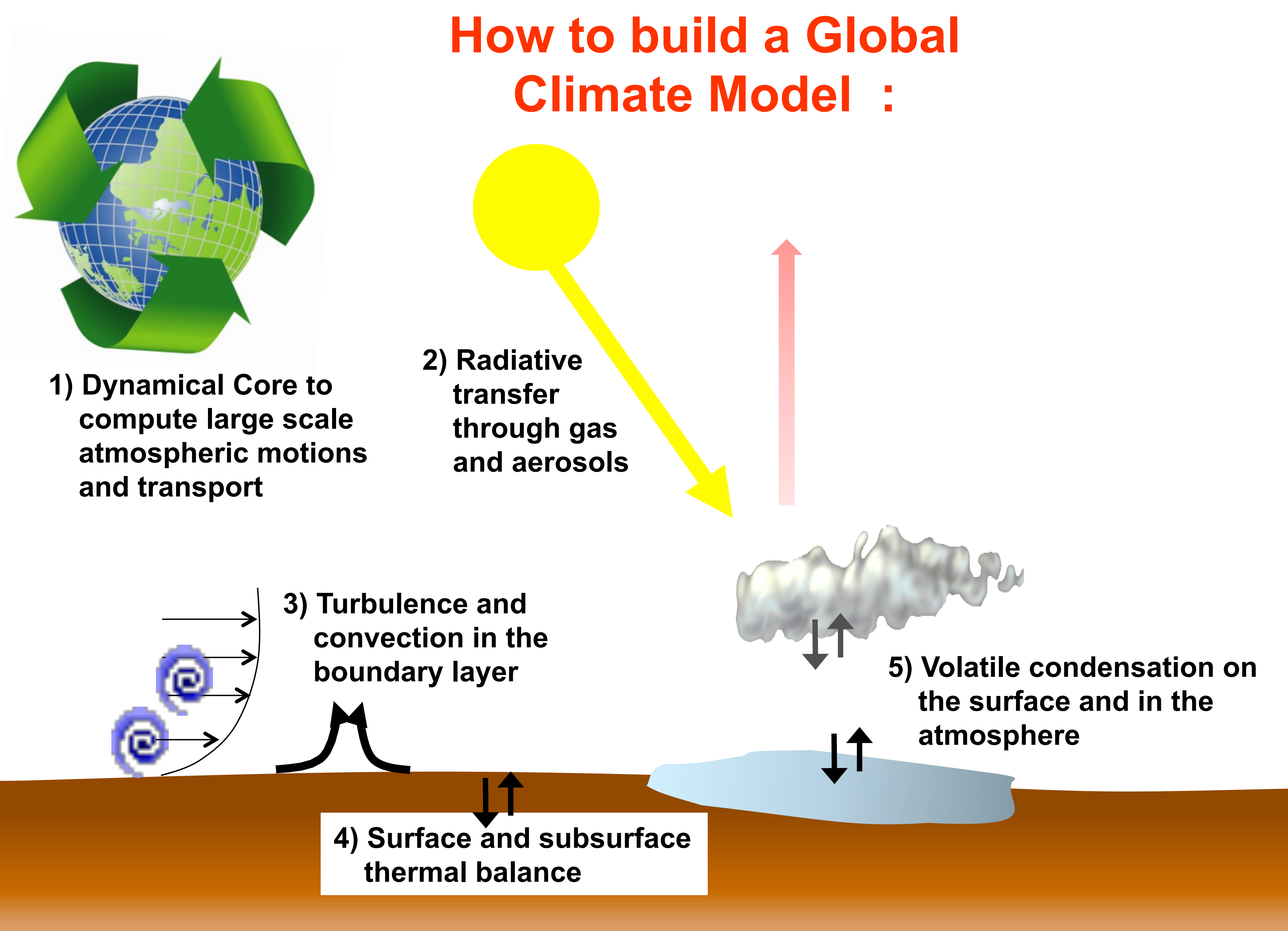
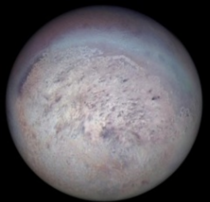

How to build a Global Climate Model :
1) Dynamical Core to compute large scale atmospheric motions and transport
2) Radiative transfer through gas and aerosols
3) Turbulence and convection in the boundary layer
4) Surface and subsurface thermal balance
5) Volatile condensation on the surface and in the atmosphere

VENUS

~2 GCMs

Coupling dynamic & radiative transfer (LMD, Ashima)



TRITON

GCM s (LMD, MIT)

PLUTO

GCMS (LMD, MIT)

EARTH

Many GCM teams

Applications:

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

MARS

Several GCMs

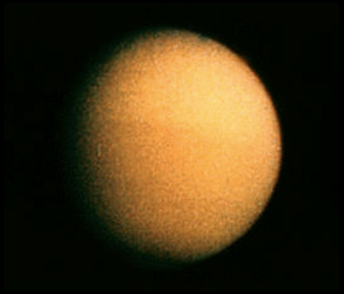
(NASA Ames, GFDL, LMD, AOPP, MPS, Ashima Research Japan, York U., Japan, etc…)

Coupled cycles:

- **CO2 cycle**
- **dust cycle**
- **water cycle**
- **Photochemistry**
- **thermosphere and ionosphere**
- **isotopes cycles**
- **etc…**

Applications:

Dynamics, assimilation; paleoclimates, etc…



TITAN

~a few GCMs

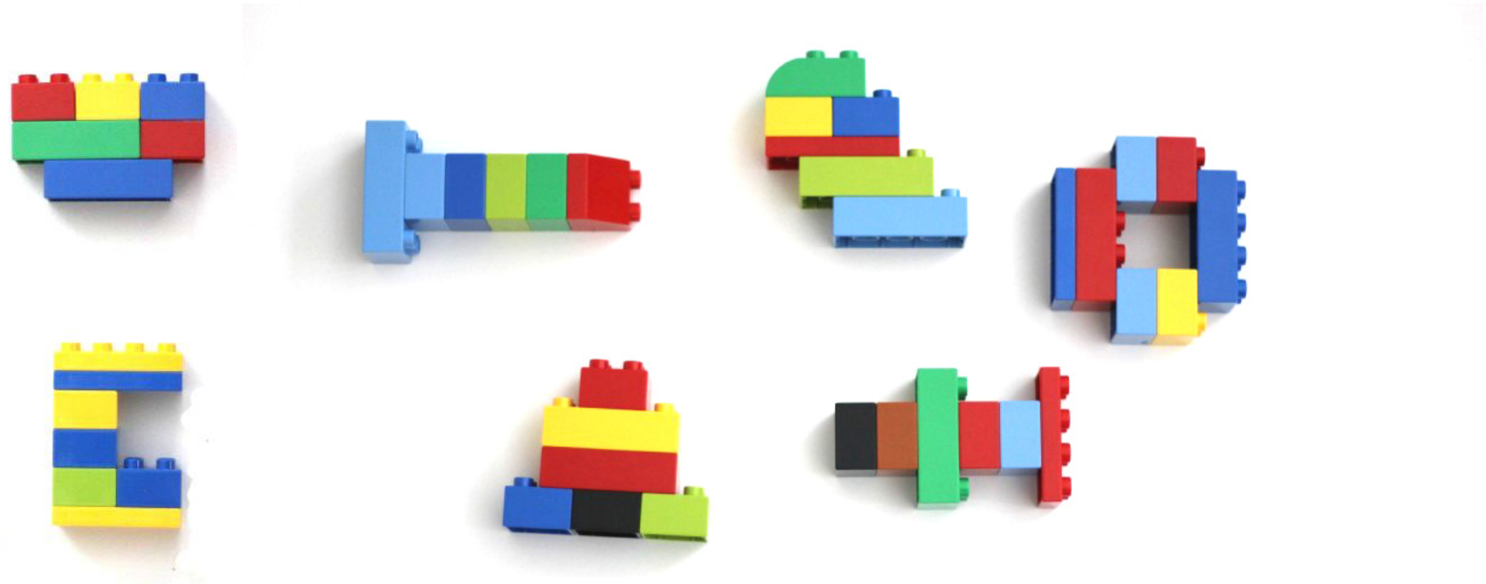
(LMD, Univ. of Chicago, Caltech, Köln…)

Coupled cycles:

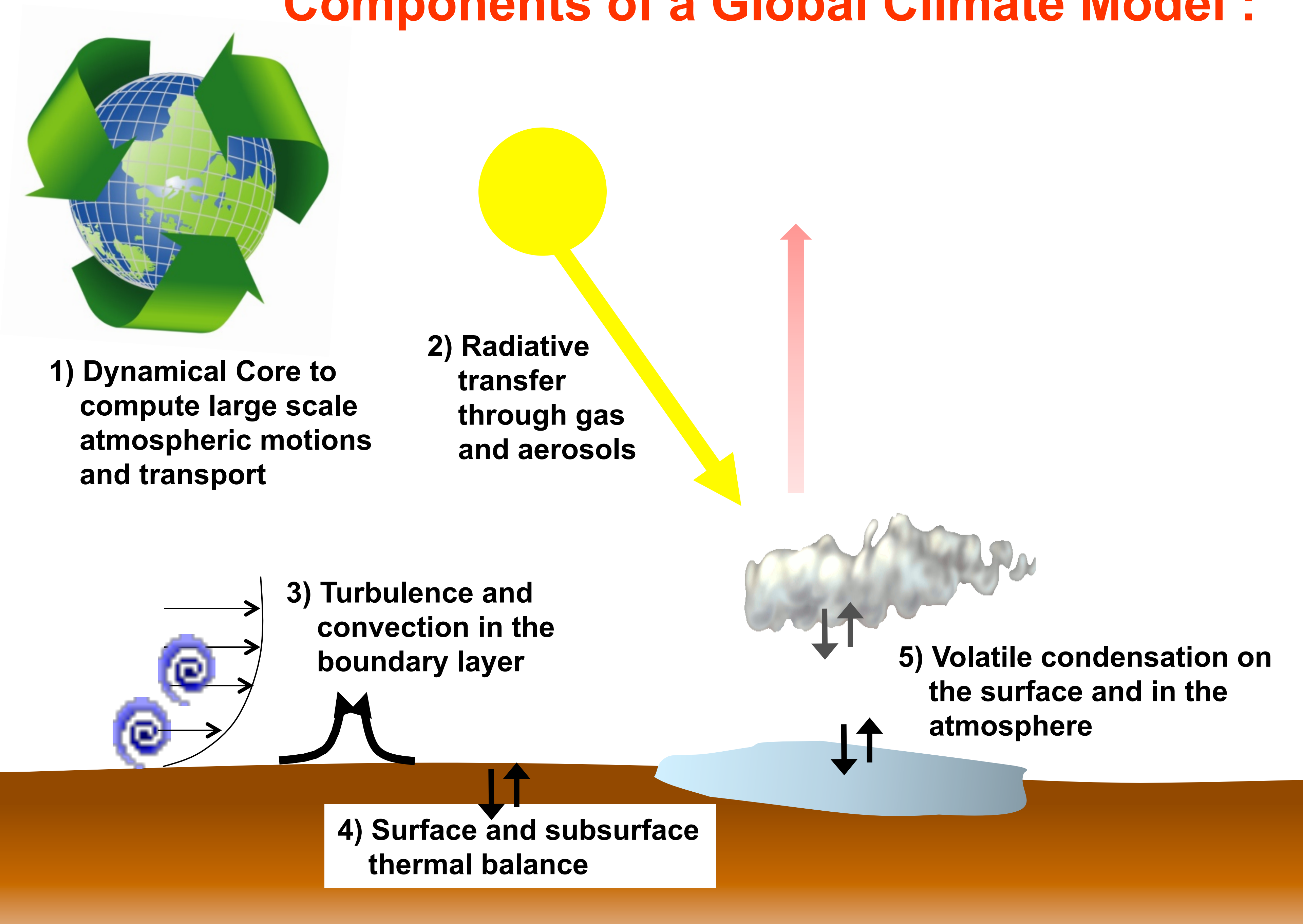
- **Aerosols**
- **Photochemistry**
- **Clouds**

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.**

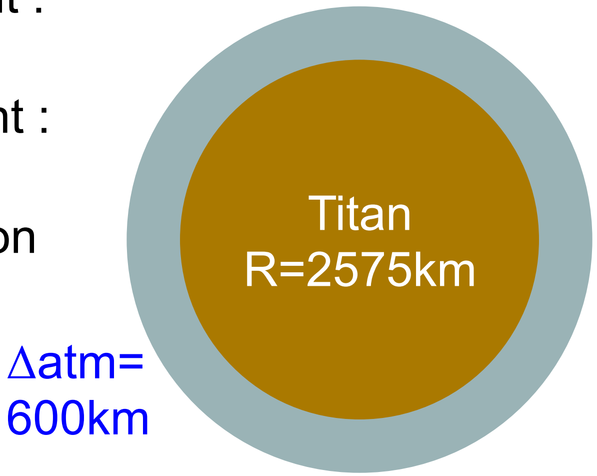


Components of a Global Climate Model :



Components of a Global Climate Model :

- 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)*



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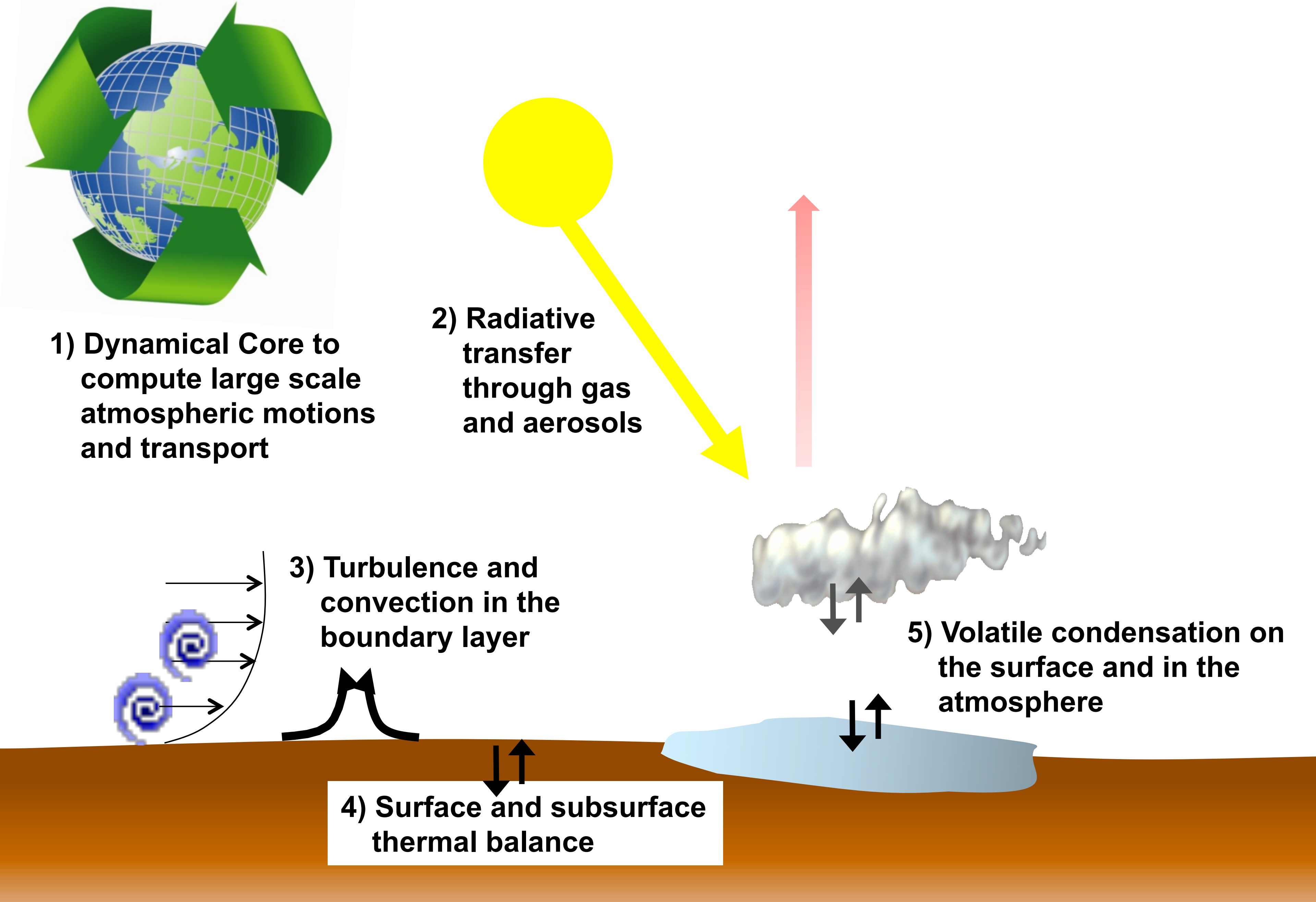

What we have learned from solar system GCMs:

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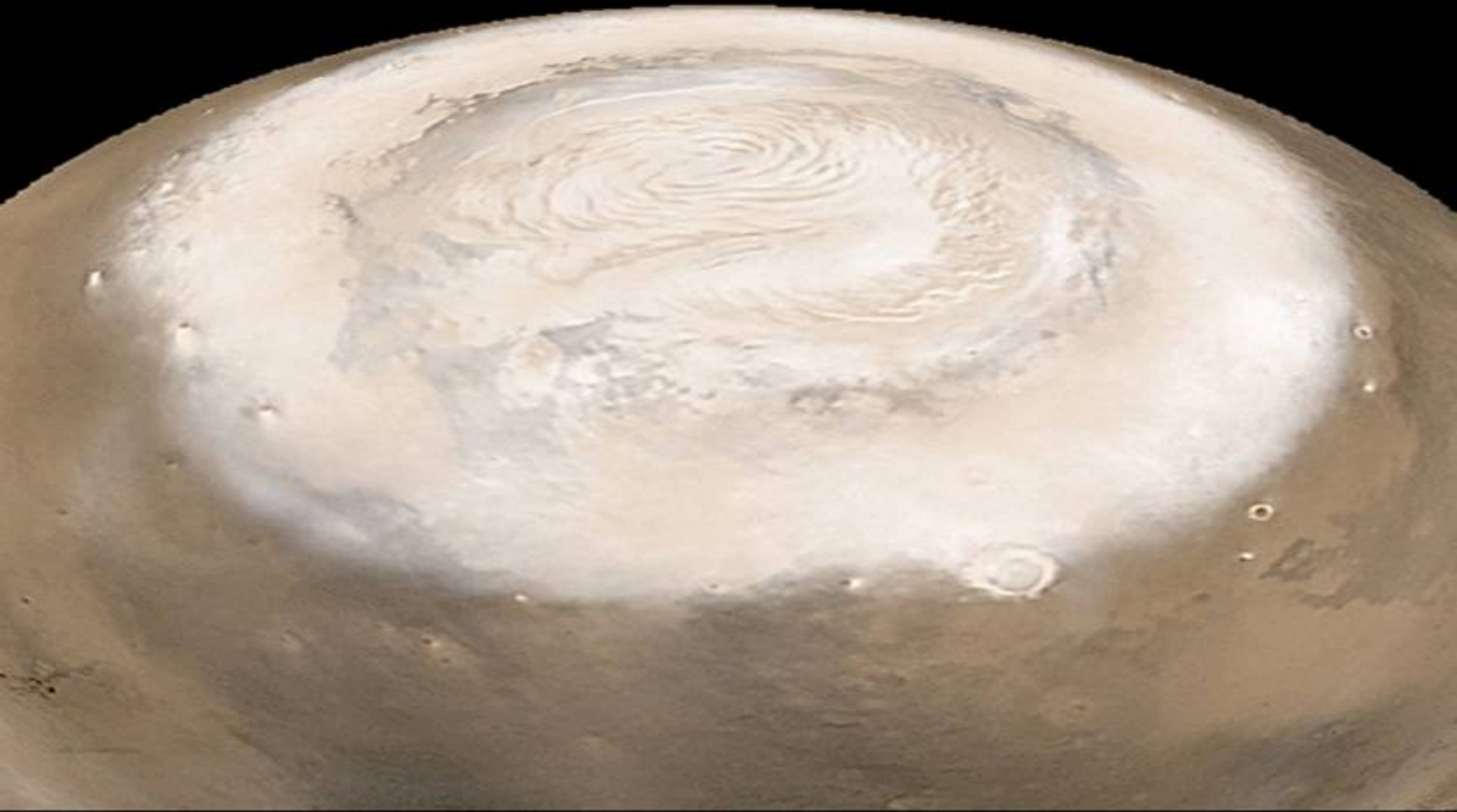
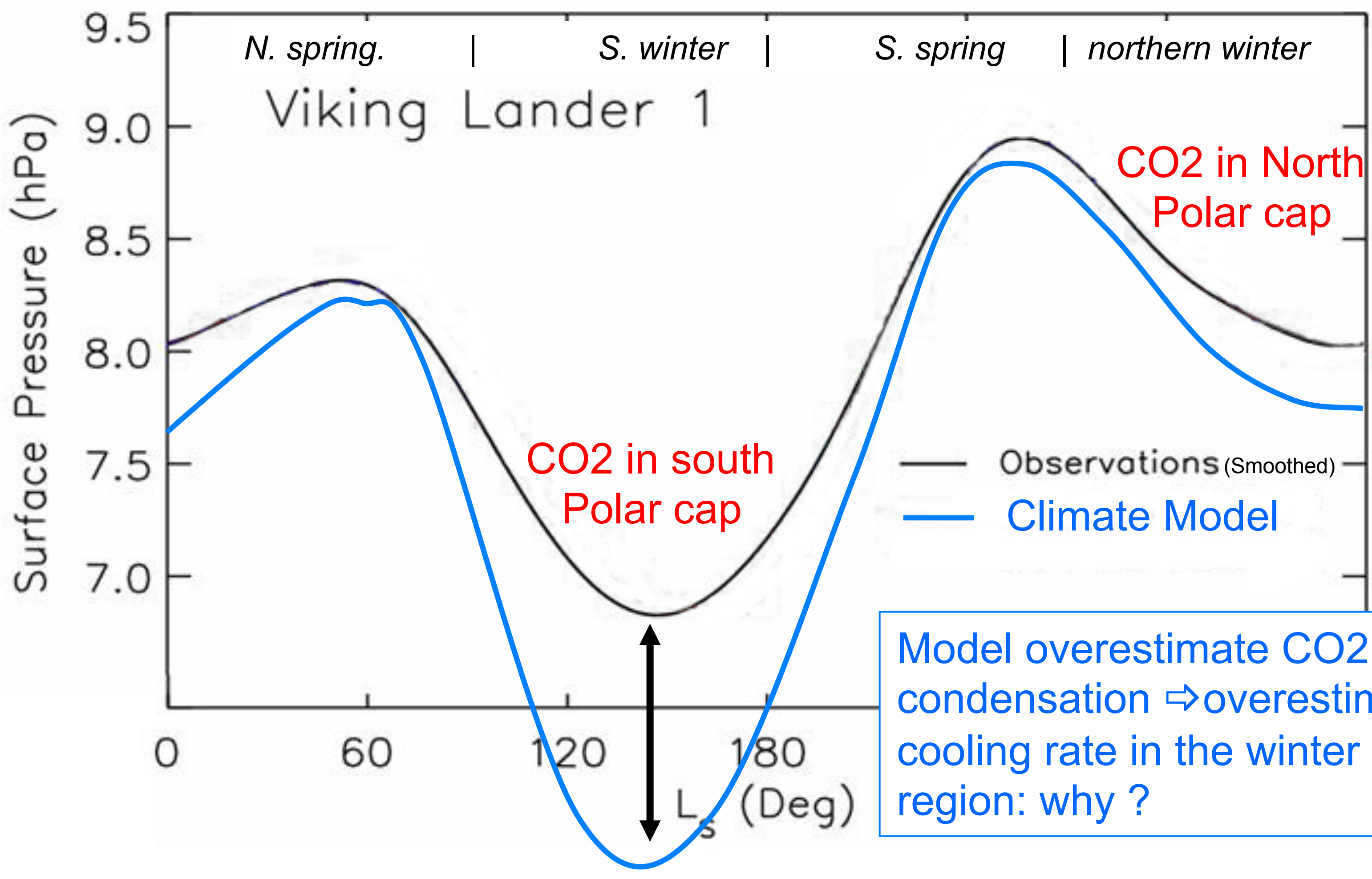
Mars CO_2 condensation/sublimation cycle

(mosaic of the northern polar cap in spring)



Surface pressure variations due to CO2 ice condensation/sublimaton

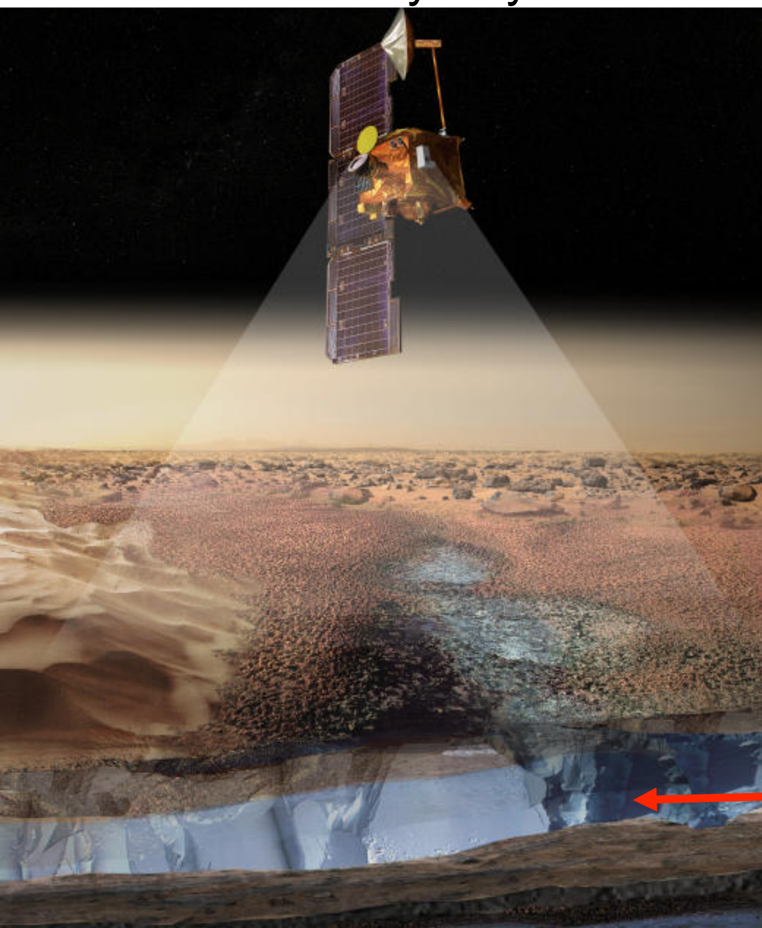
Pollack et al. 1993,1995 , Hourdin et al. 1993,1995
Forget et al. 1998 Guo et al. 2009 Haberle et al. 2008

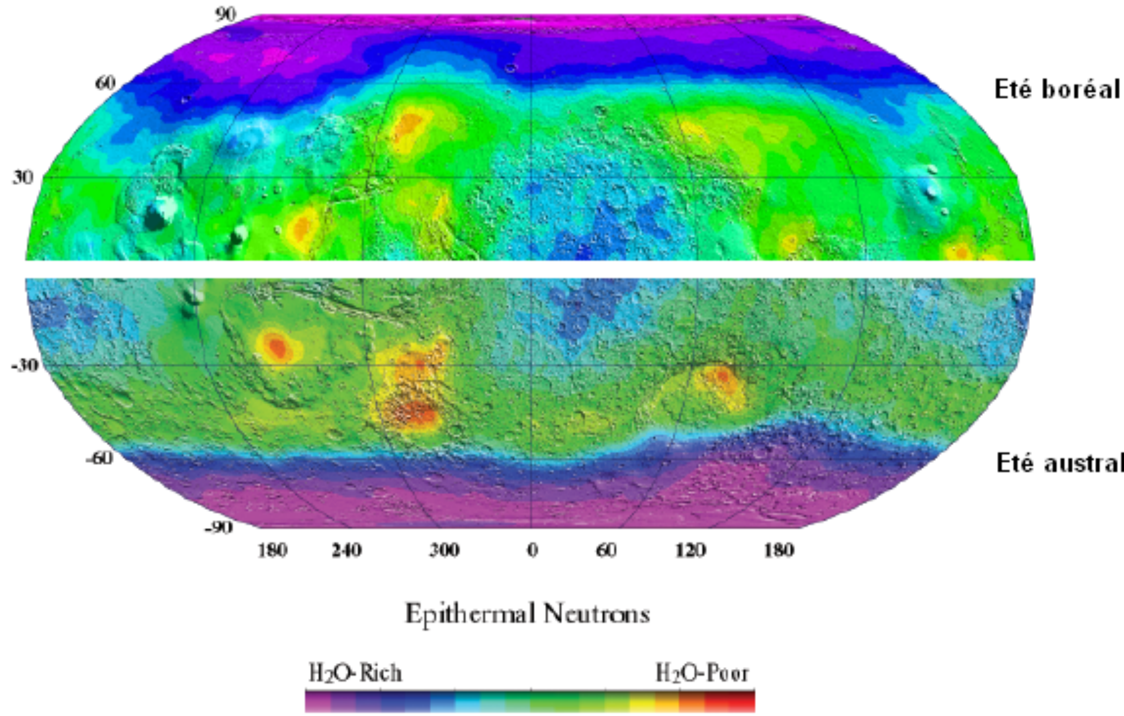


Model overestimate CO2 condensation ⇨overestimate cooling rate in the winter polar region: why ?

Near surface ice detected by Mars Odyssey GRS

NASA Mars Odyssey



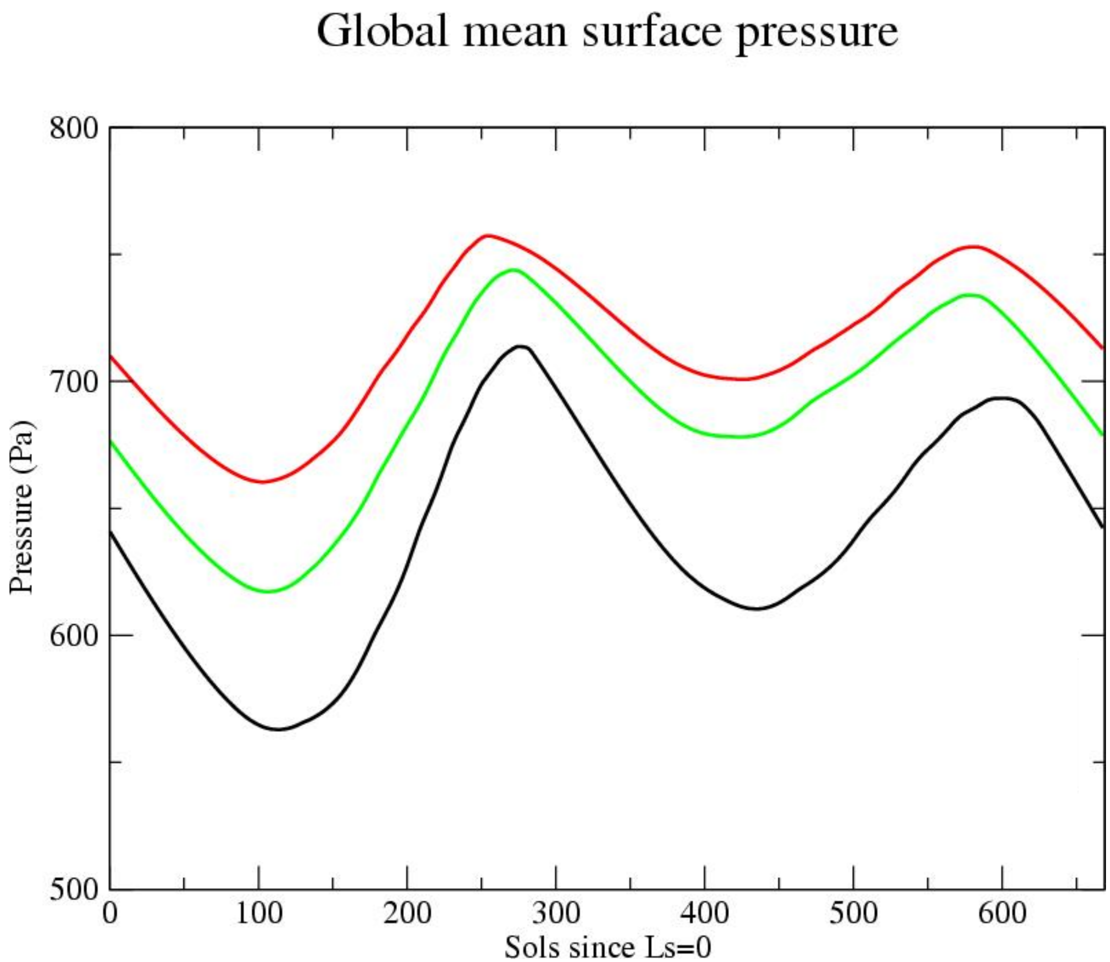


« Hidden ice with high thermal inertia:
- Store heat during summer
- Release heat in winter and reduce CO2 condensation

Impact of subsurface ice on the CO_2 cycle In Global Climate Model

Mars Odyssey

Haberle et al. 2008



Ice layer in lat= 60°-90° :

Ice depth=1cm

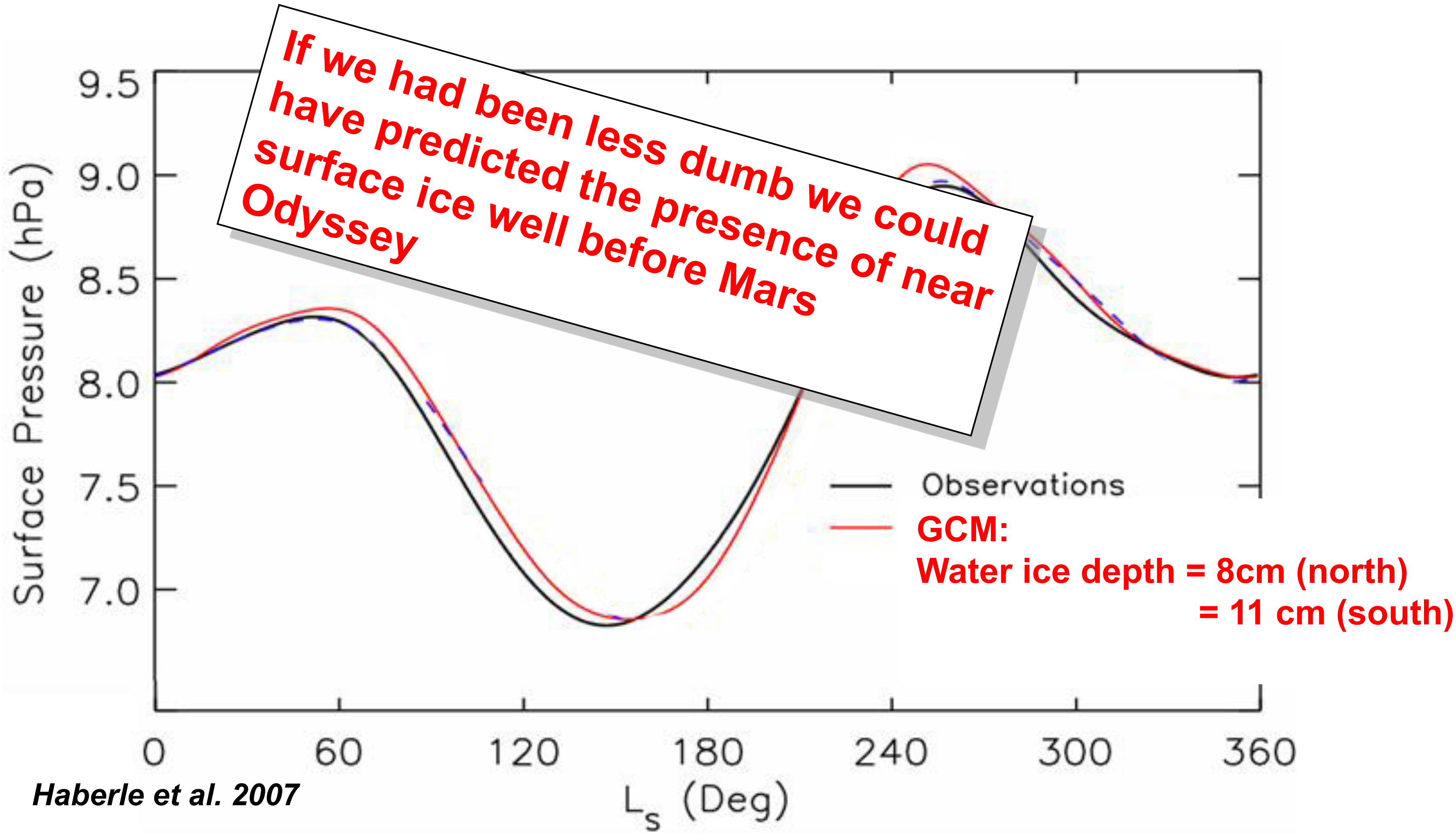
Ice depth=10cm

No Ice

LMD GCM

Impact of subsurface ice on Global Mean Surface Pressures

(Haberle et al. 2008 ; NASA Ames GCM)



Haberle et al. 2007

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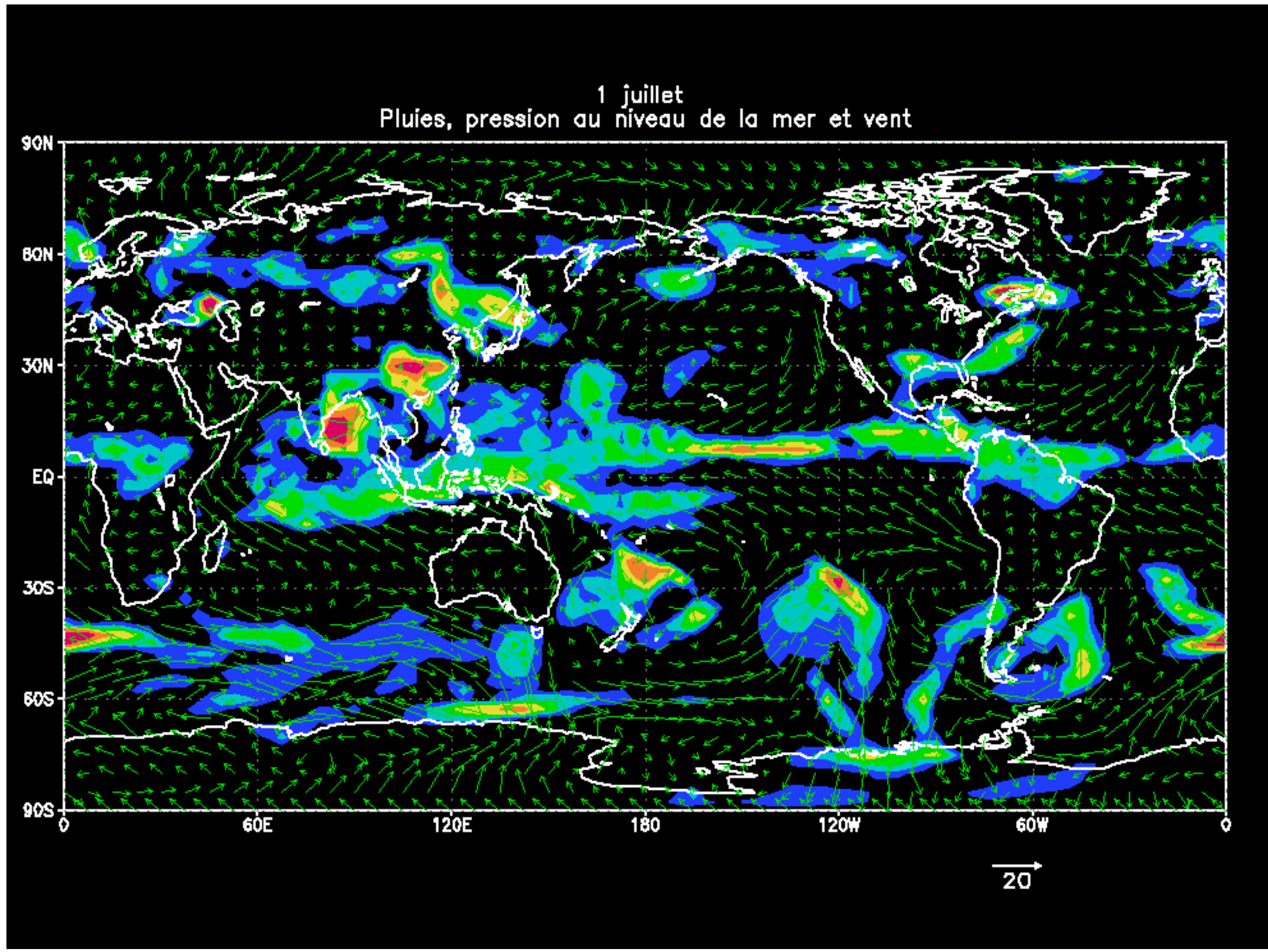
  - **Missing physical processes** (*e.g. radiative effects of Martian clouds*; *subsurface water ice affecting CO2 ice mass budget on Mars)*
  - ⇨ Complex subgrid scale process and poorly known physics *(e.g. clouds on the Earth, Gravity waves on Venus)*

Major challenge is Earth GCMs: parametrizing clouds and precipitations

Real Clouds : microphysics and small scale dynamics

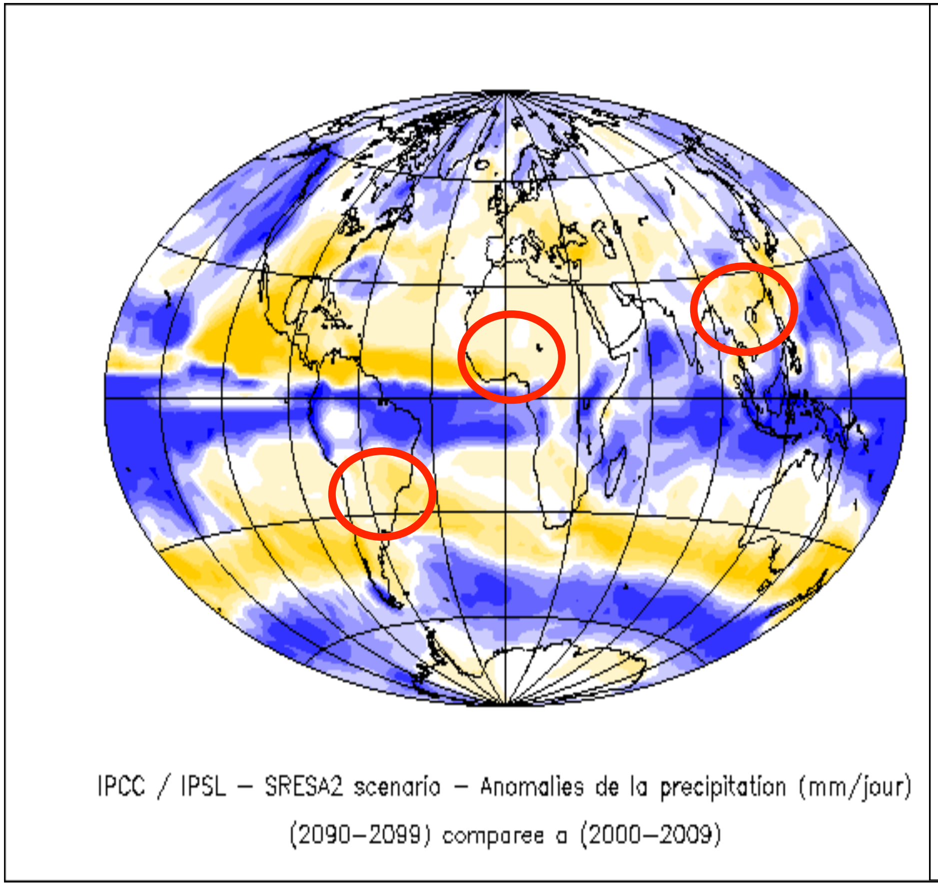
Precipitation in a GCM : global scale and coarse resolution (10^2 km)

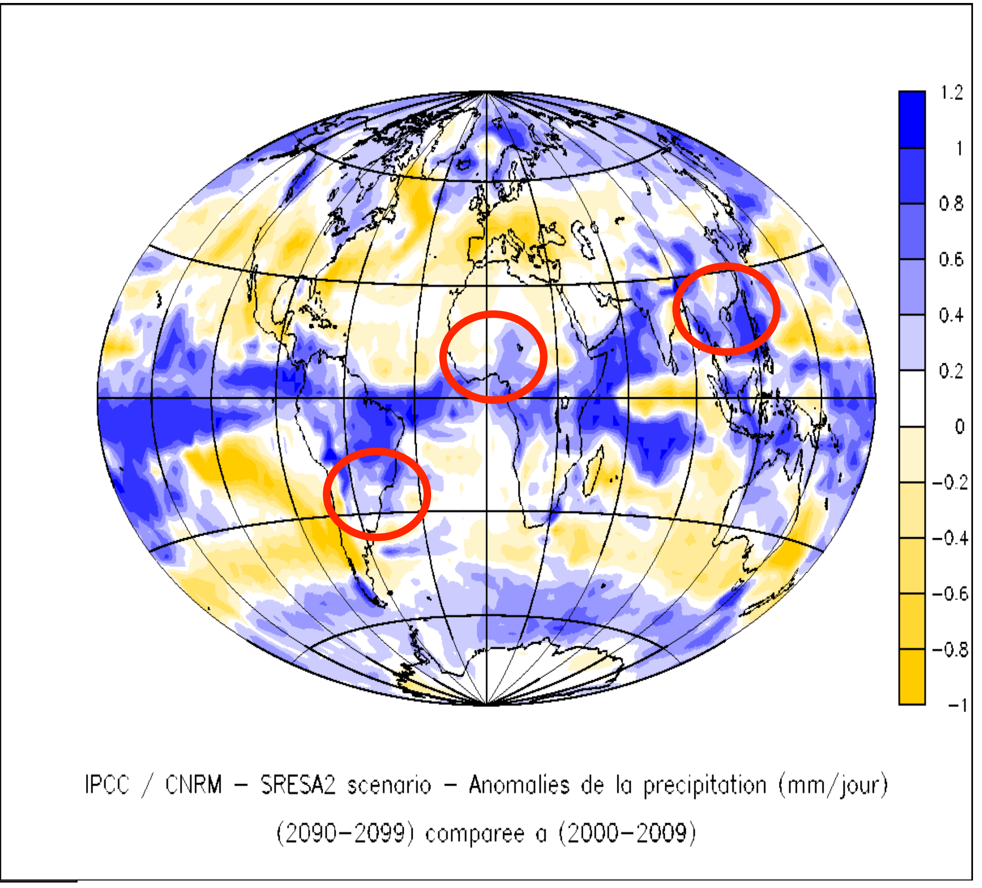


Climate change projection for year 2100 (4th IPCC)

Change in mean precipitations

(A2 scenario : ~doubling of CO_2)





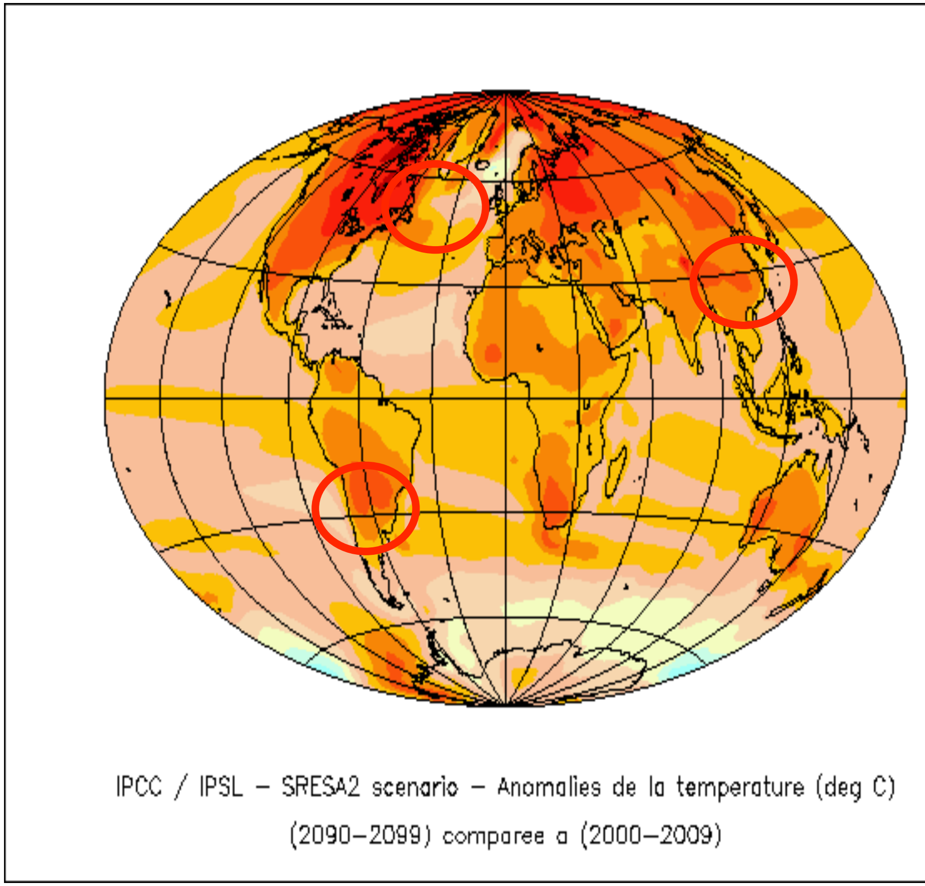
IPSL GCM **CNRM GCM**

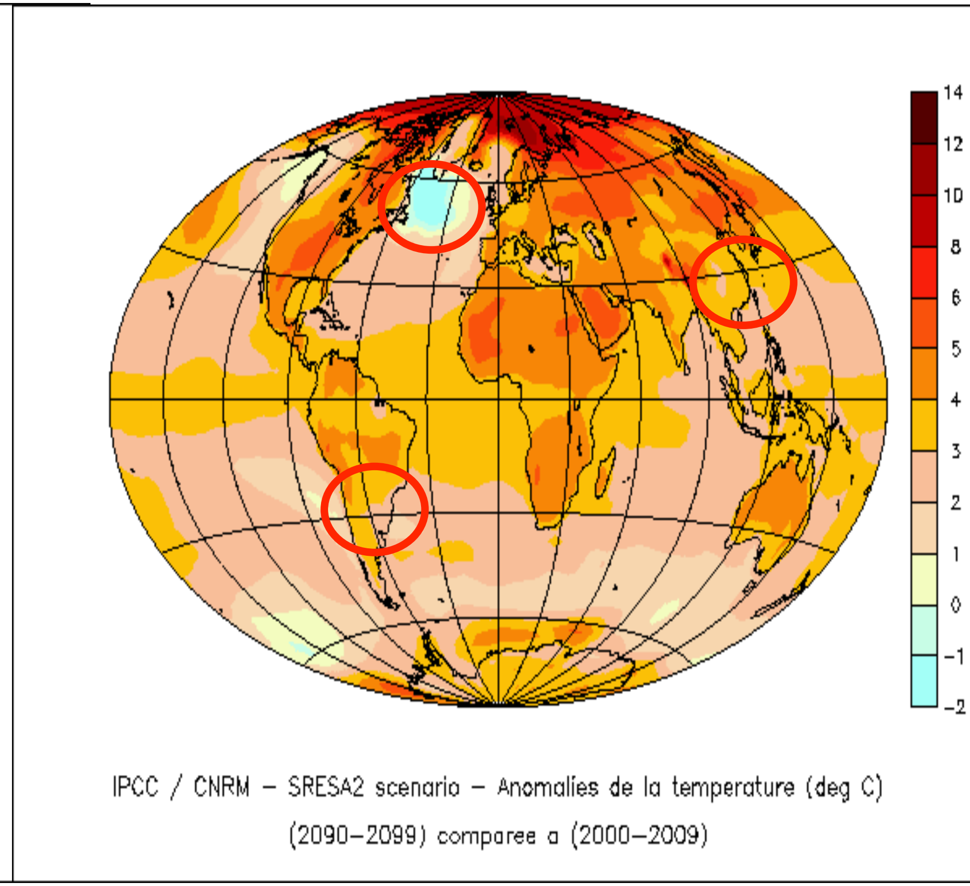
Source: CNRM et IPSL, 2006

Climate change projection for year 2100 (4th IPCC)

Change in mean temperatures

(A2 scenario : ~doubling of CO2)





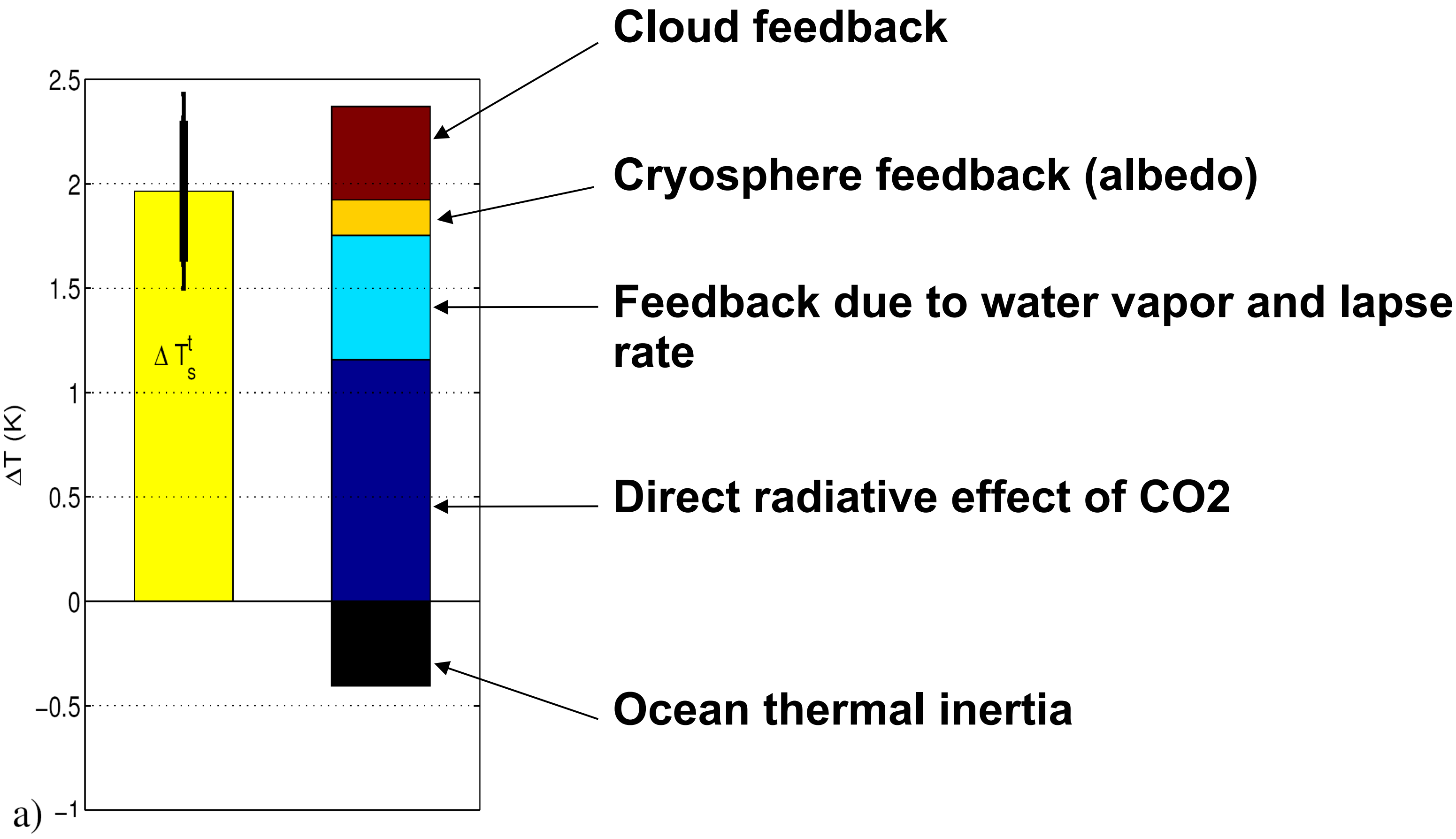
IPSL GCM

CNRM GCM

Source: CNRM et IPSL, 2006

Analysis of temperature changes in 12 coupled ocean atmosphere GCM

(increase of CO_2 by 1%/year)



multi-model average

[Dufresne and Bony, 2008]

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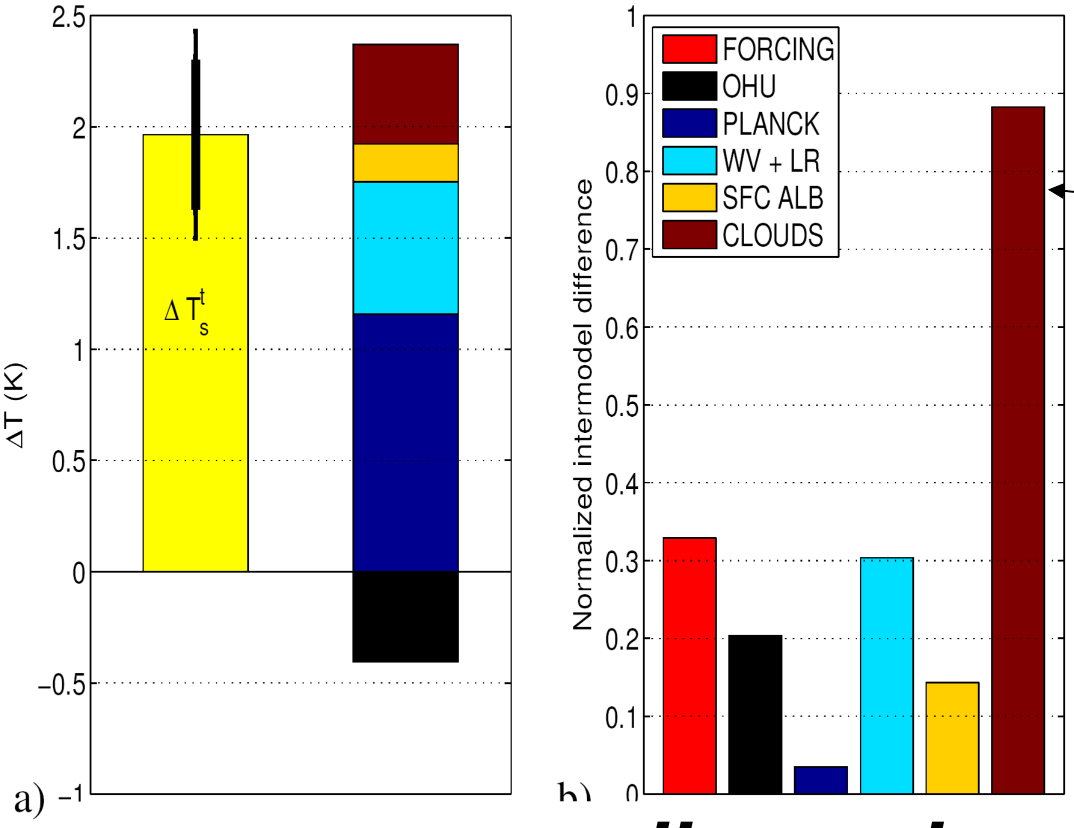

Clouds feedback !

multi-model average

dispersion Between models

[Dufresne and Bony, 2008]

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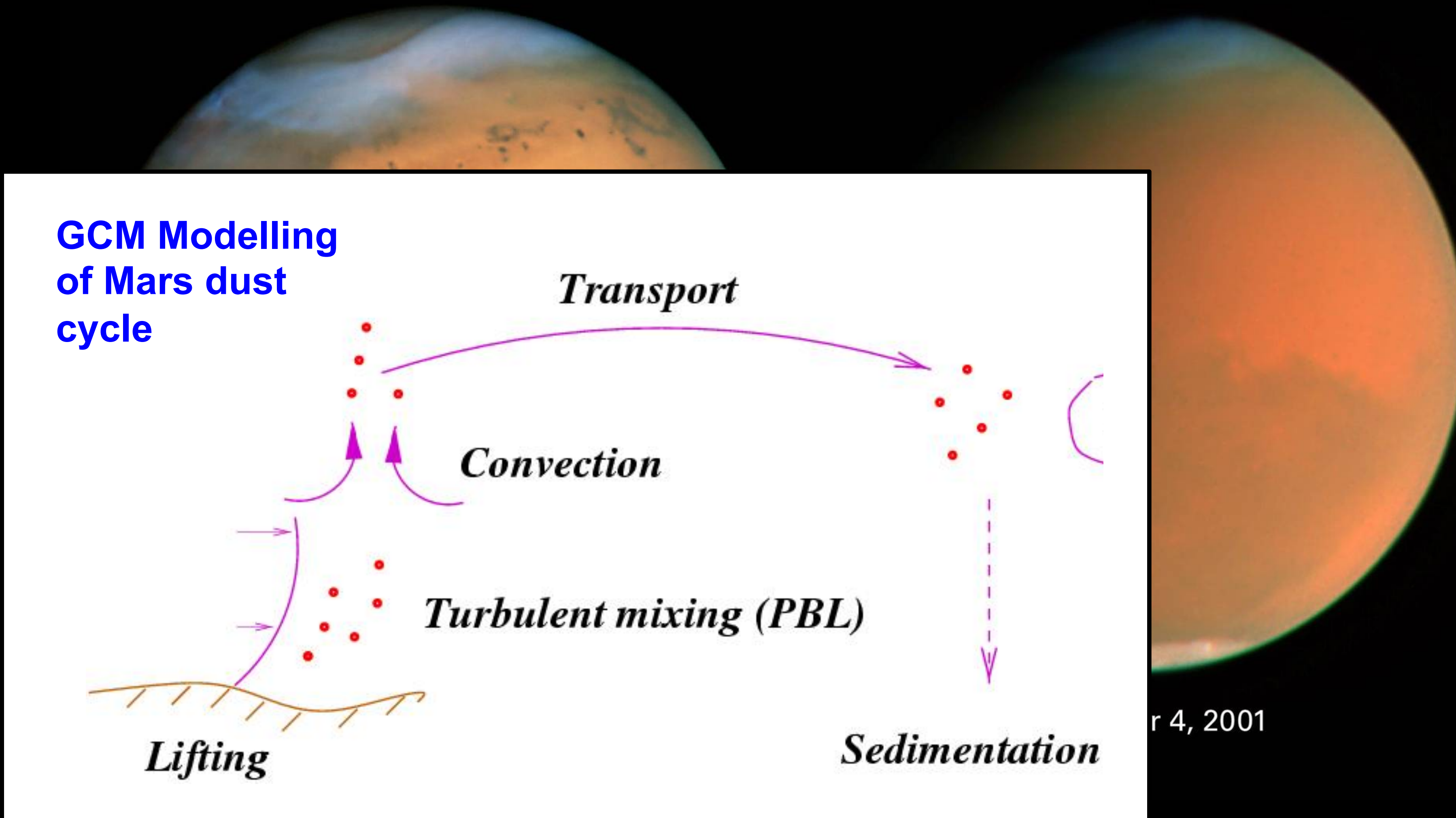
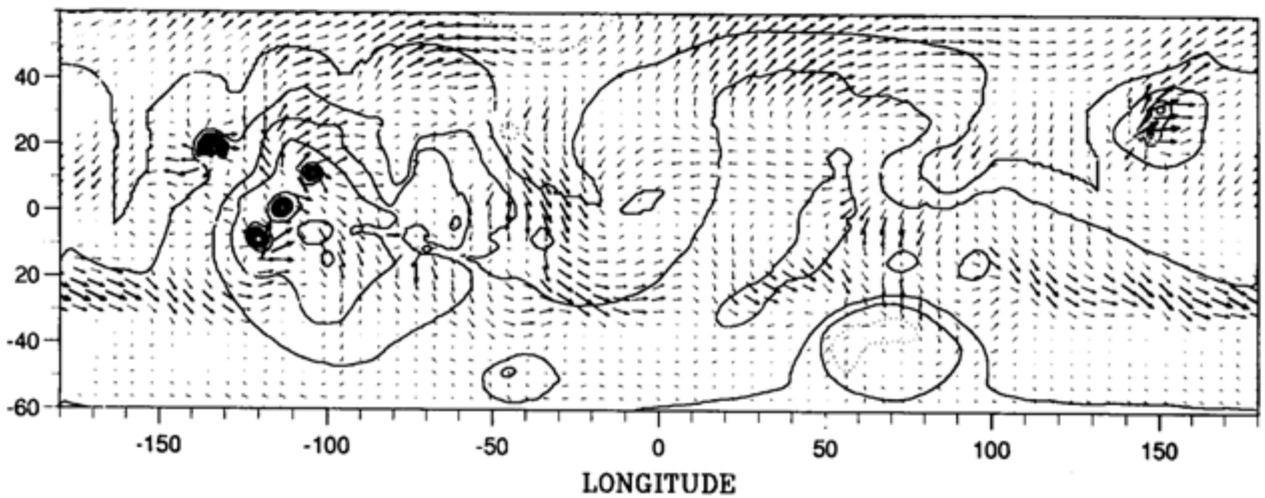
  - **Positive feedbacks and unstability** *(e.g. sea ice and land ice albedo feedback on the Earth) :* need to tune models or explore sensitivity
  - **Non linear behaviour and threshold effect** *(e.g. dust storms on Mars)*

Global dust storms

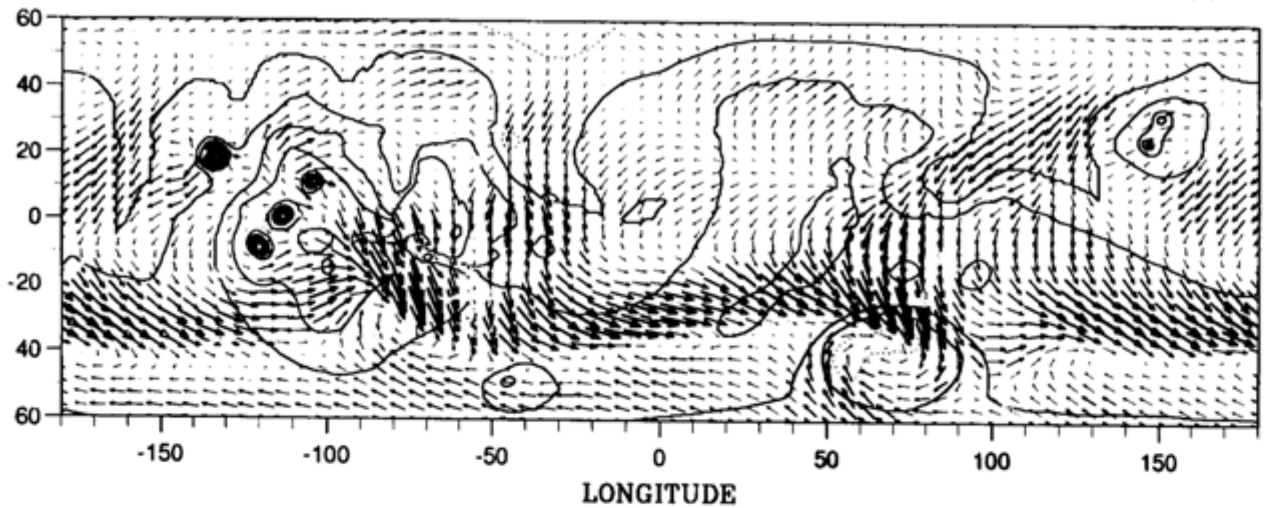


Mars : positive feedblack of the dust on atmospheric circulation and lifting *(LMD GCM simulation)*

Clear Atmosphere

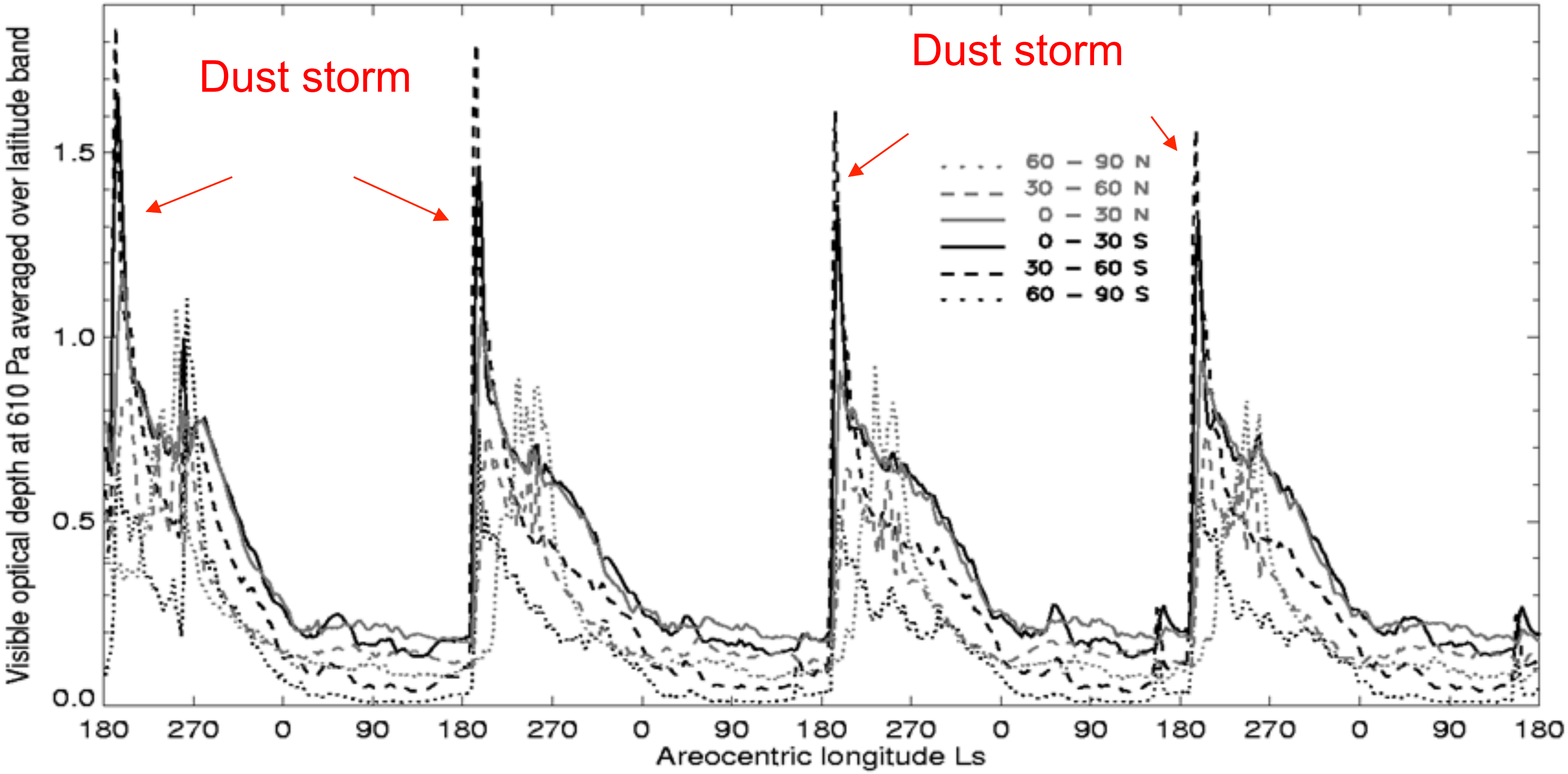


Dusty Atmosphere



4 years of numerical simulation of the Martian dust cycle : global dust storms every year !

Newman et al. 2002



Year 1 **Year 2** **Year 3** **year 4**

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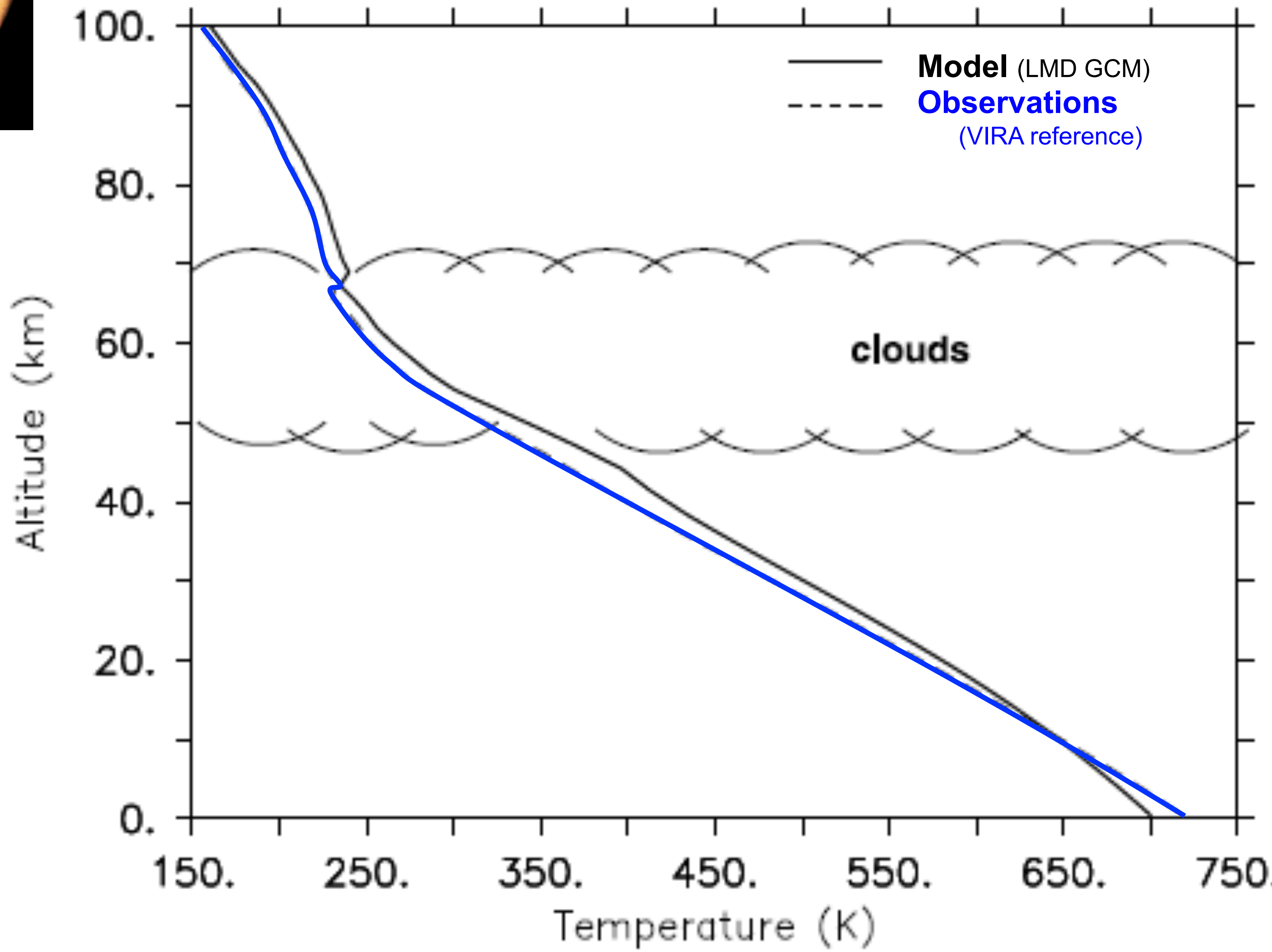
  - **Weak Forcing** : when the evolution of the system depends on a subtle balance between modeled process rather than direct forcing *(e.g. Venus circulation)*

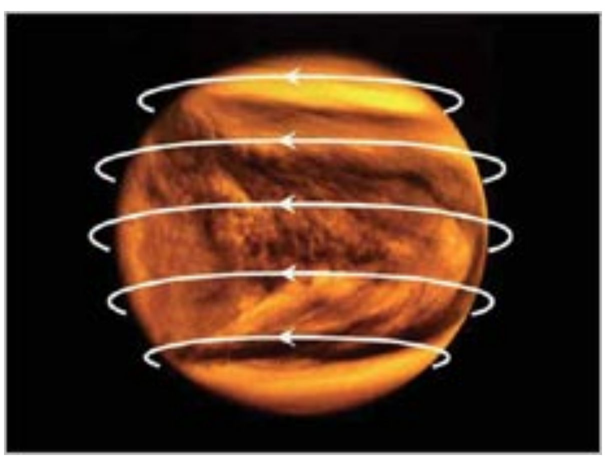
Venus climate Model : Thermal Structure

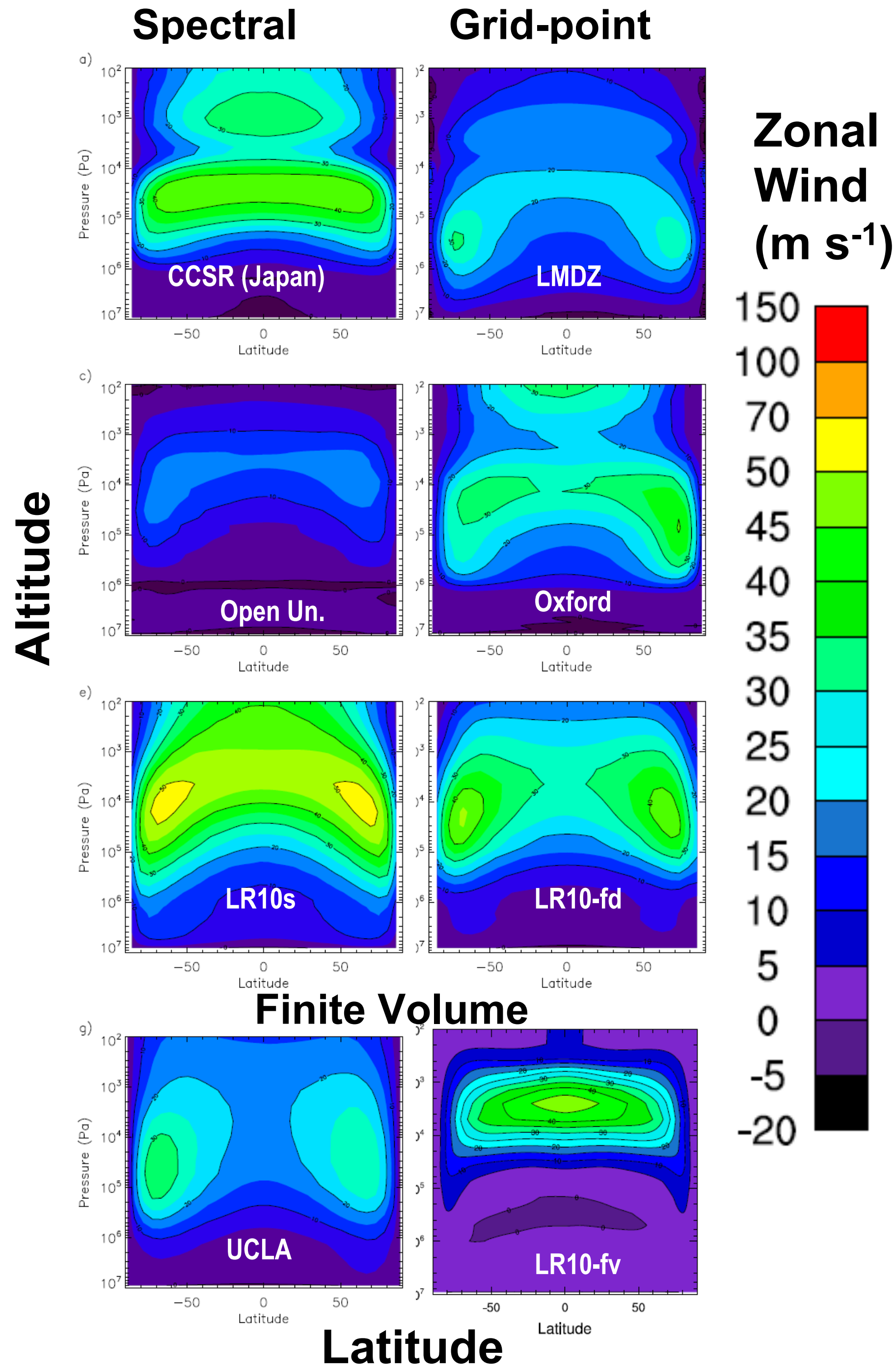


Mean zonal wind field
predicted by several GCM dynamical core with « Venus like » forcing

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

Lebonnois et al. (2011)





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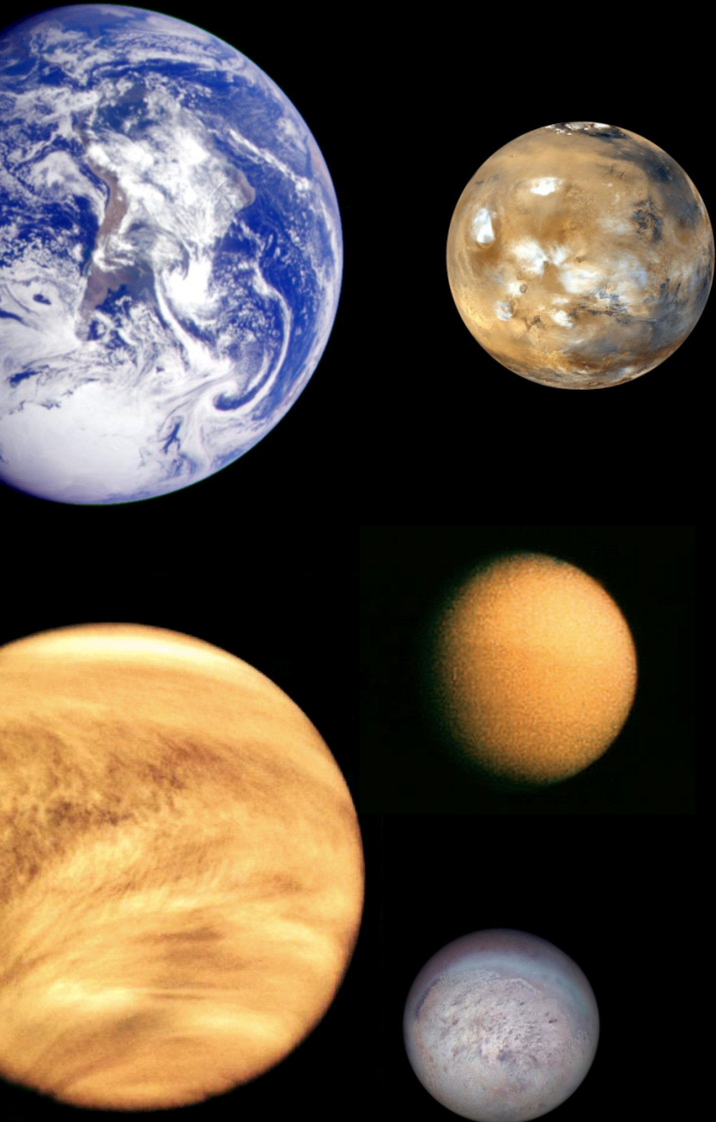
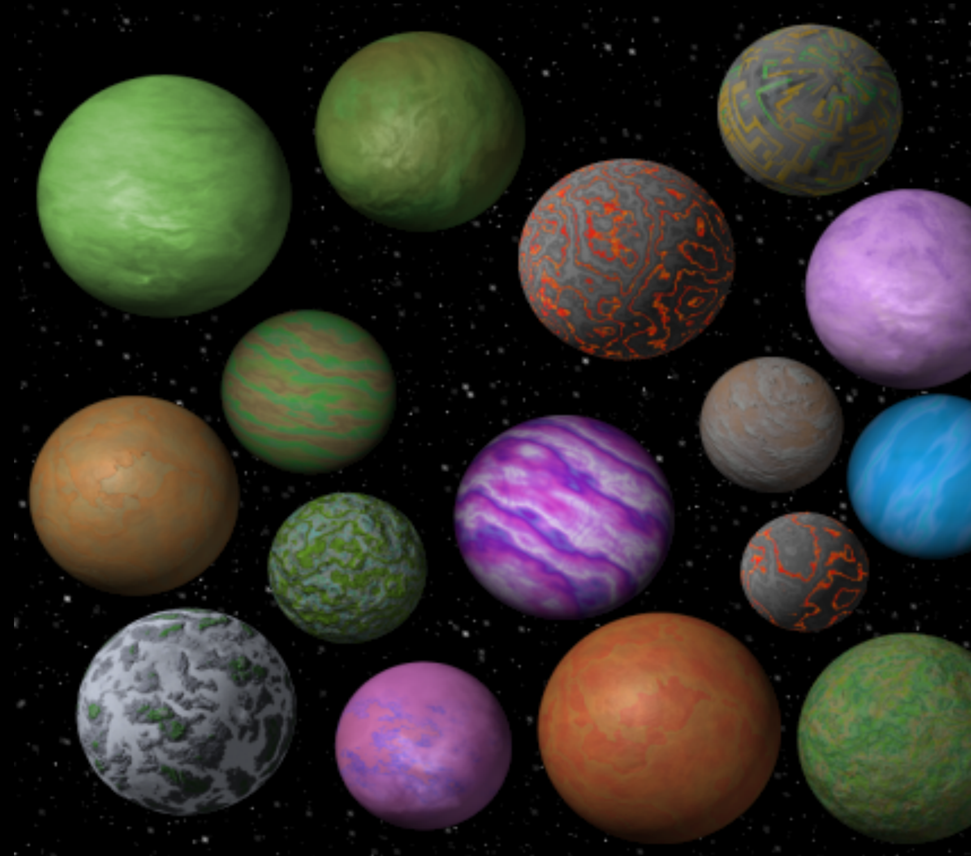
The science of simulating the unobservable:

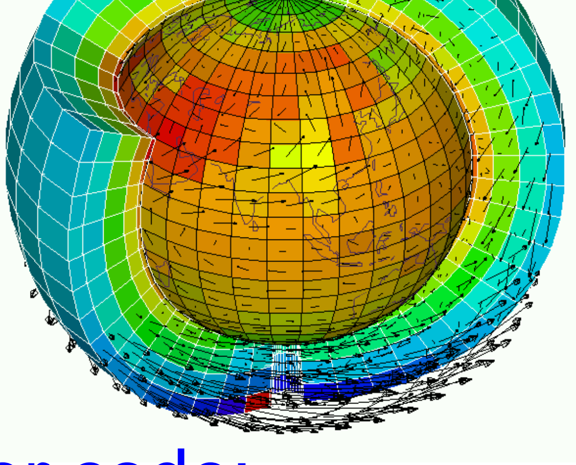
From planet GCMs to extrasolar planets

(or past atmospheres).





A 3D ‘‘generic’’ Global climate model (LMDZ Generic) designed to simulate any atmosphere on any terrestrial planet around any star.

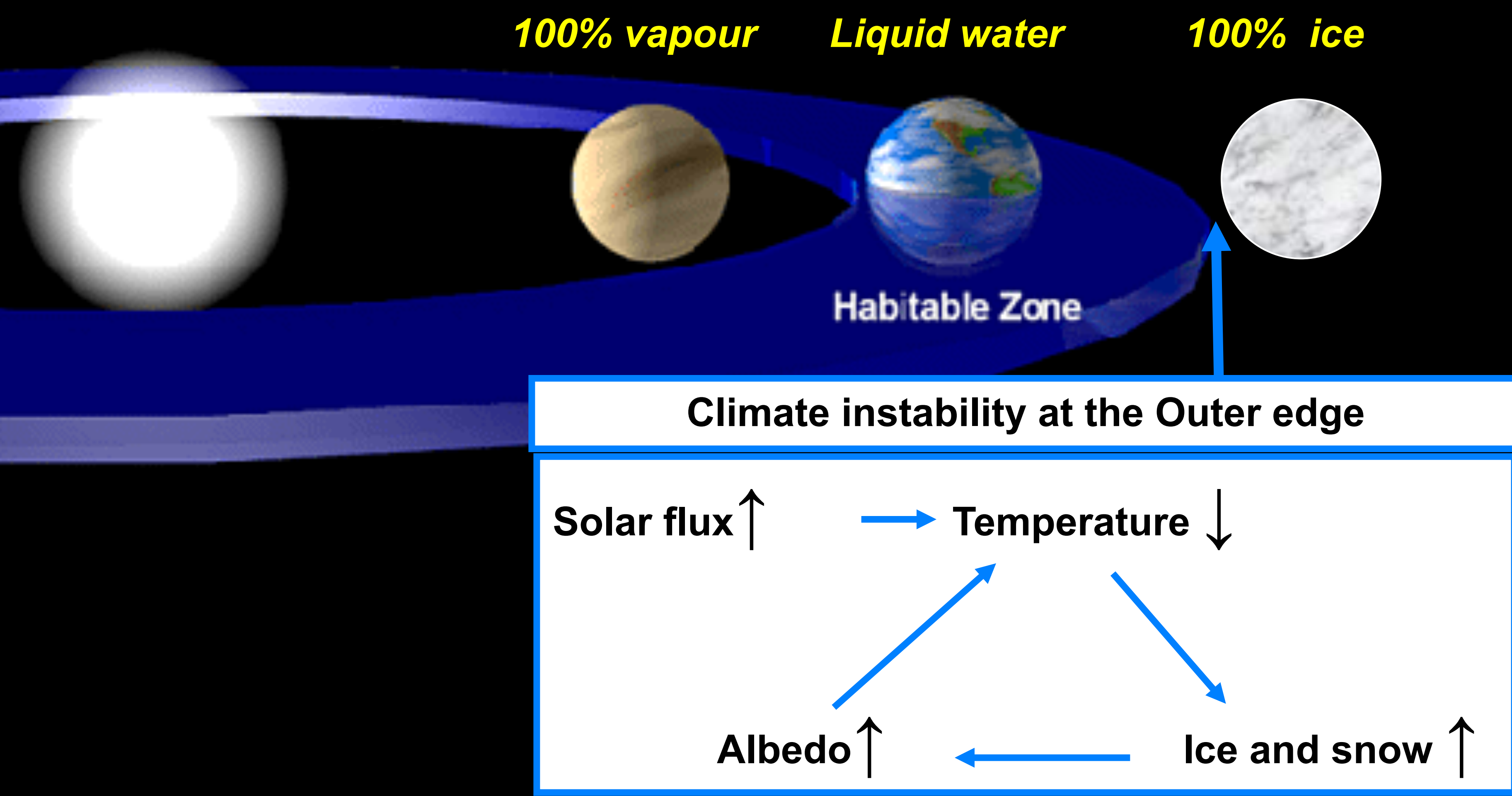


- Versatile Correlated-k radiative transfer code:
  - Spectroscopic database (Hitran 2008)
  - CIA for CO_2 (Wordsworth et al 2011) + water continuum (Clough 89)
  - Composition: N_2+CO_2+CH_4+H_2O + SO_2 +H_2S + …
- CO2 condensation/sublimation and CO2 ice clouds
- Water cycle (deep convection, cloud formation and precipitations):
  - Robust and physical parametrisations (Manabe).
  - Fixing mixing ratio of condensation nuclei OR radius of cloud droplets
  - Modified thermodynamics to handle warm wet atmosphere with water vapor as a major components.
- 2-layer dynamical ocean (Codron 2011):
  - Heat transport by diffusion and Ekman transport
  - Dynamic Sea ice

A general problem : positive feedbacks and climate instability

- Whatever the accuracy of the models, predicting the actual climate regime on a specific planet will remain challenging because **climate systems are affected by strong positive feedbacks** which can drive planets submitted to very similar volatile inventory and forcing and to completely different state.

Climate and Surface liquid water

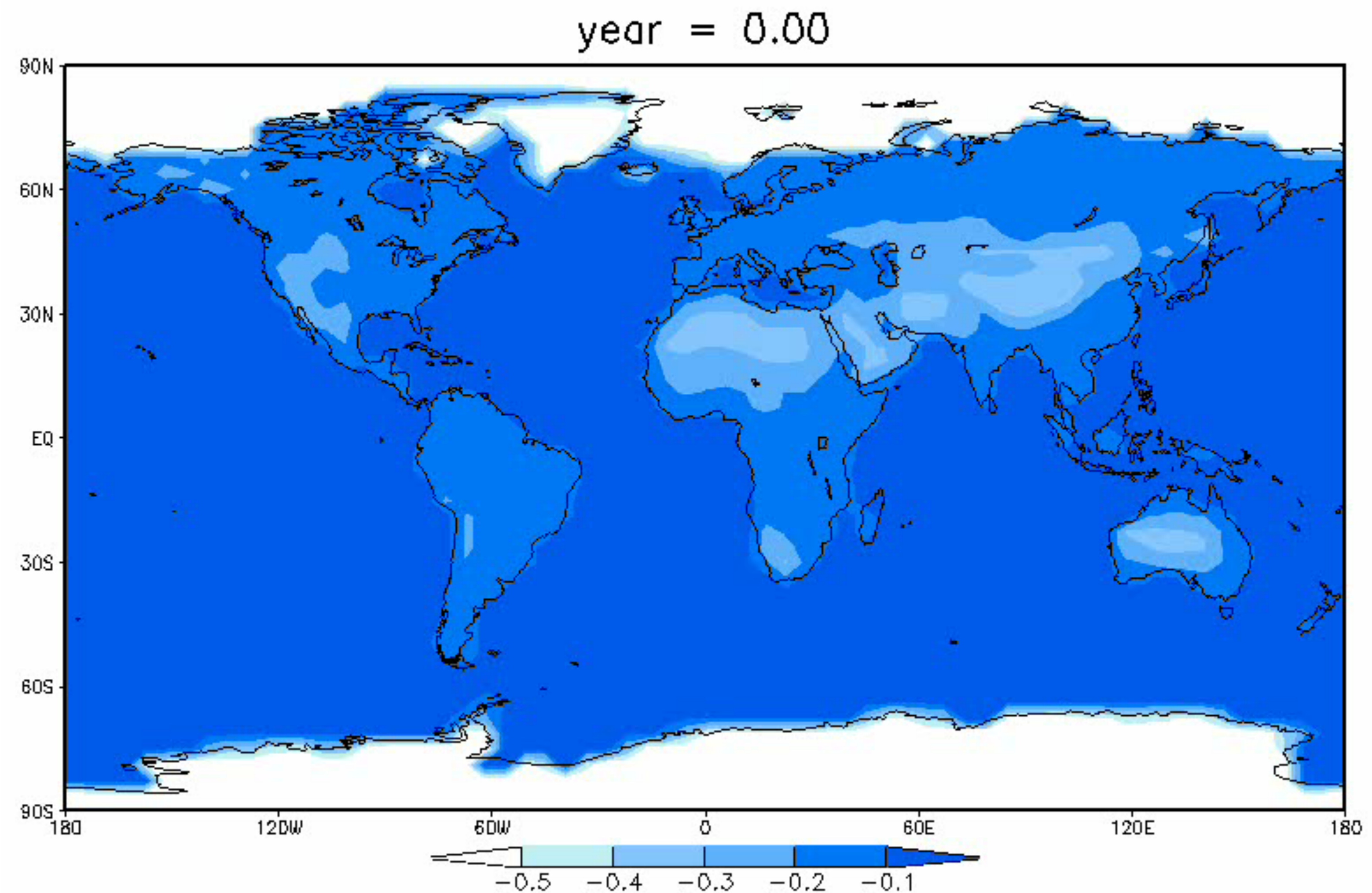


Climate Modelling: the Earth suddenly moved by 12%

(79% current insolation = the Earth 3 billions years ago)

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay)*

ALBEDO:



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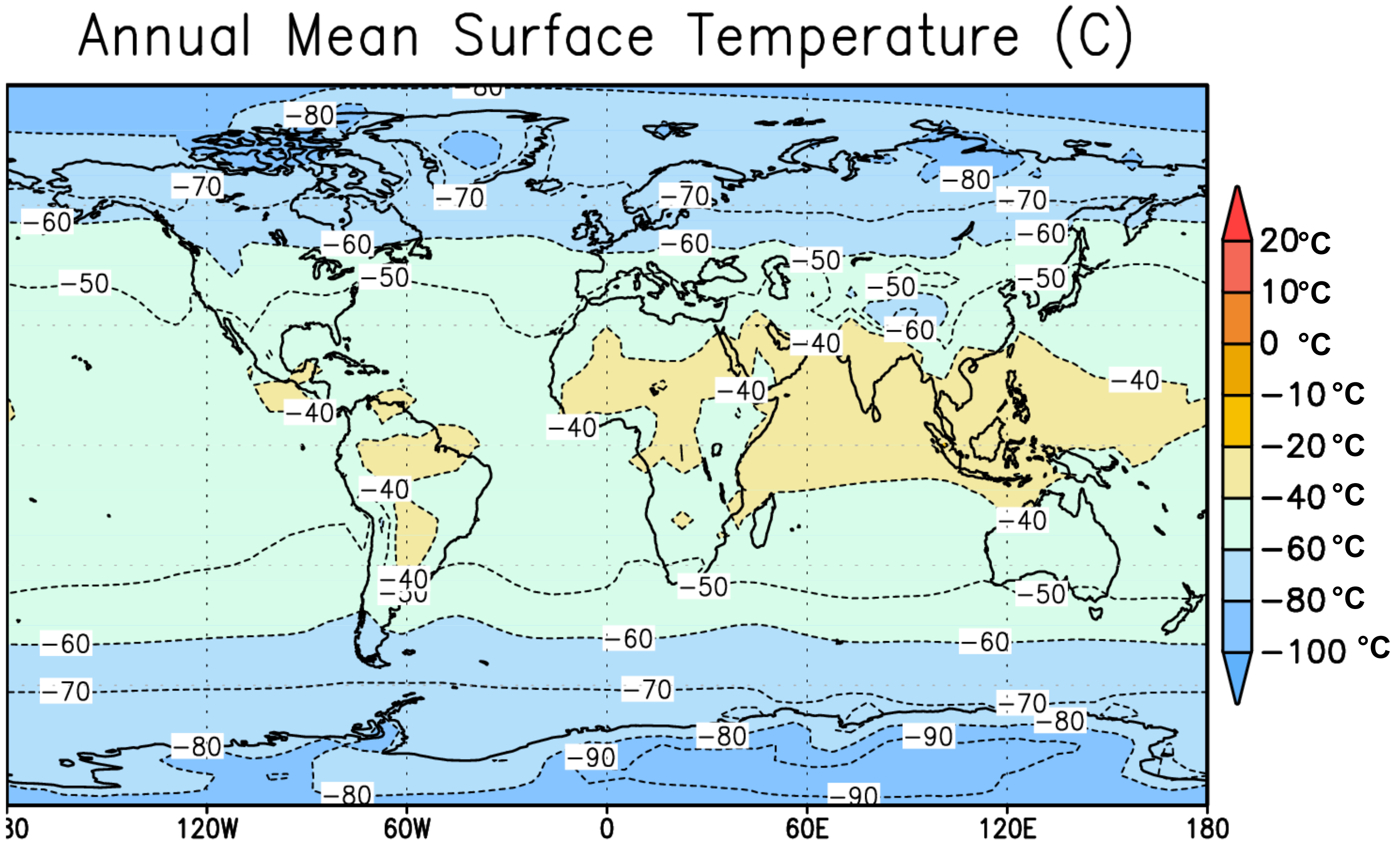
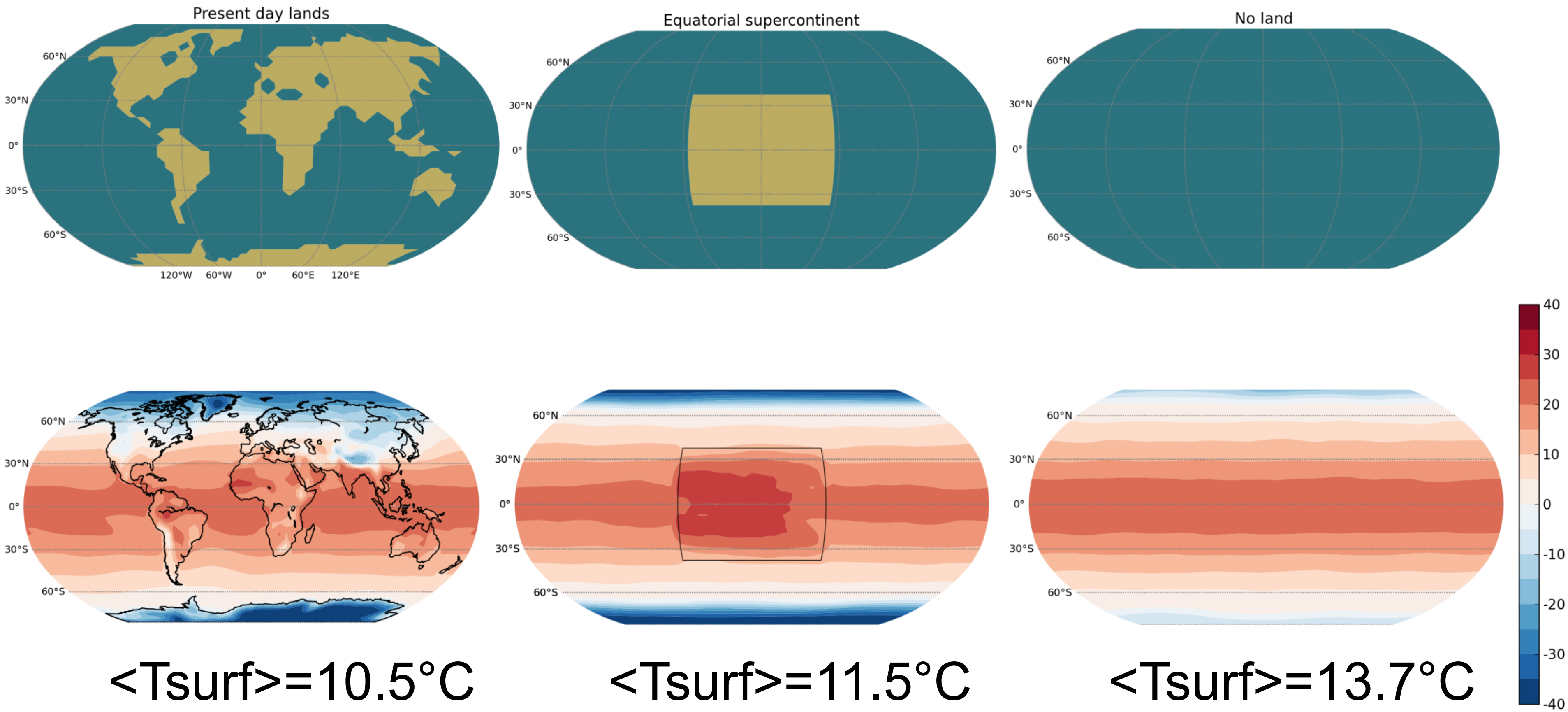


Solving the faint young sun paradox with enhanced greenhouse effect

Charnay et al., sub. to JGR atmoshere,2013

(simulations at 2.5 Ga with $C0_2$=10 mb; CH_4=2 mb)



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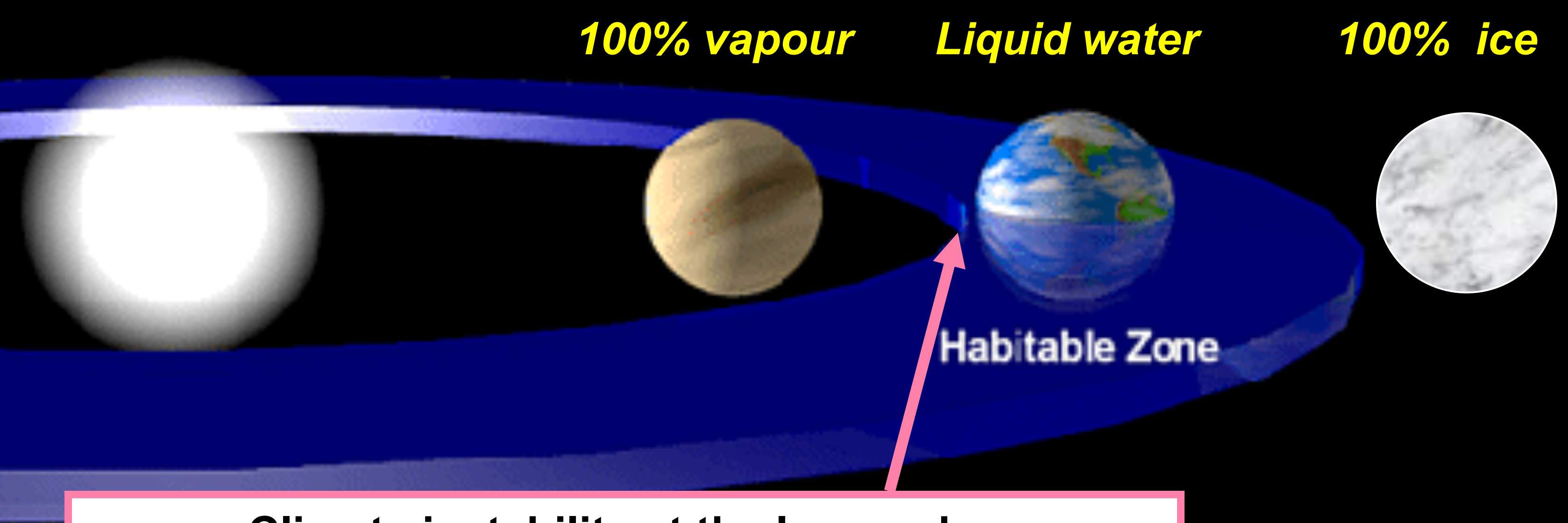
Climate and surface liquid water



Climate instability at the Inner edge

Solar flux ↑ → Temperature ↑

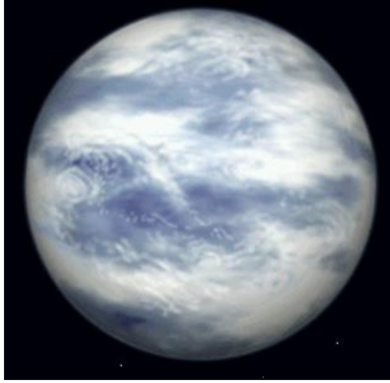
Temperature ↑ → Evaporation ↑

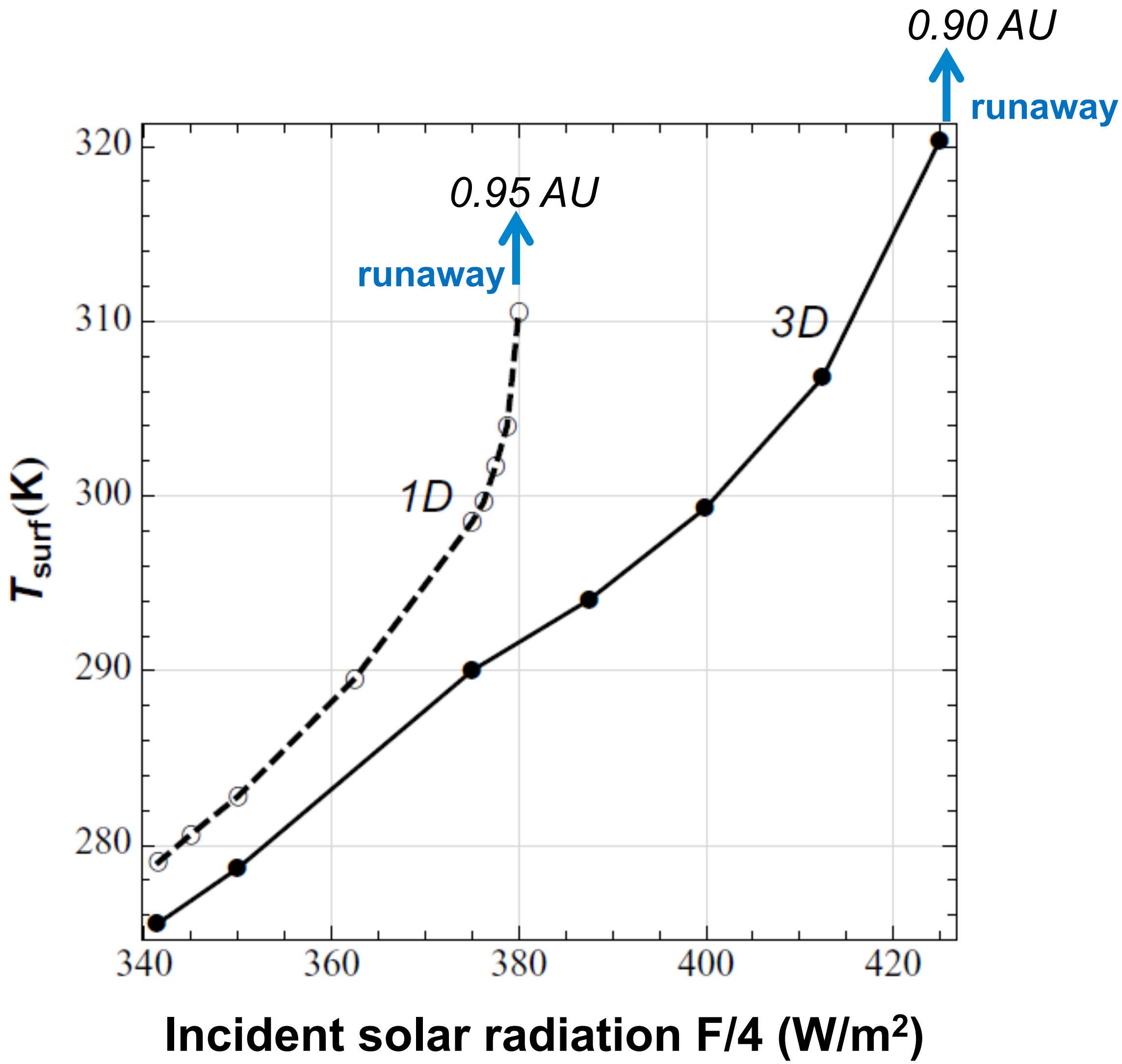
Evaporation ↑ → Greenhouse effect ↑

Greenhouse effect ↑ → Temperature ↑

3D Global Climate model simulations of runaway greenhouse on an Earth-size ocean planet around the Sun.

(Jeremy Leconte, LMD)





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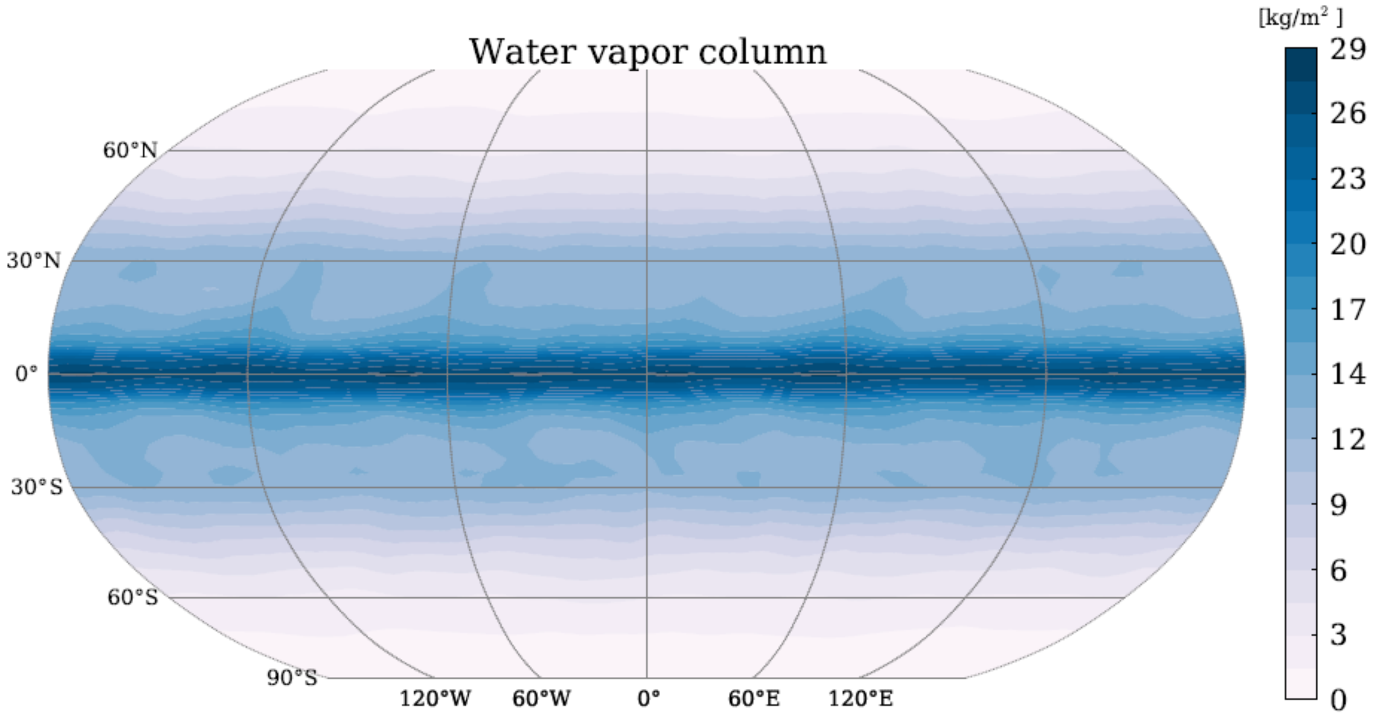

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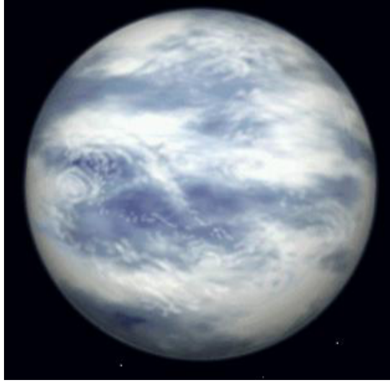

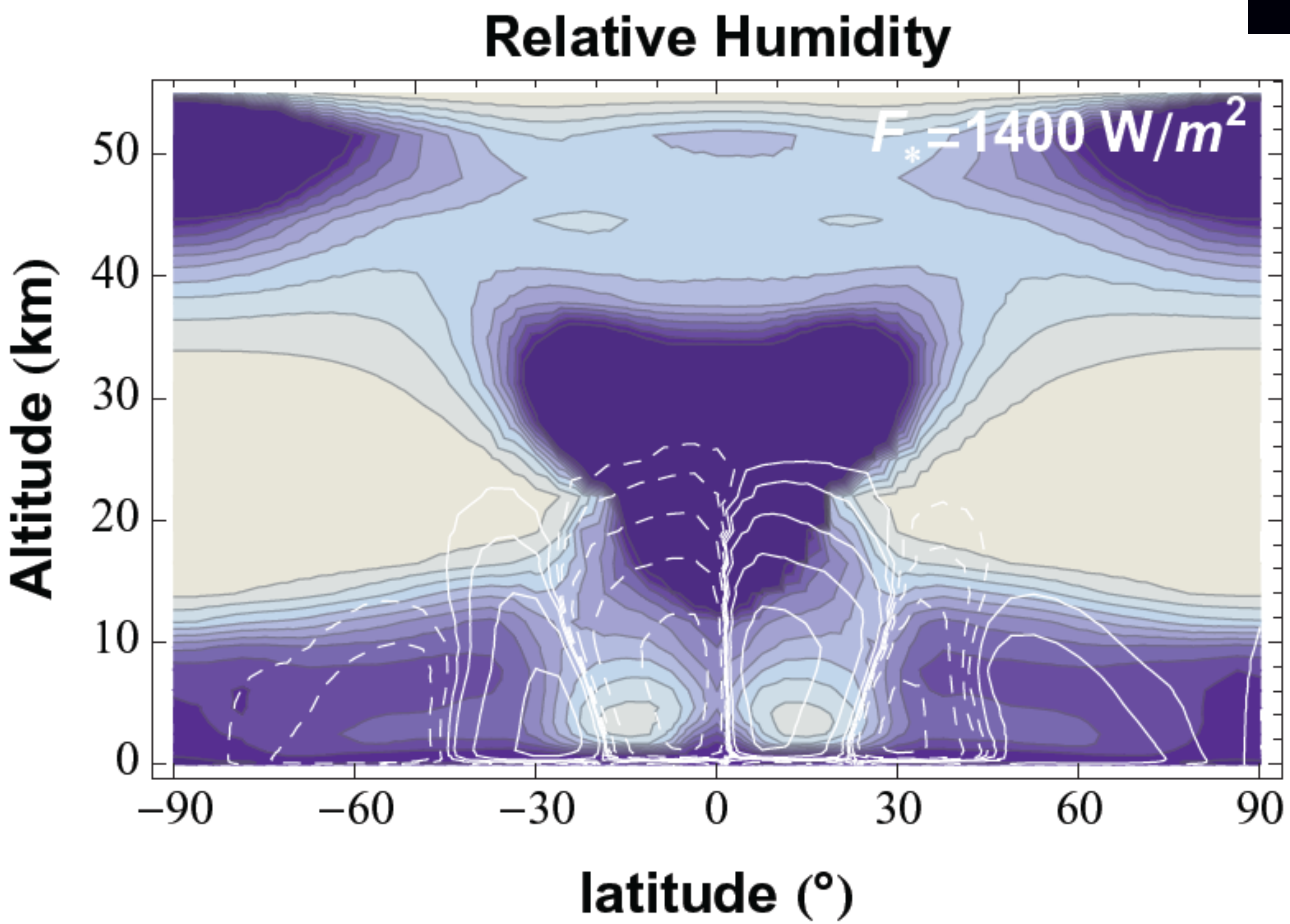

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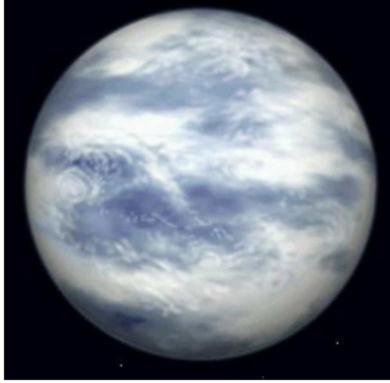

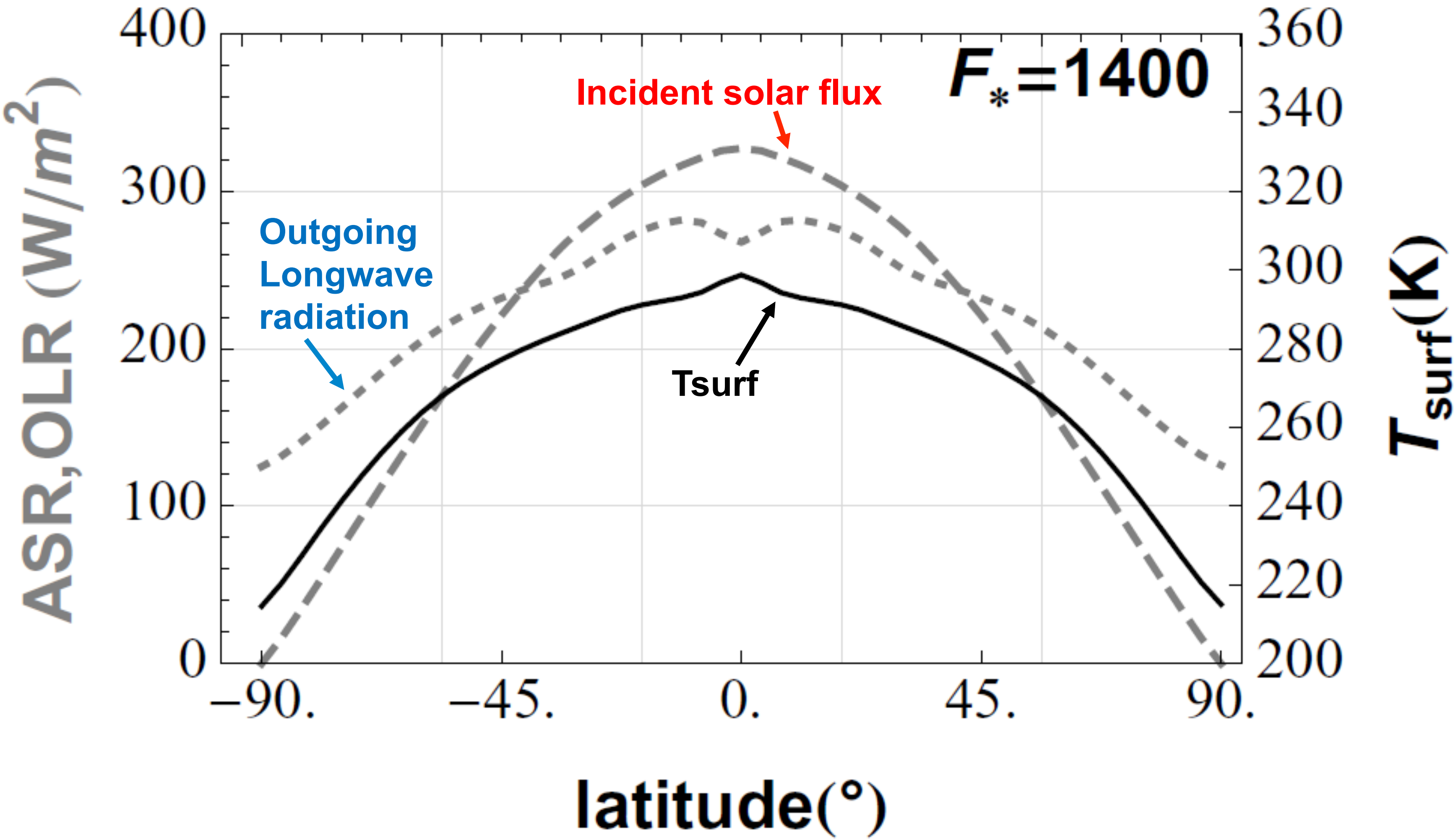

Some Conclusions

- GCMs are physically based tools that can be used to build virtual planets
  - But problems arise if models are incomplete, because of non-linearities, weak forcing…
  - A challenge : GCMs on giant planets.
- Assuming atmosphere/ocean compositions, Global Climate Models are fit to address scientic questions related to extrasolar planets:
  - – Limits of habitability
  - – Climate on specific planets (assuming a specific atmosphere)

  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 :
  - ⇨ We need observations of atmospheres
  - ⇨ We can learn a lot from atmospheres outside the Habitable zone

Some Conclusions

- **Assuming atmosphere/ocean compositions, robust, “complete” GCMs/Planet simulators may be developed to address major scientic questions related to extrasolar planets and past climates** (Preparation of observations, Habitability)
  - 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 :**

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

⇨