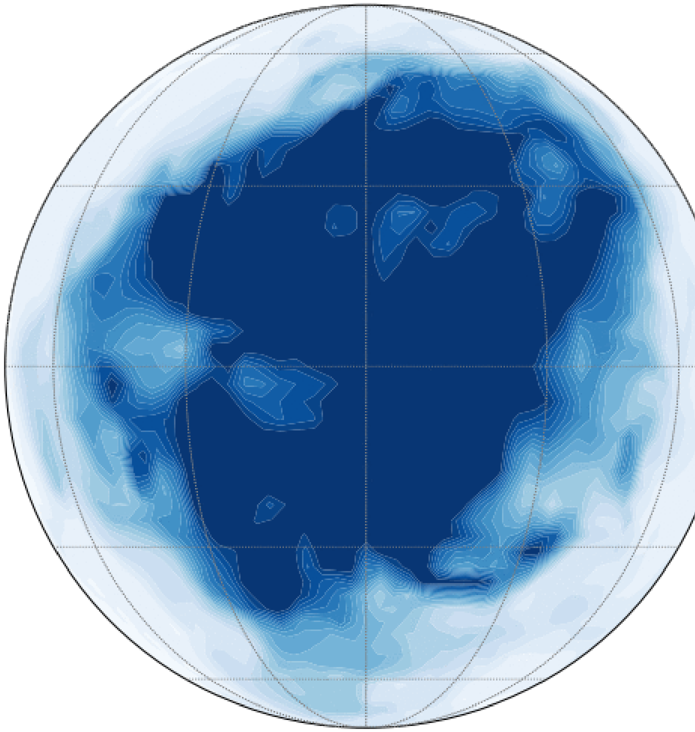
Possible climates on terrestrial exoplanets

<u>François Forget</u>*, Jeremy Leconte, Benjamin Charnay, Robin Wordsworth, Ehouarn Millour, Franck Selsis et al. …

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



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

Possible climates on terrestrial exoplanets

No observations (yet): Why speculate ?

- Need to prepare future observations
- Address key theoretical science questions
  (*e.g. probability of habitable planets in the galaxy, define the habitable zone, etc.*)

My talk today :

1) How can we predict possible climates?
   ⇨Theories and tools.
2) Examples of climates around the habitable zone
   ⇨ the challenge of climate instabilities.

Key parameters controlling the climate on a terrestrial planet:

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

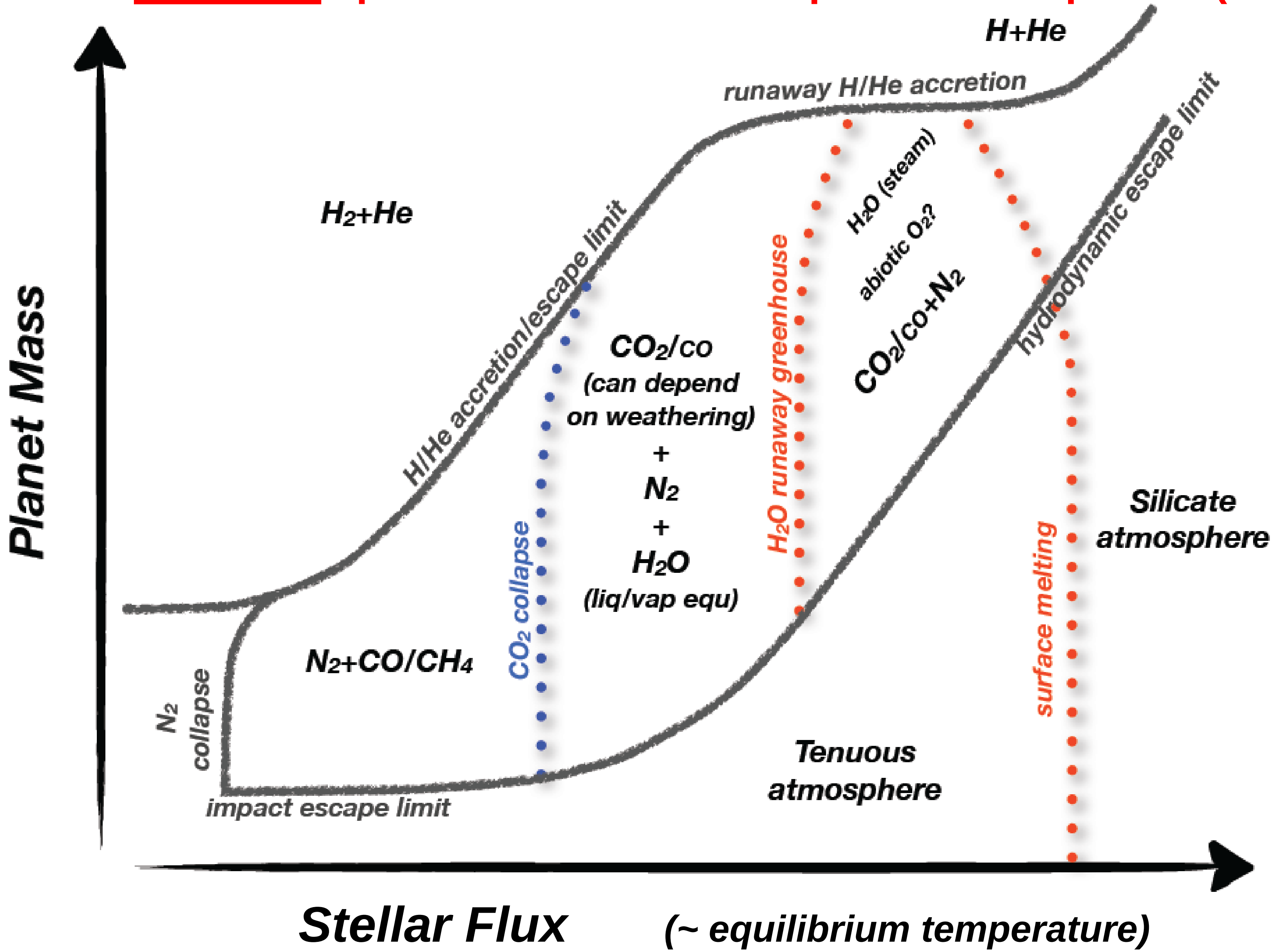
Climate

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 (thermal, impacts, non-thermal)
  - 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 (2013)**, « Possible climate on terrestrial exoplanets »*
Phil. Trans. Royal Society. A. (2014) (**arXiv:1311.3101)**

Key parameters controlling the climate on a terrestrial planet:

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

Climate

Planetary rotation & climate

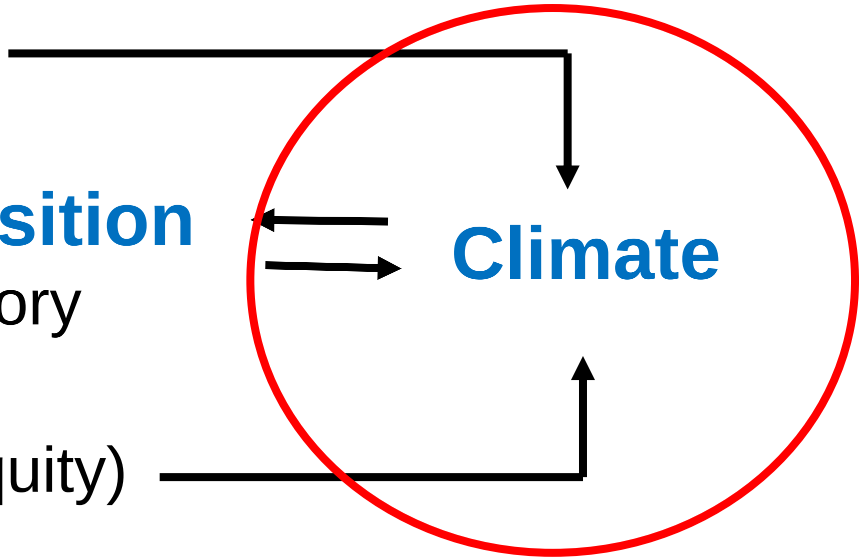
1) Govern the distribution of insolation
2) Controls circulation and heat transport.

Two "end members" :

- "Free" Planets, which seems to originally rotates "fast" (P < 100 hrs) : Mars, ~Earth, Jupiter, Saturn, Uranus, Neptune… (theory? see *Miguel and Brunini, 2010*)
- Tidally evolved bodies
  - Planets: obliquity →0° ; slow rotation or even locking (Mercury, Venus)
  - Satellites : slow rotation (Titan, Triton)

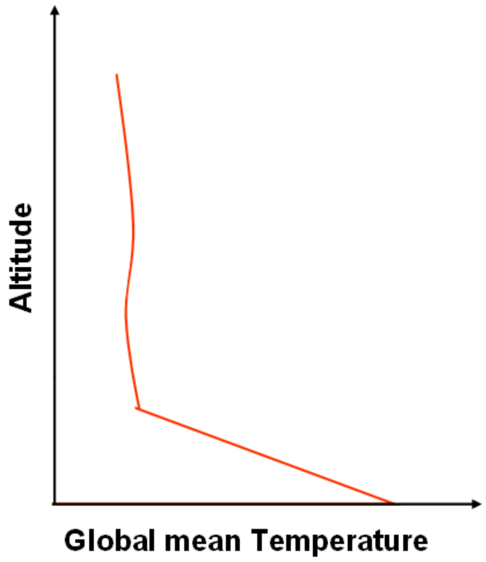
Key parameters controlling the climate on a terrestrial planet:

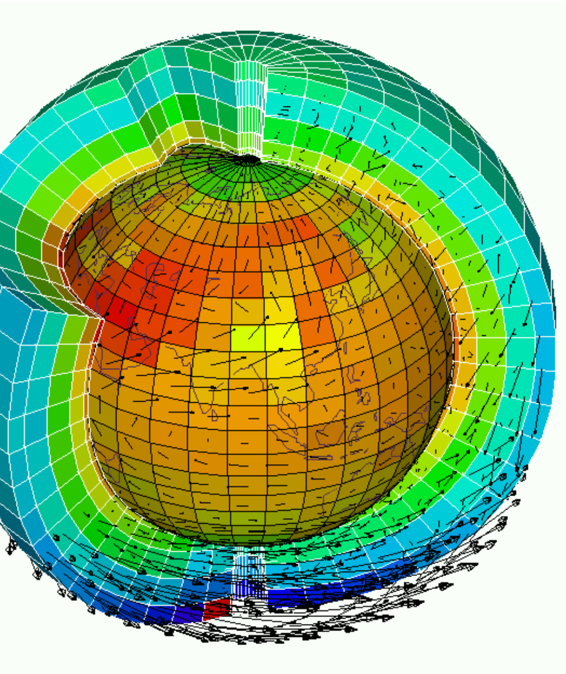
- **Stellar insolation**
- **Atmospheric composition**
  and surface volatile inventory
- **Rotation** (rate and obliquity)



Climate models

A hierarchy of models for planetary climatology





1. 1D global radiative convective models

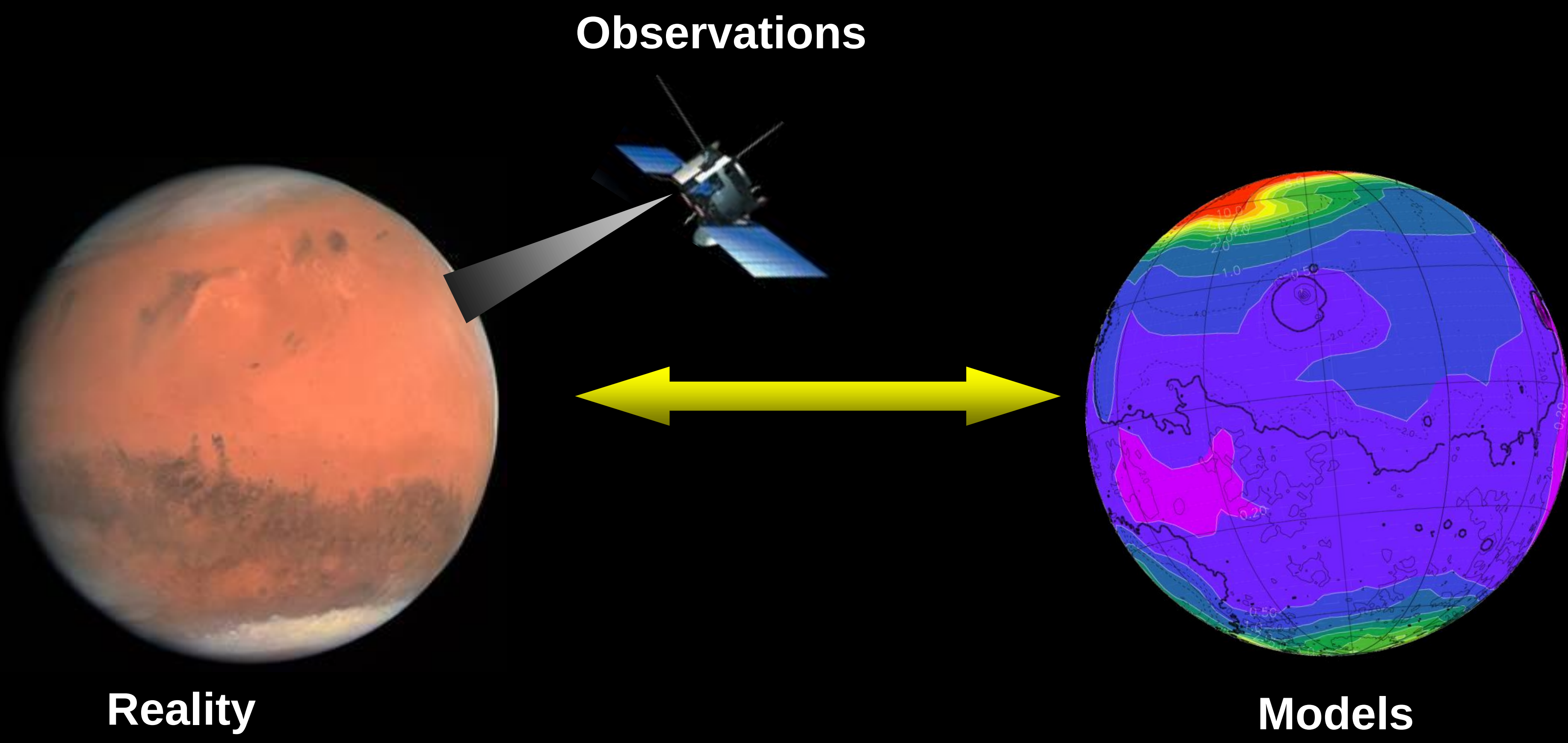
⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone *(e.g. Kasting et al. 1993)*

2. 2D Energy balance models…

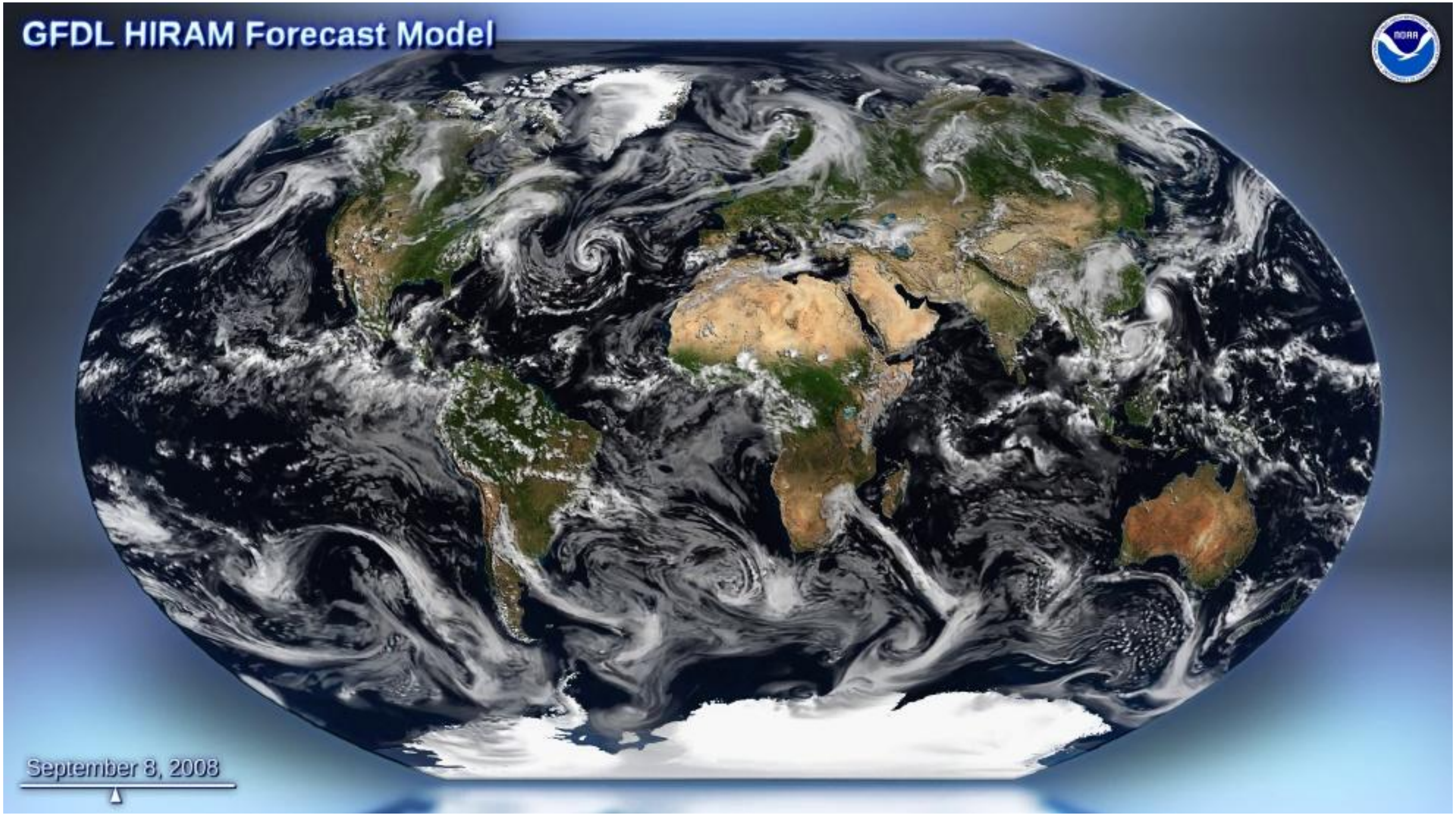
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime (*see Read 2011, Showman et al. 2013, etc)*

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

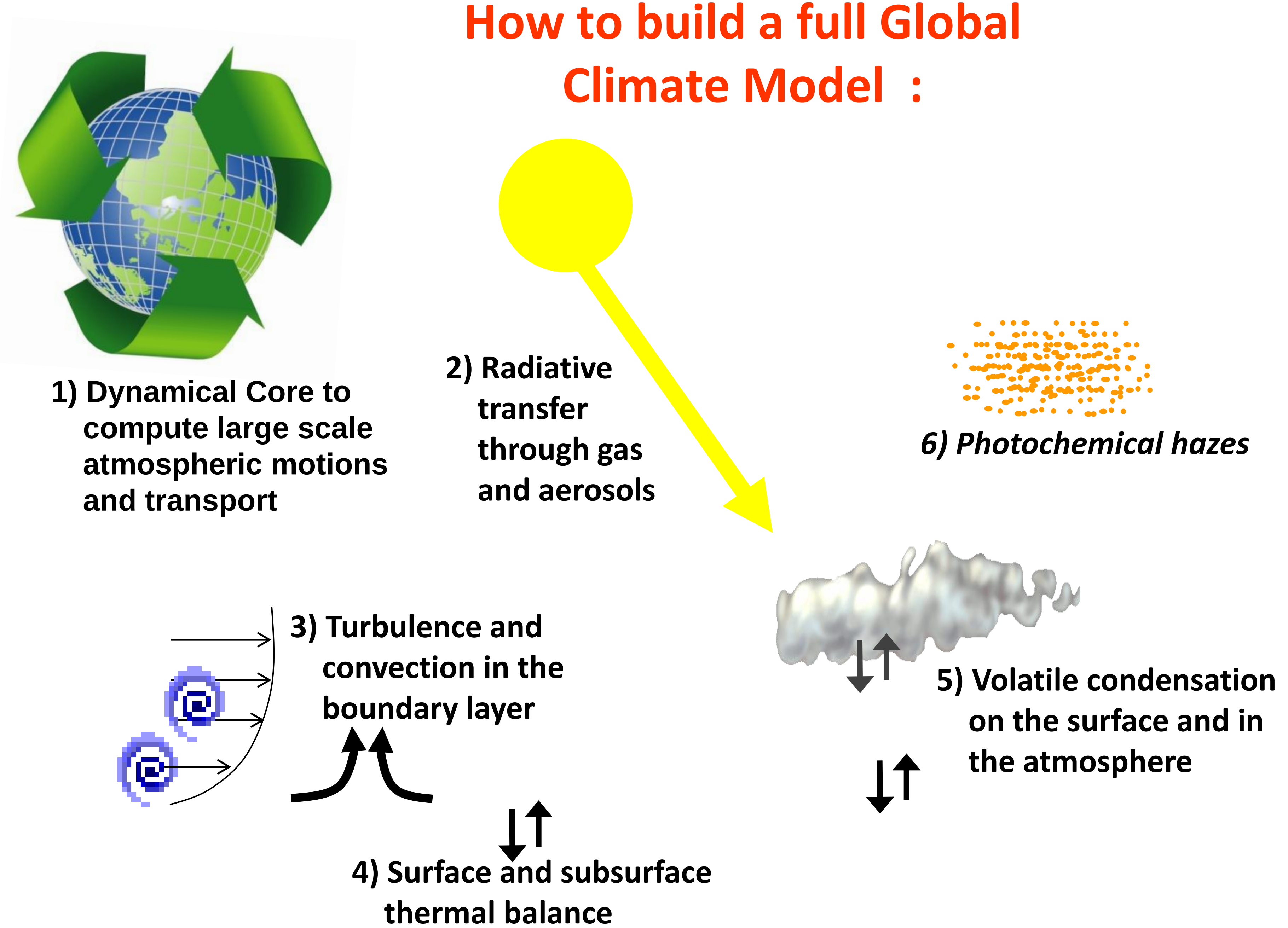


How to build a full Global Climate Simulator :



How to build a full Global Climate Simulator :

How to build a full Global Climate Model :



IN THE SOLAR SYSTEM:

VENUS

~2 GCMs
Coupling dynamic & radiative transfer (LMD, Ashima)

EARTH

Many GCM teams
Applications:

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

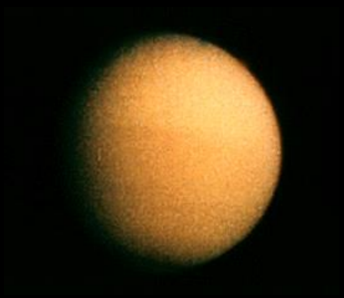
MARS

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**

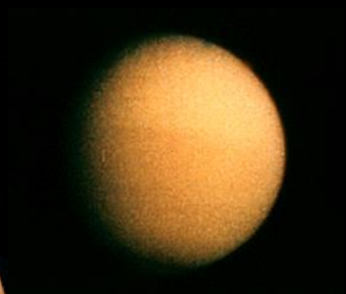
TRITON

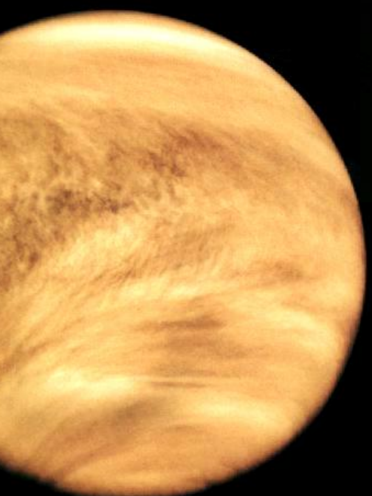
GCM s
(LMD, MIT)

PLUTO

GCMS
(LMD, MIT)

Lessons from Climate Models in the solar system





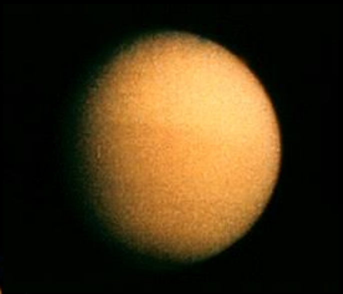
Lesson # 1: By many measures: GCMs work

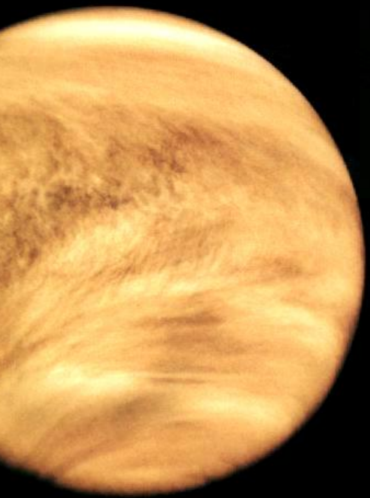
Lesson # 2 Climate model components can be applied without major changes to most terrestrial planets.

Lesson # 3: Why and when GCMs fail (missing physical processes, non-linear processes and threshold effects, positive feedbacks and unstability, etc…)

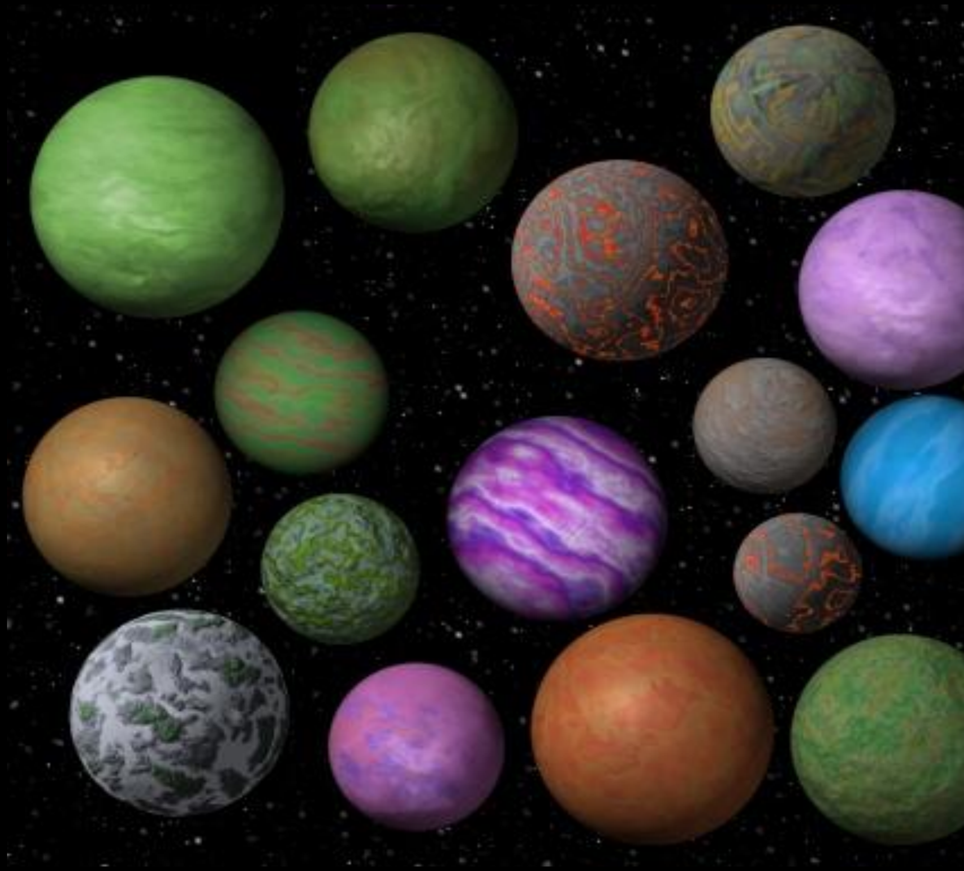
Forget and Lebonnois (2013) In "Comparative Climatology of Terrestrial Planets" book, Univ of Arizona press 2013.

Lessons from Climate Models in the solar system



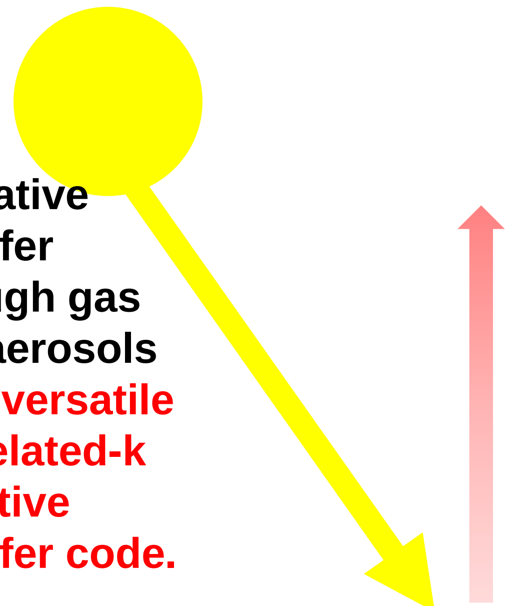


Simulating the unobservable:
From planet GCMs to extrasolar planets
(or past atmospheres)**.**



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

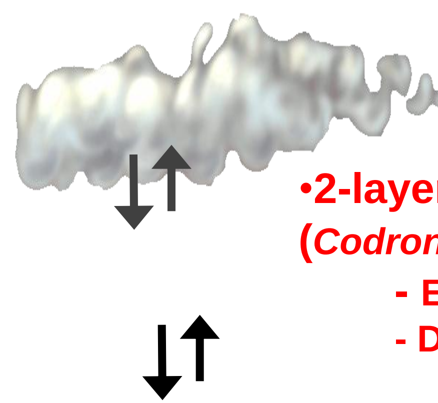
1) Dynamical Core : ~universal



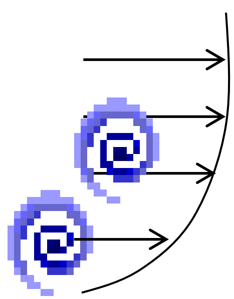
2) Radiative transfer through gas and aerosols
⇨ New versatile Correlated-k radiative transfer code.

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

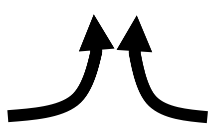
- Robust microphysics: Fixing mixing ratio of condensation nuclei
- Modified thermodynamics to handle condensation of major constituants (H_2O, CO_2, N_2)

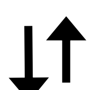


•2-layer dynamical ocean (*Codron 2011*):
- Ekman transport
- Dynamic Sea ice



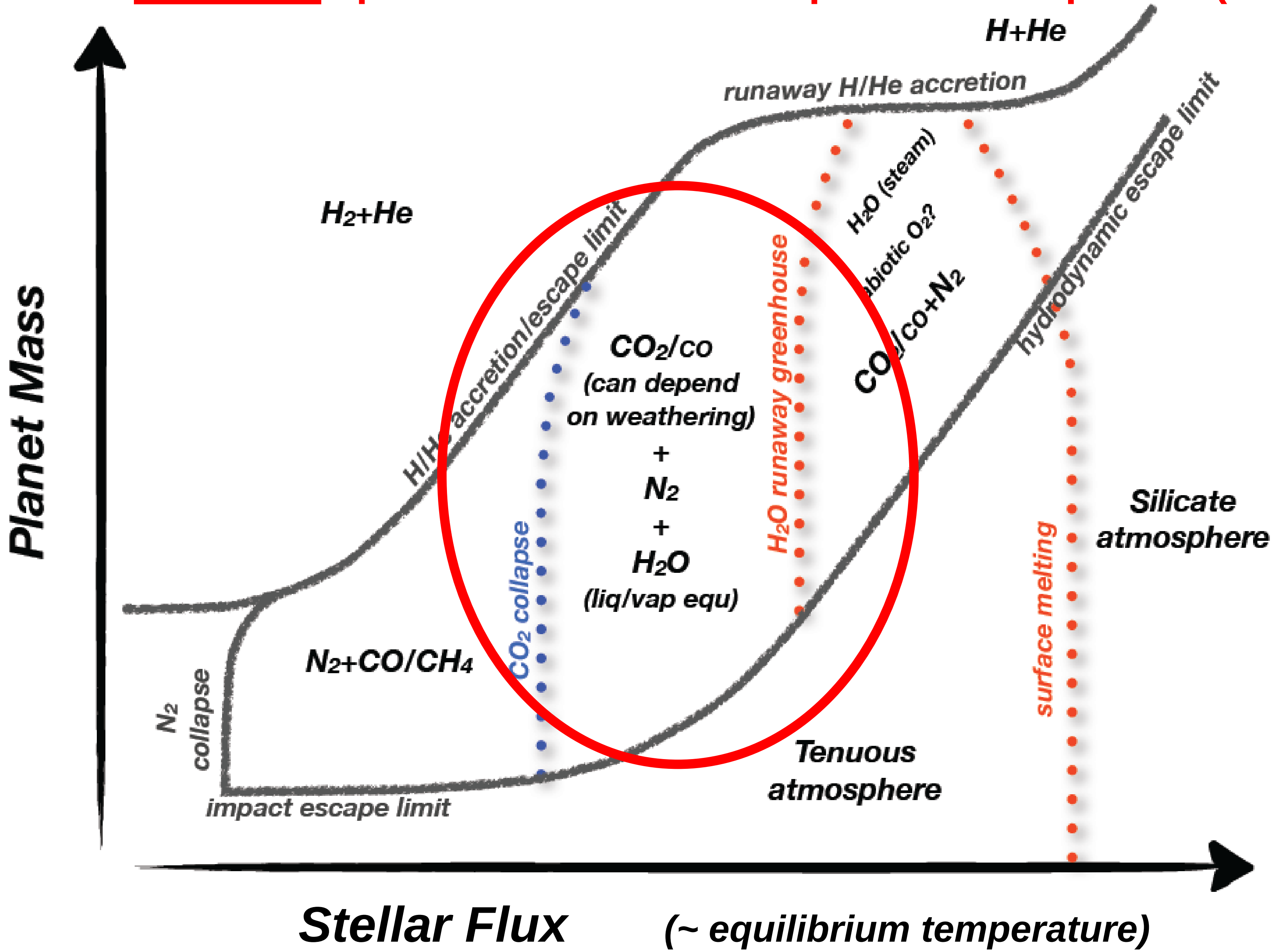
3) Turbulence and convection in the boundary layer
⇨ Universal turbulent sheme
⇨ Robust convection scheme





4) Surface and susurface thermal balance ~universal

Expected **dominant** species in an terrestrial planet atmospheres (abiotic)



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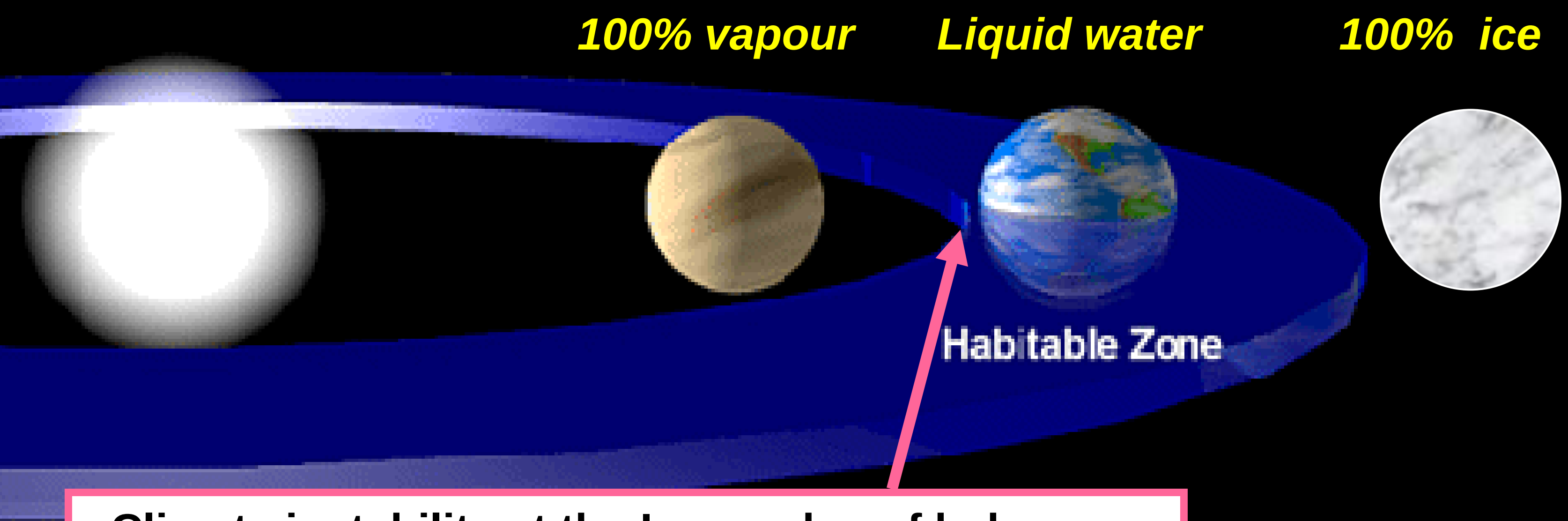
Around the « surface liquid water » habitable zone.



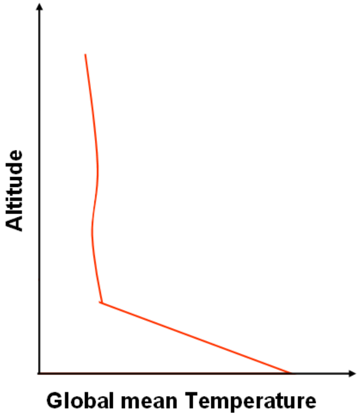
Climate instability at the Inner edge of hab. zone

Solar flux ↑ → Temperature ↑

Temperature ↑ → Evaporation ↑

Evaporation ↑ → Greenhouse effect ↑

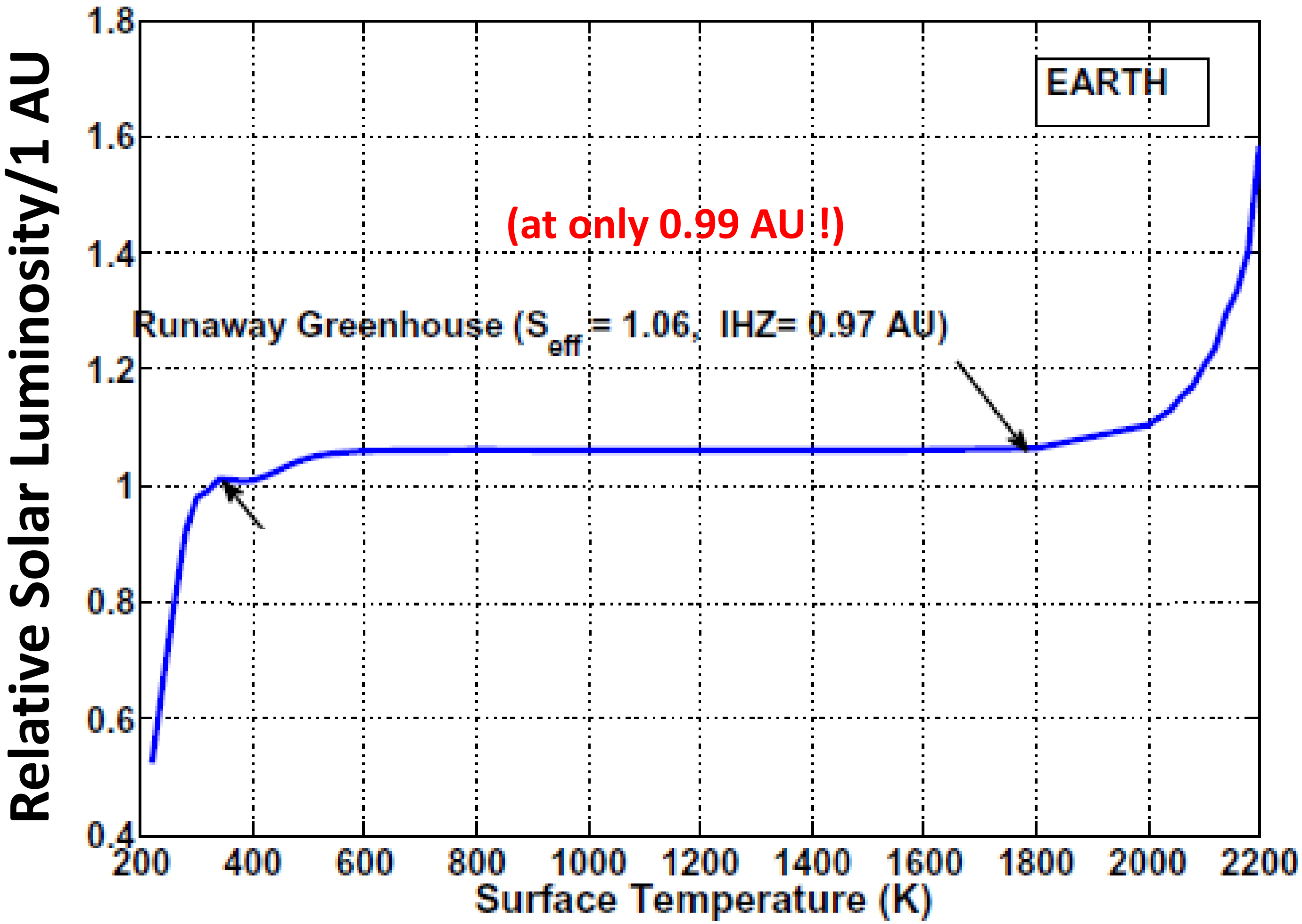
Greenhouse effect ↑ → Temperature ↑



Runaway Greenhouse effect in 1D models

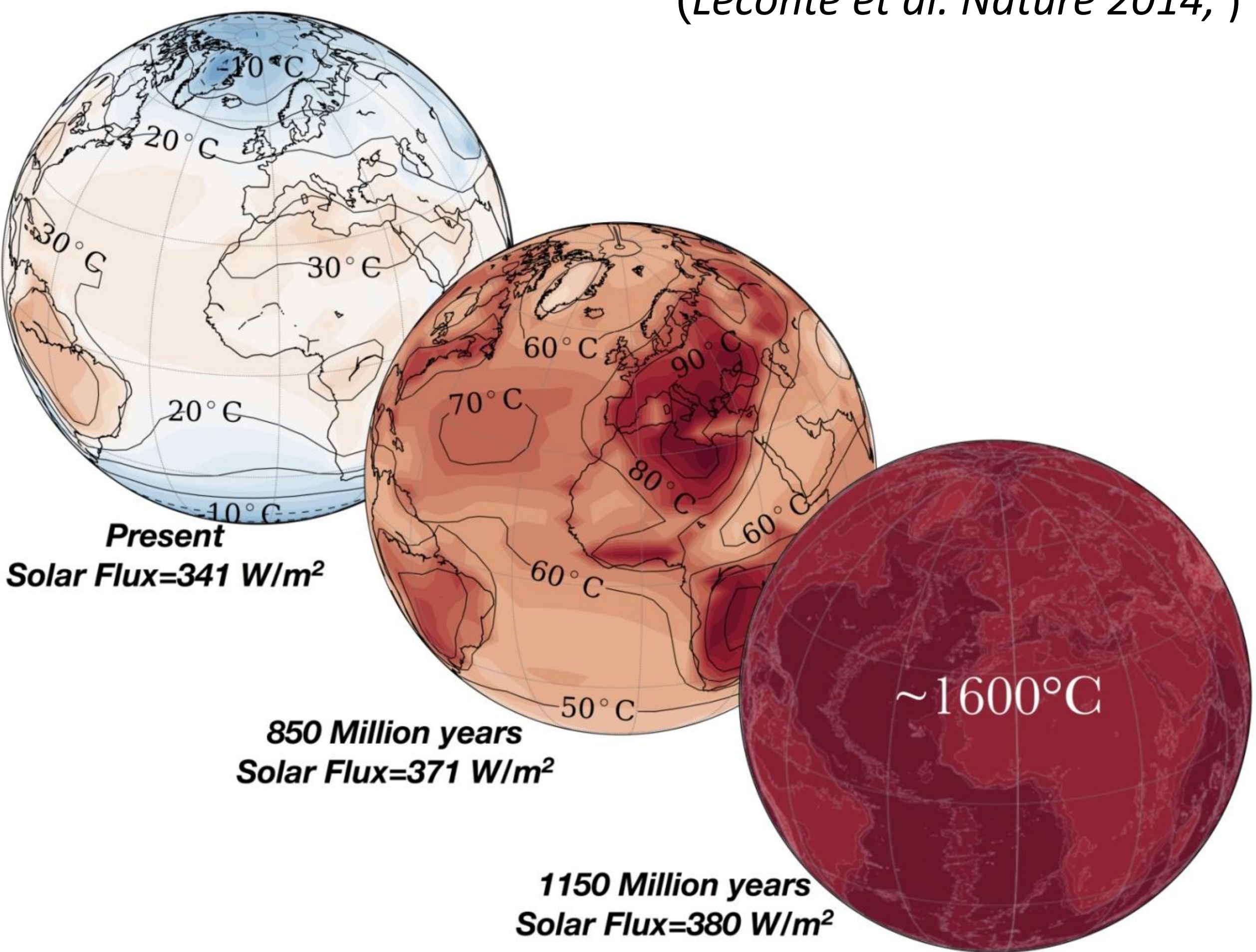
(for an Earth-like planet around a sun)

(*Ingersoll 1969, Kasting 1988, Kasting et al. 1993, Goldblaytt et al. 2013, Kopparapu et al. 2013*)



Runaway Greenhouse effect in a complete 3D Global Climate model

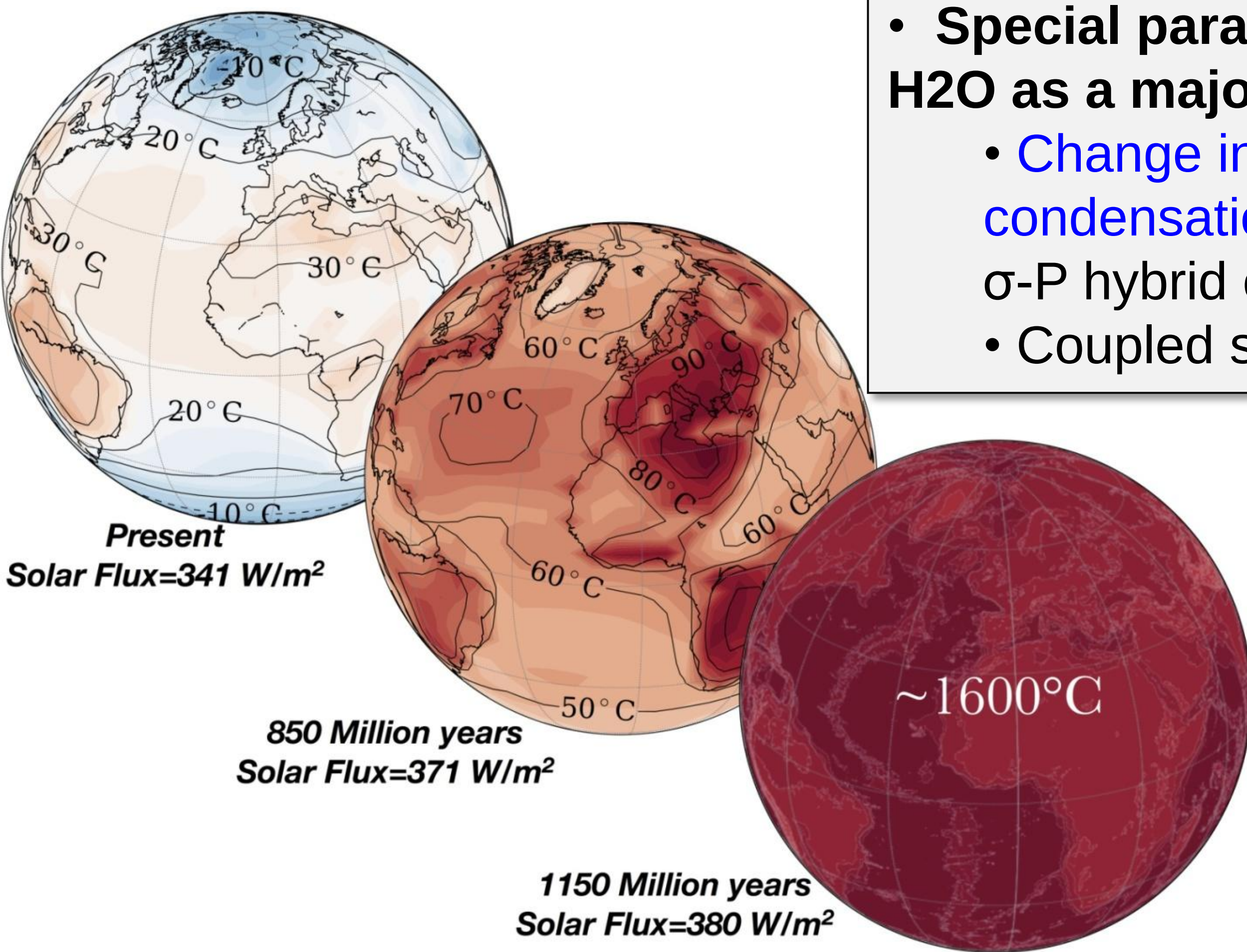
(*Leconte et al. Nature 2014,*)



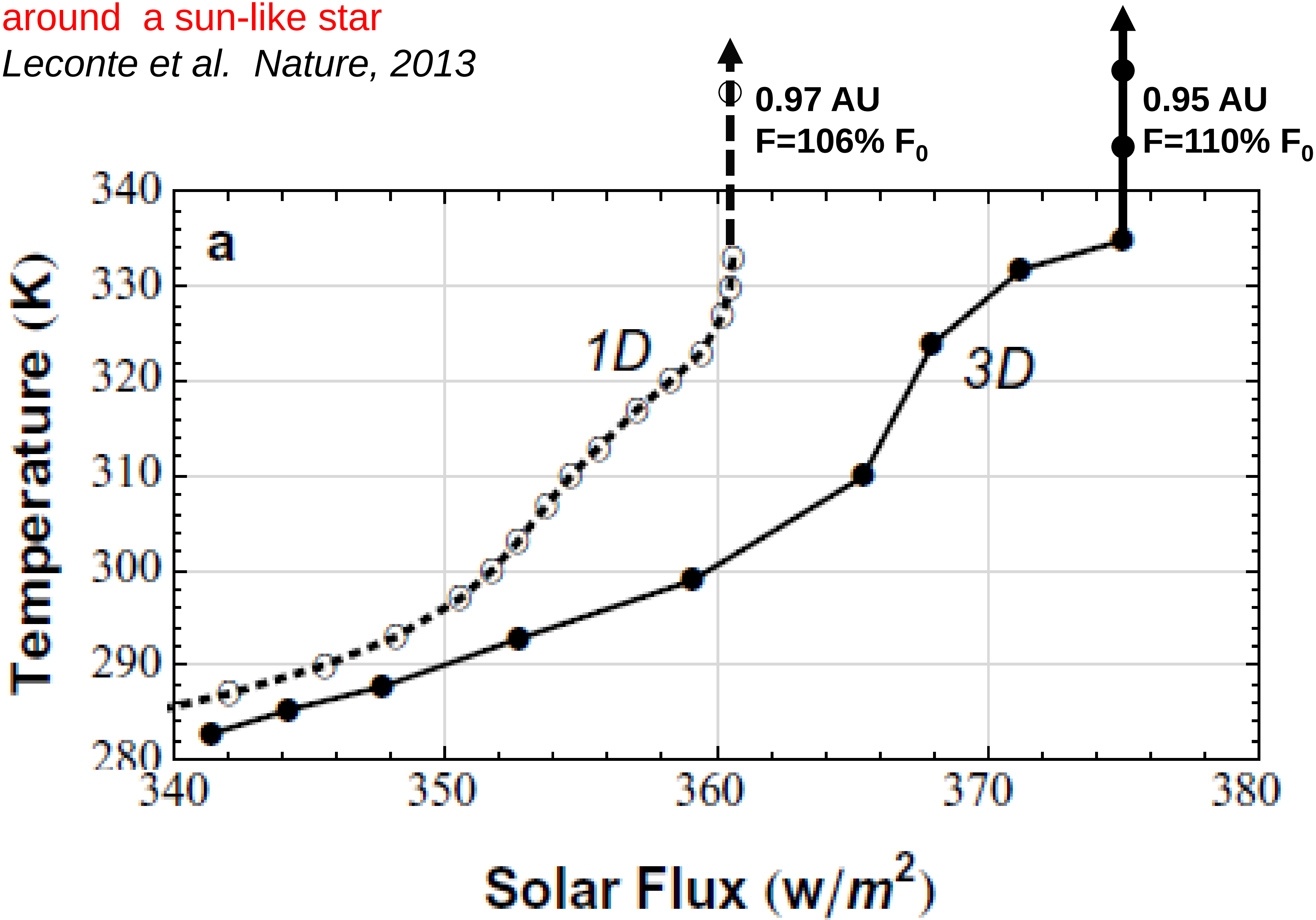
Leconte et al. « *3D Increased insolation threshold for runaway greenhouse processes on Earth like planets*". Nature, 2013

LMD 3D Generic Climate Model

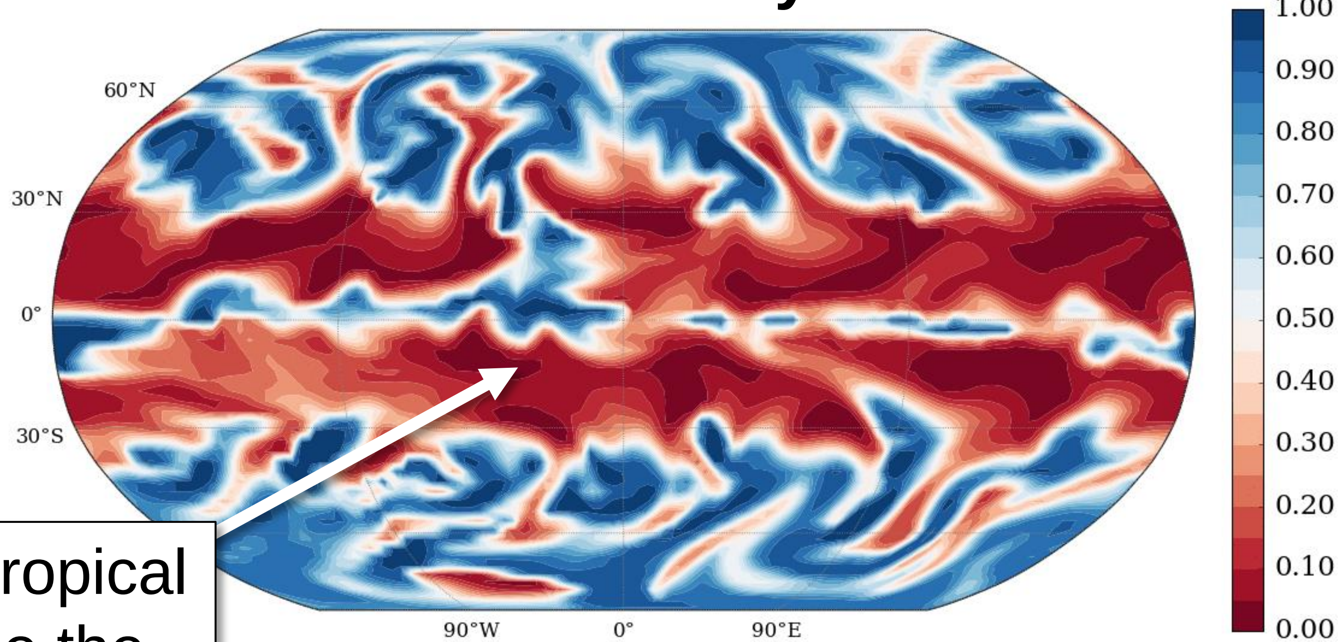
- Earth like planet
- 64x48x30 resolution
- Radiative transfer (correlated k)
  - 19 IR bands
  - 18 solar bands
- **Special parametrization to handle H2O as a major constituant :**
  - Change in Ps with condensation/evaporation ⇨ case of σ-P hybrid coordinates.
  - Coupled system [H2O]+T+Ps



LMD Model : Earth like planet
around a sun-like star
Leconte et al. Nature, 2013



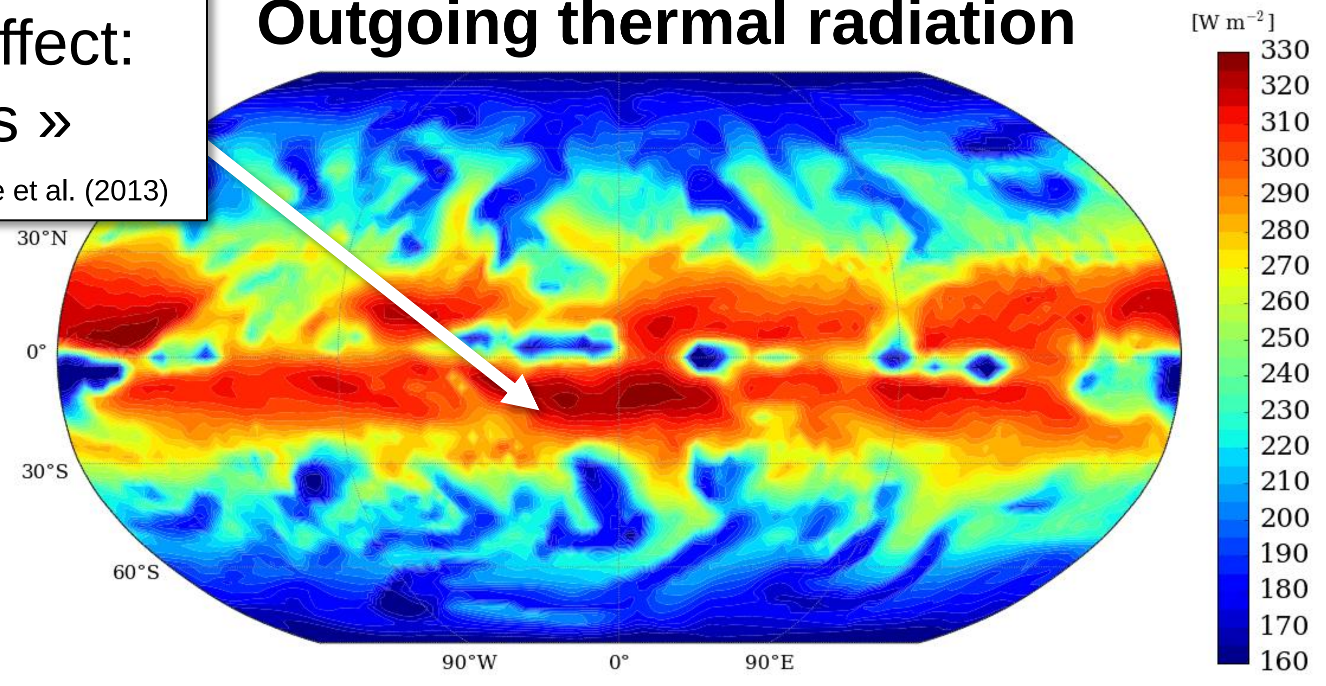
Relative humidity



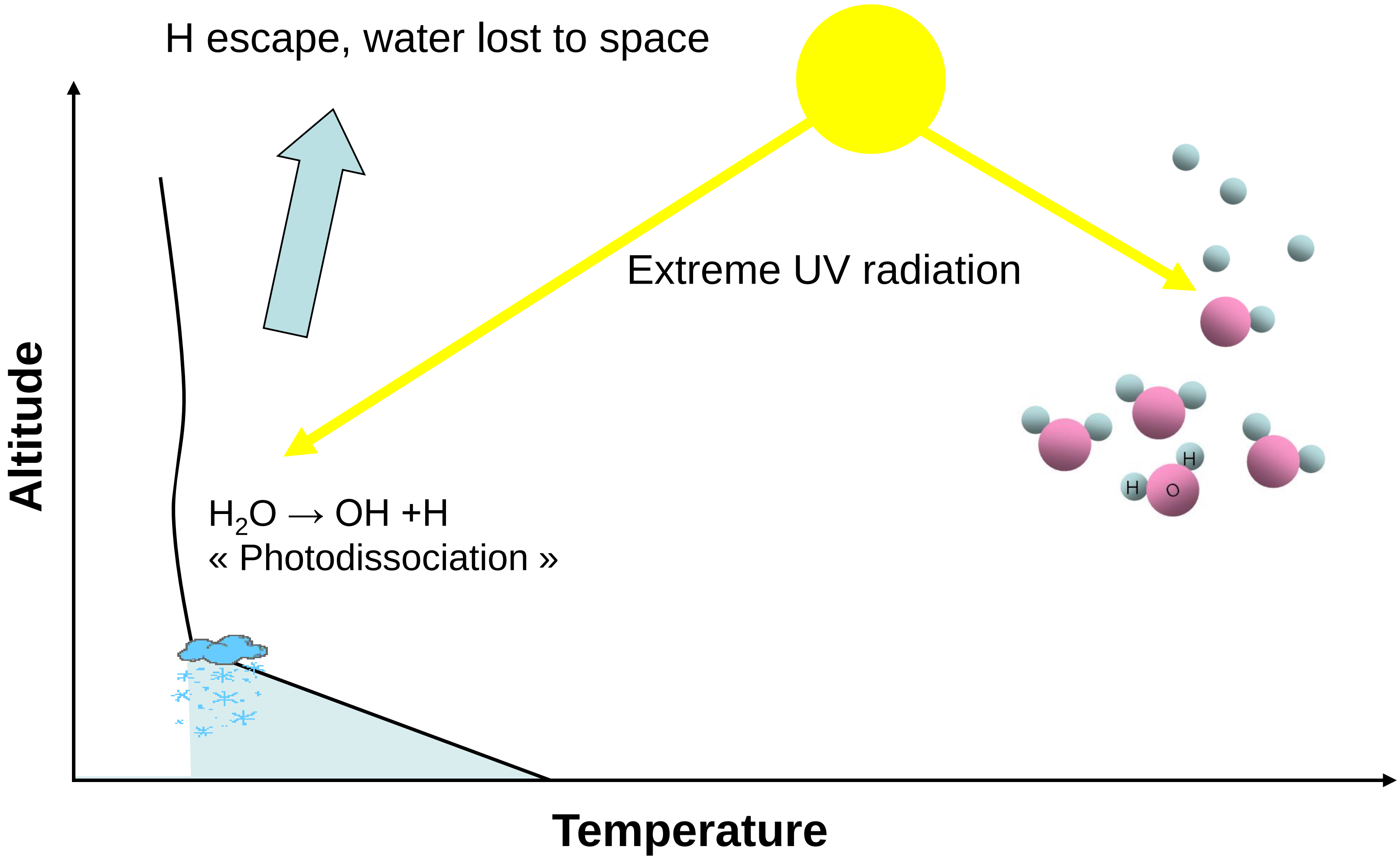
Unsaturated tropical regions reduce the greenhouse effect: « radiative fins »

Pierrehumbert (1995), Leconte et al. (2013)

Outgoing thermal radiation

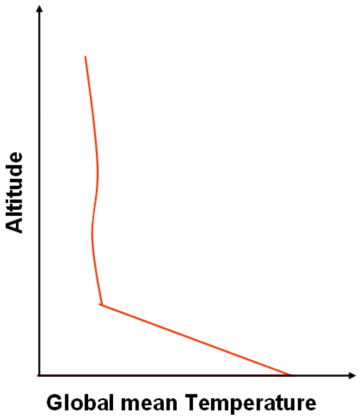


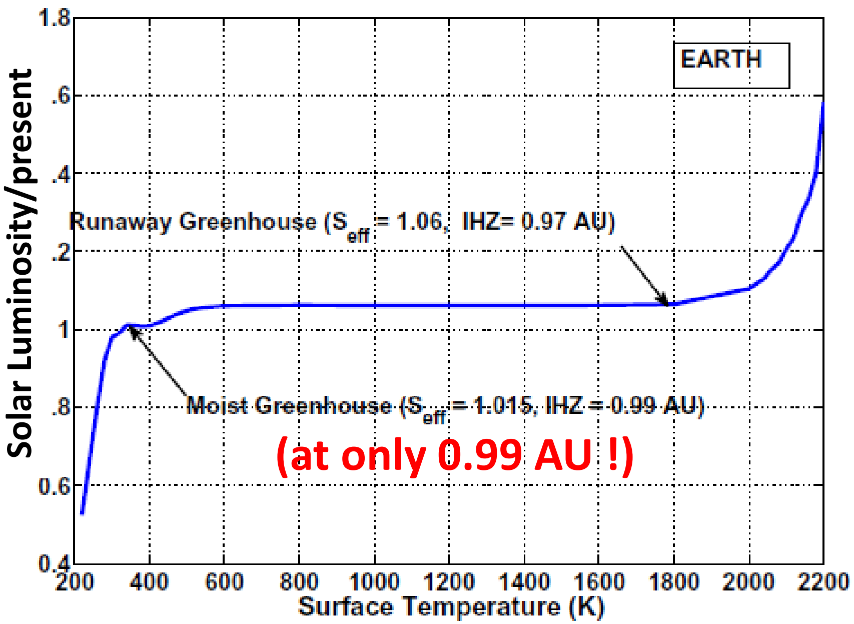
Impact of temperature increase on water vapor distribution and escape: the « water loss limite »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)

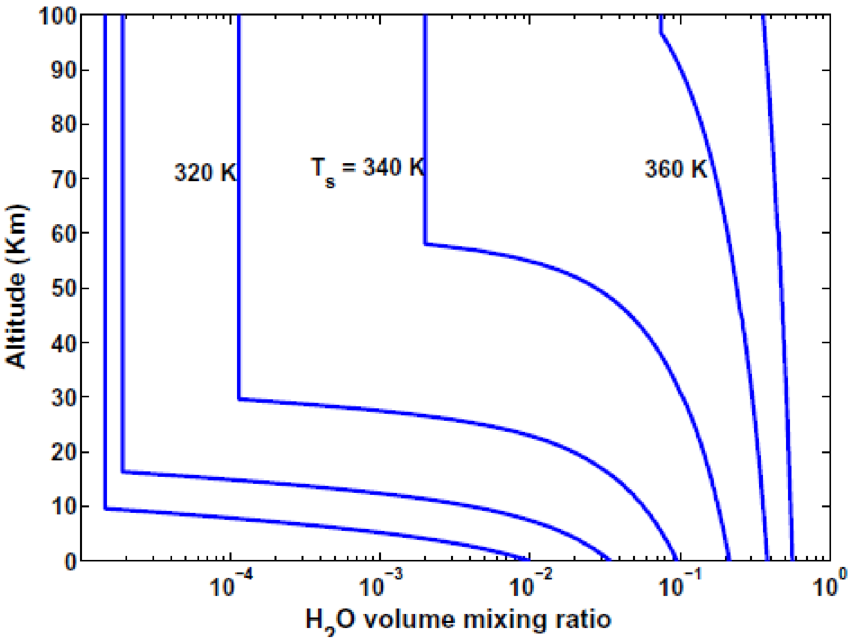


« Water loss limit » in 1D models

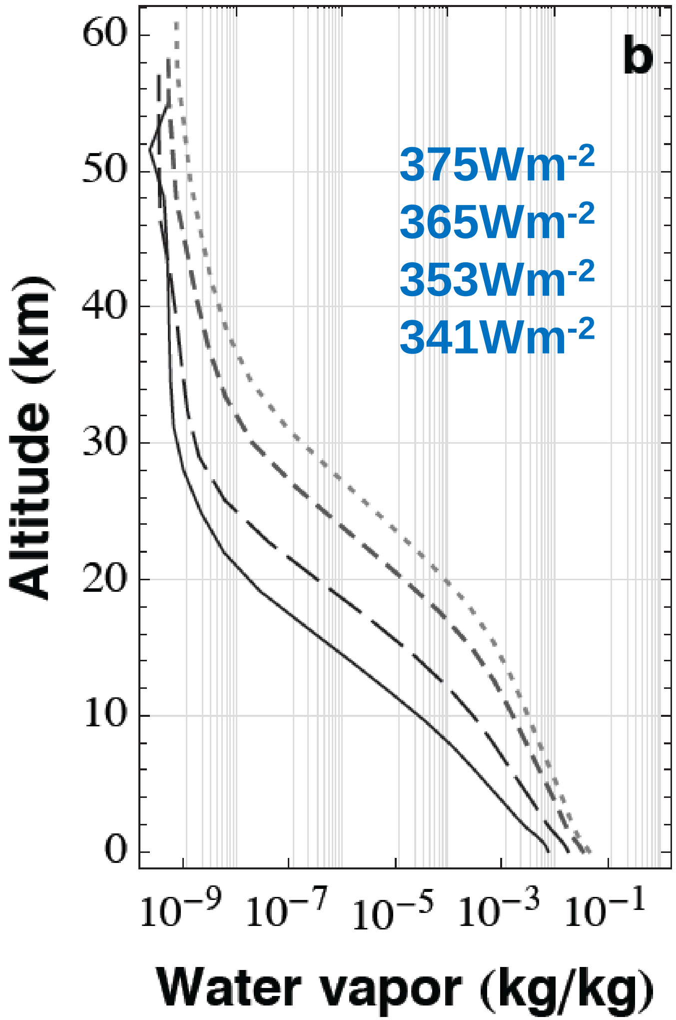
(*Ingersoll 1969, Kasting 1988, Kasting et al. 1993, Kopparapu et al. 2013*)

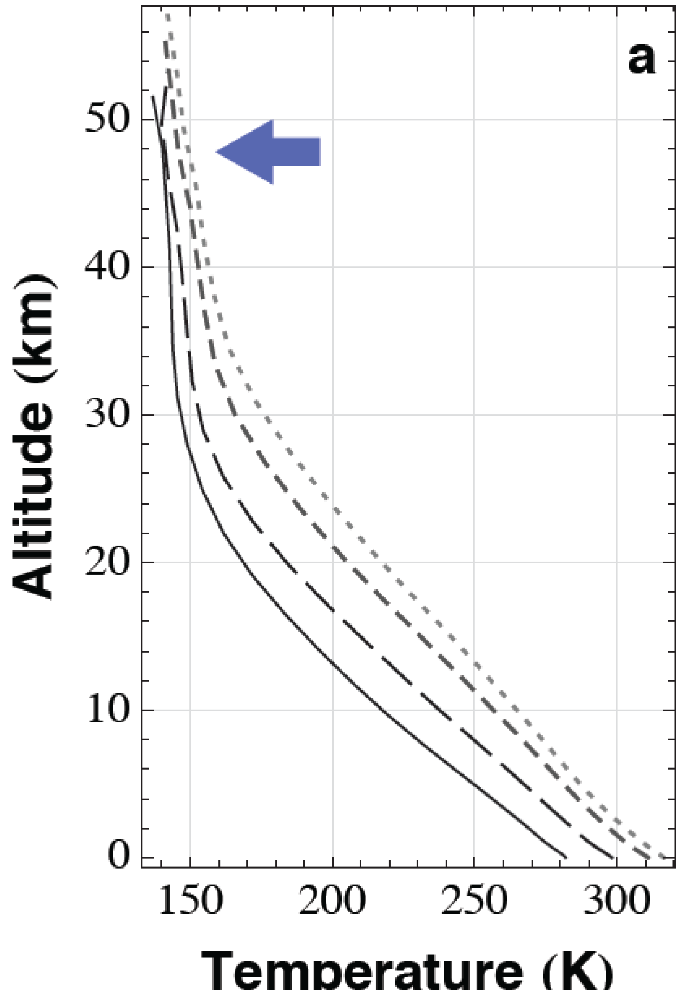






Earth like Simulation with detailed radiative transfer in the upper atmosphere: no water loss limit !





Leconte et al. (Nature; 2013)

Runaway greenhouse effect around K and M dwarf star

Redder stellar spectrum

• Weak atmospheric Rayleigh Scaterring

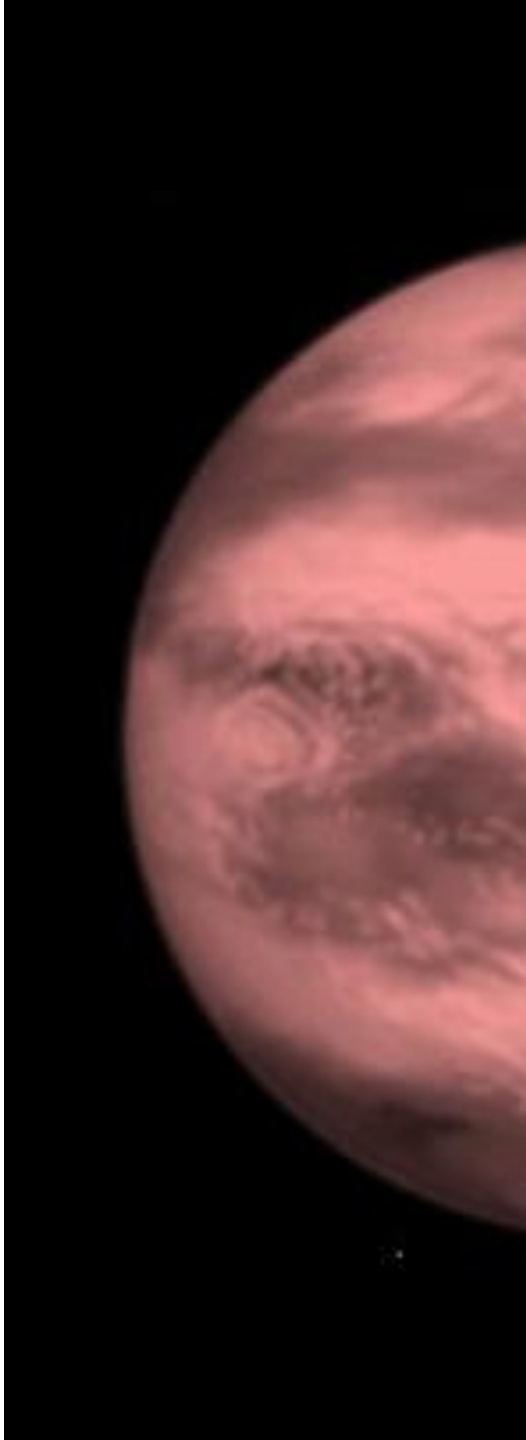
⇨ lower albedo

Effect of tides:

• Resonnant rotation with zero obliquity

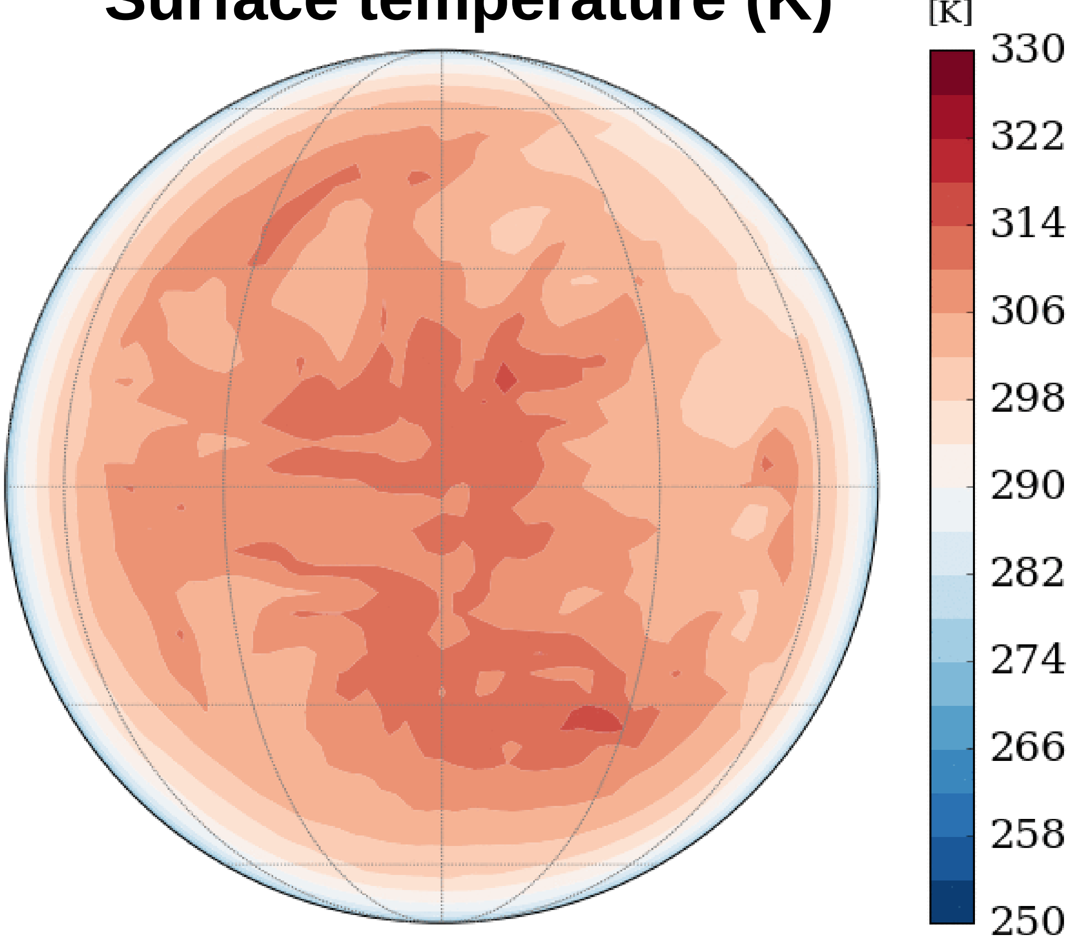
⇨ Possible Locking with permanent night side

(see Leconte et al. A&A 2013, Yang et al. ApJL2013)

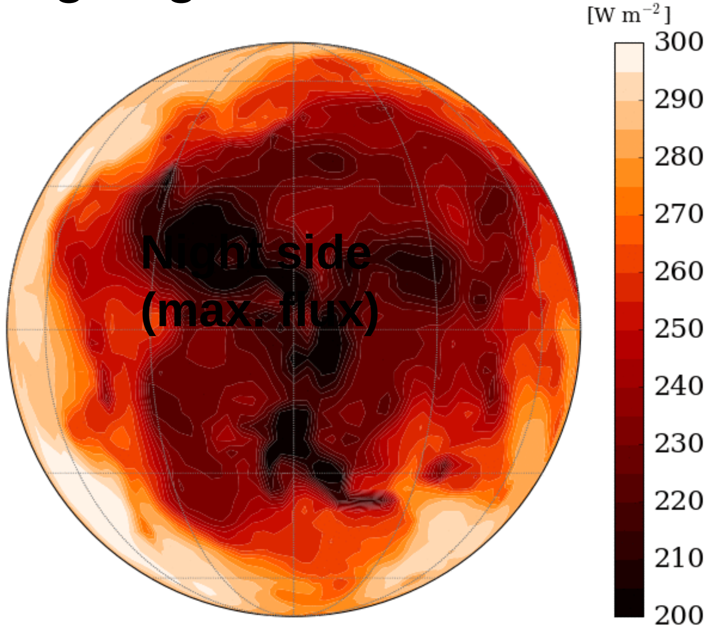


Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

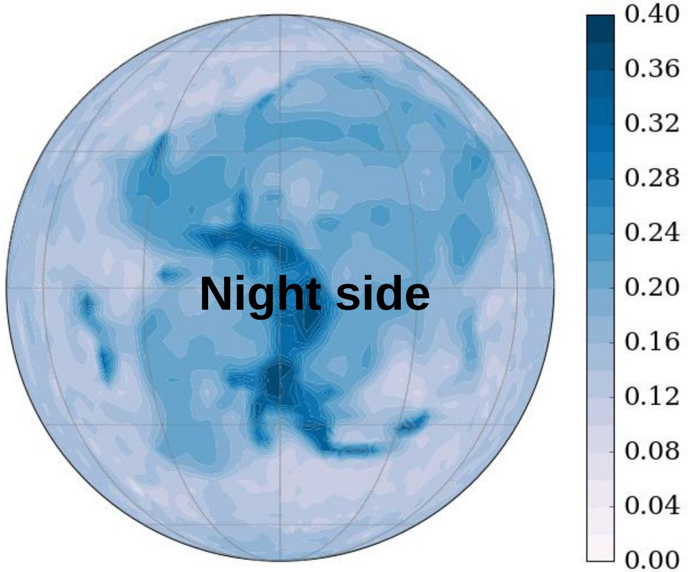
Surface temperature (K)



Outgoing Thermal radiation

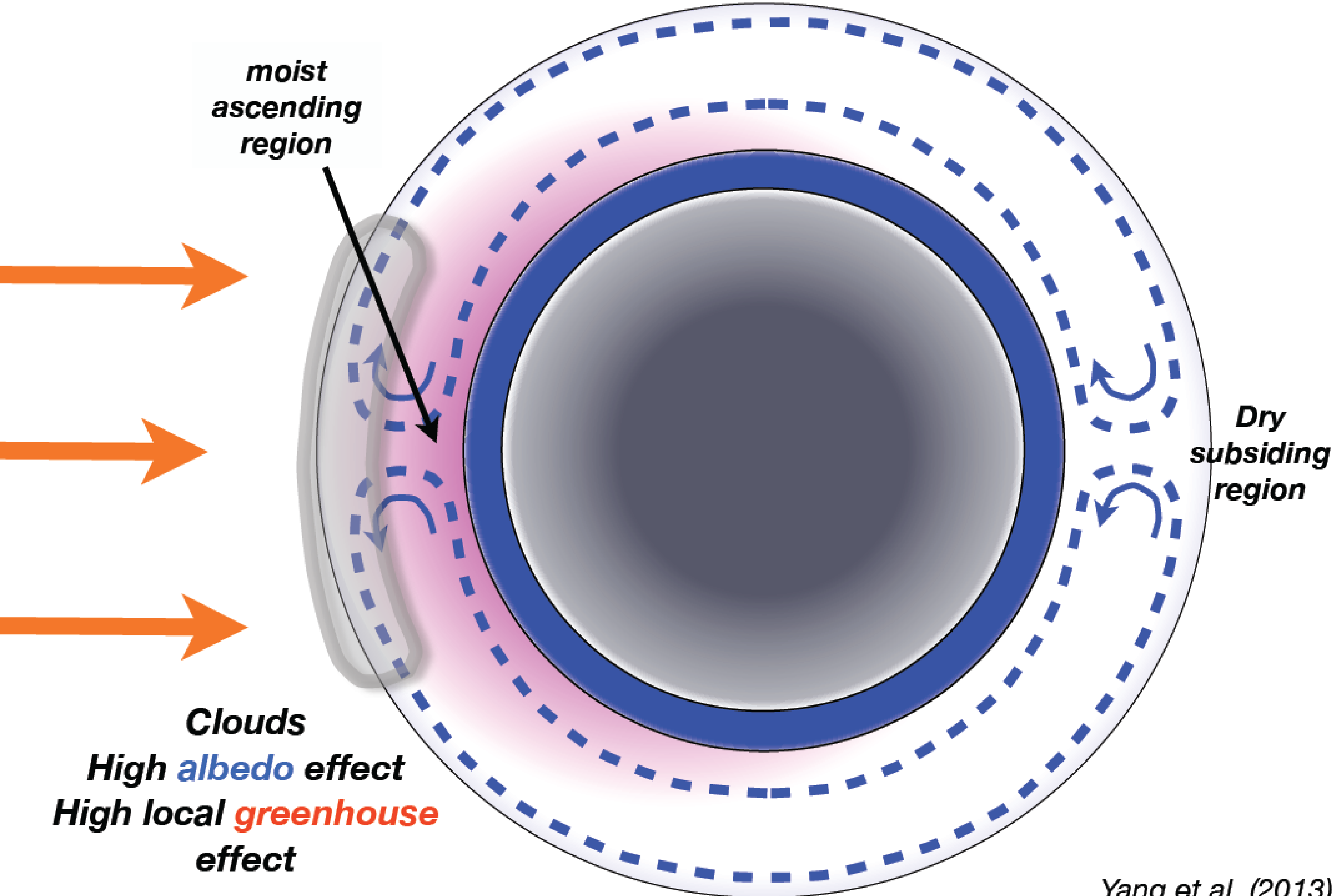


Planetary Albedo



View from a distant point throughout the orbit

Large scale cloud pattern on tidally locked planets



The Astrophysical Journal Letters, Volume 771, Issue 2, article id. L45, 6 pp. (2013).

STABILIZING CLOUD FEEDBACK DRAMATICALLY EXPANDS THE HABITABLE ZONE OF TIDALLY LOCKED PLANETS

Jun Yang
The Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA

Nicolas B. Cowan
Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 2131 Tech Drive, Evanston, IL 60208, USA

and

Dorian S. Abbot
The Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA

Draft version June 28, 2013

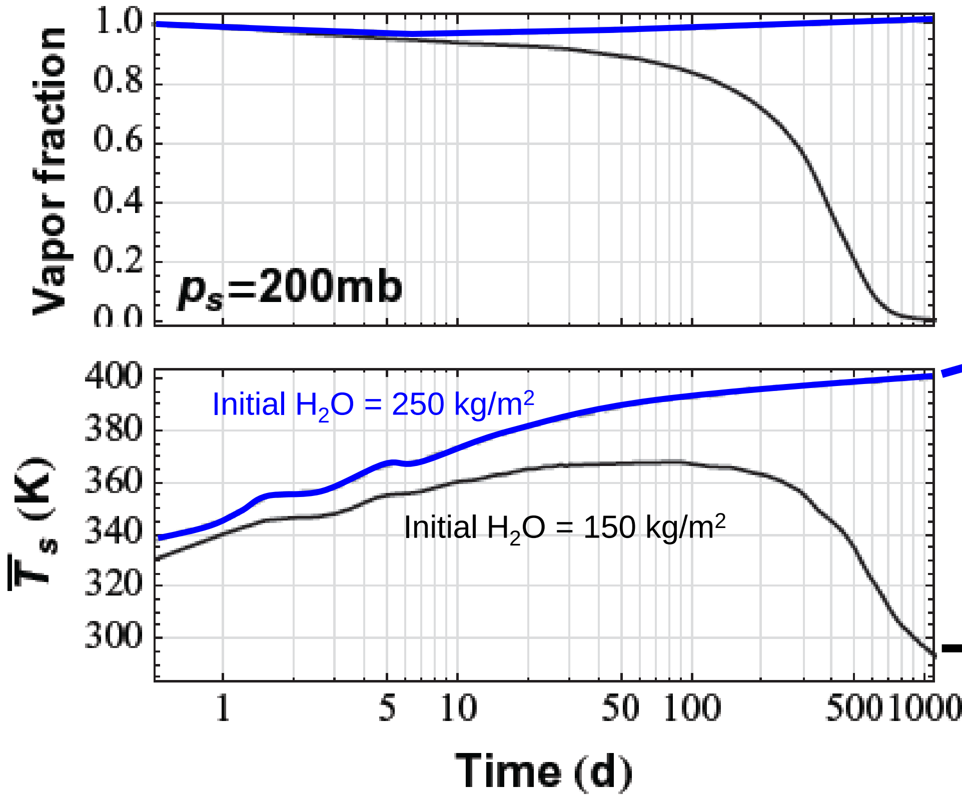
ABSTRACT

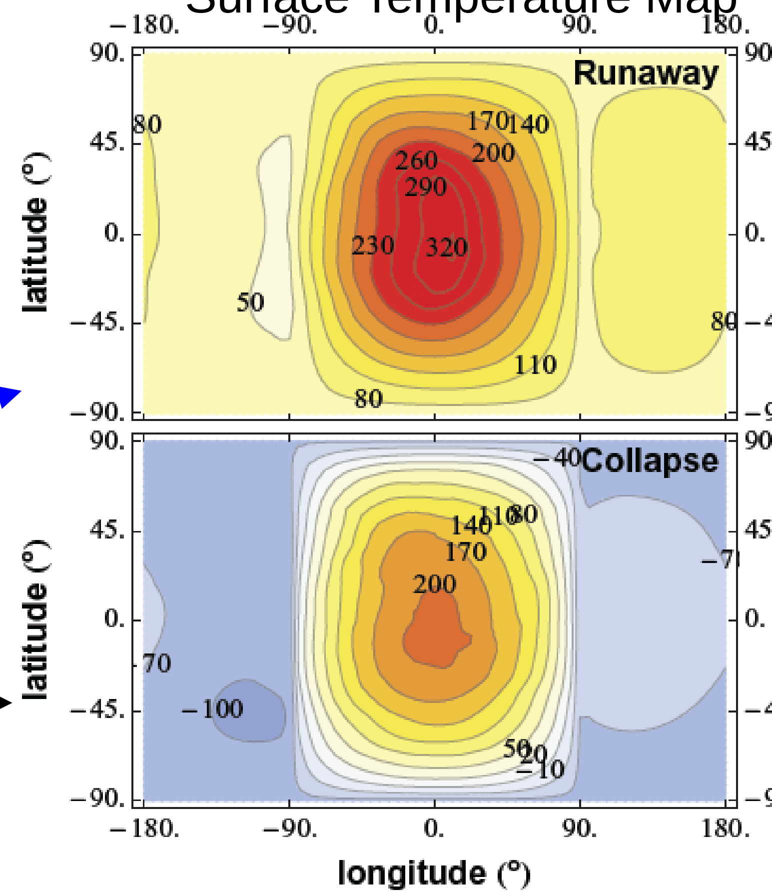
The Habitable Zone (HZ) is the circumstellar region where a planet can sustain surface liquid water. Searching for terrestrial planets in the HZ of nearby stars is the stated goal of ongoing and planned extrasolar planet surveys. Previous estimates of the inner edge of the HZ were based on one dimensional radiative–convective models. The most serious limitation of these models is the inability to predict cloud behavior. Here we use global climate models with sophisticated cloud schemes to show that due to a stabilizing cloud feedback, tidally locked planets can be habitable at twice the stellar flux found by previous studies. This dramatically expands the HZ and roughly doubles the frequency of habitable planets orbiting red dwarf stars. At high stellar flux, strong convection produces thick water clouds near the substellar location that greatly increase the planetary albedo and reduce surface temperatures. Higher insolation produces stronger substellar convection and therefore higher albedo, making this phenomenon a stabilizing climate feedback. Substellar clouds also effectively block outgoing radiation from the surface, reducing or even completely reversing the thermal emission contrast between dayside and nightside. The presence of substellar water clouds and the resulting clement surface conditions will therefore be detectable with the James Webb Space Telescope.

Tidally locked hot planet: Modeling of Gliese 581c and HD85512b

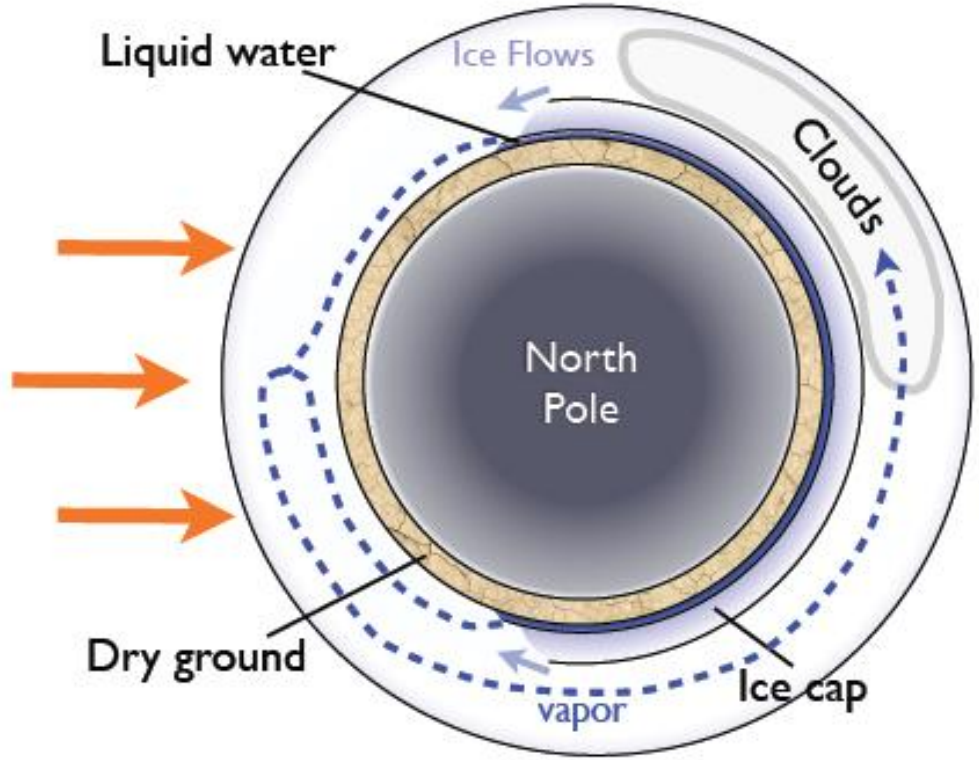
S/4=860 W/m² (**250% Earth flux!**) (*Leconte et al. A&A 2013)*

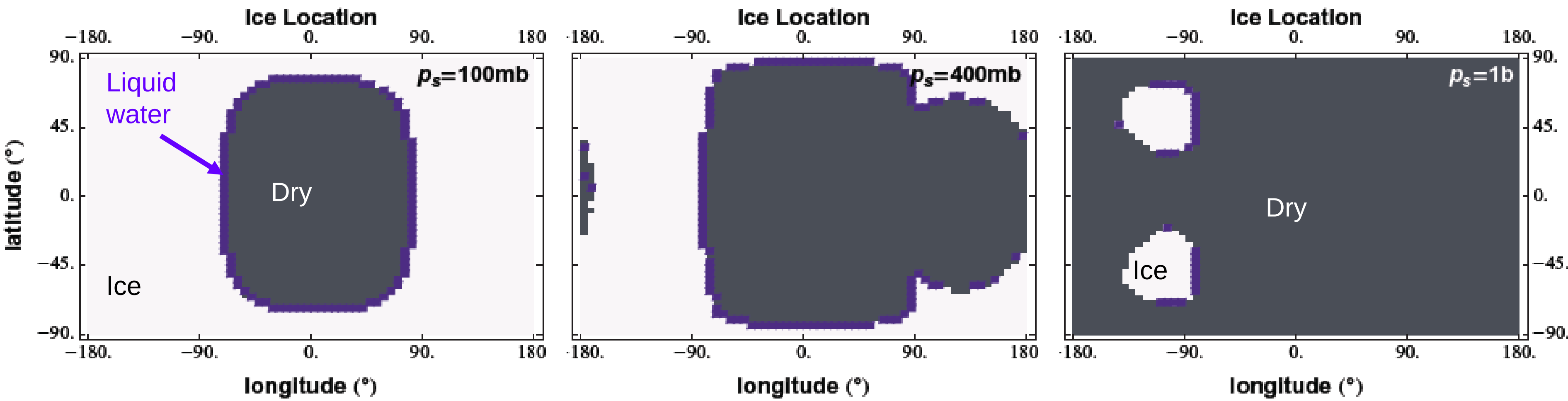
- **A bistable climate**
  - Planet in “runaway greenhouse state” : with all water vapor in the atmosphere : super-hot climate
  - Water collapsed (frozen) on the night side.





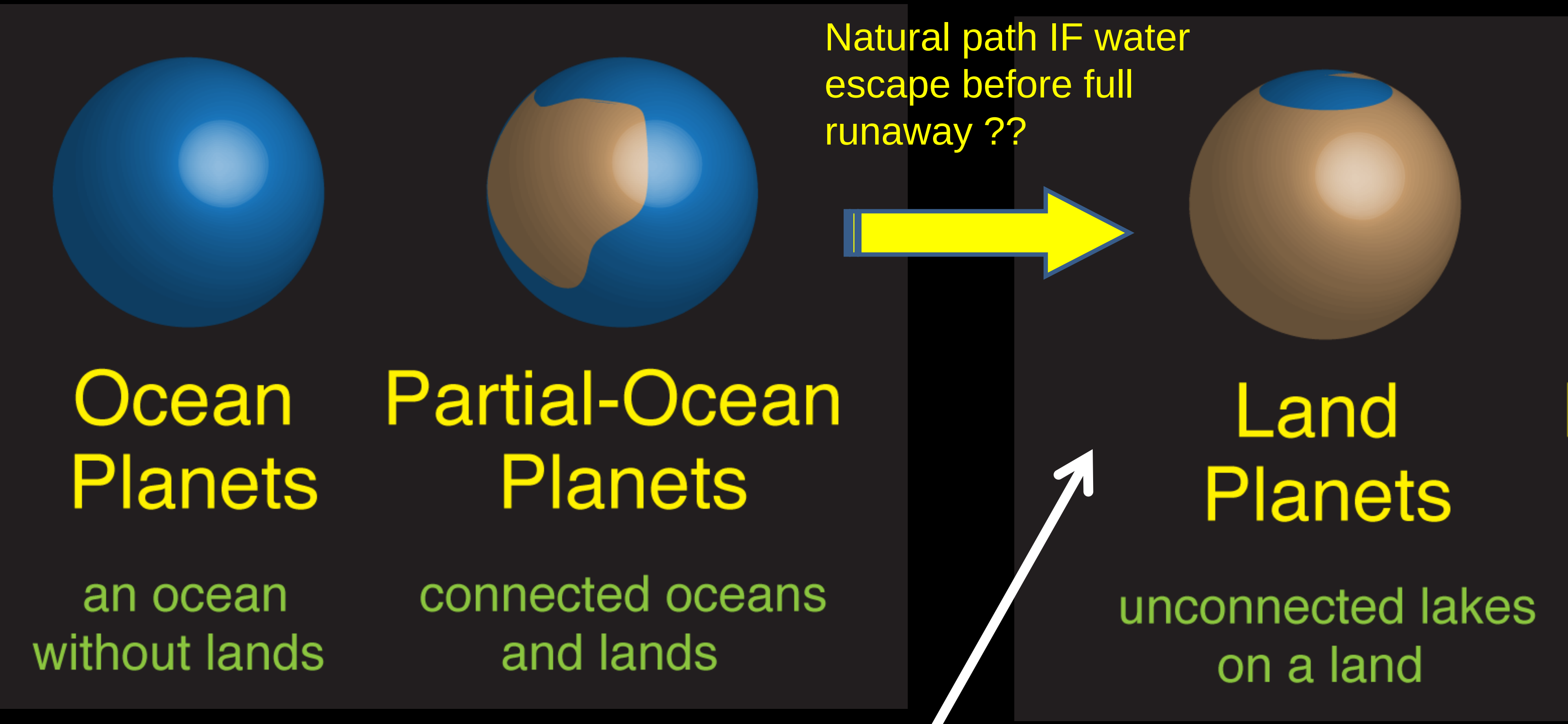
Possibility of liquid water on tidally locked hot planet *(Leconte et al. A&A 2013)*





Climate depends on the amount of available water

(e.g. Abe et al. 2011)



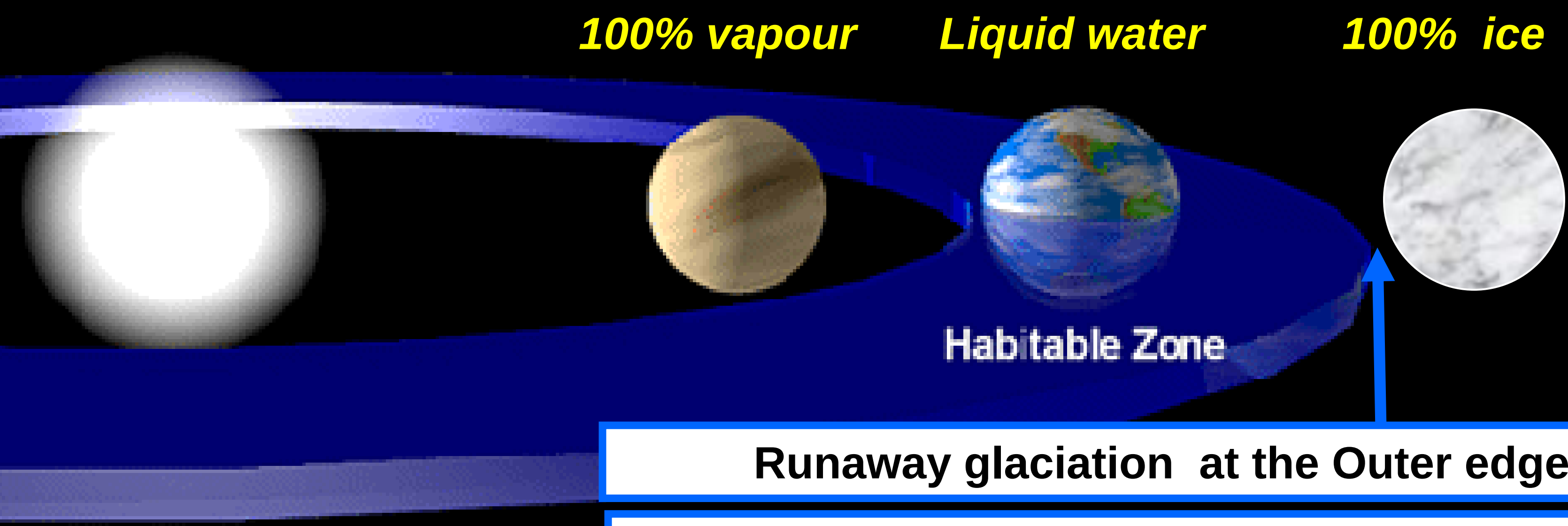
- Runaway greenhouse depends on mean insolation at the edge of the polar sea (cold trap)
- « Runaway limit significantly extended »

Sensitivity to atmospheric composition

For moderately thick atmosphere with some water:

- Runaway greenhouse processes dominates
- To first order: runaway limit not very sensitive to atmospheric composition including other greenhouse gases (e.g. *Goldblatt and Watson 2012; Wordsworth and Pierrehumbert 2013*)

Climate at the outer edge of the « surface liquid water » habitable zone.



Runaway glaciation at the Outer edge

Solar flux ↑ → **Temperature ↓**

Temperature ↓ → **Ice and snow ↑**

Ice and snow ↑ → **Albedo ↑**

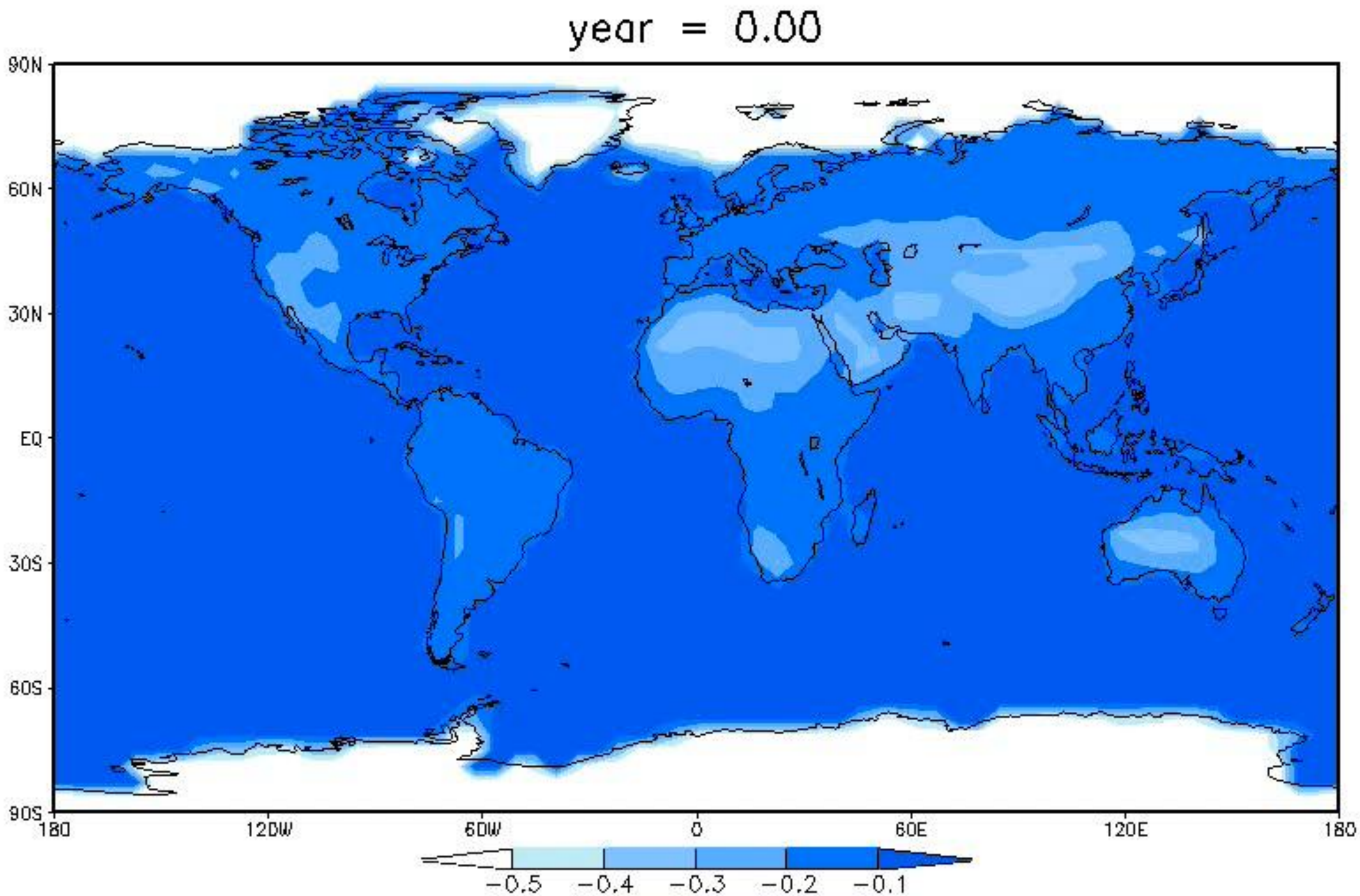
Albedo ↑ → **Temperature ↓**

Climate Modelling: the Earth suddenly moved out by 12%

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

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*

ALBEDO:



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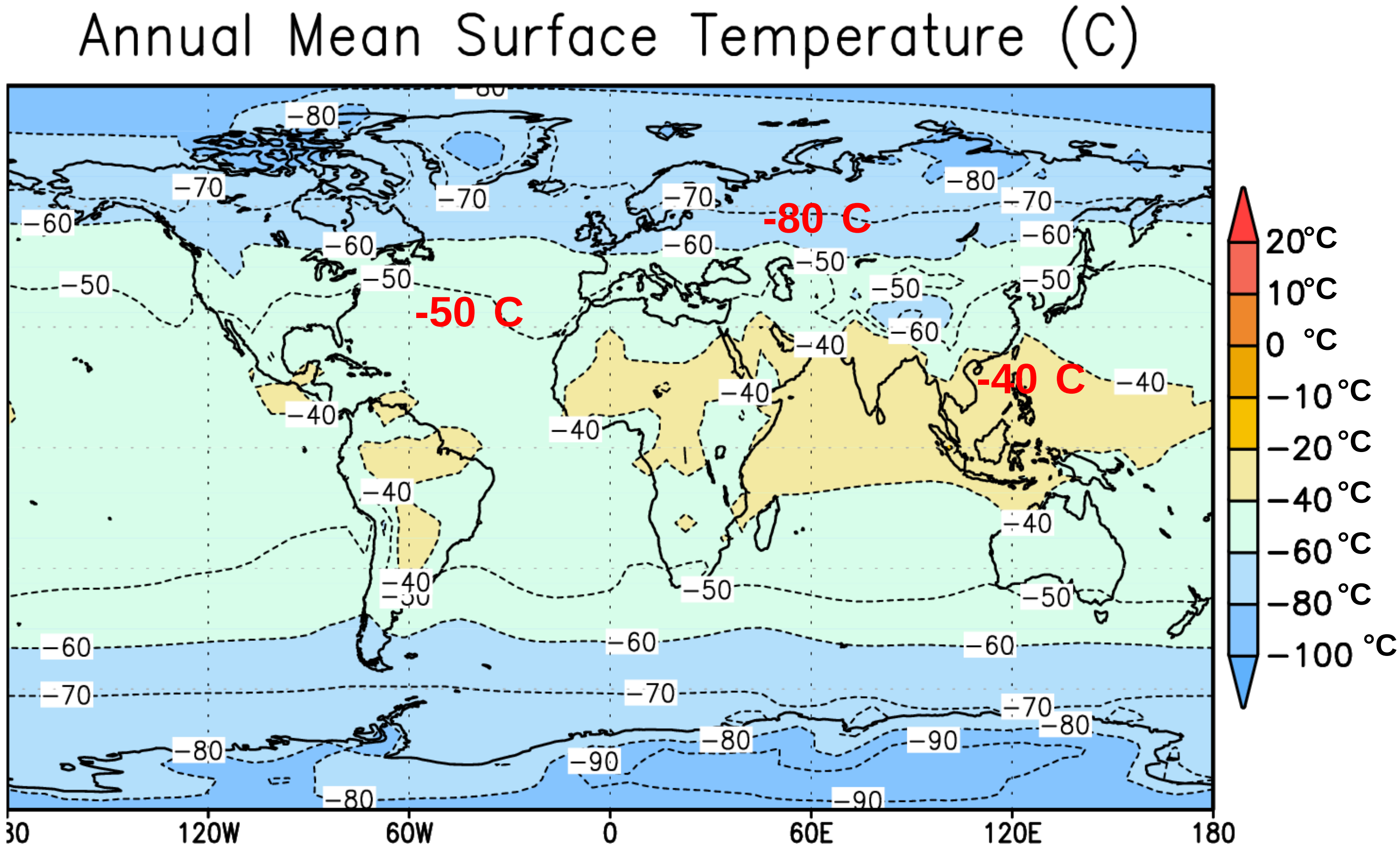
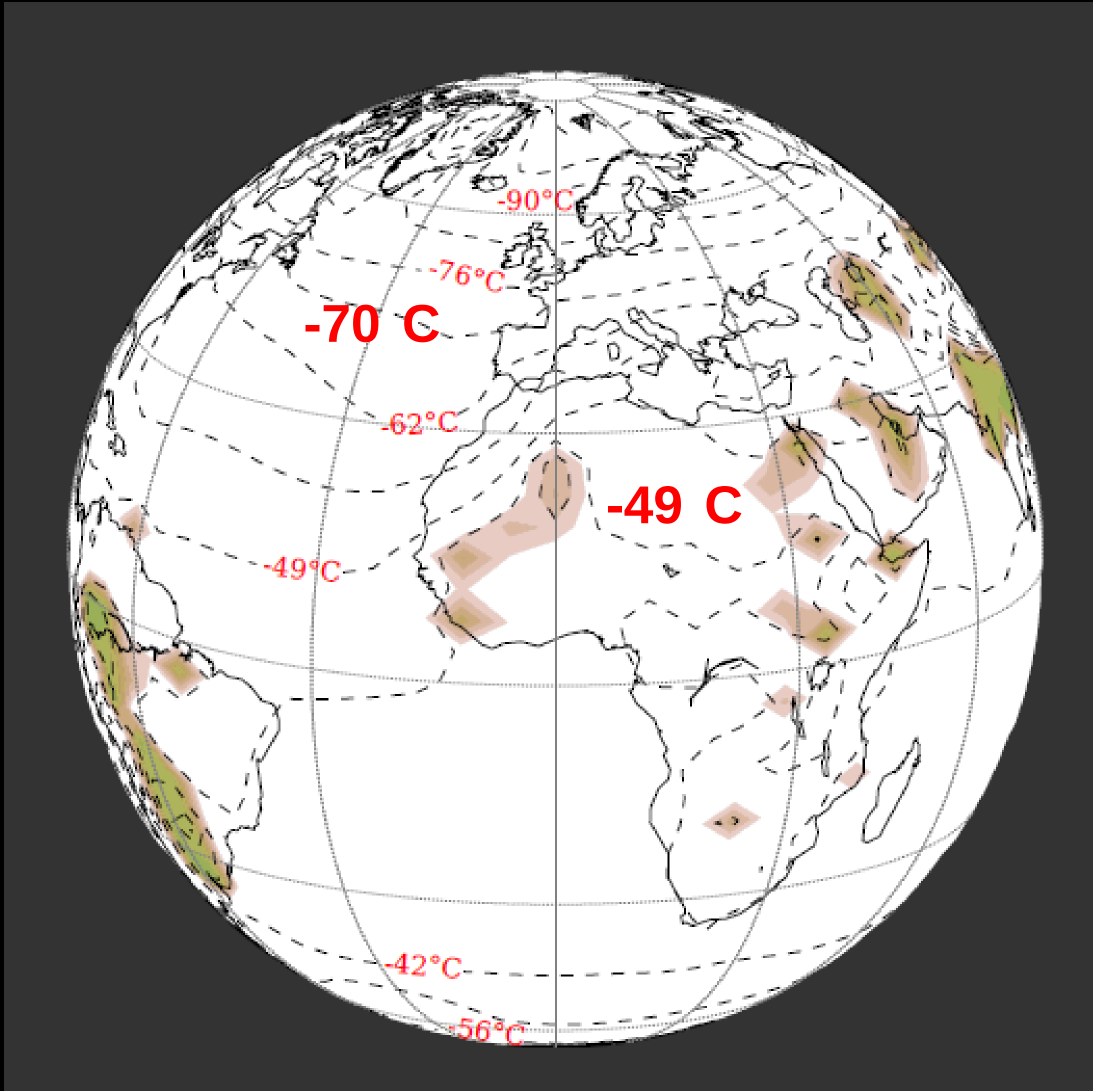


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere

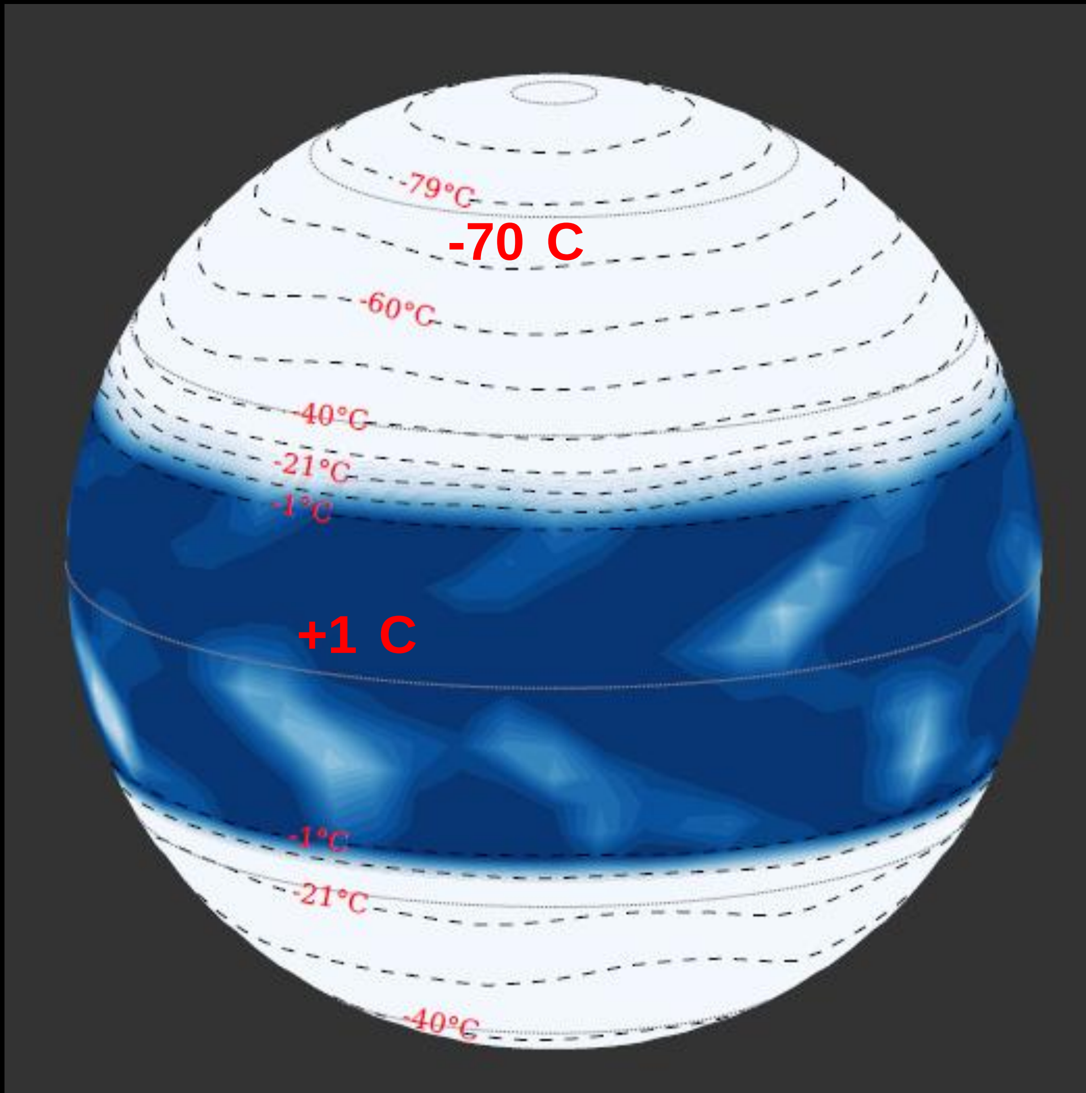


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

$[CO_2]$ x 2.5

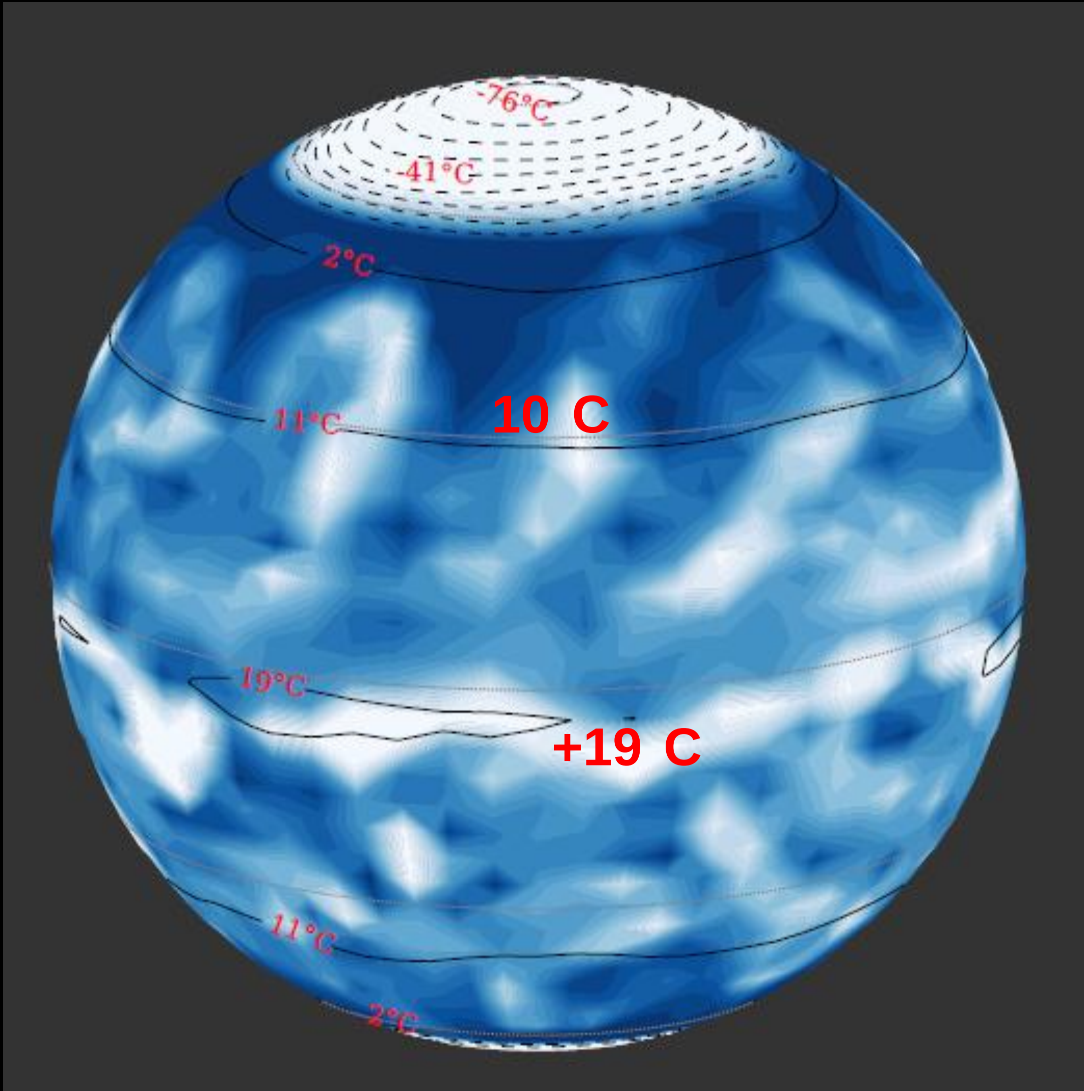


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

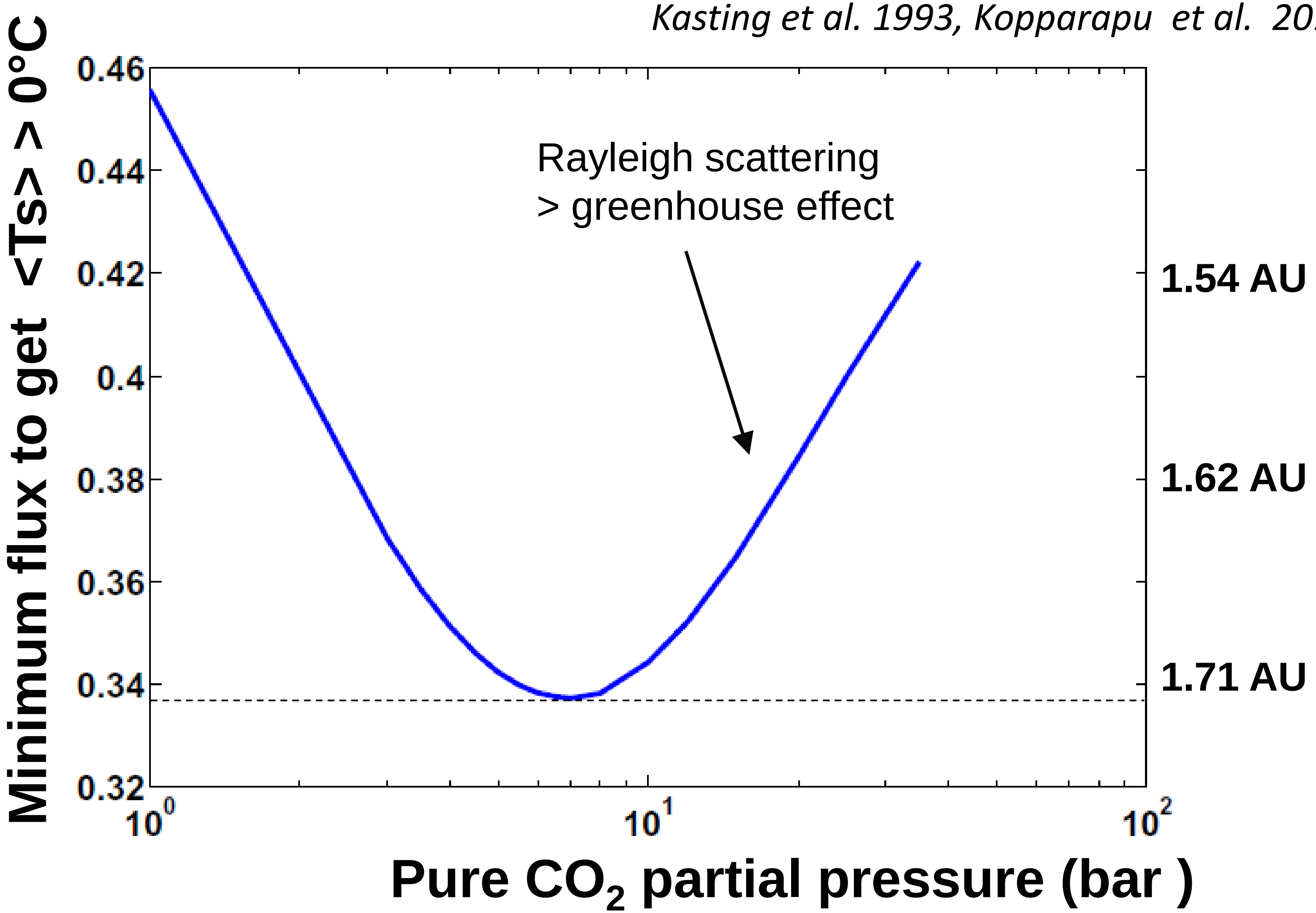
$[CO_2]$ x 250
[CH4] x 1000



Charnay et al., JGR 2013

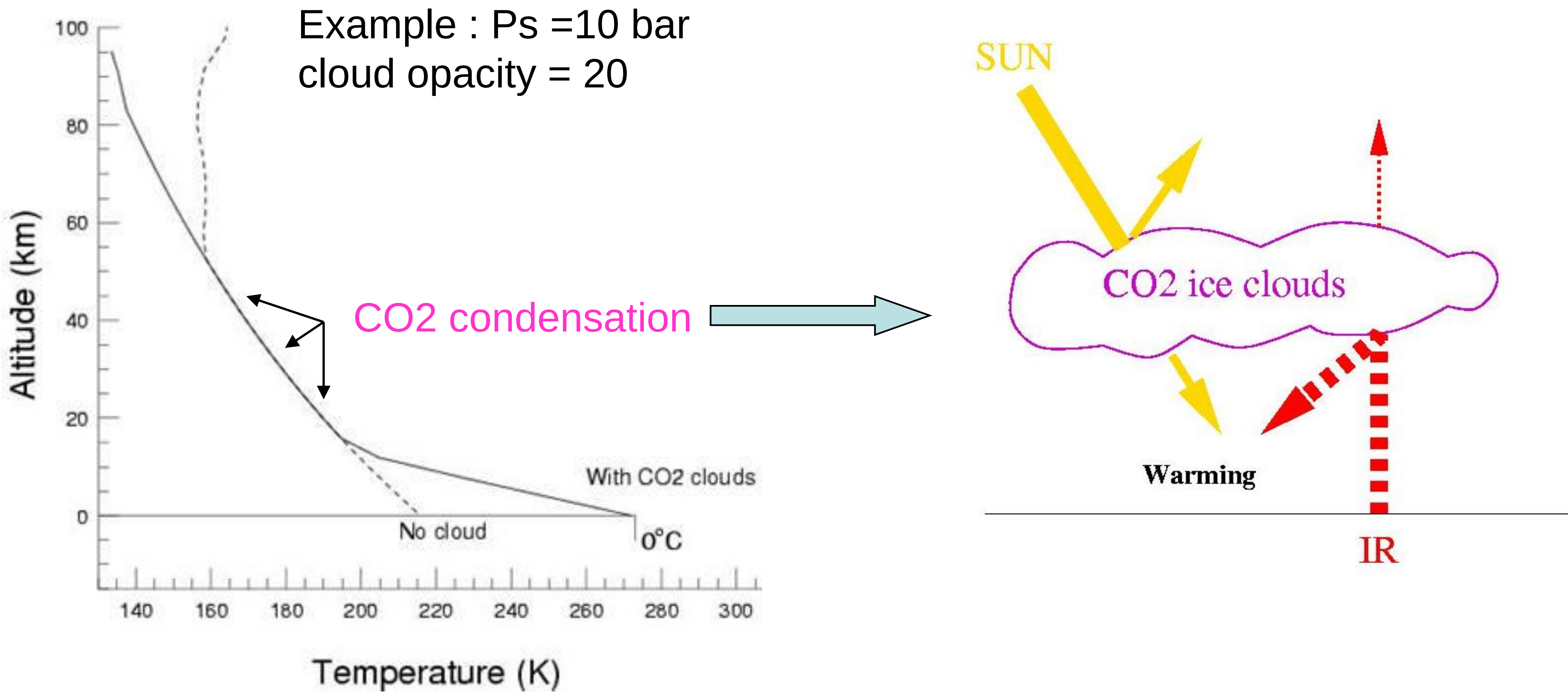
How far can greenhouse effect can keep a planet warm?

Kasting et al. 1993, Kopparapu et al. 2013

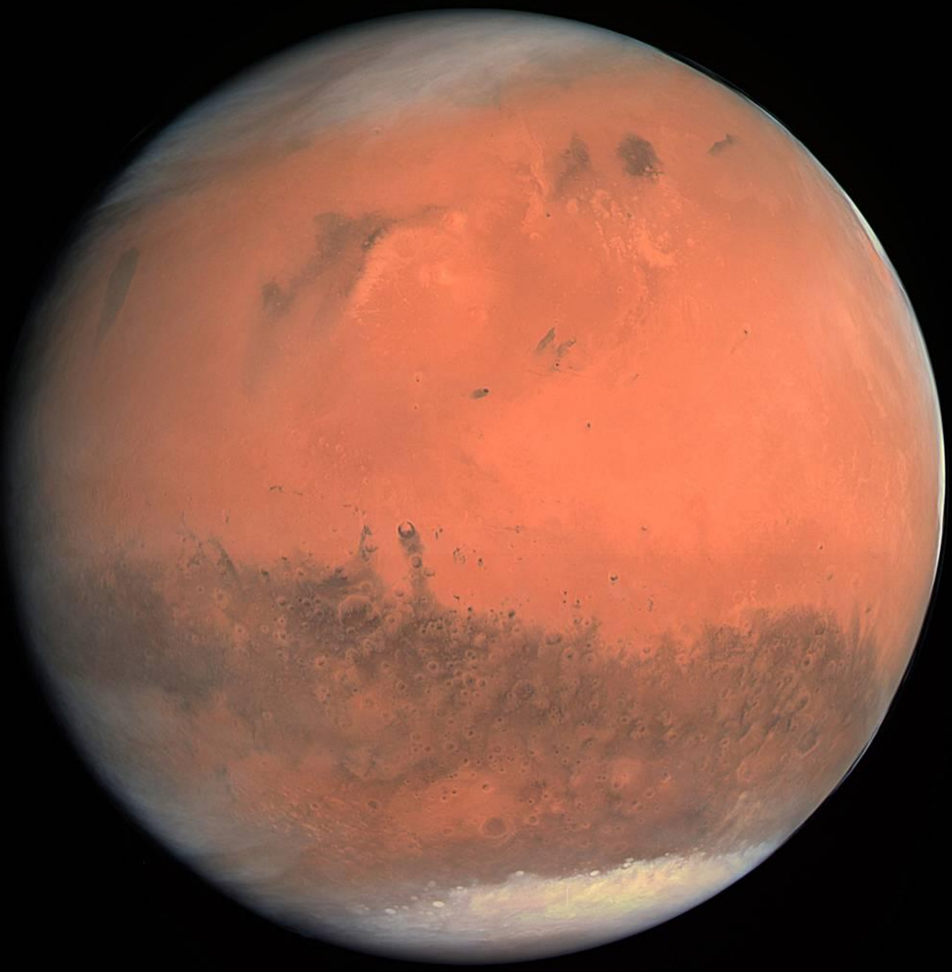


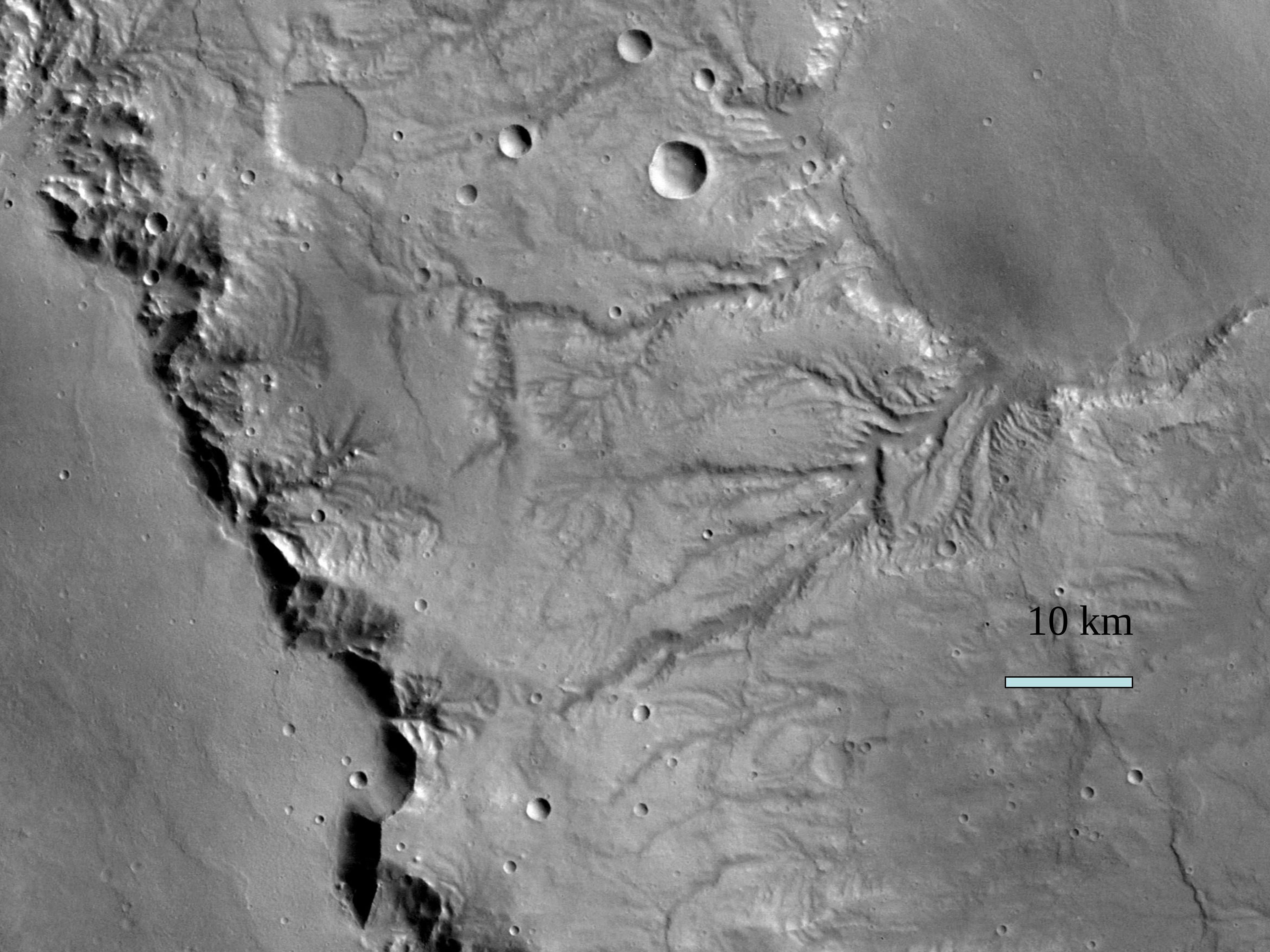
Scattering Greenhouse effect of CO_2 ice clouds
⇨ 0°C as far as 2.5 AU from the Sun ?

Forget and Pierrehumbert (1997)



MARS




10 km

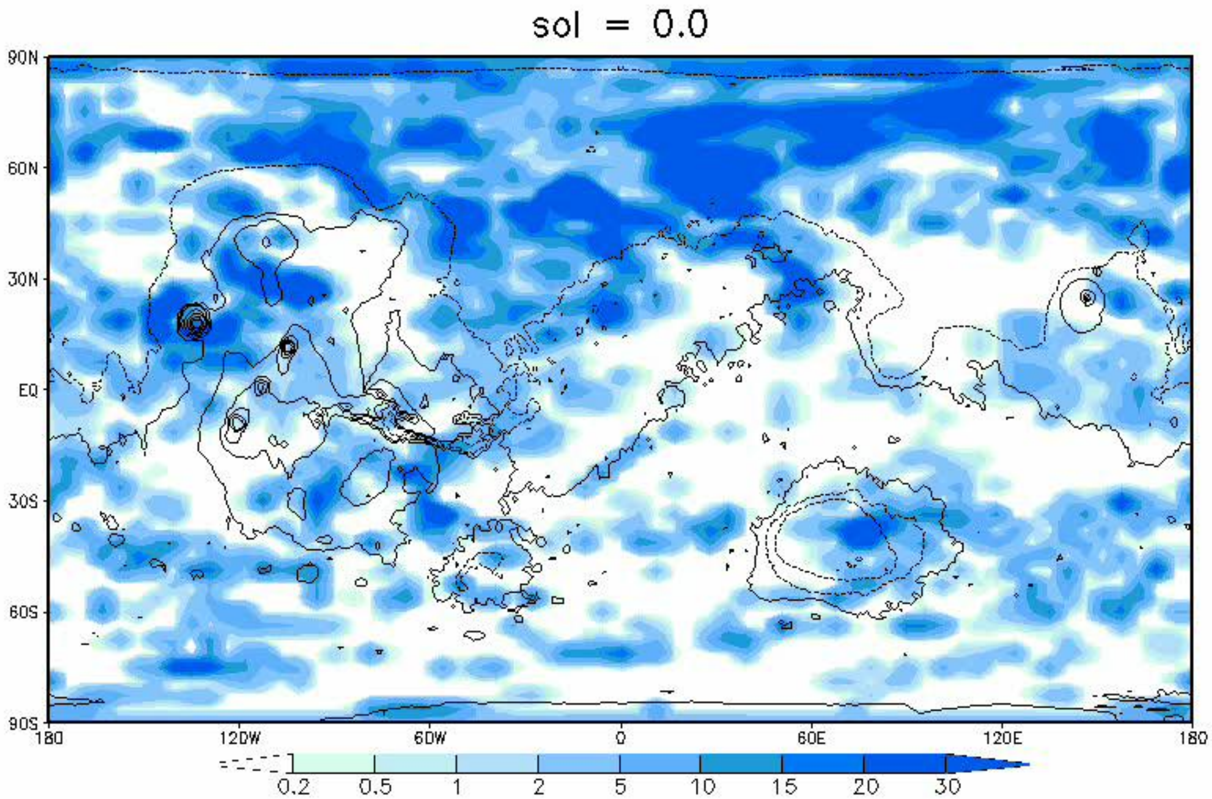
Ancient deltas

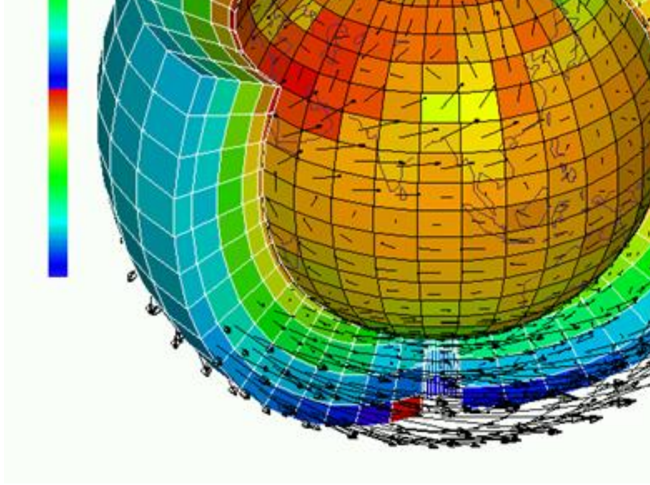
Mars 4 billions years ago ?

(distance to the Sun equivalent to 1.75 UA ; 34% Earth flux)

3D Global climate simulations of Early Mars

(distance equivalent to 1.75 UA)



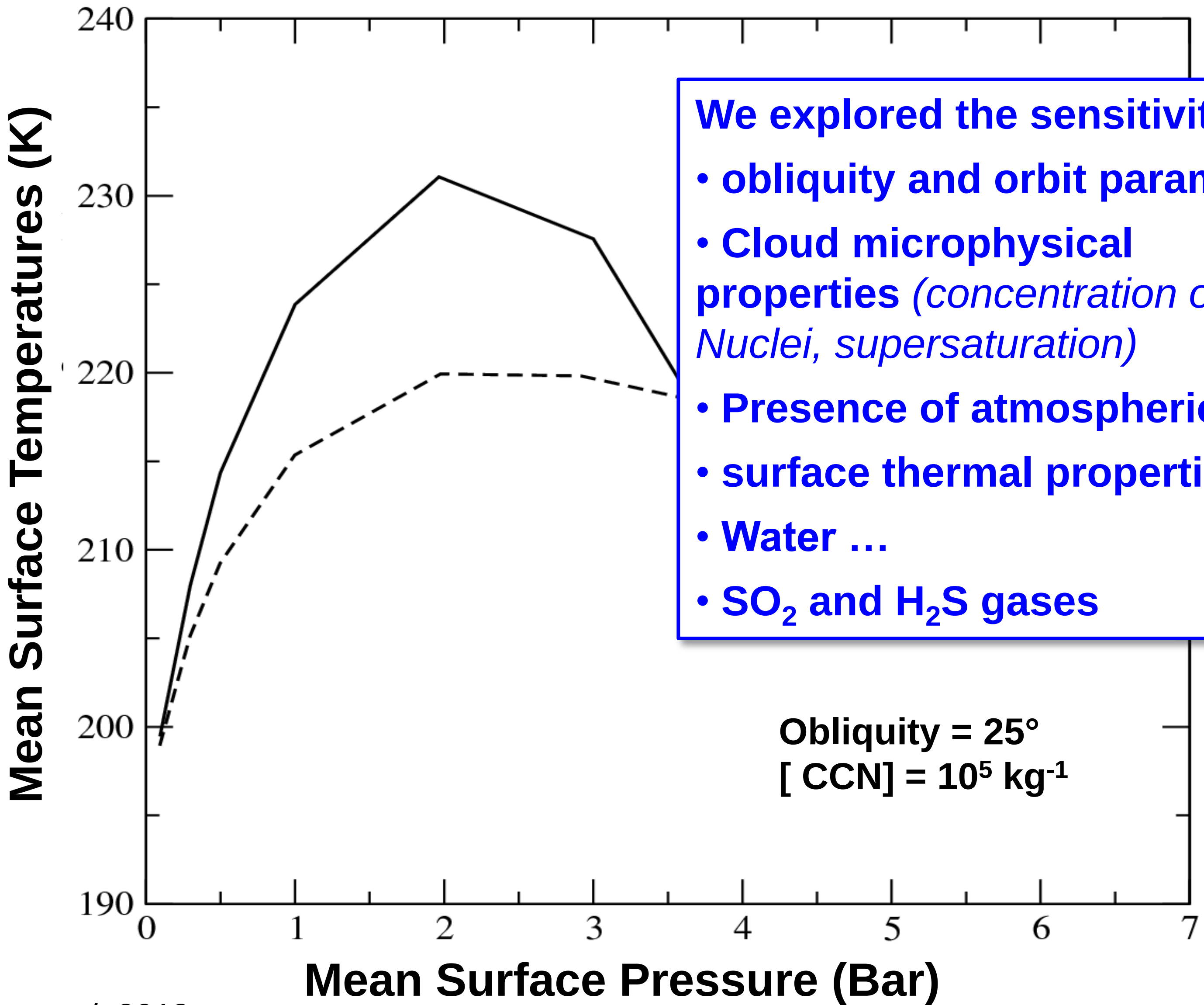


Forget and Pierrehumbert 1997

CO2 ice Cloud optical depth

Forget et al. Icarus 2013,
Wordsworth et al. Icarus 2013

Simulated Global mean surface temperature (K)



We explored the sensitivity to

- **obliquity and orbit parameters**
- **Cloud microphysical properties** *(concentration of Nuclei, supersaturation)*
- **Presence of atmospheric dust**
- **surface thermal properties**
- **Water …**
- **SO_2 and H_2S gases**

Forget et al. 2013

Glaciation around K & M dwarf stars:

Redder stellar spectrum

- No albedo water ice feedback *(Joshi and haberle, 2012)*
- Weak atmospheric Rayleigh Scaterring

  ➩ higher albedo

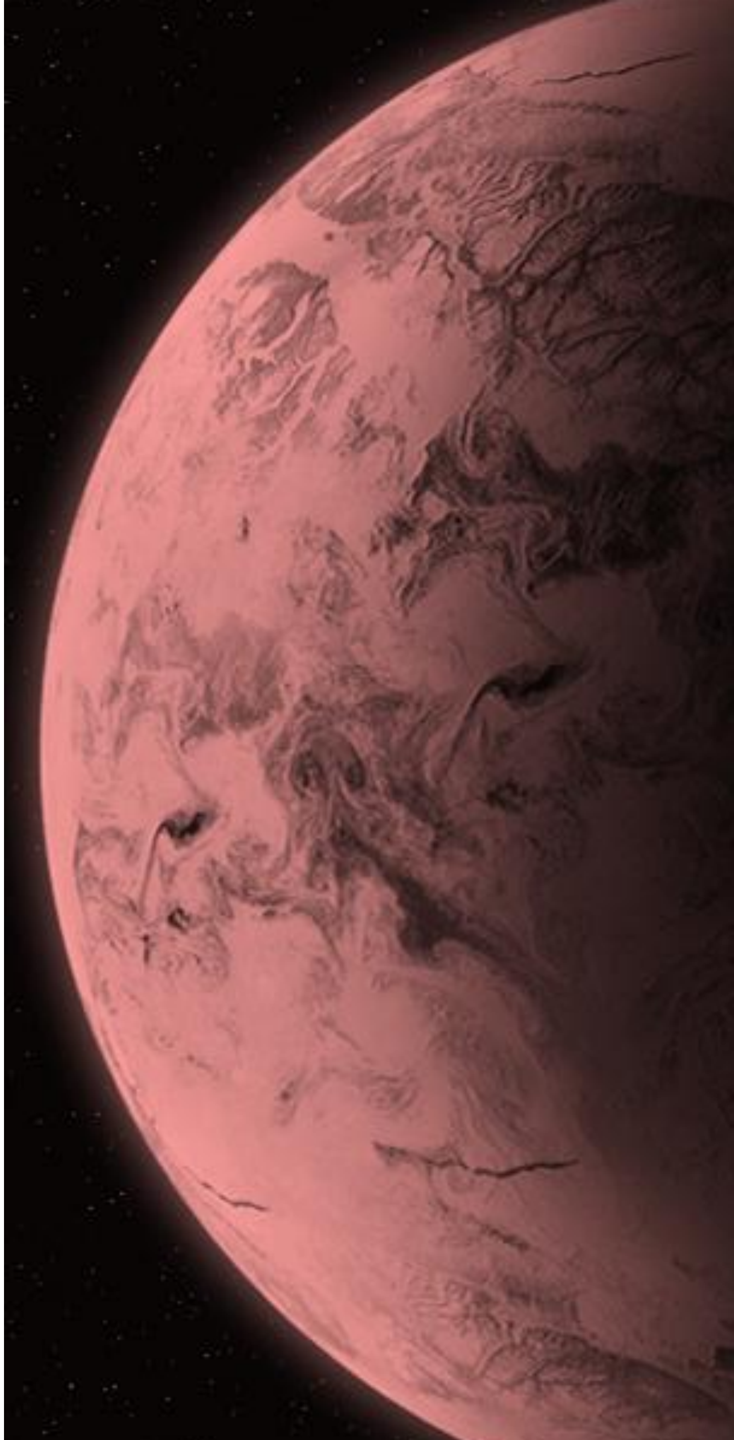
  ➩ Enhanced high pressure CO2 greenhouse effect

But : Effect of tides on rotation:

- Resonnant rotation with zero obliquity

➩ No insolation at the pole

➩ Possible Locking with permanent night side

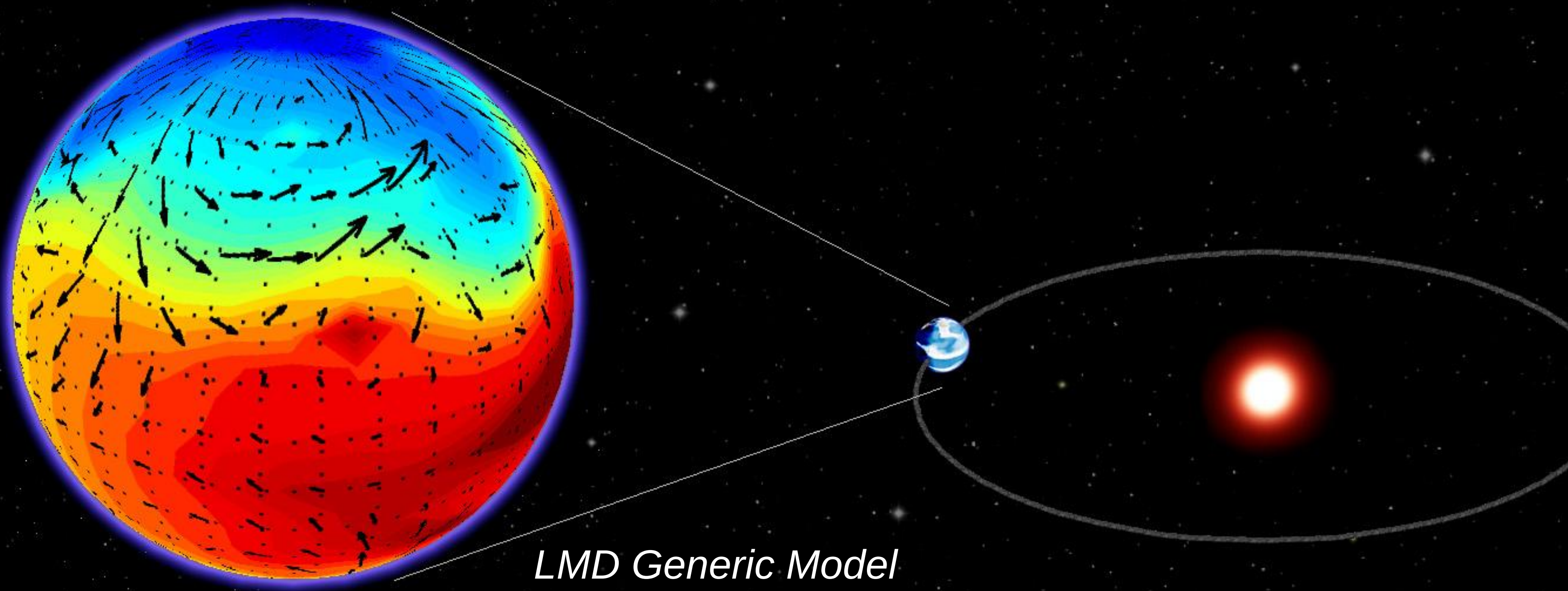


An example of application : Exoplanet Gliese 581d

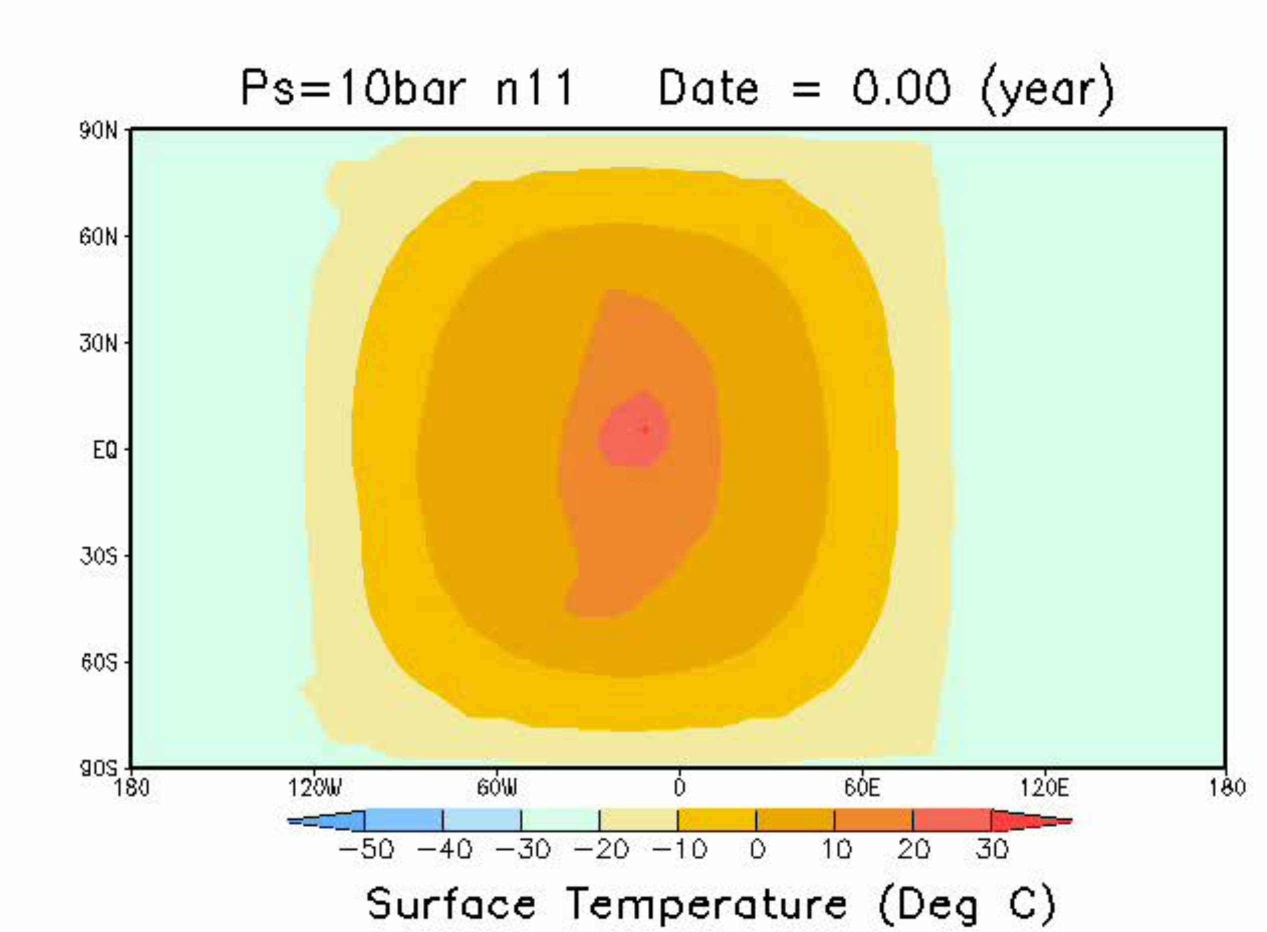
Super-Earth? : M sin*i* $\approx$ 7 M_{Earh} around Mdwarf (0.31 Msun)

Incident Stellar flux = 27% flux on Earth (less than Early Mars)

"Gliese 581D is the First Discovered Terrestrial-mass Exoplanet in the Habitable Zone", *Wordsworth et al.* APJL 733 (2011)

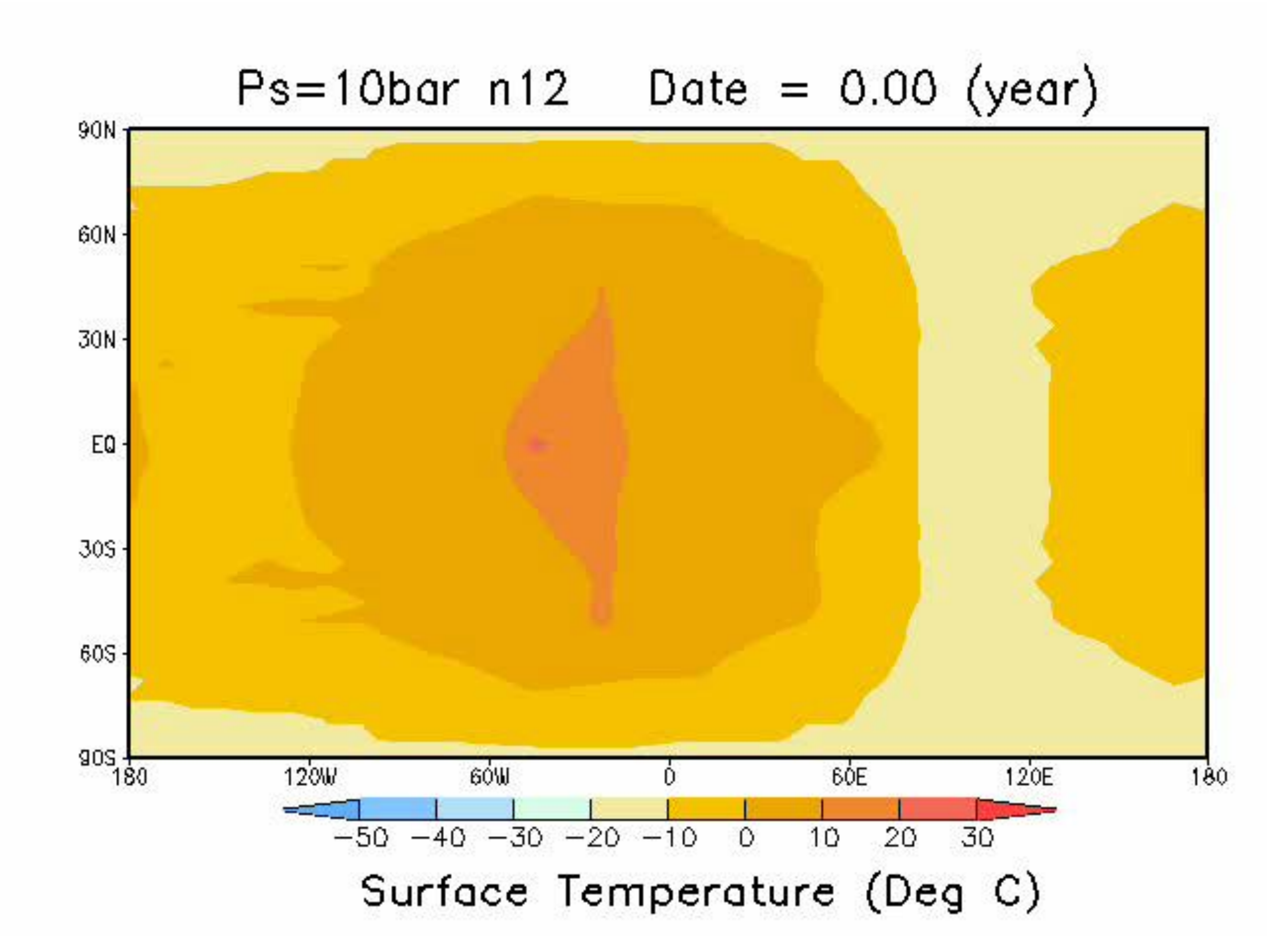


Tidal locked dry Gl581d Ps=10bar
Surface Temperature



Wordsworth et al. 2011

Resonnant 2/1 dry Gl581d Ps=10bar
Surface Temperature



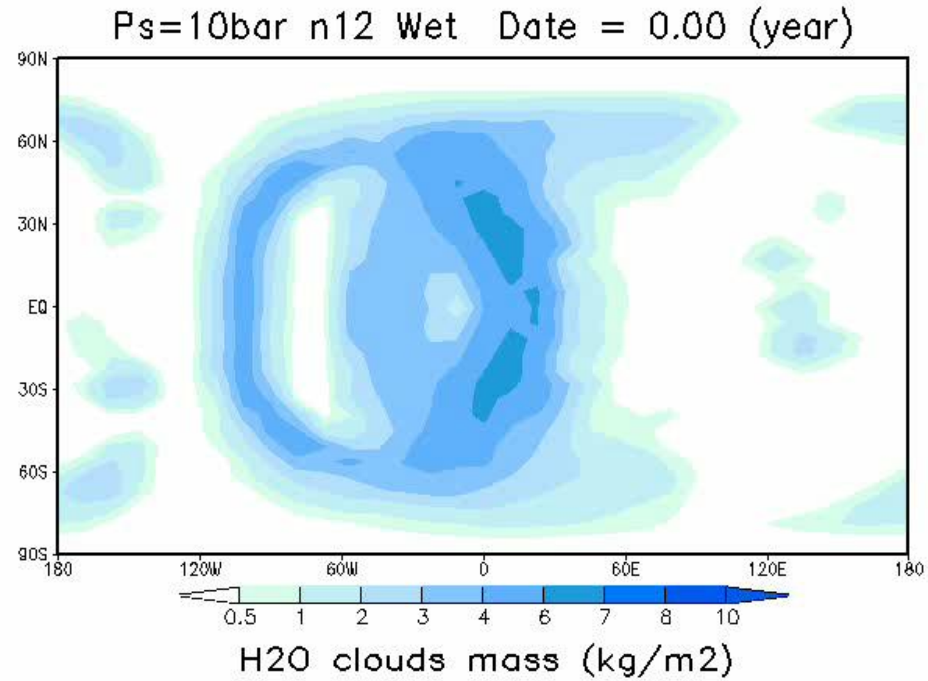
Wordsworth et al. 2011

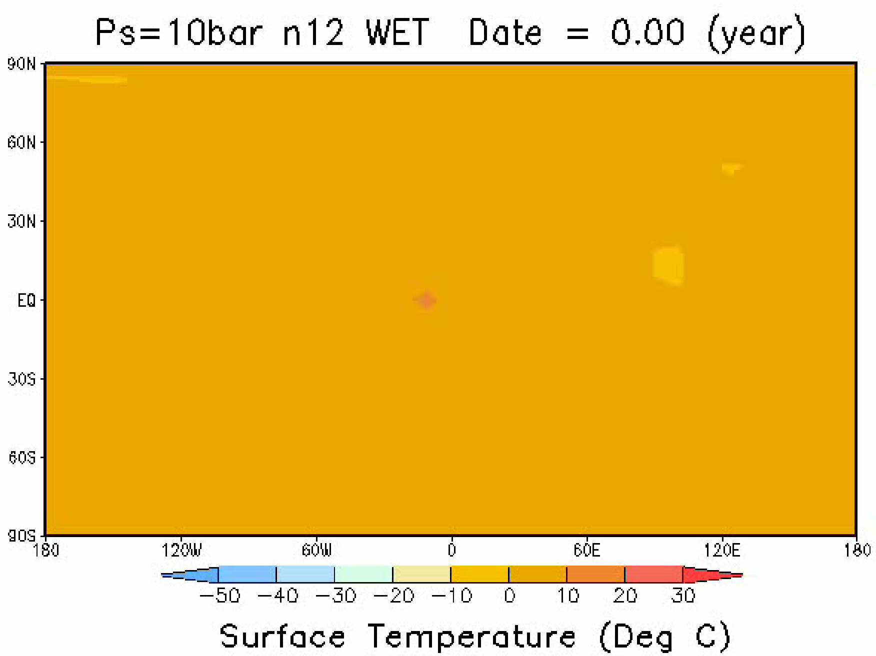
Assuming an ocean planet

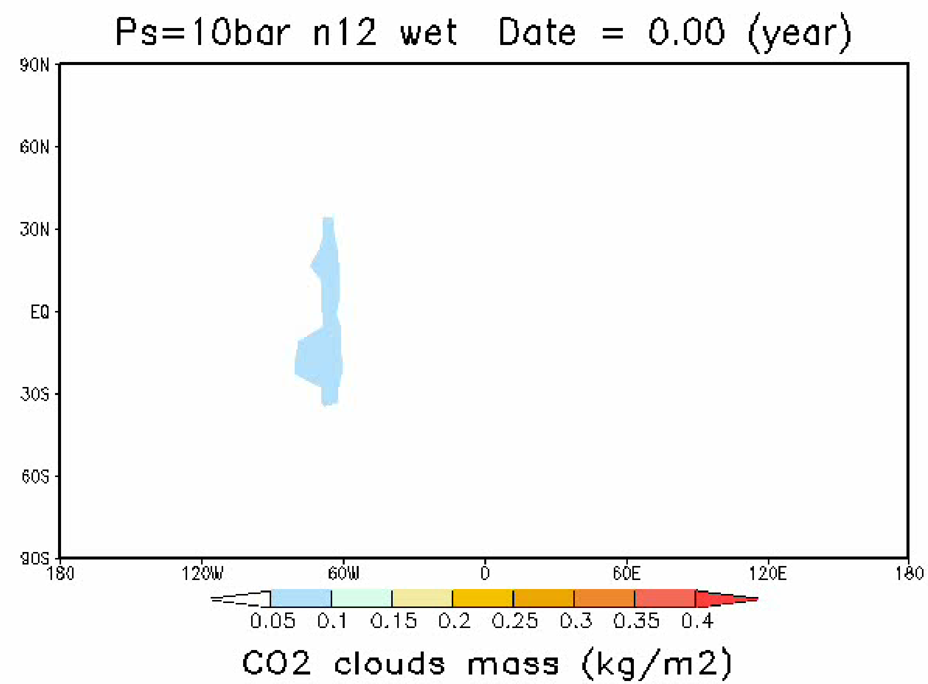
Water clouds

CO2 ice clouds

Surface temperature (K)

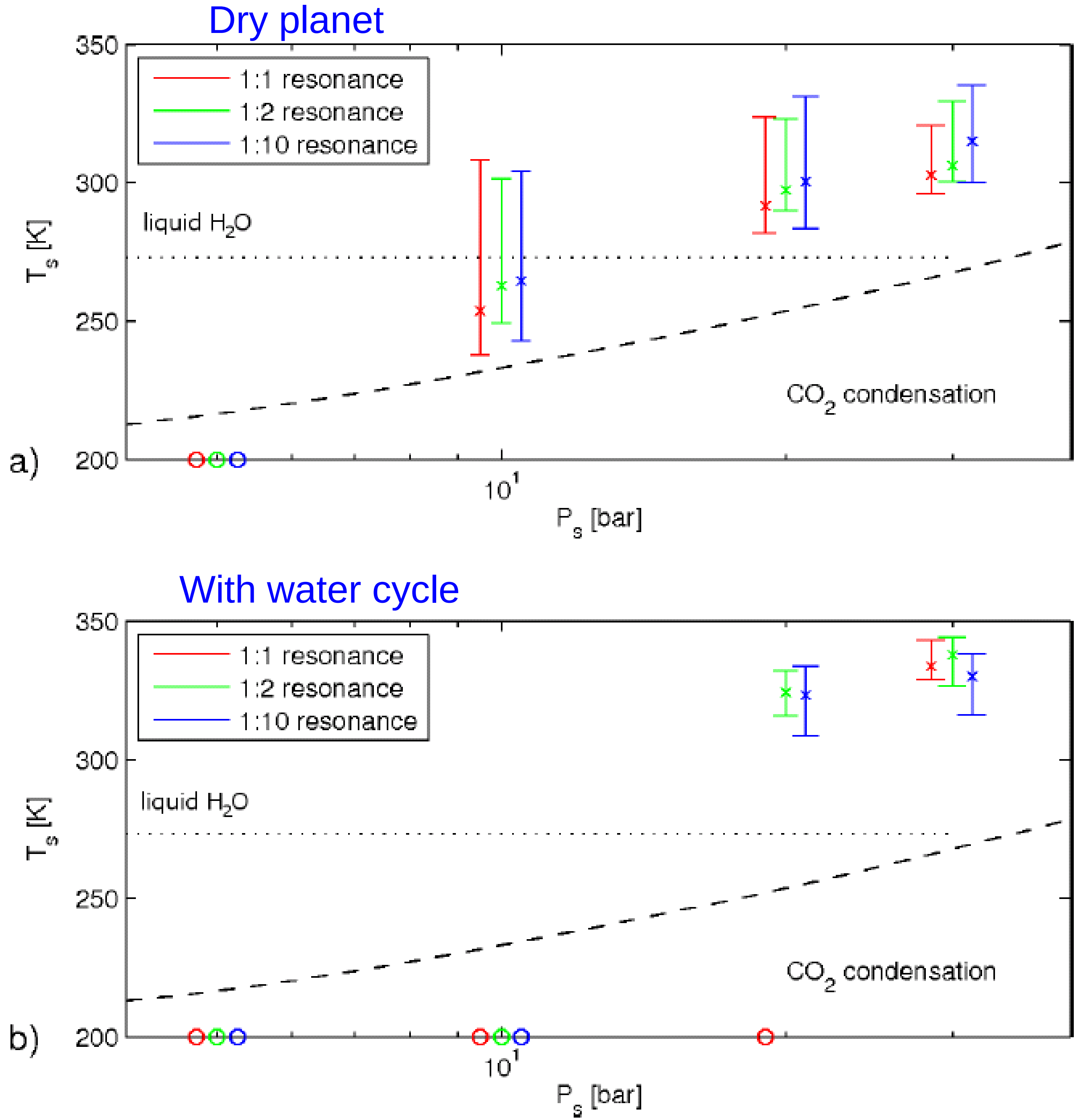






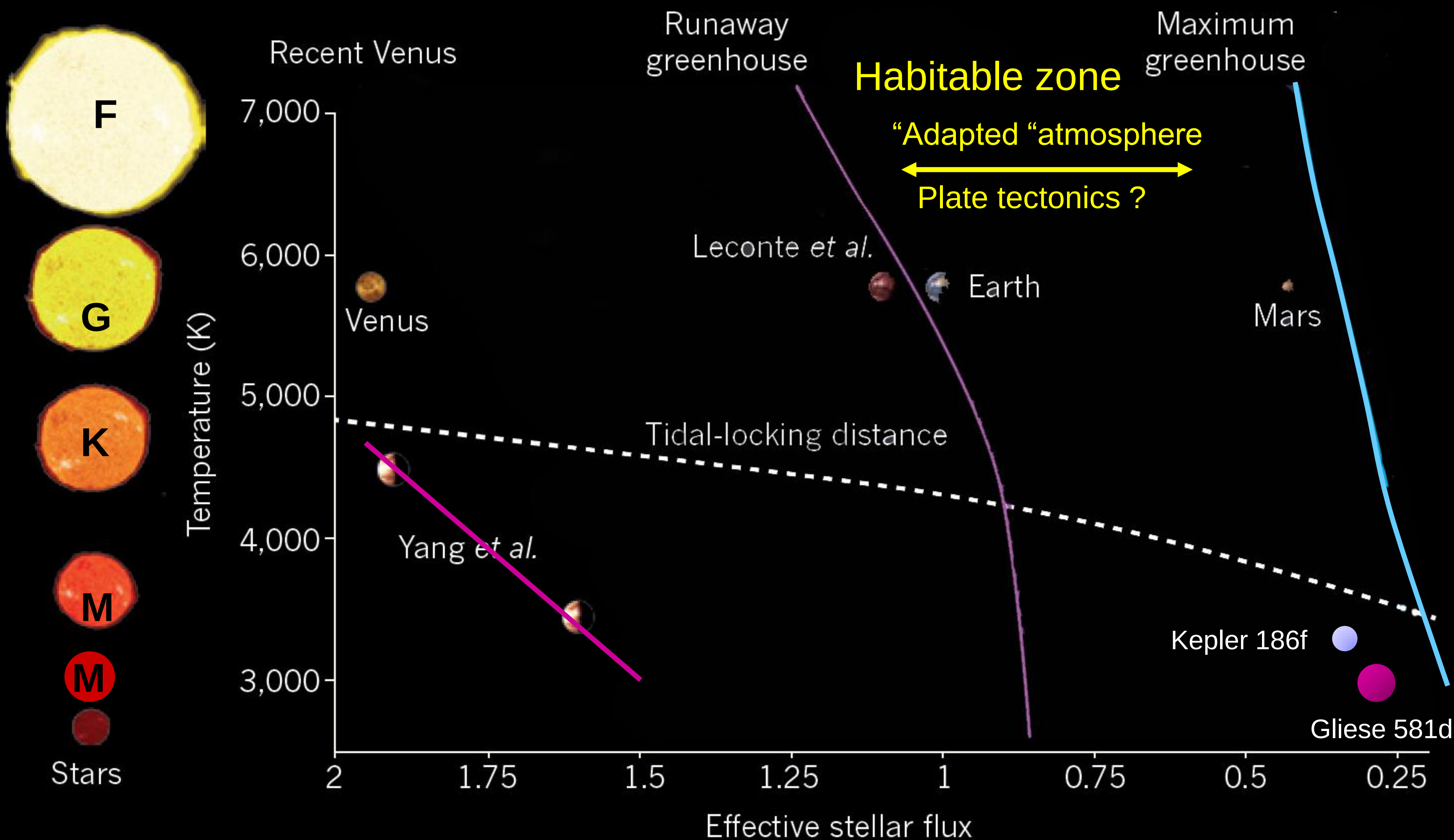
Gliese 581d: conclusions

Assuming enough CO2 and H2O (which is not unlikely), Gliese 581d WOULD be habitable.
The first discovered planet in the Habitable zone!



Wordsworth et al. 2011

Toward a better understanding of the habitable zone with full climate models…



Adapted and modified from Kasting and Harman (2013)

Some Conclusions

- Assuming atmosphere/ocean compositions, Global Climate Models are fit to explore the climate of terrestrial exoplanets.
  - 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 :
  - Formation of planets and origin of terrestrial atmospheres
  - Escape to space
  - Interaction with the surface (e.g. plate tectonic)
  - Photochemical evolution

⇨ **We need observations of atmospheres**

⇨ We can learn a lot from atmospheres well outside the Habitable zone

Forget F. *« on the probability of habitable planets » International Journal of Astrobiology (2013)*
Forget and Leconte (2013)*, « Possible climate on terrestrial exoplanets » Phil. Trans. Royal Society. A. (2014)* *(*arXiv:1311.3101)