GLOBAL CLIMATE MODELS APPLIED TO TERRESTRIAL EXOPLANETS

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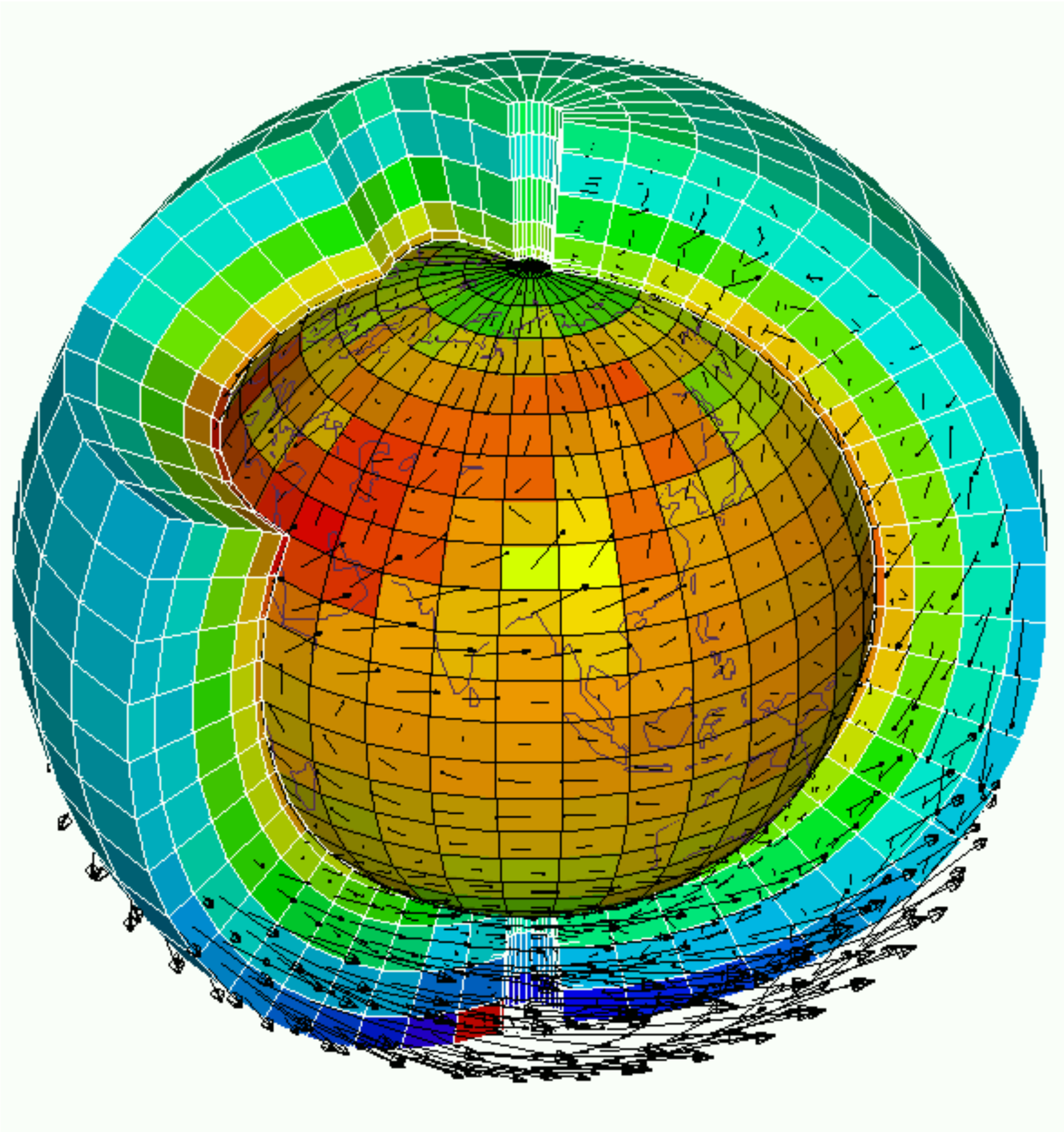
General Circulation Models/ Global Climate models

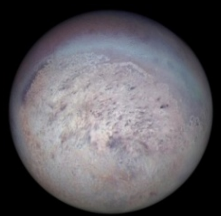
⇒ GCMs



3D Numerical simulators of a planetary environment: designed to simulate the « entire reality »

VENUS

~2 true GCMs
Coupling dynamic & radiative transfer (LMD, Kyushu/Tokyo university)



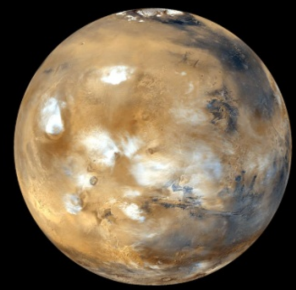
TRITON
1 GCM (LMD)

TERRE

Many GCM teams

Applications:

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

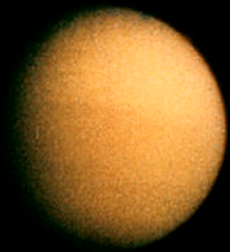


MARS

Several GCMs
(NASA Ames, Caltech, GFDL, LMD, AOPP, MPS, Japan, York U., Japan, etc…)

Applications:

- Dynamics & assimilation
- CO2 cycle
- dust cycle
- water cycle
- Photochemistry
- thermosphere and ionosphere
- isotopes cycles
- paleoclimates
- etc…



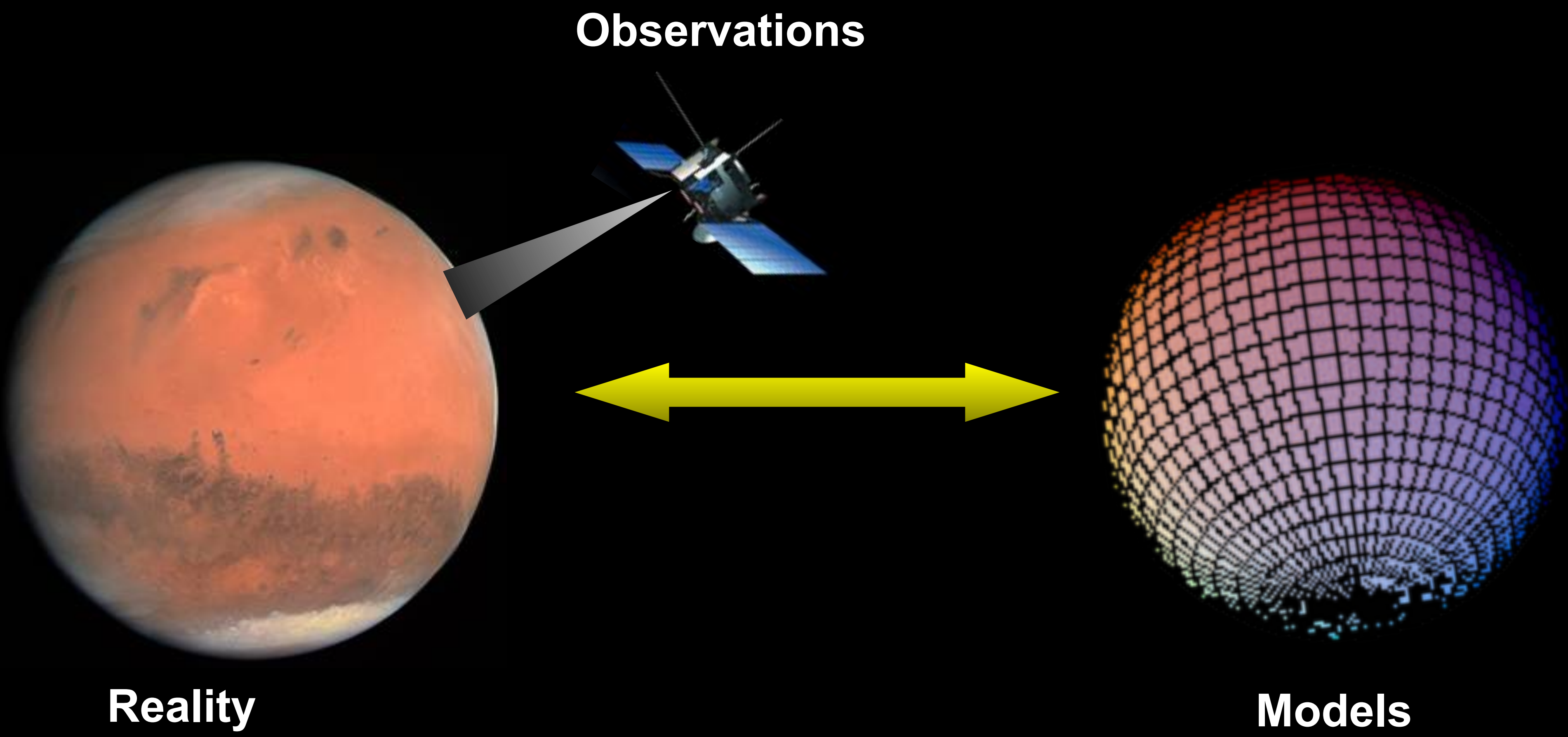
TITAN

~a few GCMs
(LMD, Univ. Od Chicago, Caltech, Köln…)

Coupled cycles:

- Aerosols
- Photochemistry
- Clouds

An ambitious goal : Building virtual planets behaving like the real ones, on the basis of universal equations



How GCM work ? :

The minimum General Circula Model for a terrestrial planet

Most processes can be described by equations that we have learned to solve with some accuracy

1) 3D Hydrodynamical code

⇒ ***to compute large scale atmospheric motions and transport***

2) At every grid point : Physical parameterizations

⇒ ***to force the dynamic***

⇒ ***to compute the details of the local climate***

- **Radiative heating & cooling of the atmosphere**
- **Surface thermal balance**
- **Subgrid scale atmospheric motions**
  - Turbulence in the boundary layer • Convection *•Relief drag* *•Gravity wave drag*
- **Specific process** : ice condensation, cloud microphysics, etc…

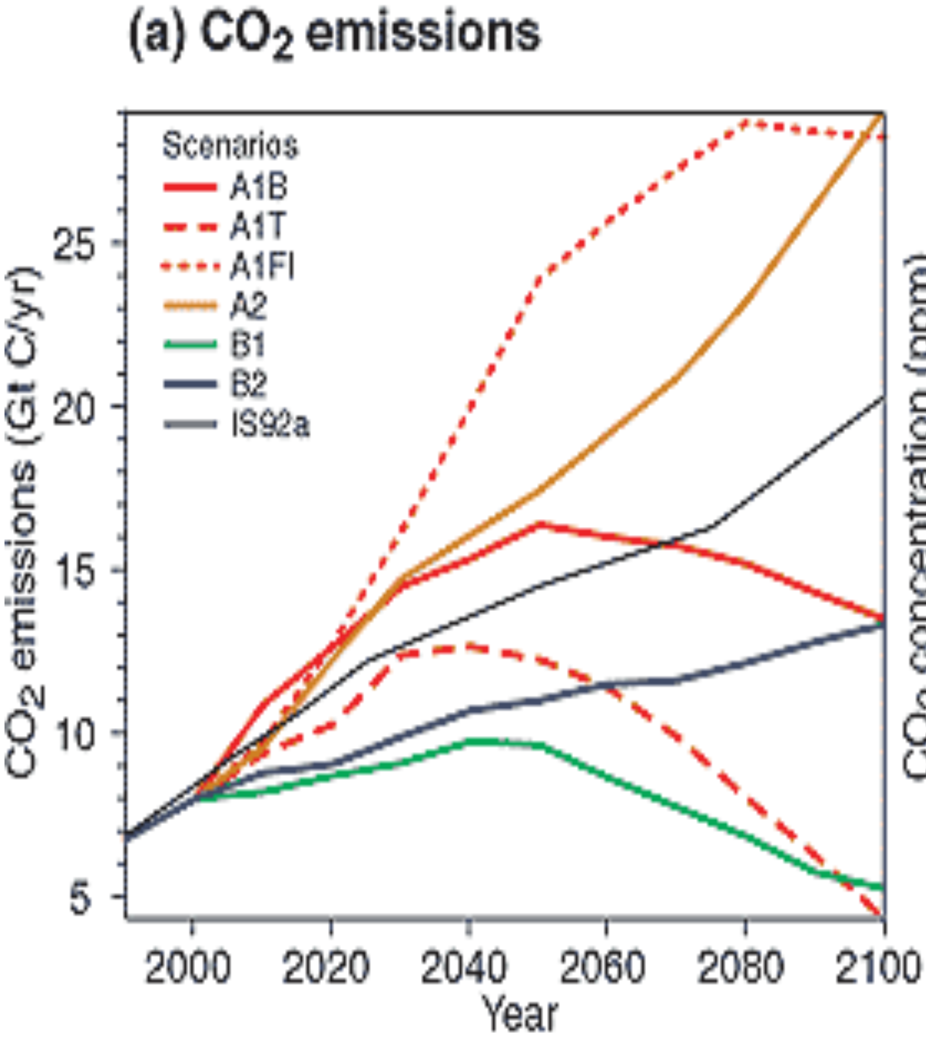
What we have learned from solar system GCMs

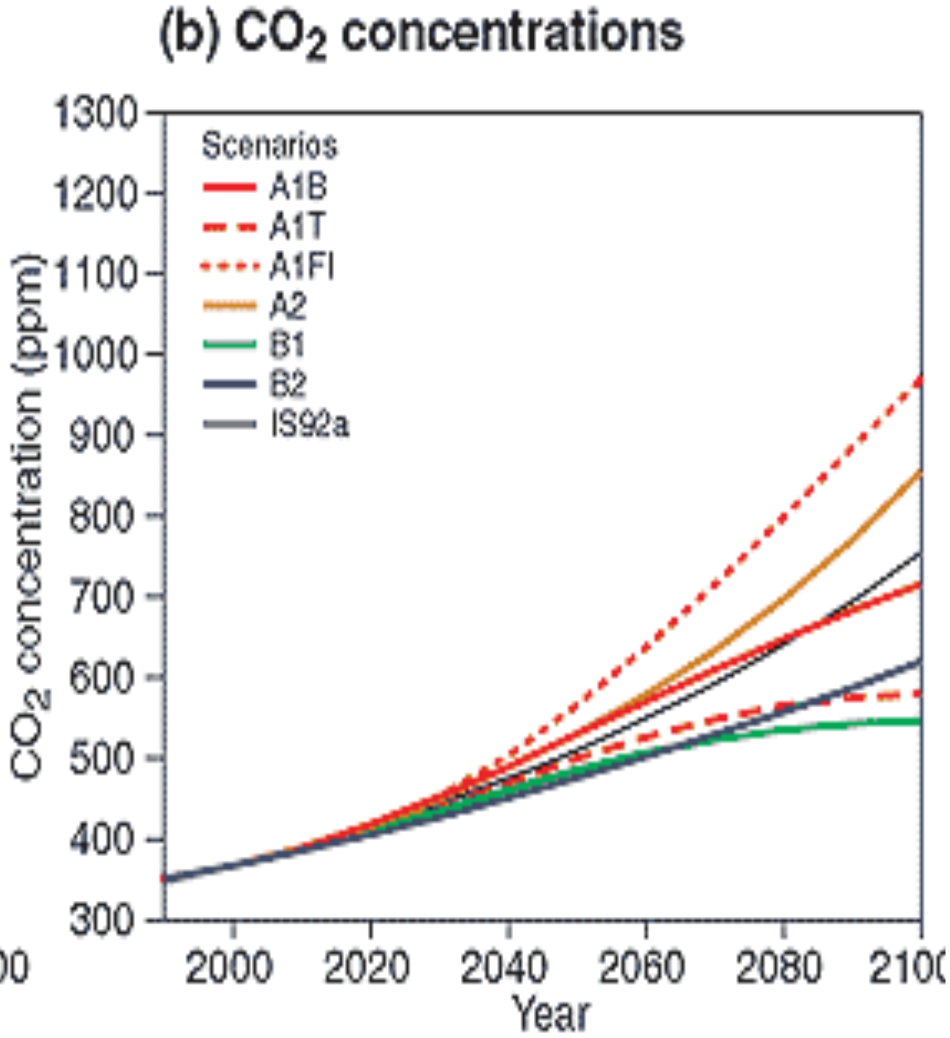
- **To first order**: GCMs work
  - A few equations can build « planet simulators » with a realistic, complex behaviour and strong prediction capacities

- However the devil is in the details:
  - Problems with
    - Negative feedbacks and unstability *(e.g. sea ice and land ice albedo feedback on the Earth)*
    - Non linear behaviour and threshold effect *(e.g. dust storms on Mars)*
    - Complex subgrid scale process and poorly known physics *(e.g. clouds on the Earth)*
    - System with extremely long « inertia » with small forcing *(e.g. Venus circulation).* Sensitivity to initial state

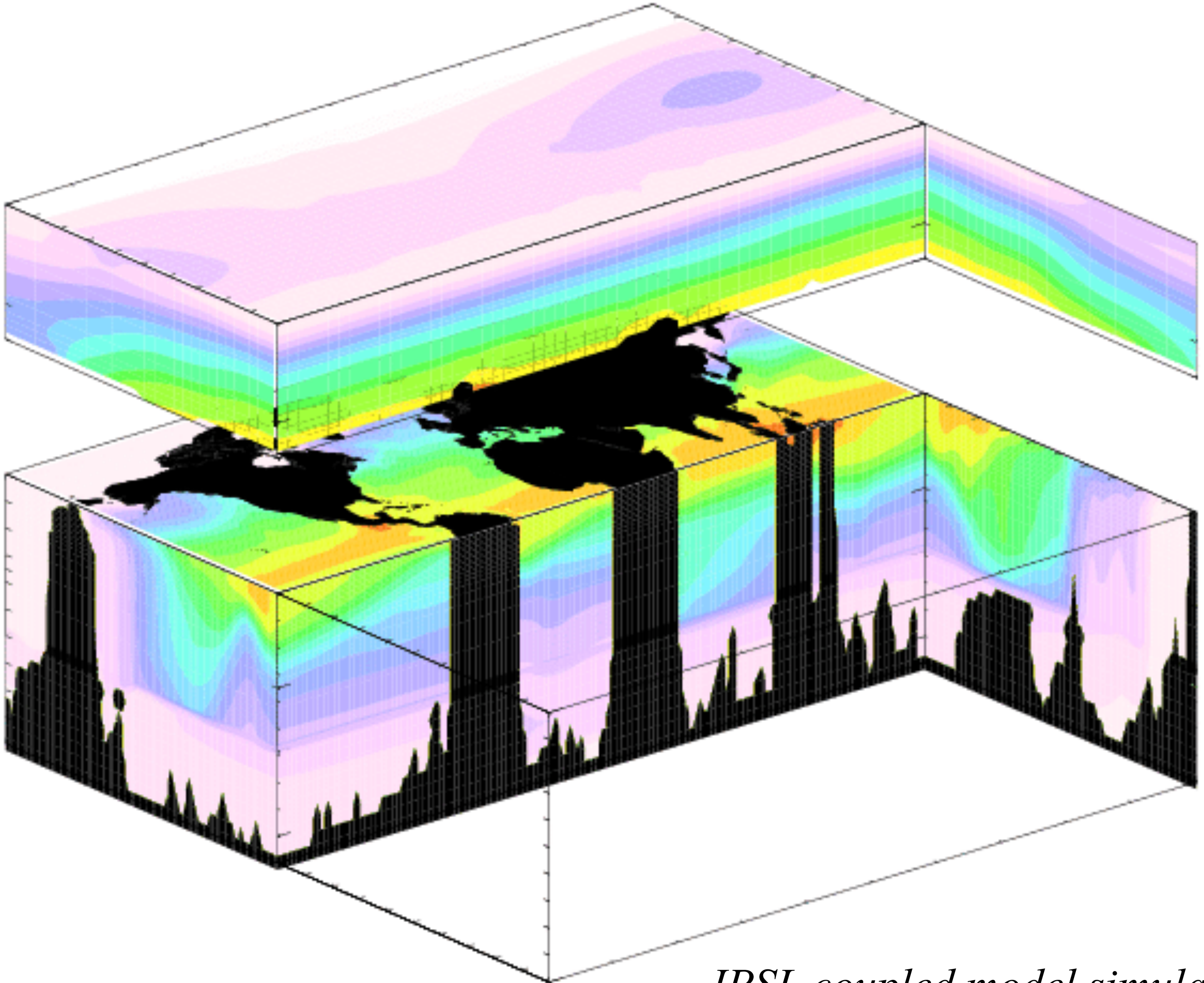
⇨ Need to somewhat « tune » a few model parameters to accurately model an observed planet and predict its behaviour

Simulating the future of the Earth with GCMs (IPCC scenarios)





The Earth : a coupled system ocean + atmosphere (+ biosphere etc…)

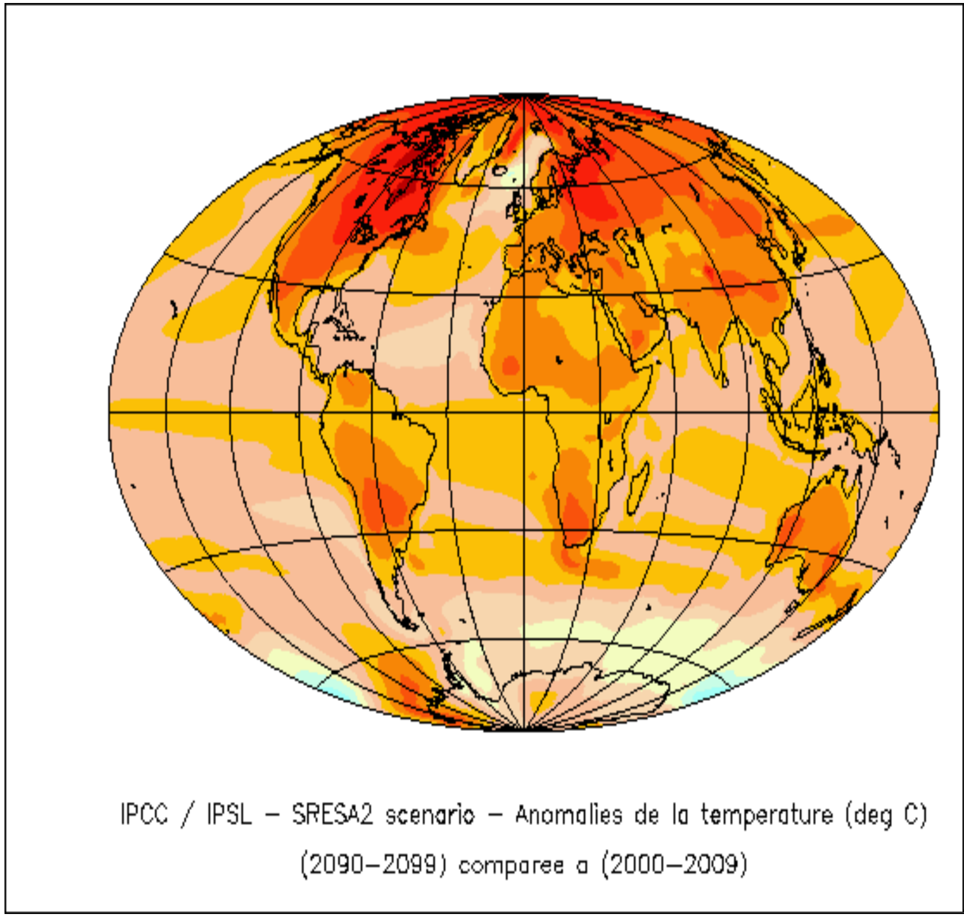


IPSL coupled model simulation

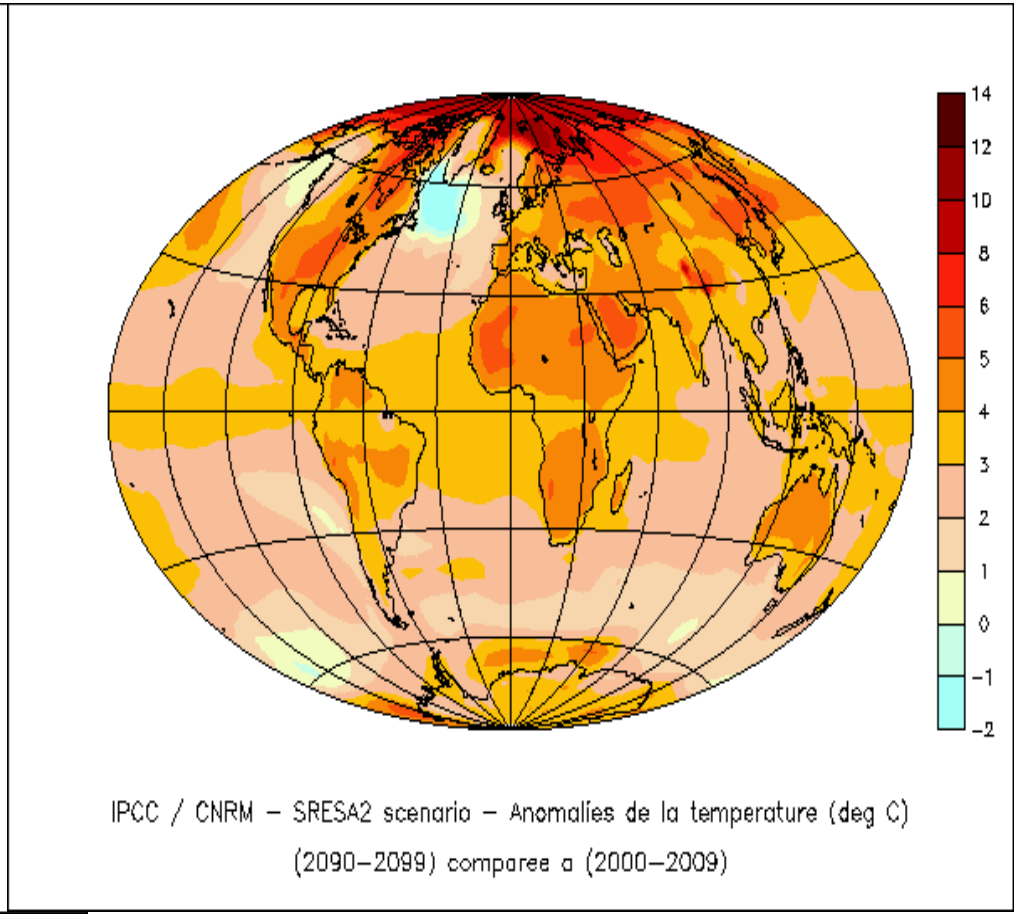
Projection for year 2100

Change in mean temperatures

(A2 scenario : ~doubling of CO2)



IPSL GCM



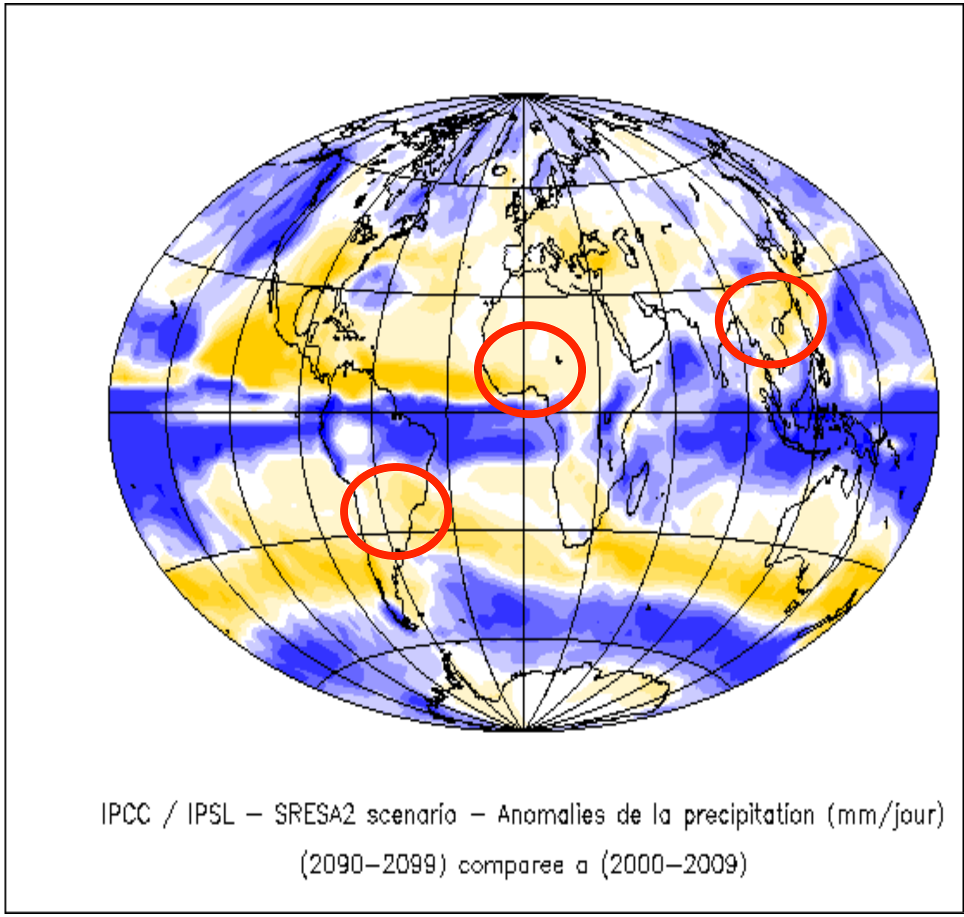
CNRM GCM

Source: CNRM et IPSL, 2006

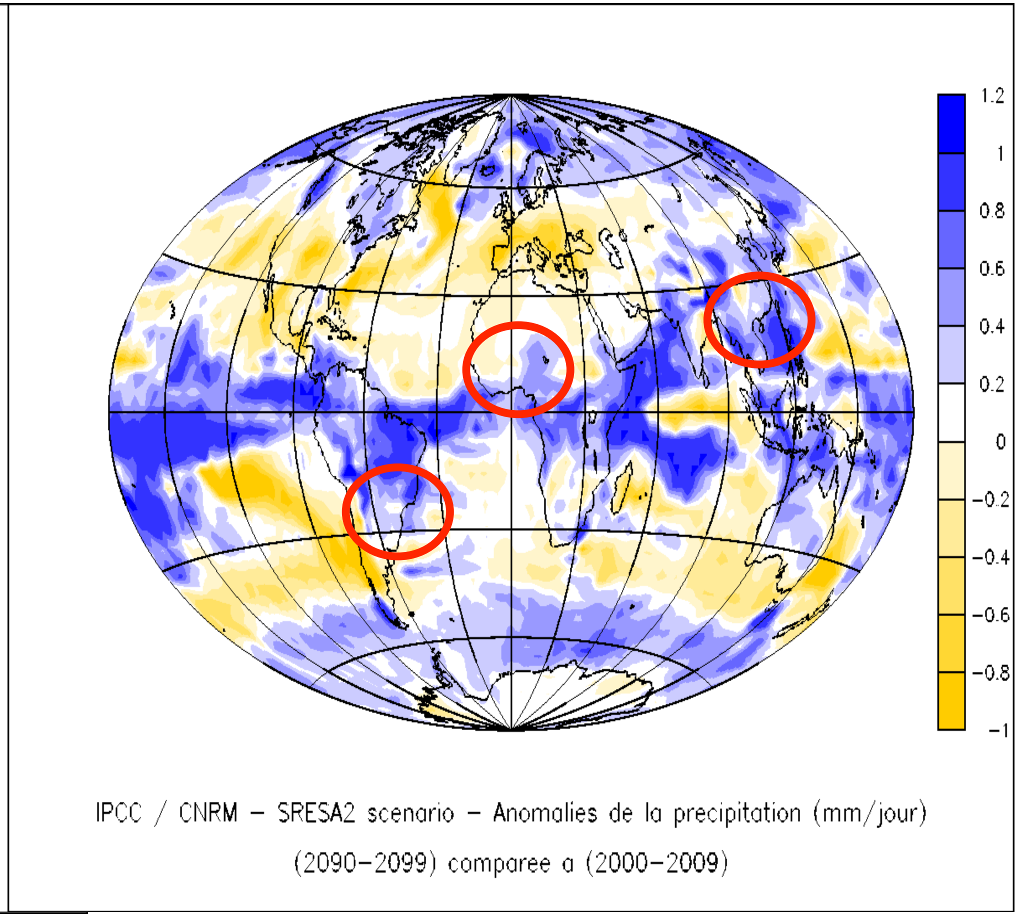
Projection for year 2100

Change in mean precipitations

(A2 scenario : ~doubling of CO_2)



IPSL GCM



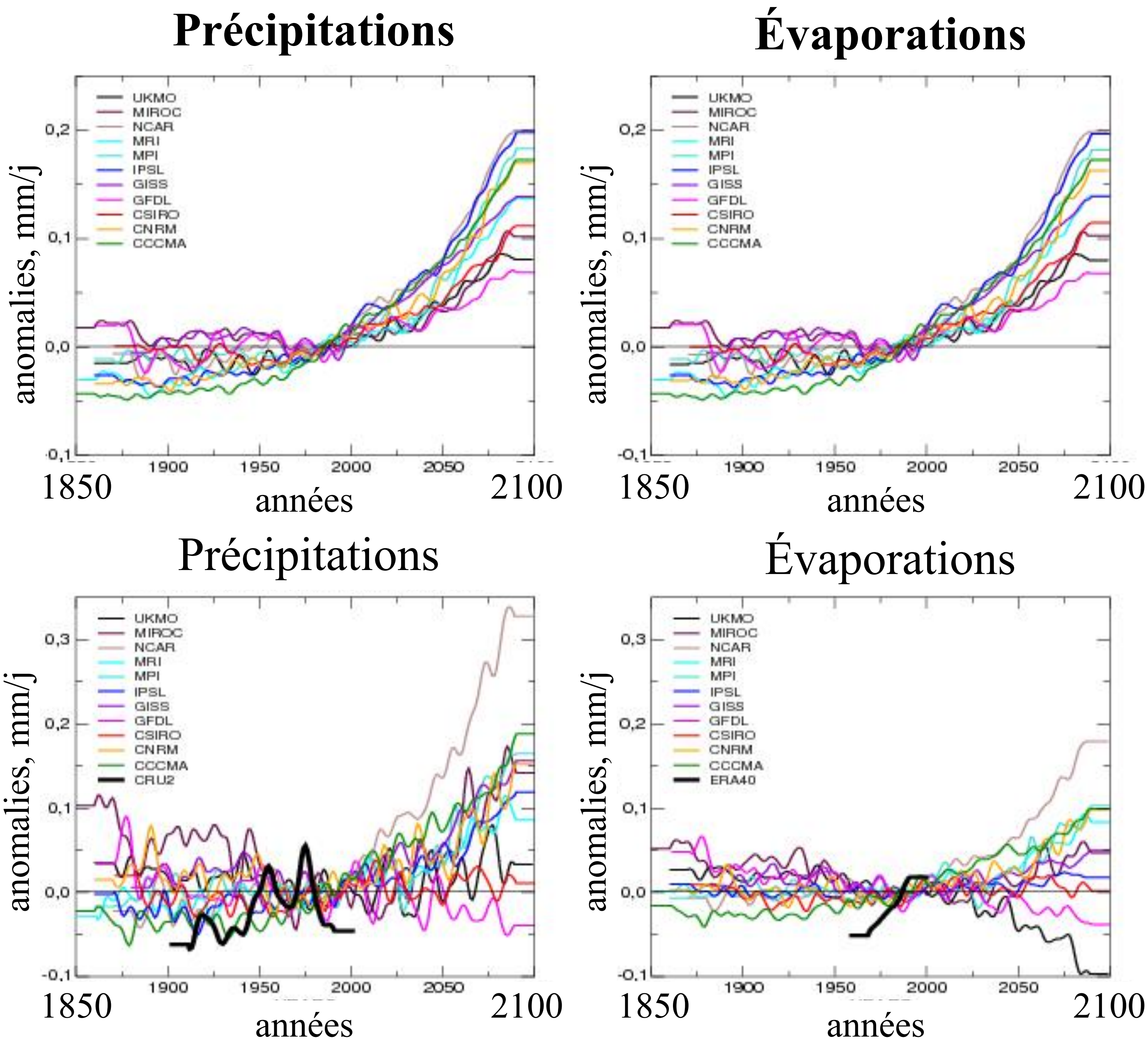
CNRM GCM

Source: CNRM et IPSL, 2006

Evolution over 1850 - 2100 (scénarios A2)

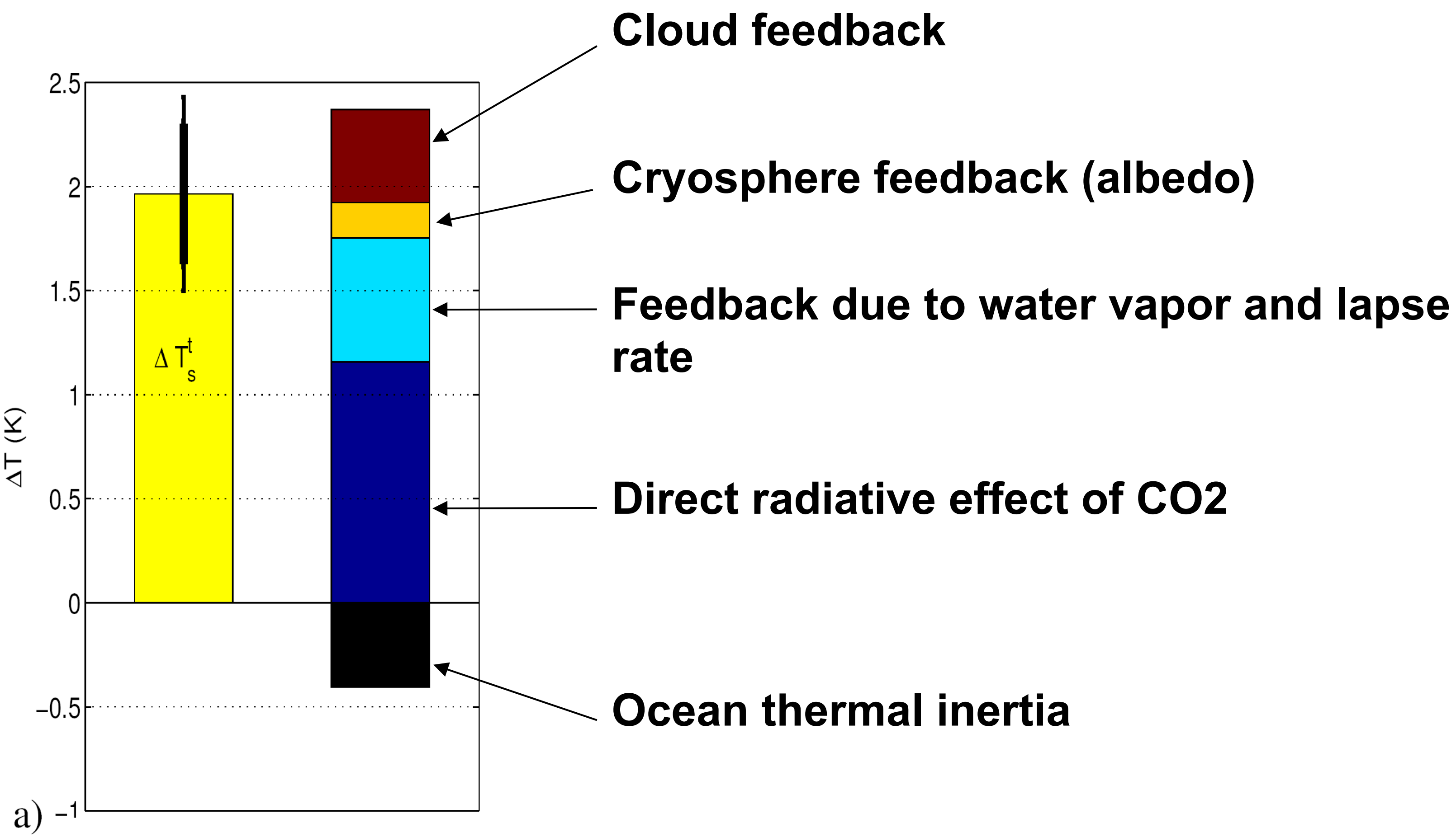
Global mean

Continental



[Douville et al., 2006]

Analysis of temperature change
(increase of CO_2 by 1%/year)

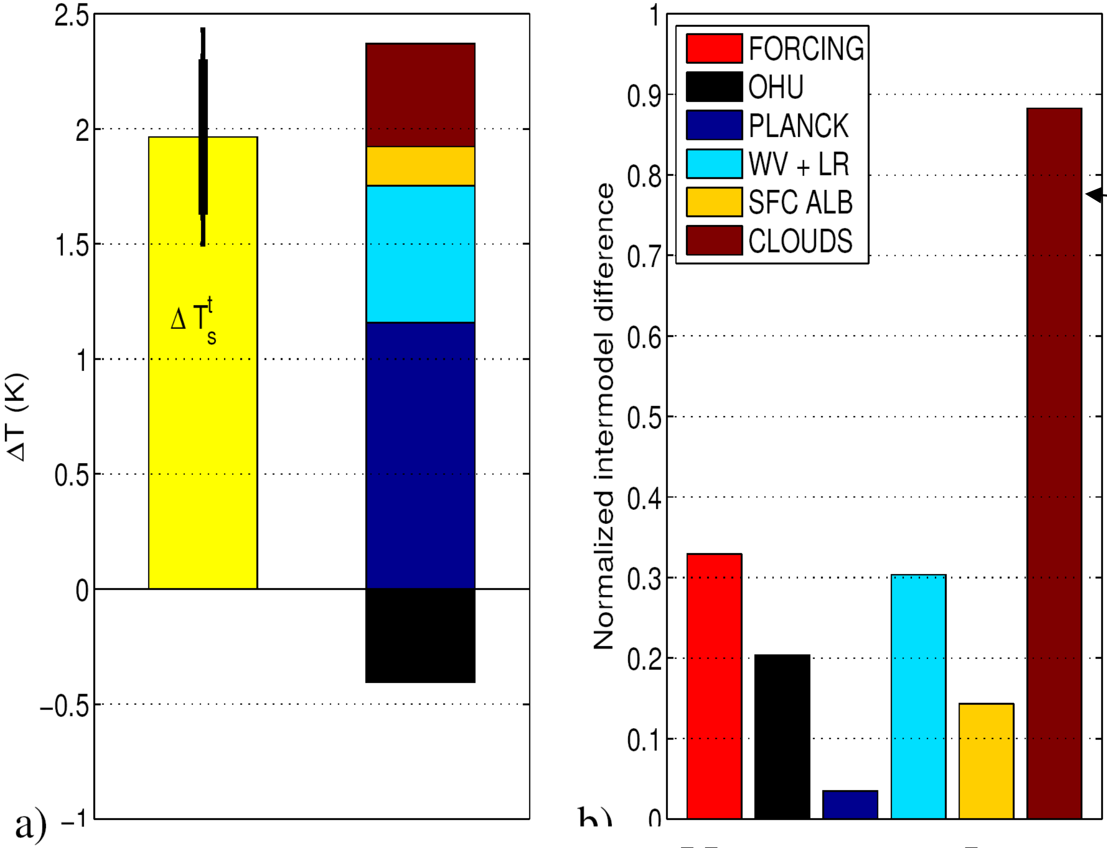


multi-model average

[Dufresne and Bony, 2008]

Analysis of temperature change

(increase of CO_2 by 1%/year)



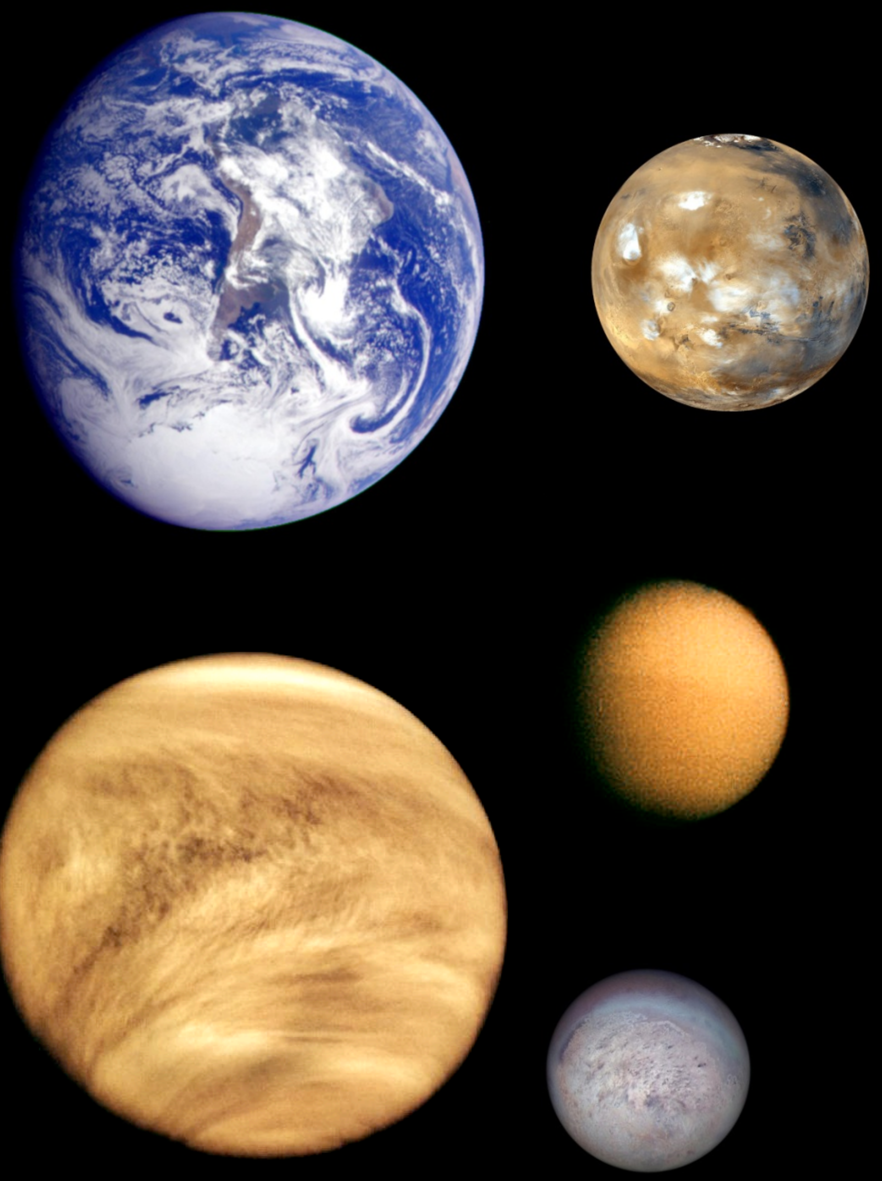
Clouds feedback !

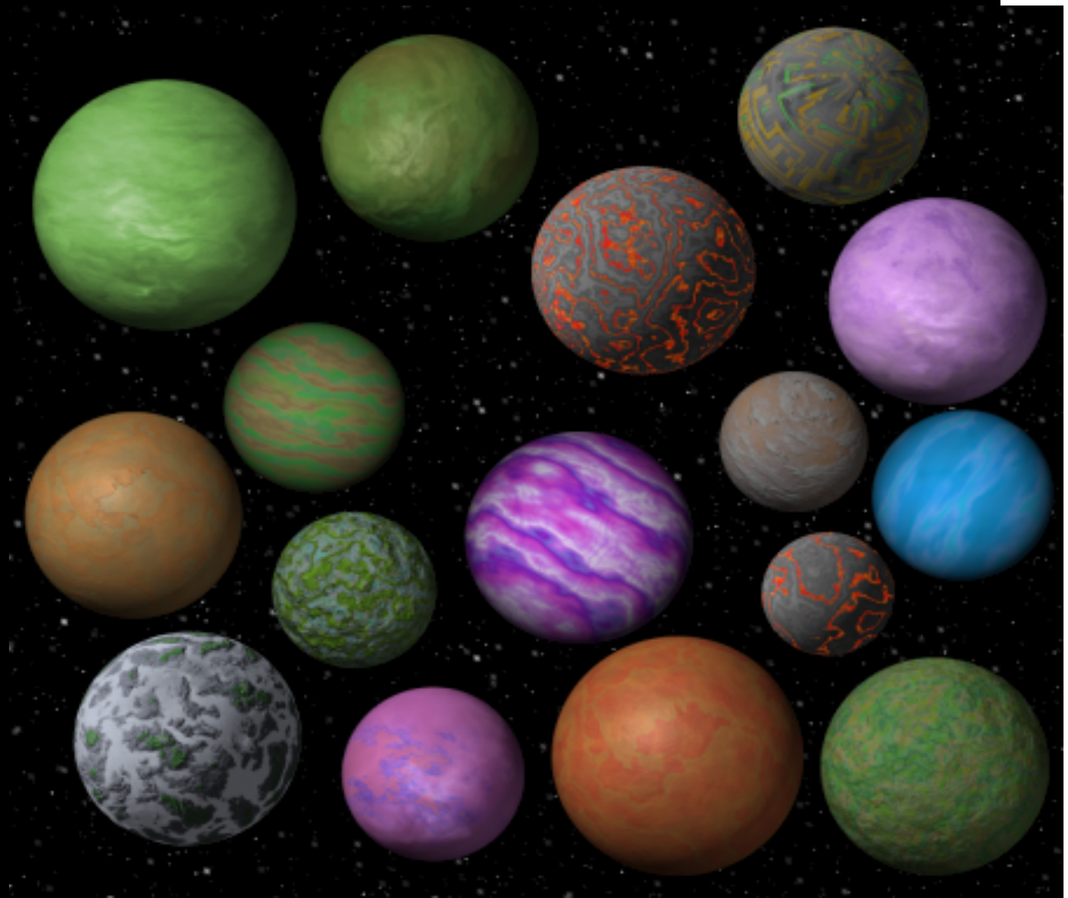
multi-model average

dispersion Between models

[Dufresne and Bony, 2008]

The science of Simulating the unknown: From planet GCMs to extrasolar planet GCMs.

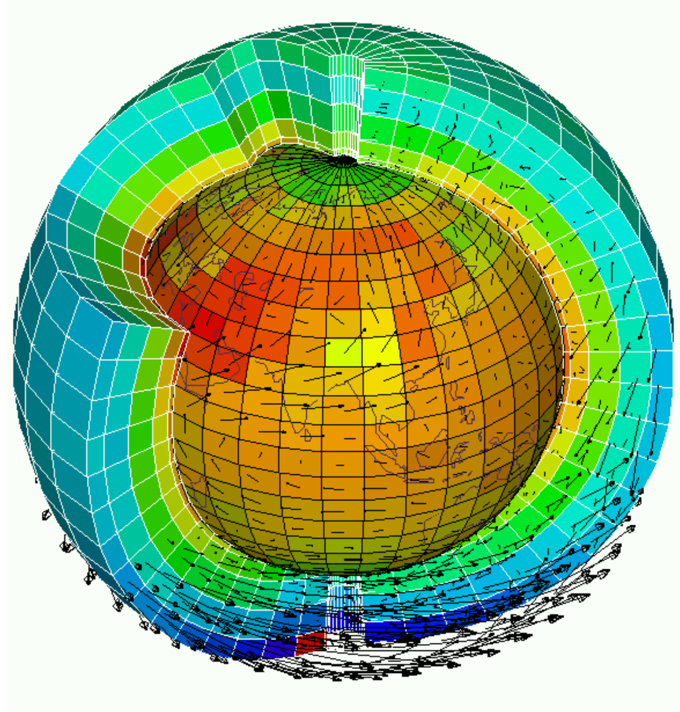




Why develop full GCMs for extrasolar planets in 2010 ?

- No observations to interpret, match or predict (yet)
- BUT GCMs can help address major scientic questions :
  - Limit of habitability
  - Specific cases. “Could my new planet be habitable” ?
  - Prepare observations
- **Strategy** : Build physically based, robust model + intense exploration of model sensitivity to parameters, test extreme cases, etc…

Toward a "generic" Global climate model (LMD)



1) Use "universal" parametrisations for all planets:
   - Standard dynamical core
   - Surface and subsurface thermal model
   - "Universal" Turbulent boundary layer scheme
2) The key : Versatile, fast and accurate radiative transfer code (see next slide)
3) Simple, Robust, physically based parametrisation of volatile phase change processes

   (including robust deep convection representation : wet convection)
4) If needed : simplified physical"slab ocean + sea ice" scheme.

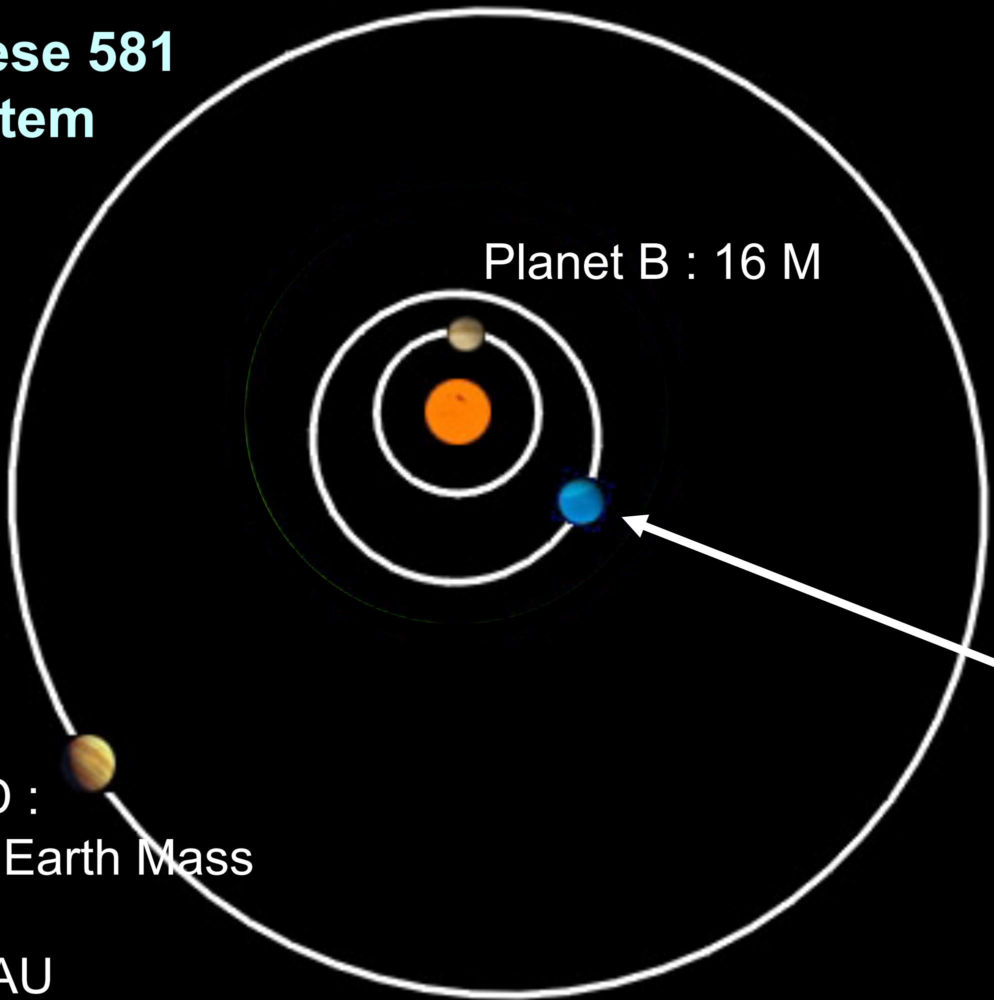
Developping a Versatile, fast and accurate radiative transfer code for GCM

- **Input : assumption on the atmosphere**:
  - Any mixture of well mixed gases (ex: $CO_2 + N_2 + CH_4 + SO_2$)
  - Add 1 variable gases (H_2O). Possibly 2 or 3 (e.g. Titan)
  - Refractive Indexes of aerosols.
- Semi automatic processes: Spectroscopic database (Hitran 2008) ⇨ Line by line spectra (k-spectrum model) ⇨ correlated k coeeficients⇨ radiative transfer model
- RT Model can also simulate scattering by several kind of aerosols (size and amount can vary in space and time)
- Key technical problems:
  - gas spectroscopy in extreme cases
  - Predicting aerosol and cloud properties
- Key scientific problem : assumption on the atmosphere !

An example of application : Gliese 581d

Gliese 581 system

Star = 0.31 Msun
Distance = 20.4 Light Year



Bonfils et al. 2005
Udry et al. 2007

Gliese 581d

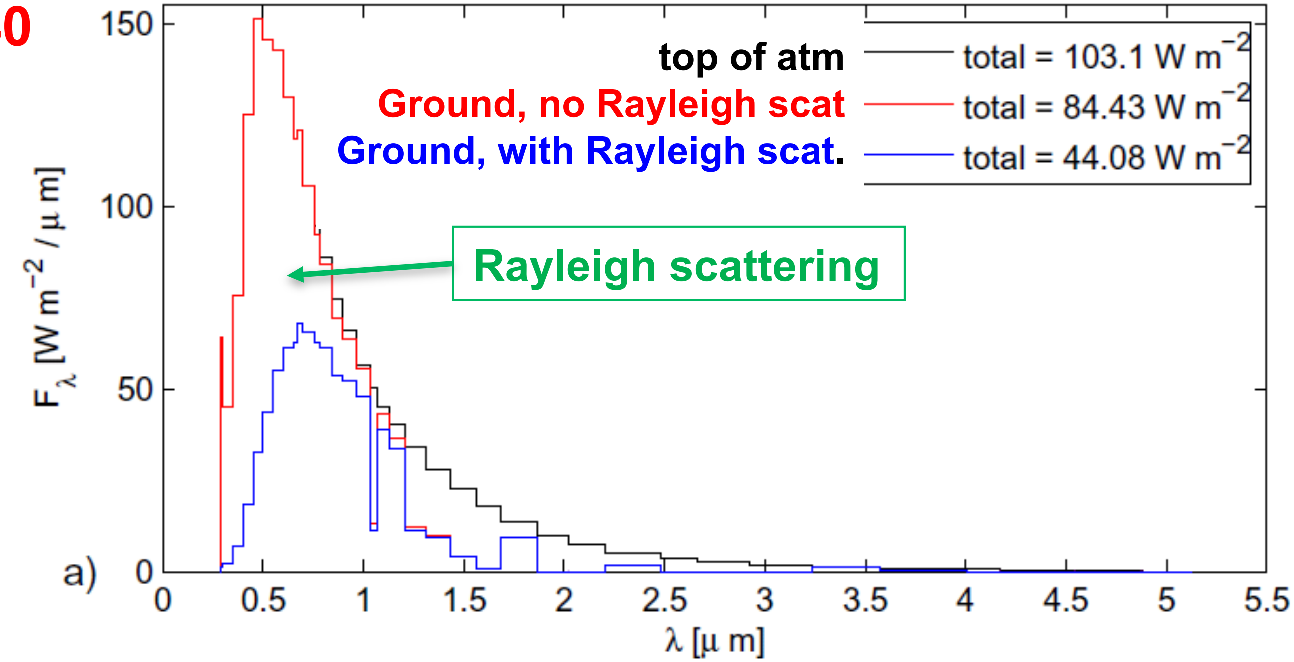
- Mass > 8.3 Earth Mass
- Orbit around a small cold M star
  - 1 year ~ 67 Earth days
  - Excentricity ~ 0.38
  - Equilibrium temperature ~ -80°C
- Gravity : between 10 and 30 m s^{-2}
- Tidal forces :
  - Possibly locked in synchronous rotation or a resonance
  - Most likely low obliquity (like Venus or Mercury)

A GCM for Gliese 581d

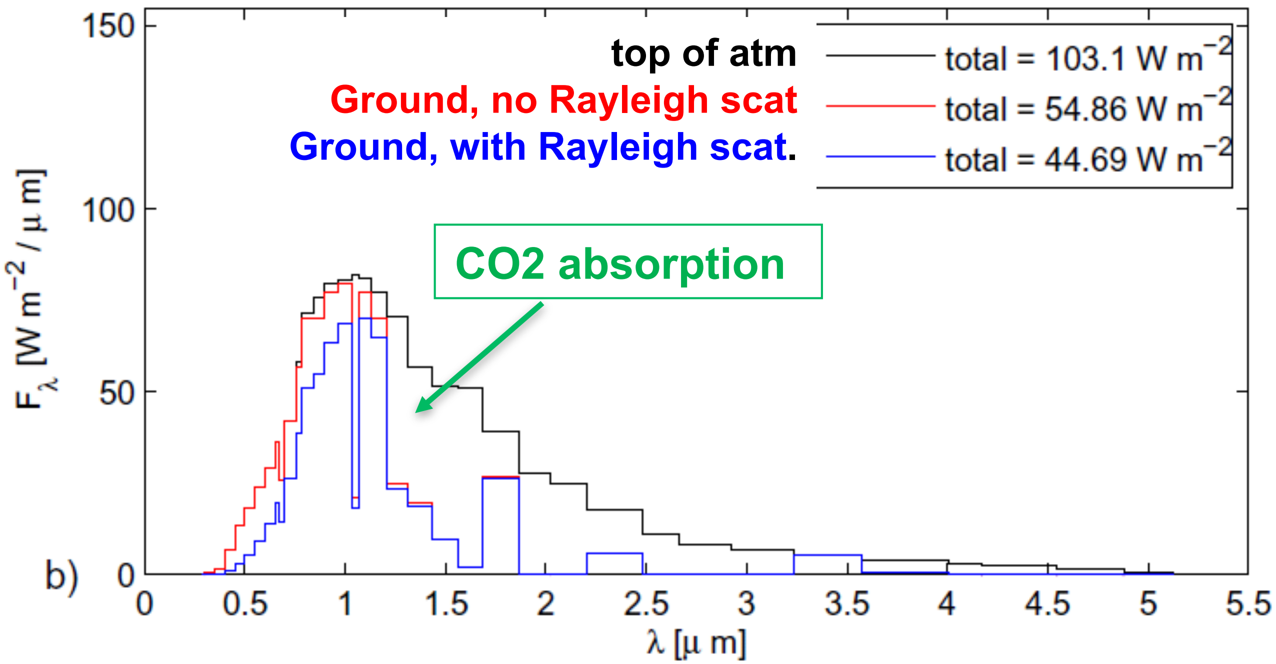
- **The question: what could be the climate *assuming a CO2 – N2 – H2O atmosphere* ? Could Gliese 581d be habitable ?**
- **The model :**
  - Low spatial resolution (11.25° lon x 5.6° lat resolution)
  - Radiative transfer :
    - 32 spectral bands in the longwave and 36 in the shortwave
    - Include improved Collision Induced absorption parametrisation (*Wordsworth et al. Icarus, 2010*)
    - Assume stellar spectra from Virtual planet laboratory (AD Leo, slightly warmer than Gliese 581).
  - CO2 condensation (surface + clouds) included

Incident solar flux on a 40 bars CO_2 atmosphere

G-class spectrum (Sun)



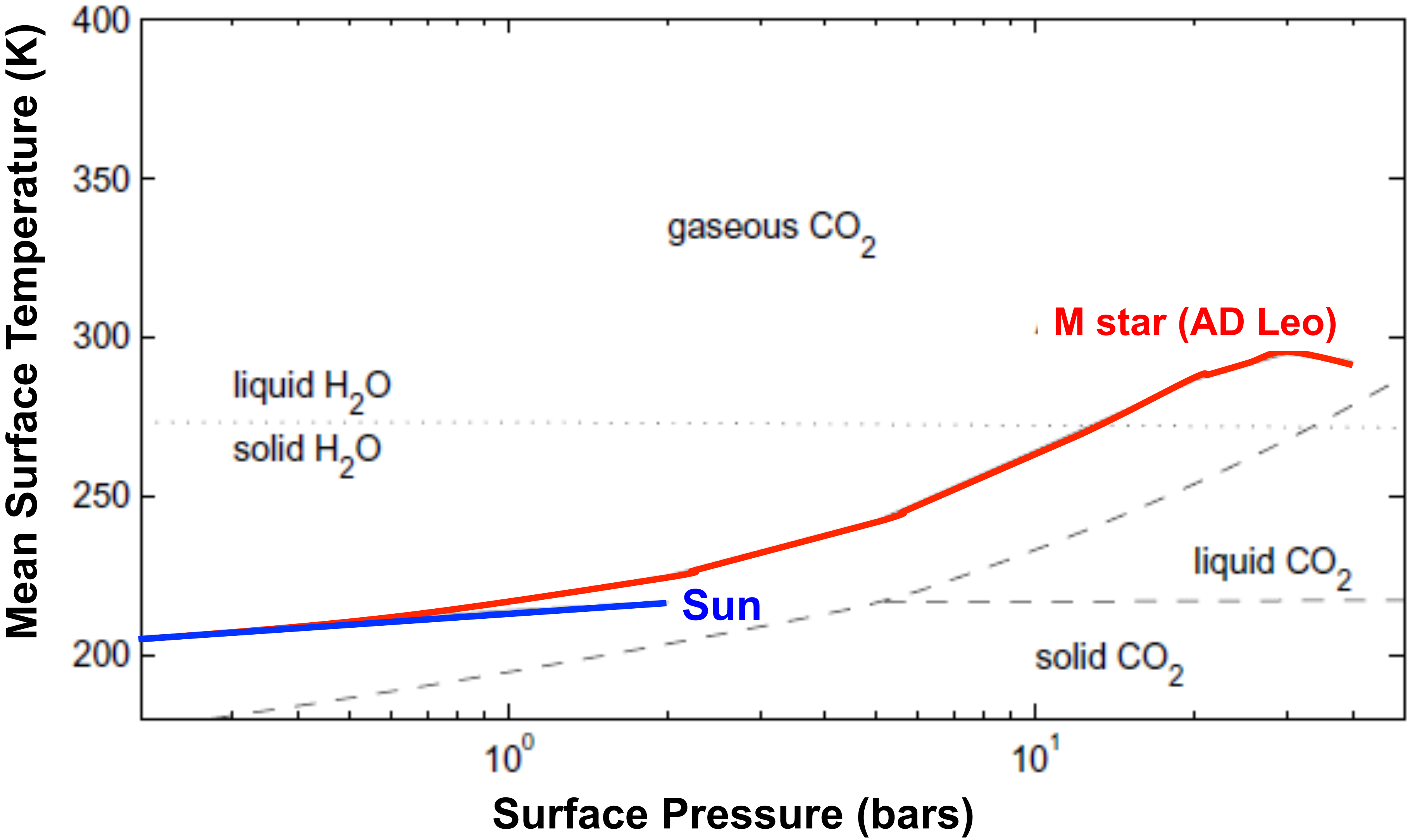
M-Class spectrum (AD Leo and ~Gliese 581)



Global Mean results

(1D radiative convective models)

Wordsworth et al. (A&A , 2010)



Global Mean results

(1D radiative convective models)

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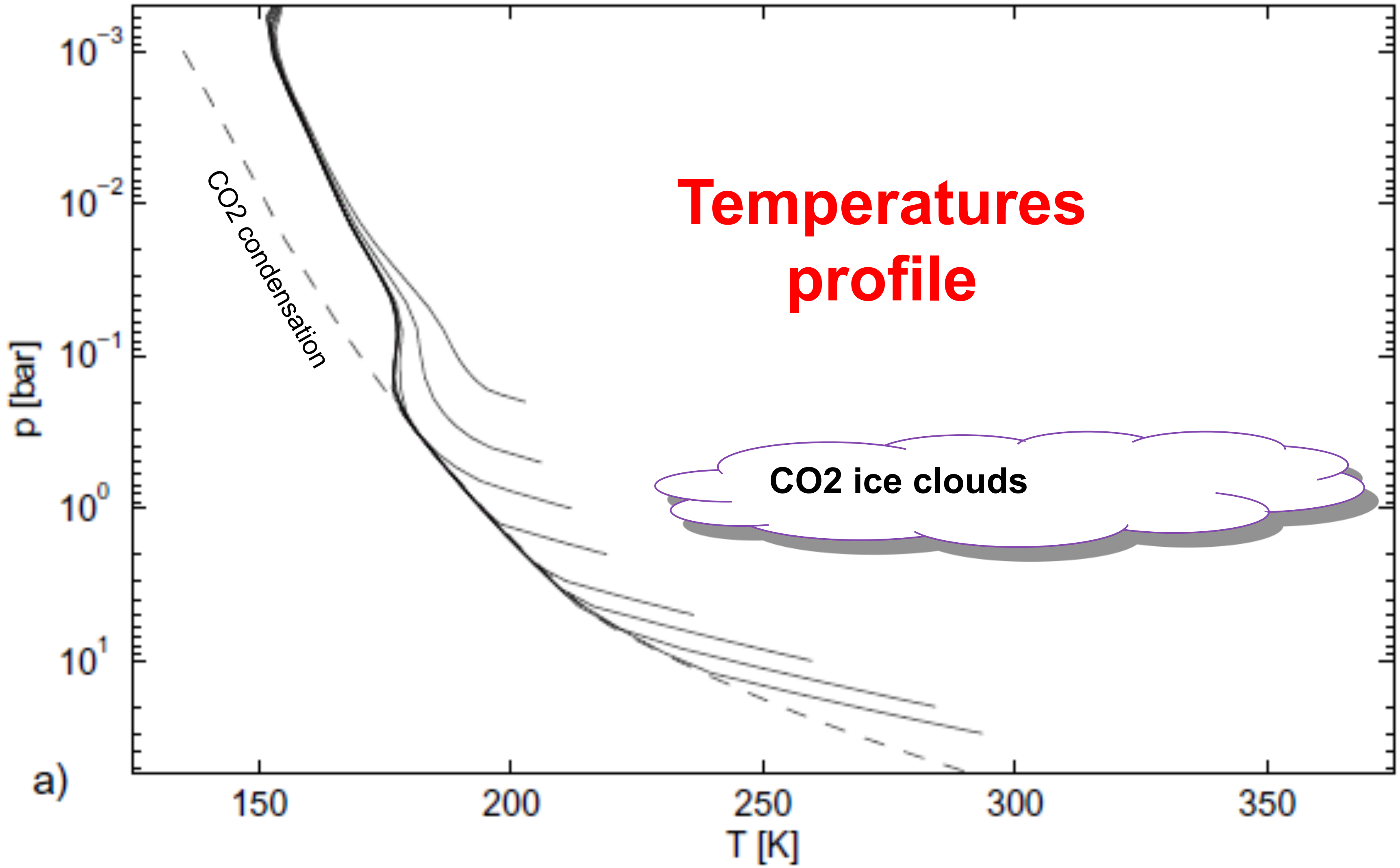
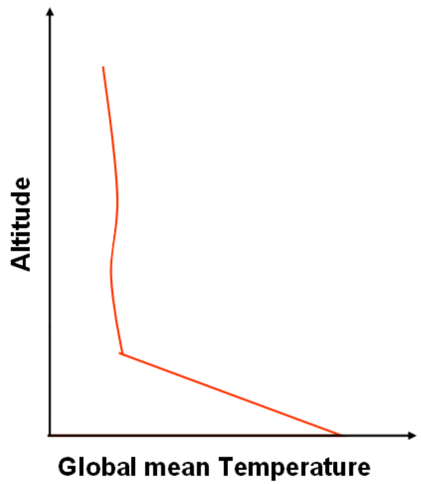
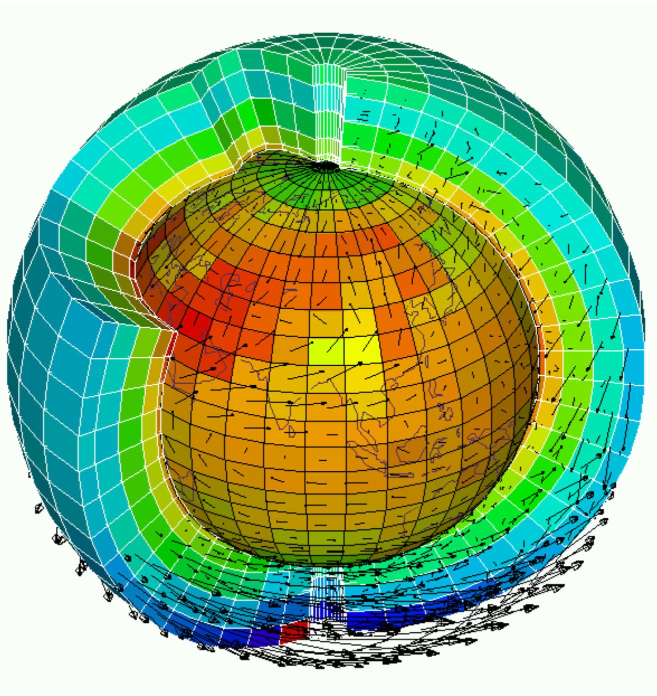


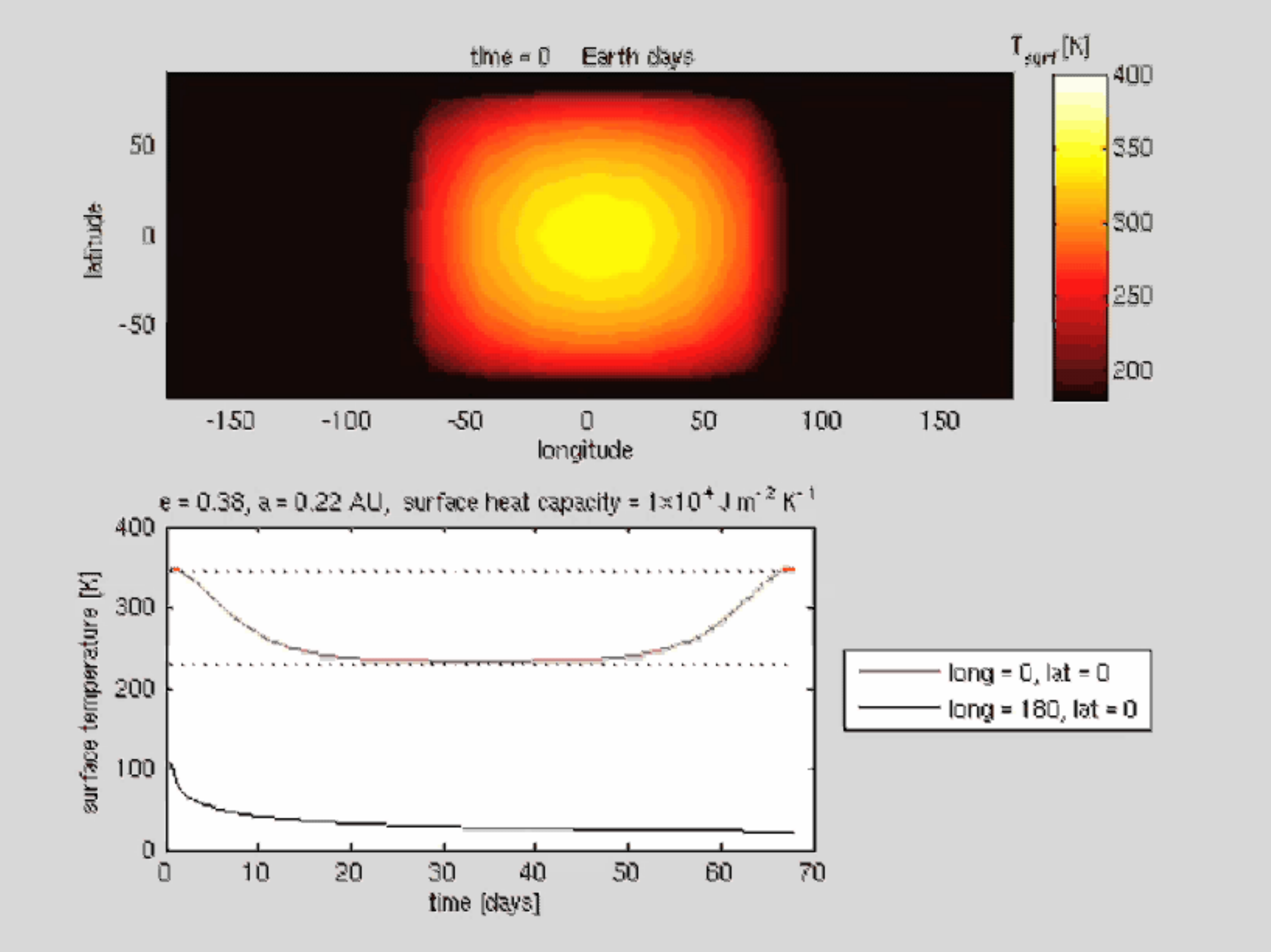
From 1D to 3D



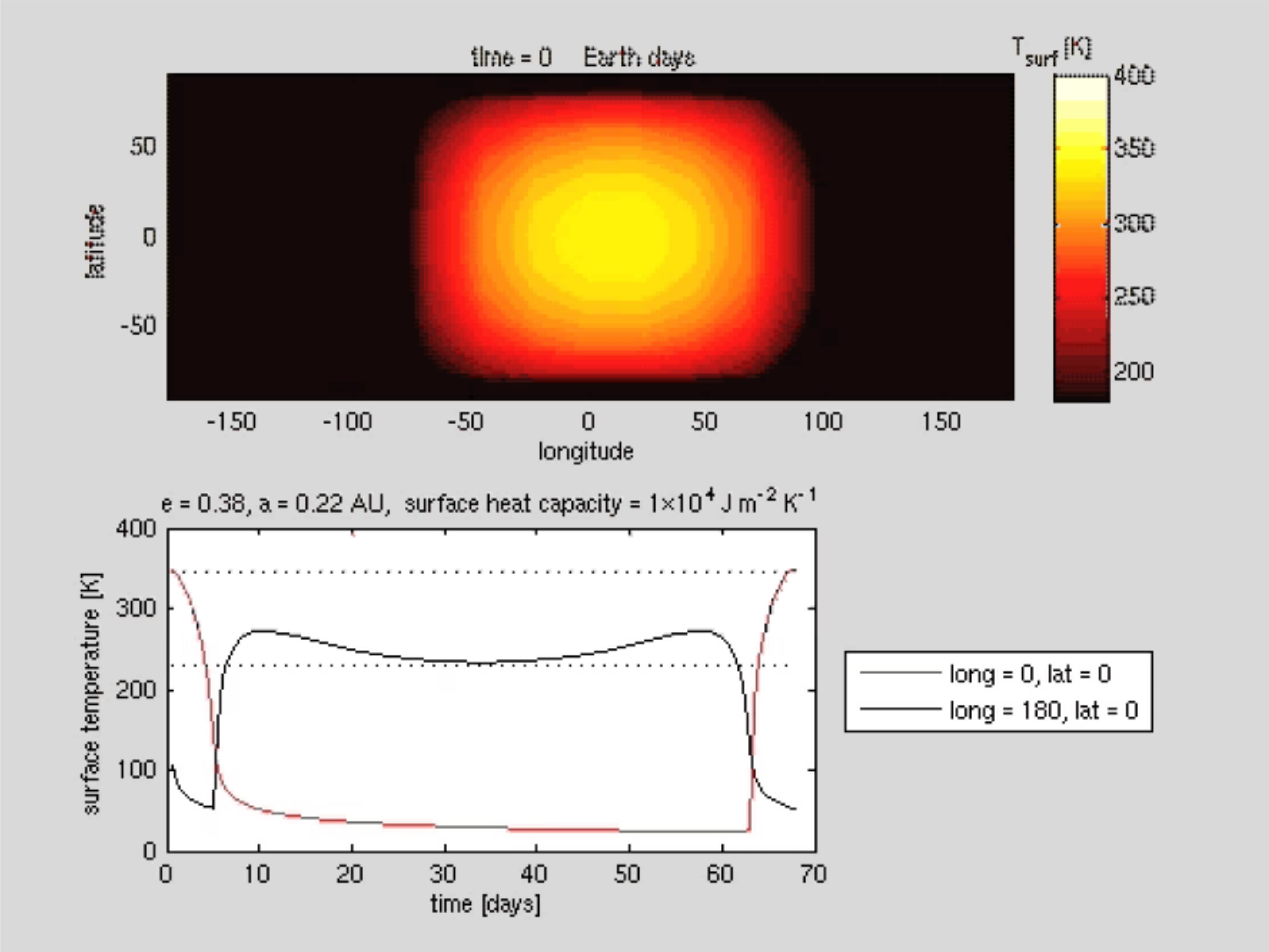


- Distribution of clouds
- Water cycle : cold trapping of water ?
- Impact of heterogeneous heating (cold hemisphere, poles)

Tidal locked Gliese 581d with no atmosphere

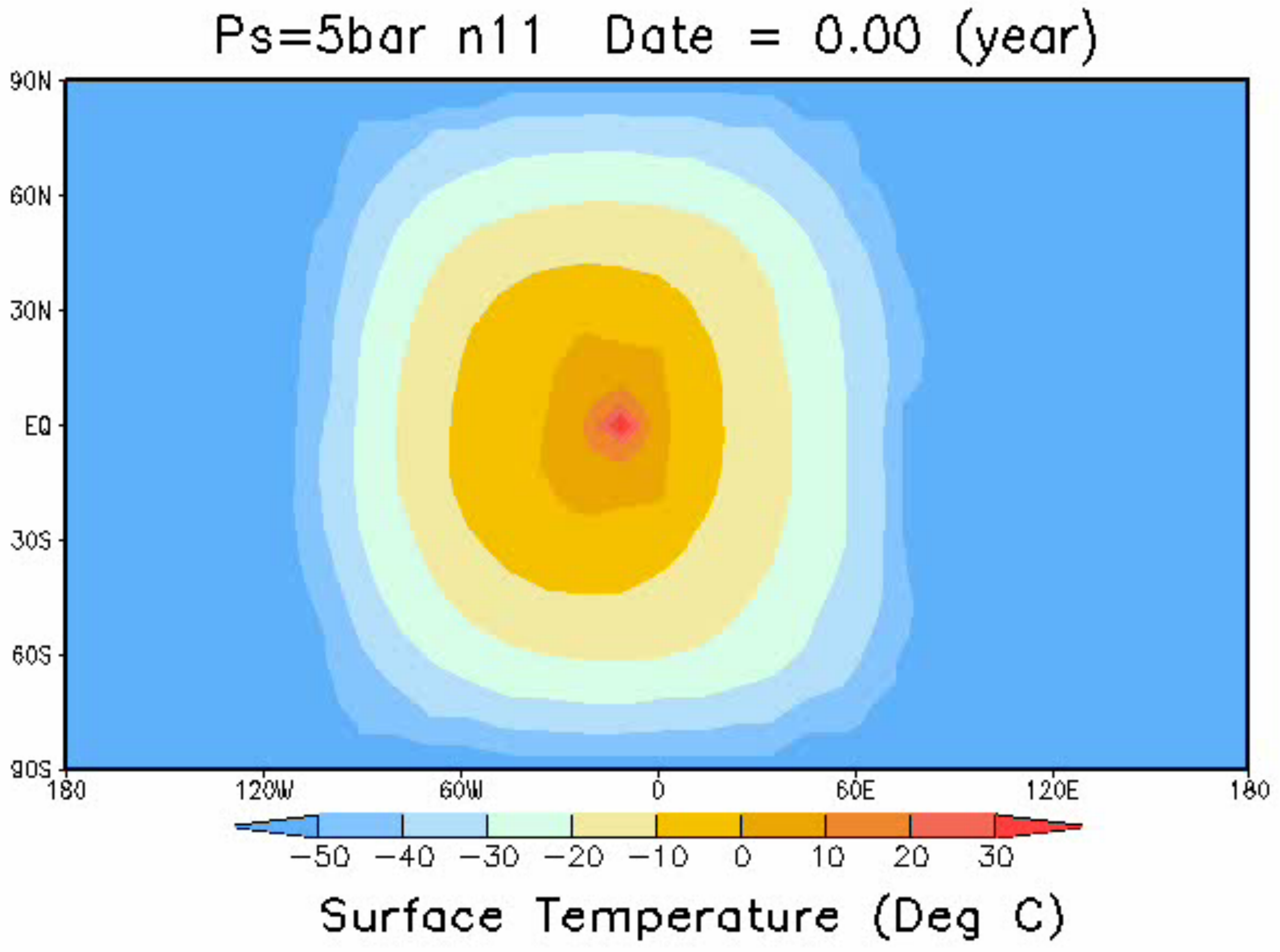


Gliese 581d (resonnance 2/1) wth no atmosphere



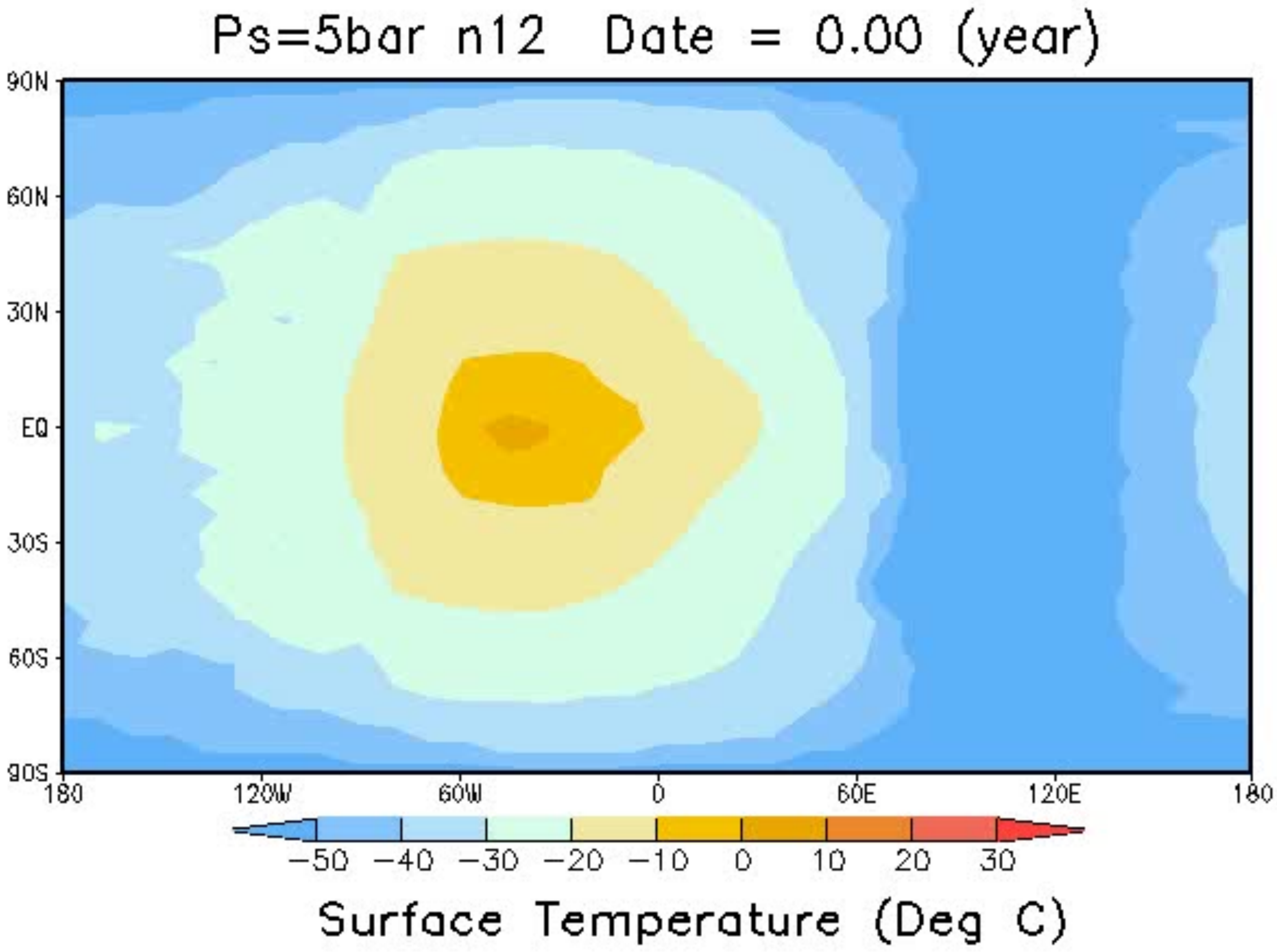
Tidal locked Gl581d Ps=5bar

Surface Temperature



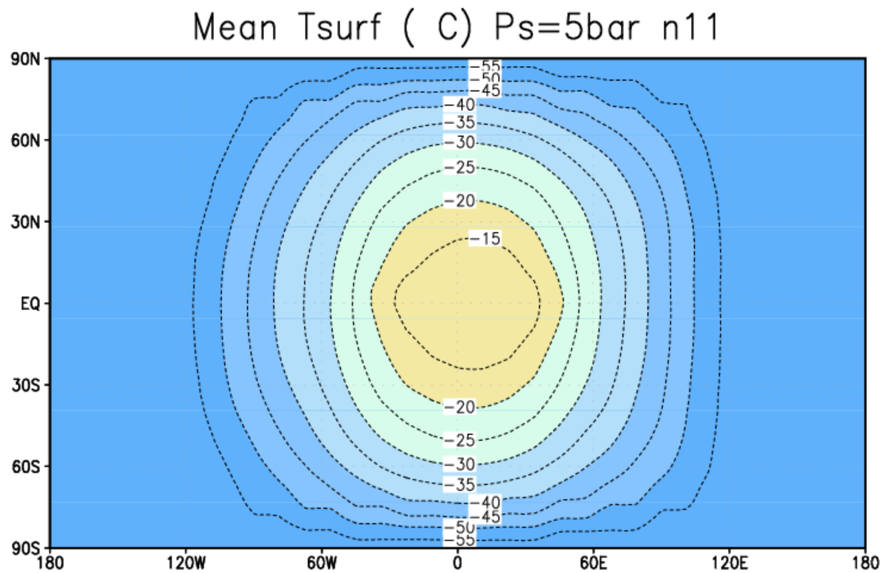
Resonnant 2/1 Gl581d Ps=5bar

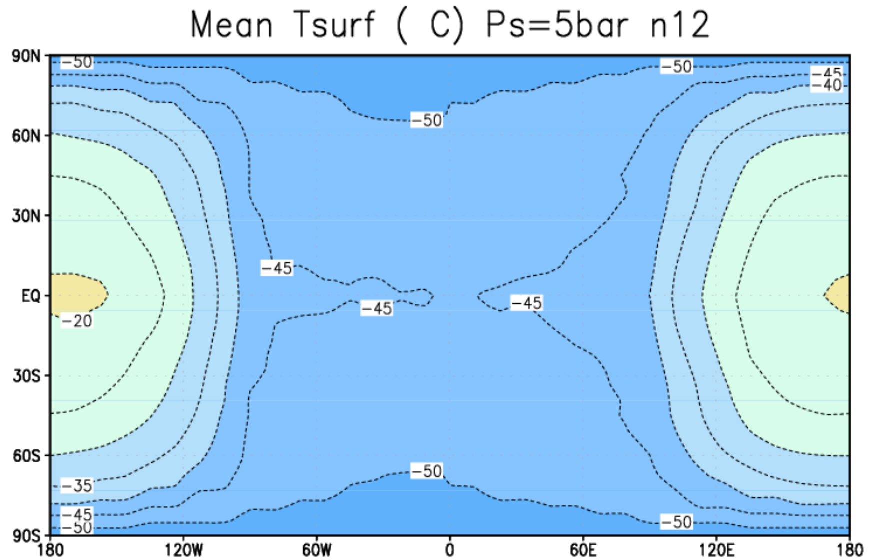
Surface Temperature

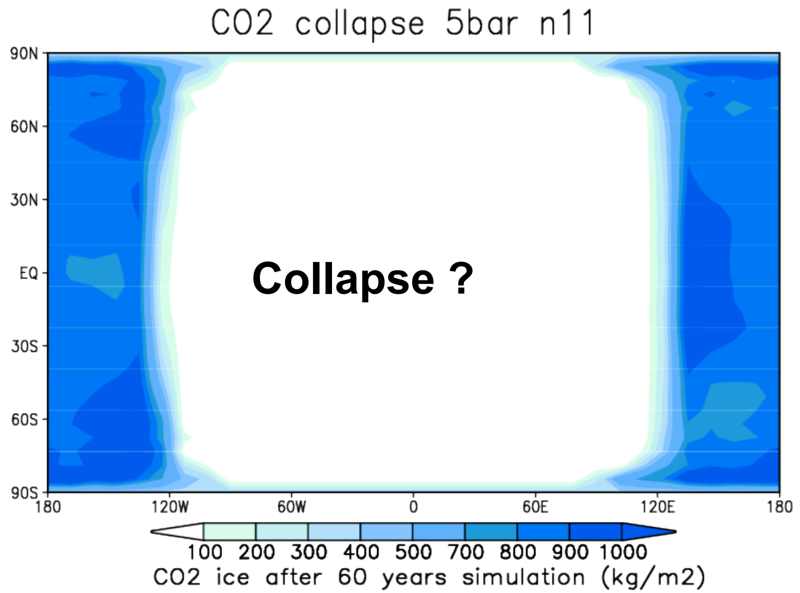


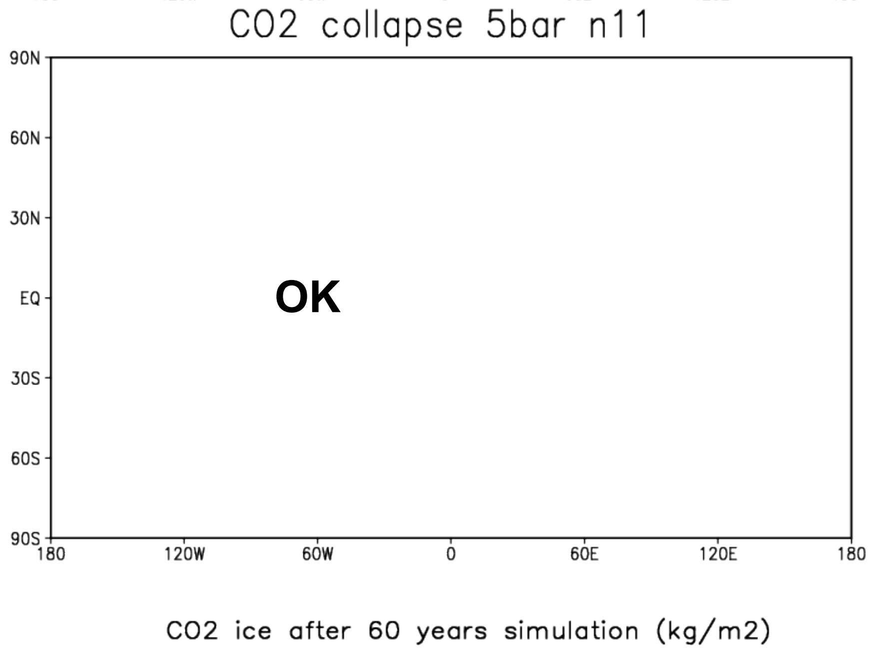
Mean surface temperature and atmospheric CO_2 collapse

5 bars



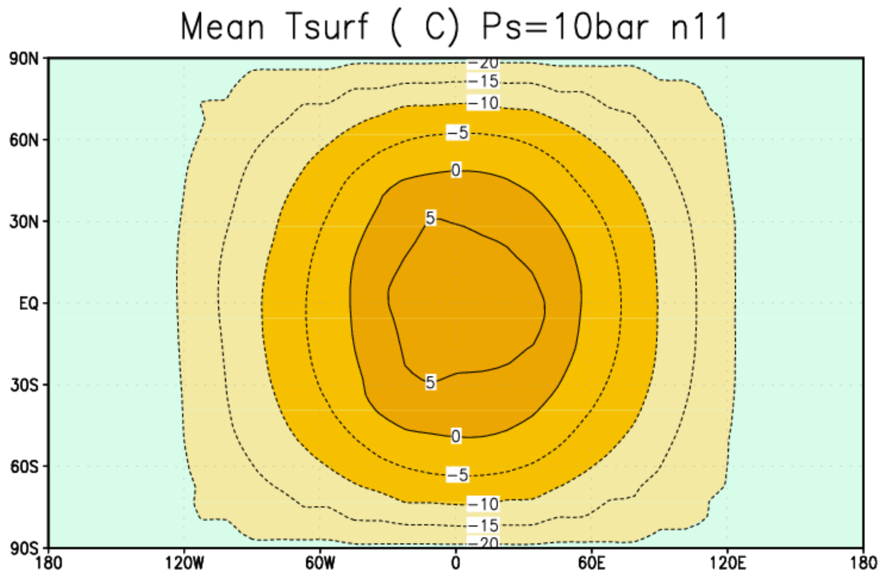


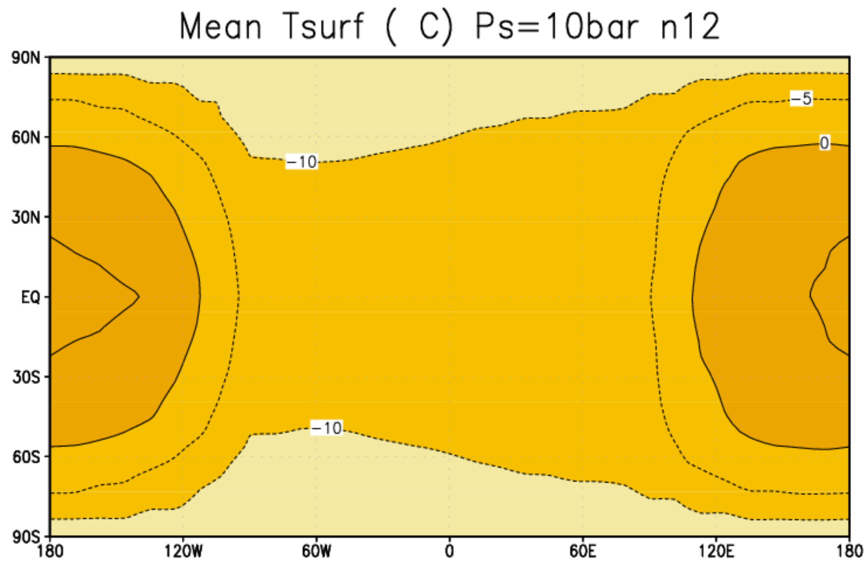


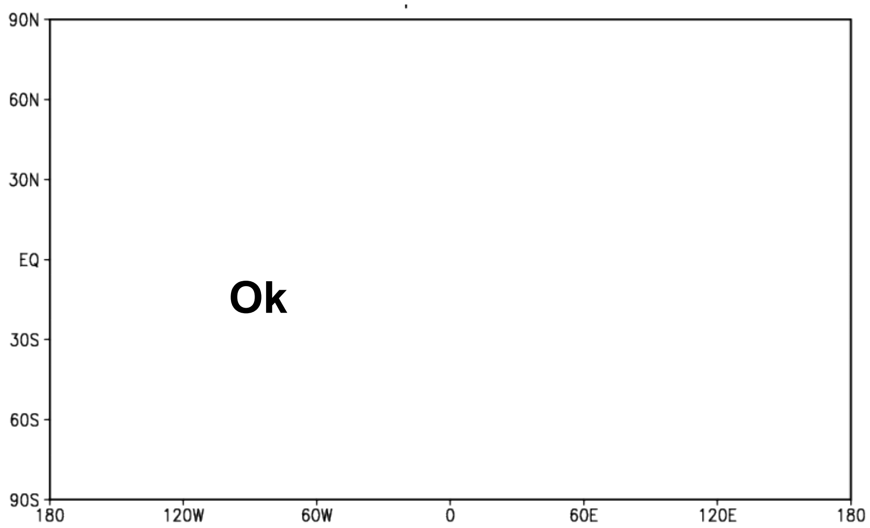


Mean surface temperature and atmospheric CO_2 collapse

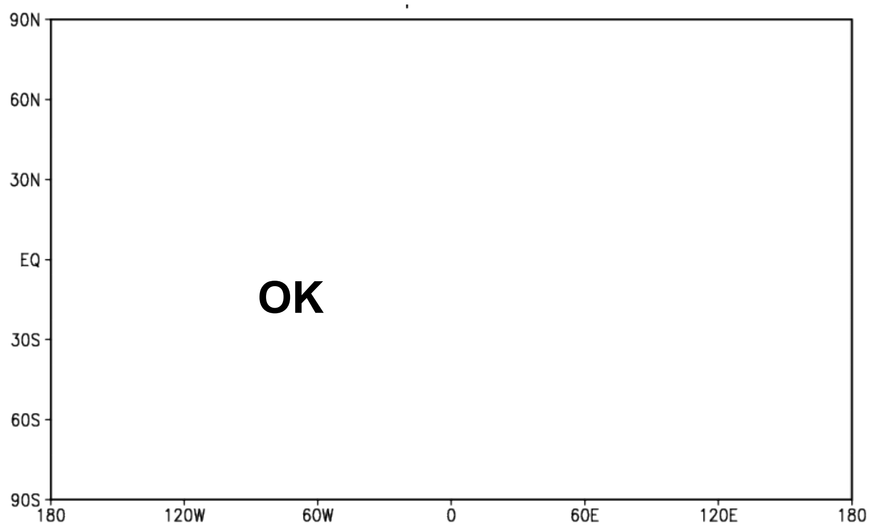
10 bars







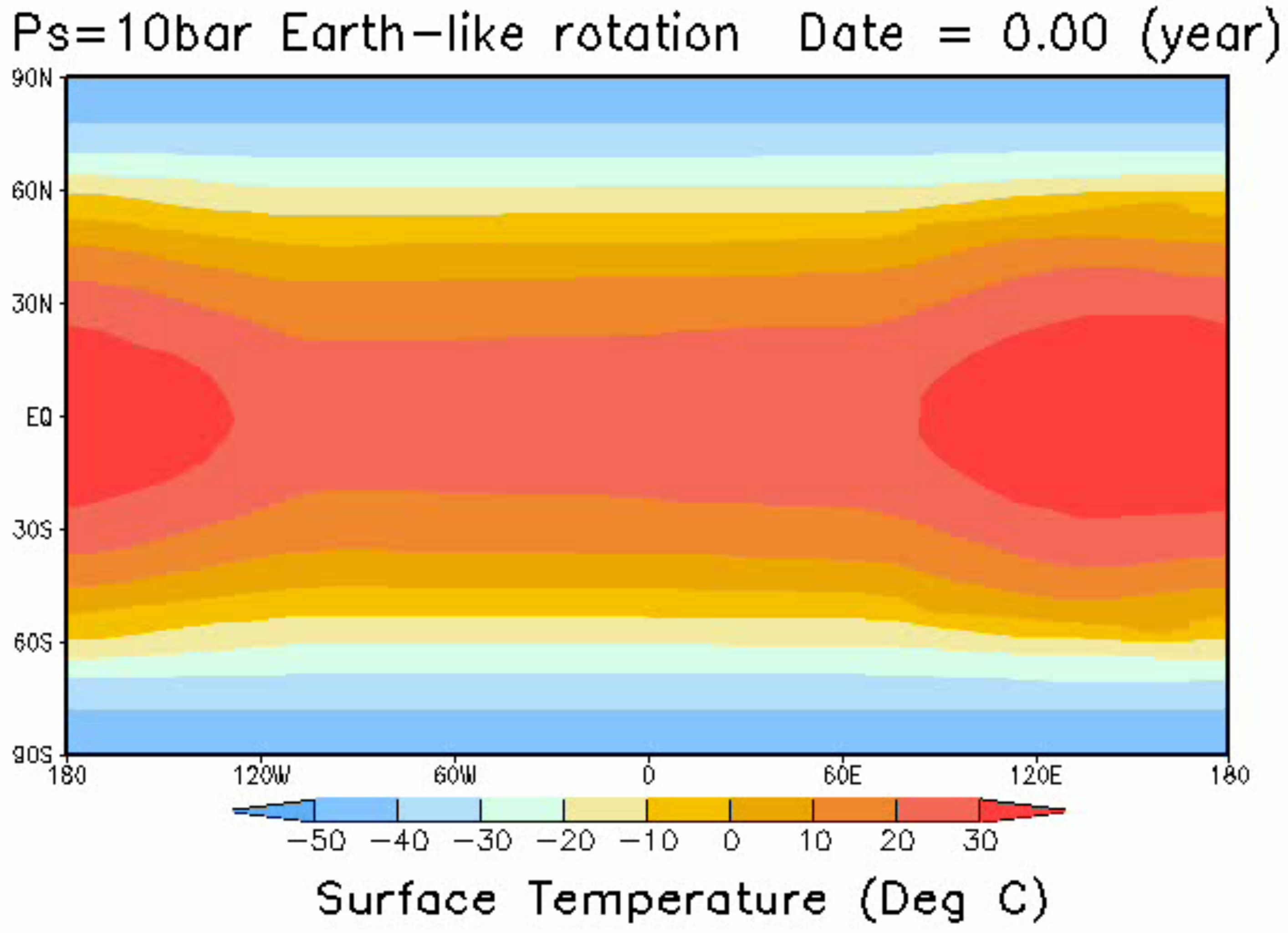
CO2 ice after 60 years simulation (kg/m2)



CO2 ice after 60 years simulation (kg/m2)

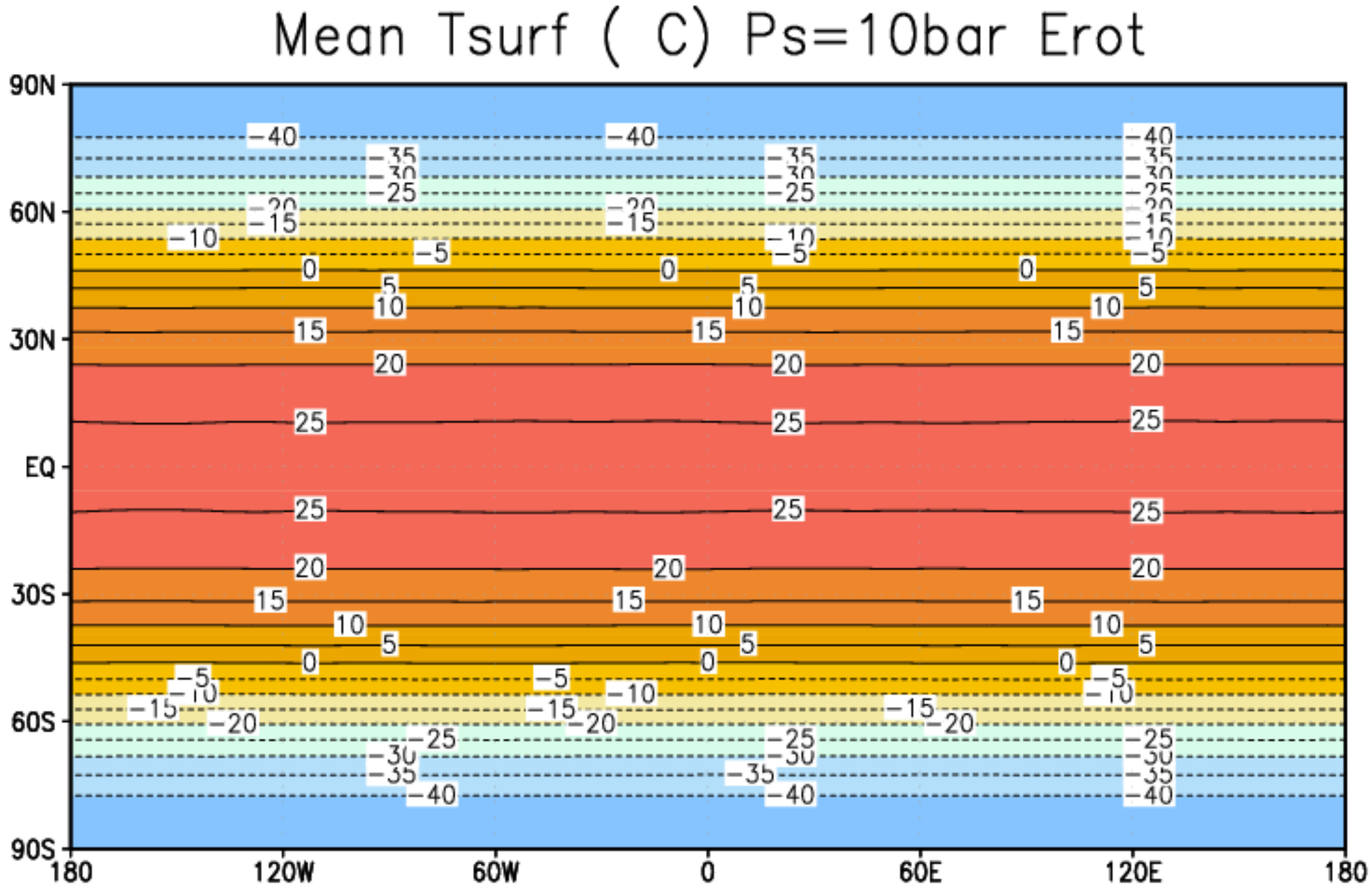
Earth-like rotation Gl581d Ps=10bar

Surface Temperature



Earth-like rotation Gl581d Ps=10bar

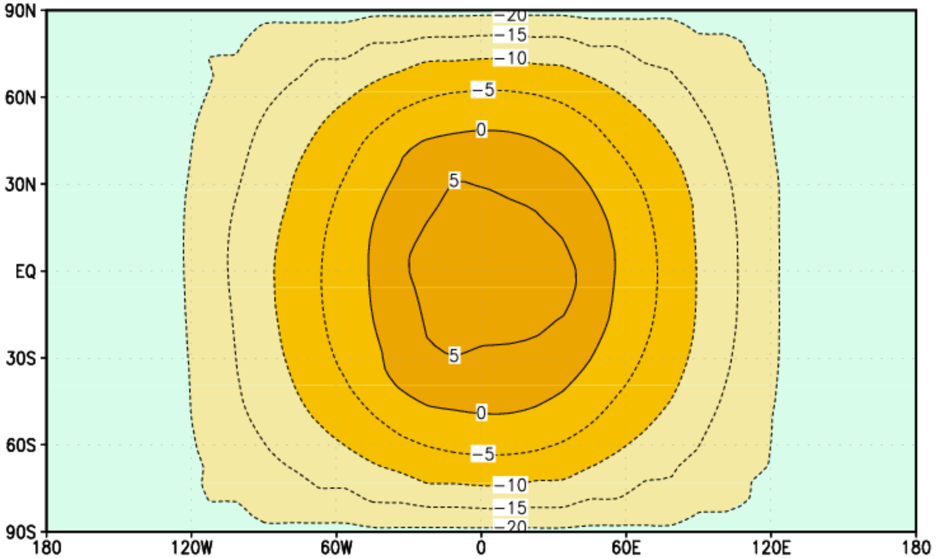
Mean Surface Temperature



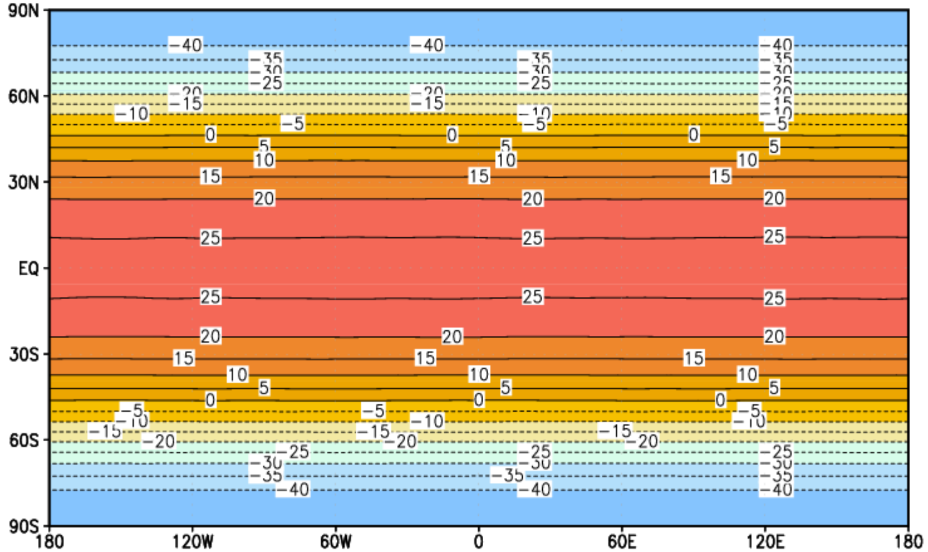
Mean surface temperature and atmospheric CO2 collapse

10 bars

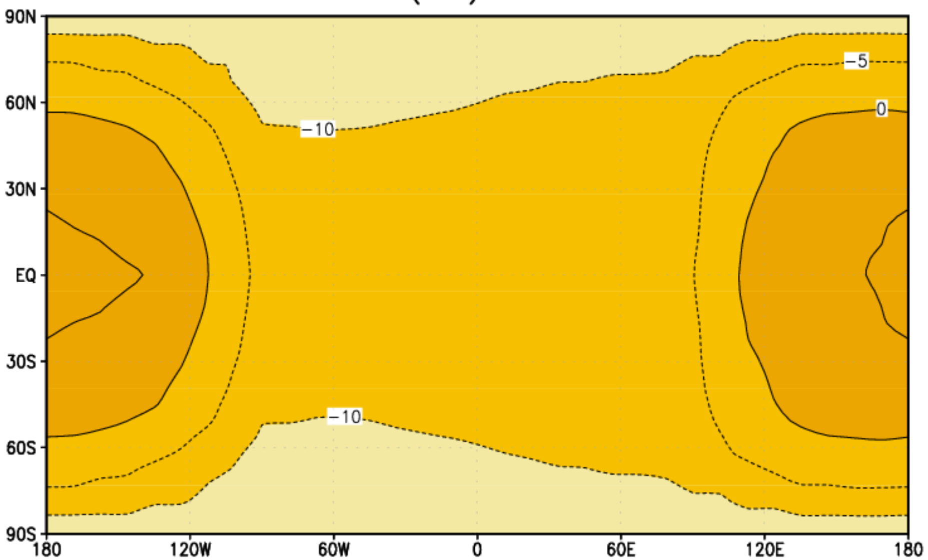
Mean Tsurf (C) Ps=10bar n11



Mean Tsurf (C) Ps=10bar Erot

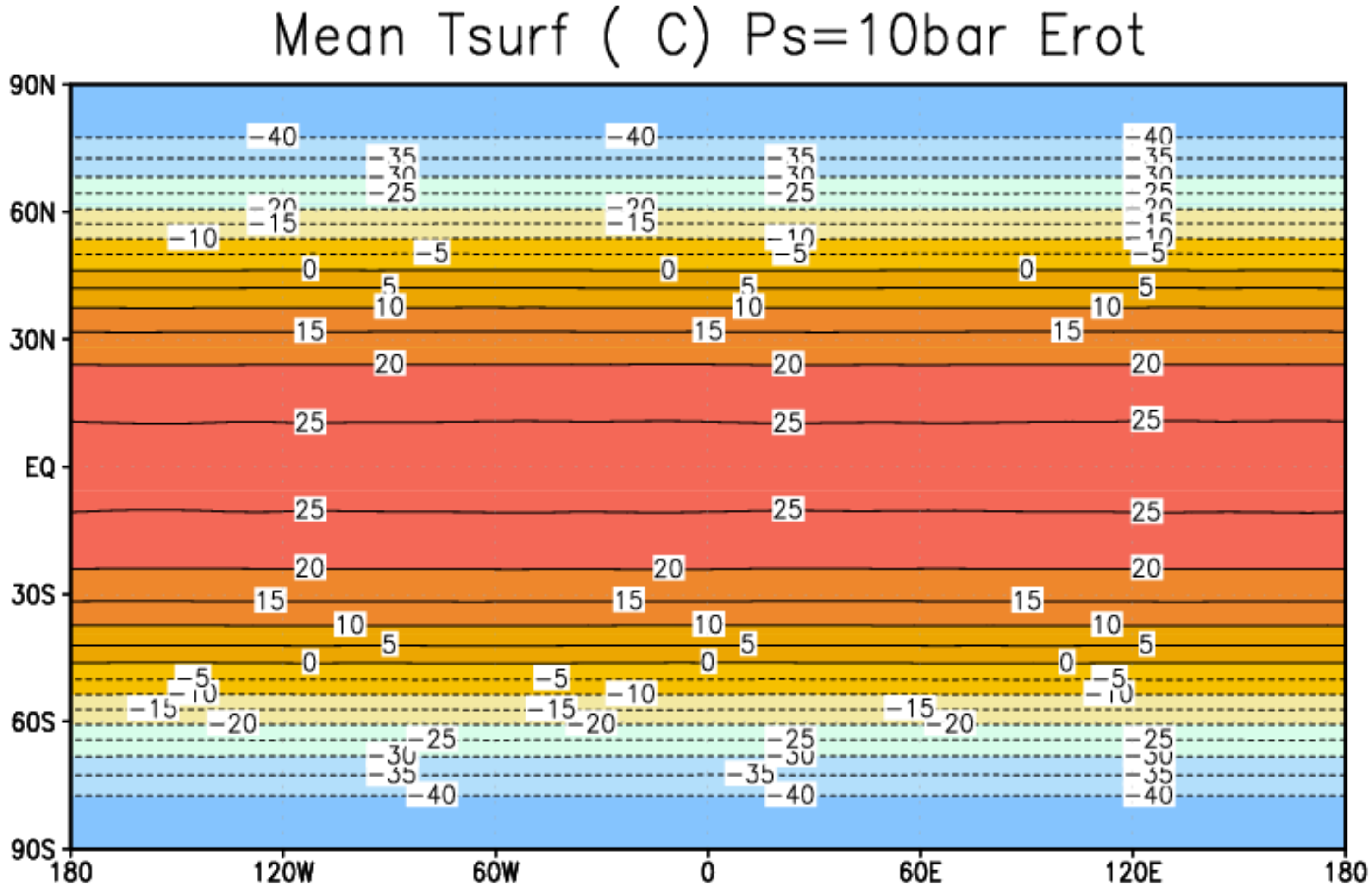


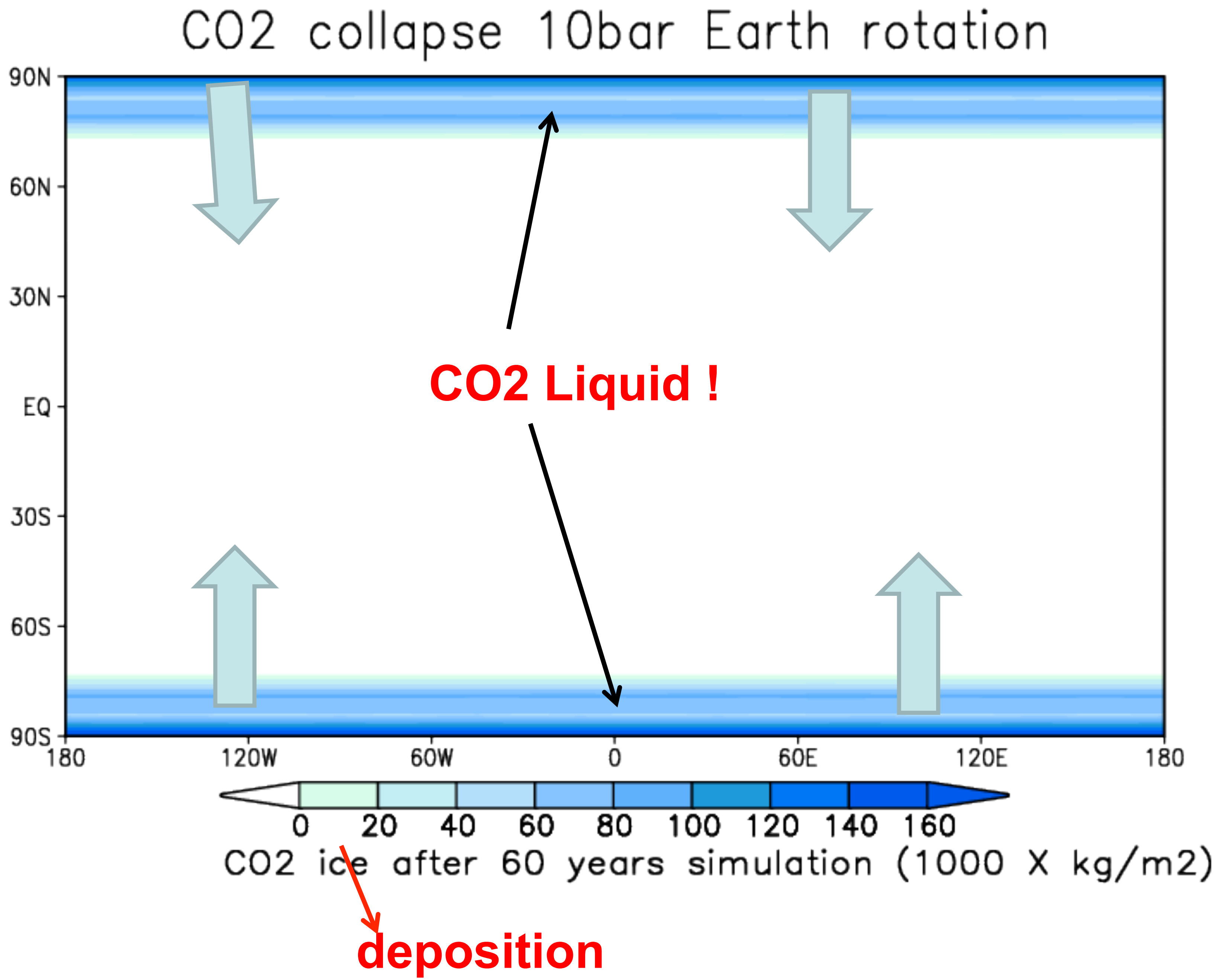
Mean Tsurf (C) Ps=10bar n12



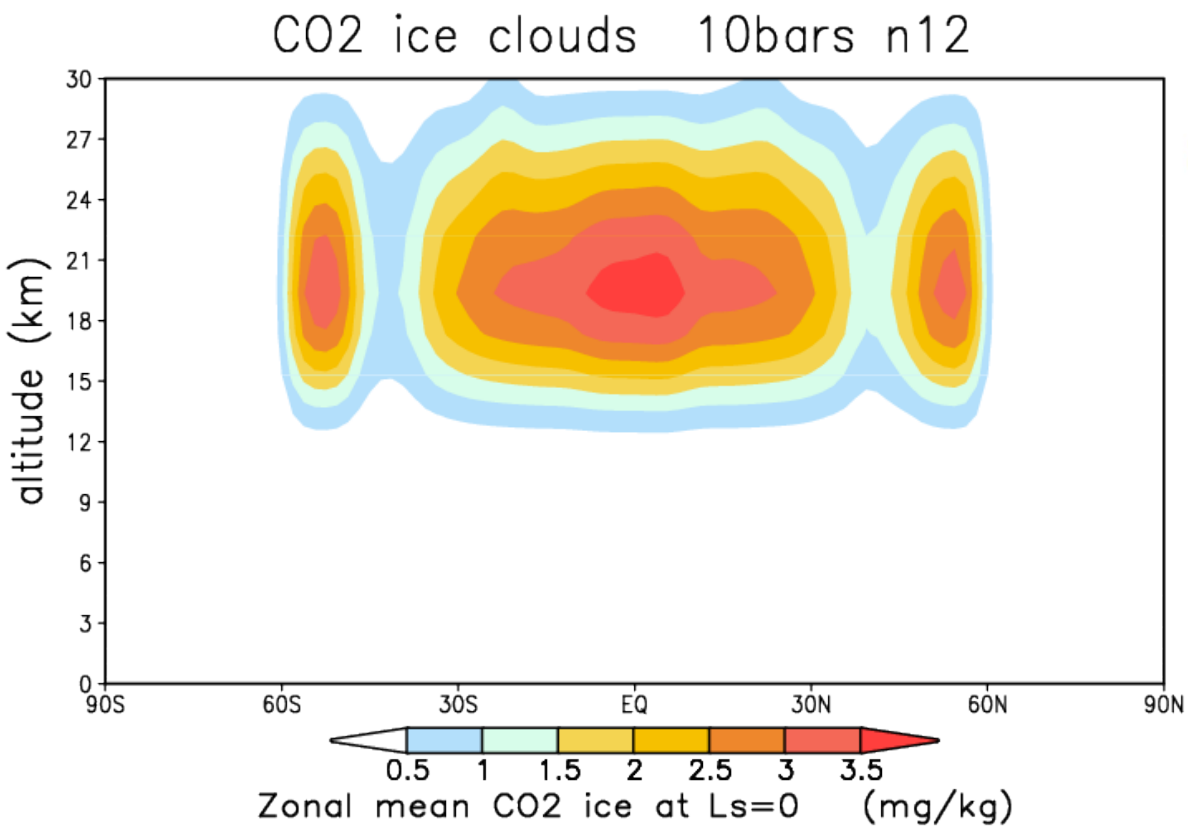
Earth-like rotation Gl581d Ps=10bar

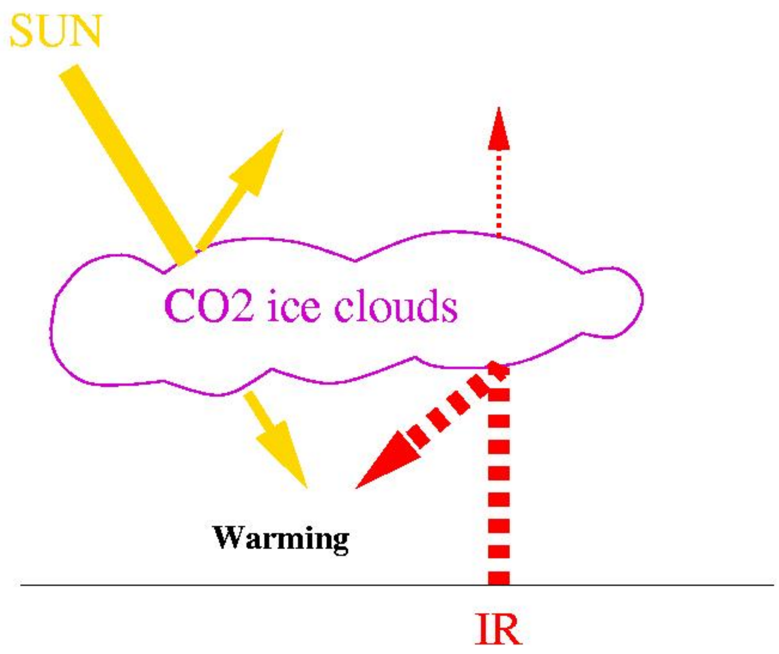
Mean Surface Temperature




CO2 collapse 10bar Earth rotation
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
CO2 Liquid !
0
20
40
60
80
100
120
140
160
CO2 ice after 60 years simulation (1000 X kg/m2)
deposition

(*Forget and Pierrehumbert 1997*)



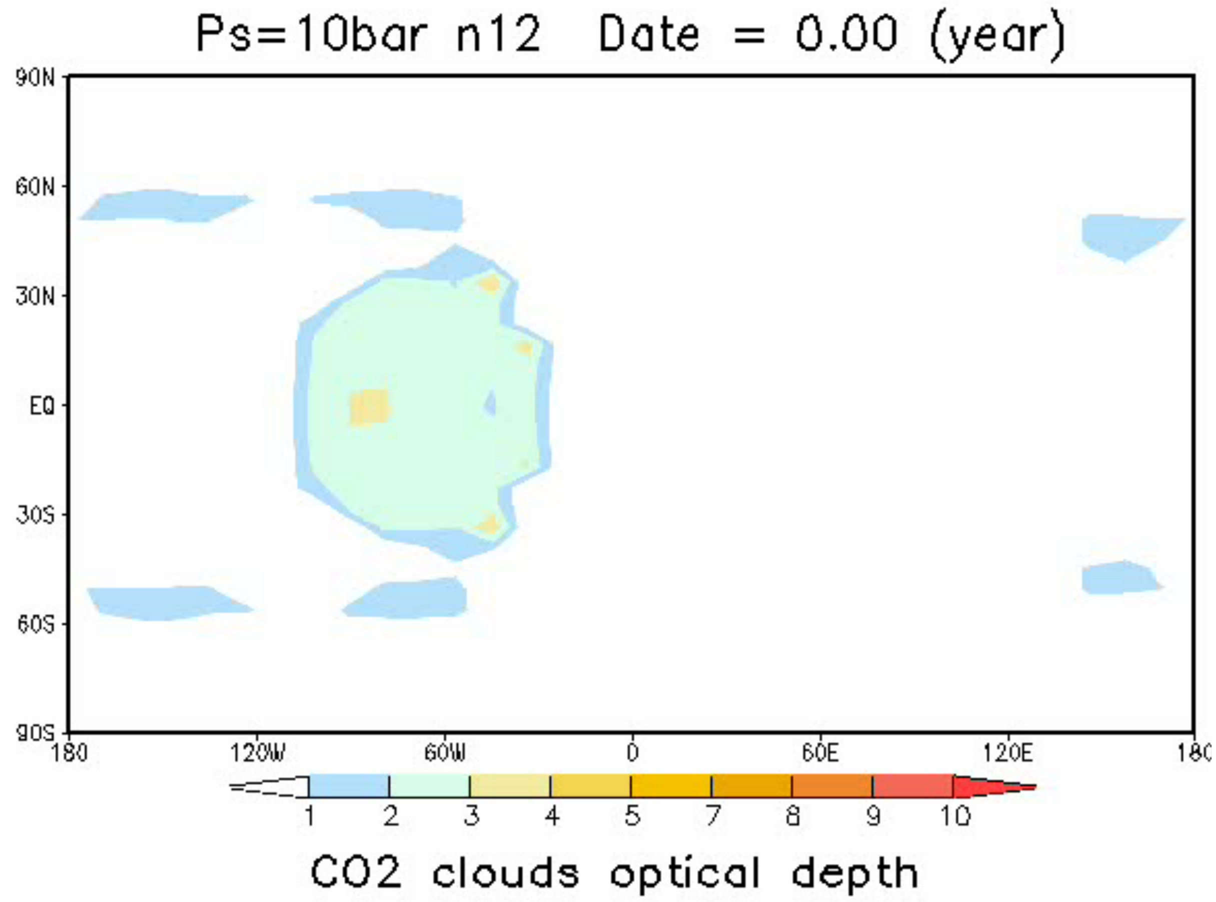


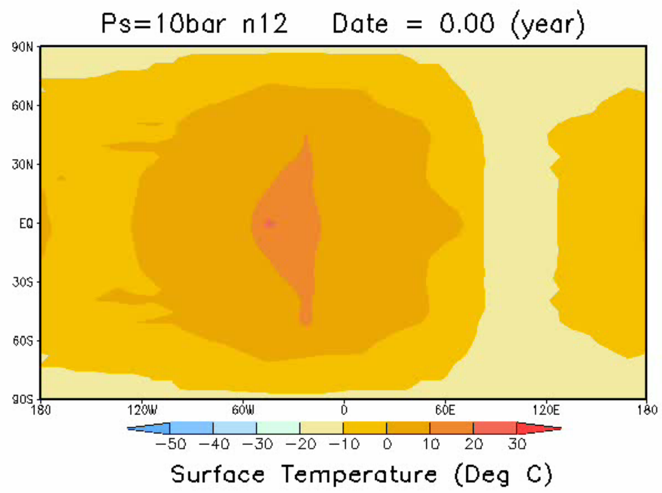
Simple CO_2 ice cloud scheme

1. In each model mesh: If T<Tcond : condensation and latent heat release ⇒ T=Tcond
2. CO_2 ice is splitted in small particles (The number of particle / kg is prescribed)
3. Transport and mixing by winds, turbulence, convection
4. Gravitional sedimentation
5. Interaction with Solar and IR radiation (assuming Mie theory and Hansen et al. (1996) radiative properties
6. If T>Tcond : sublimation to get T=Tcond or no more ice

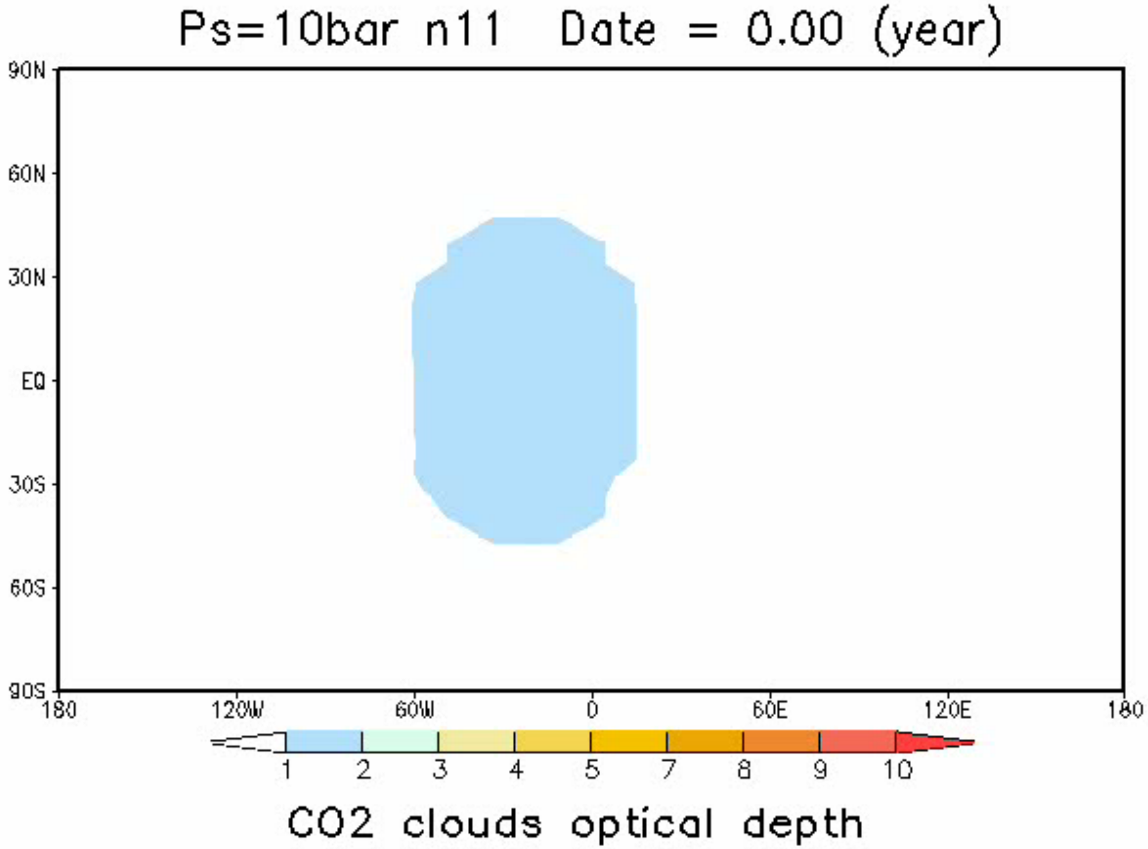
CO2 ice clouds maps: Res 2/1 gl581b

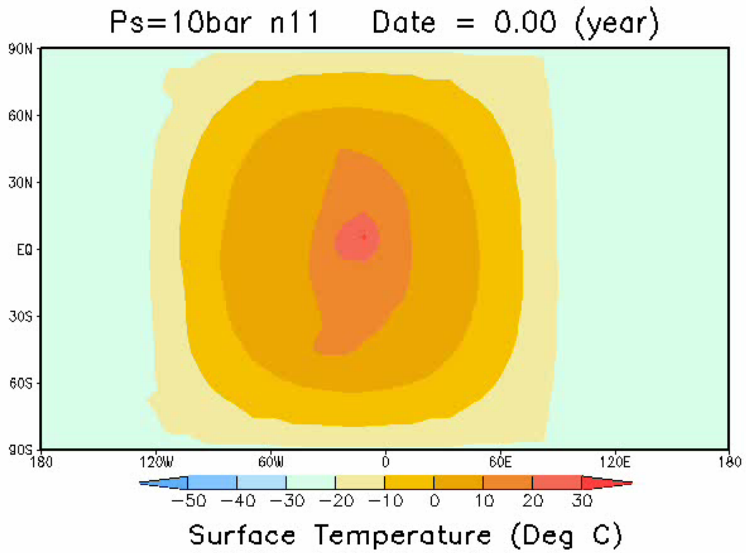
Ice condense in ascendance (adiabatic cooling)





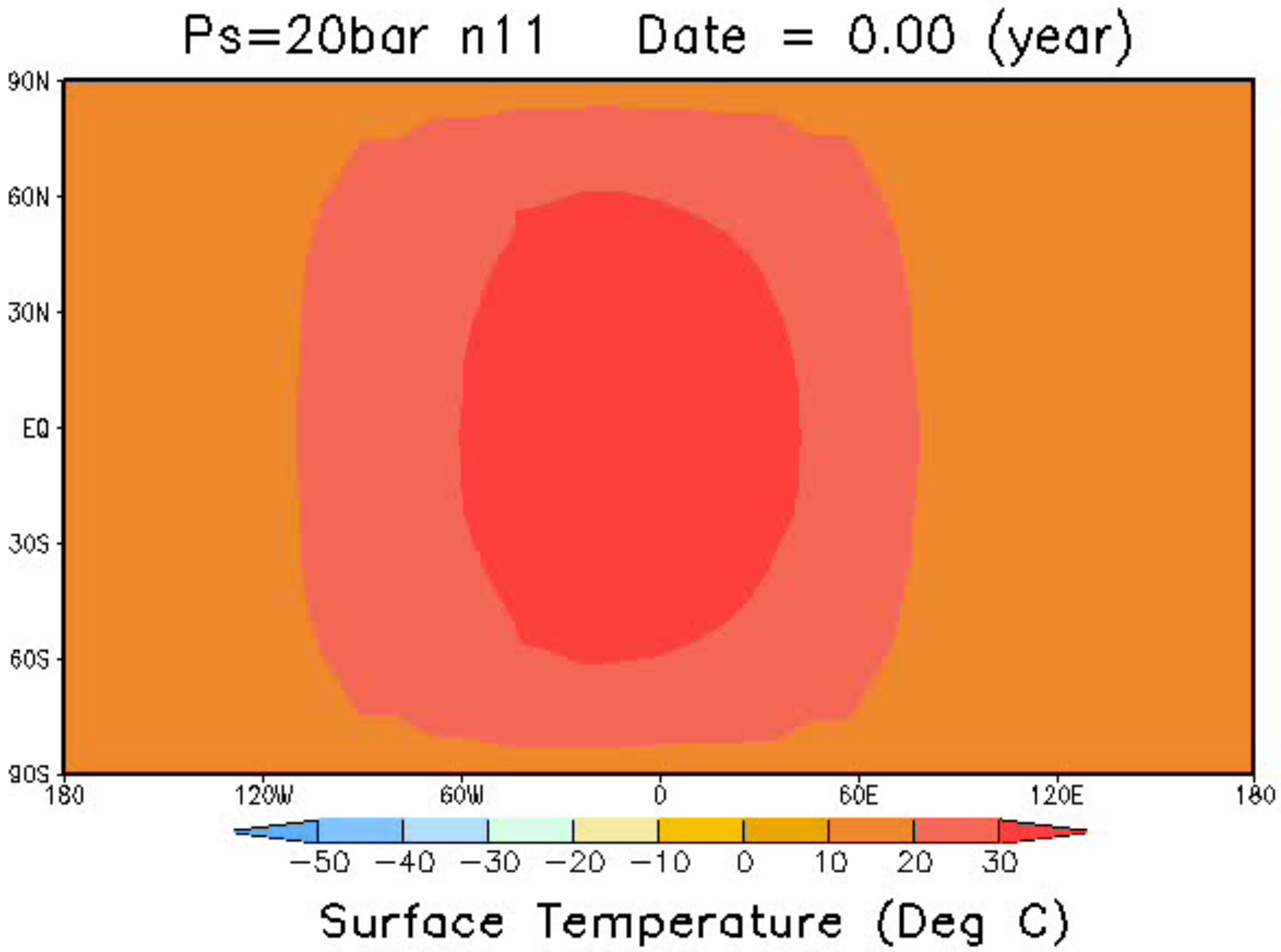
CO2 ice clouds maps: tidal locked gl581b





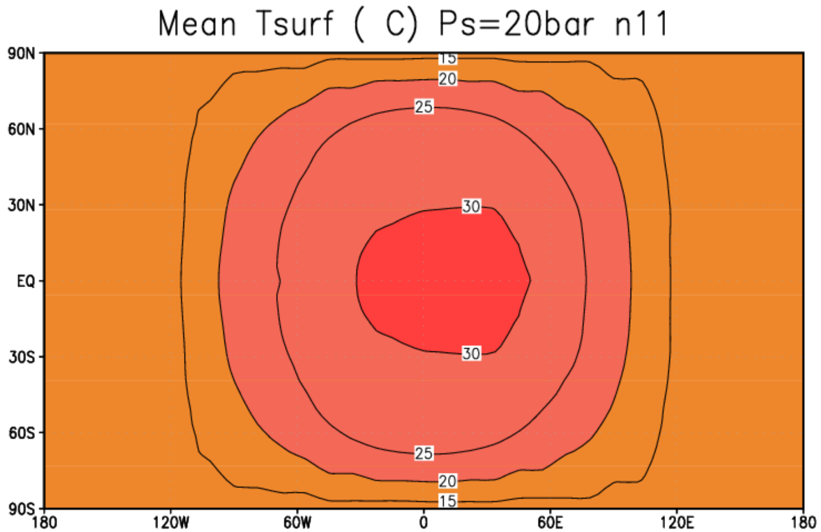
Tidal locked Gl581d Ps=20bar

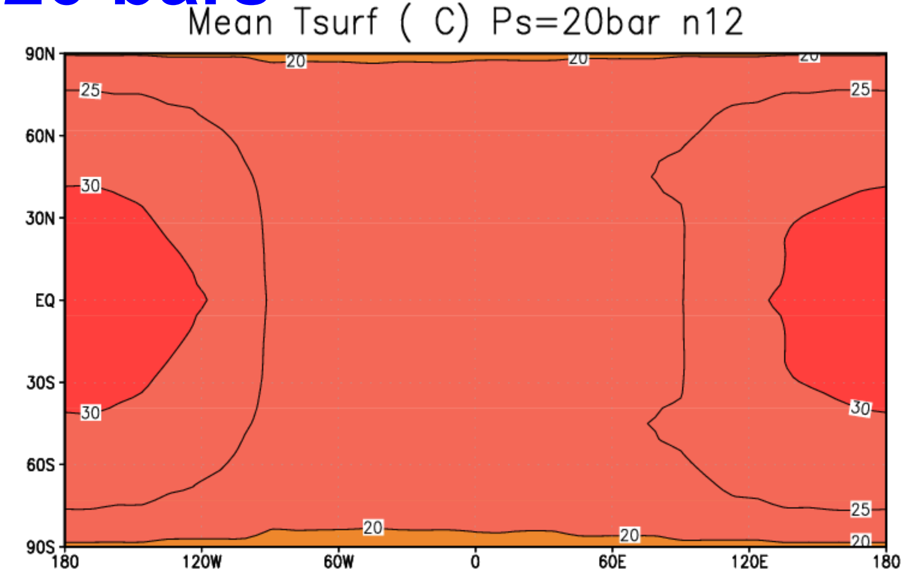
Surface Temperature

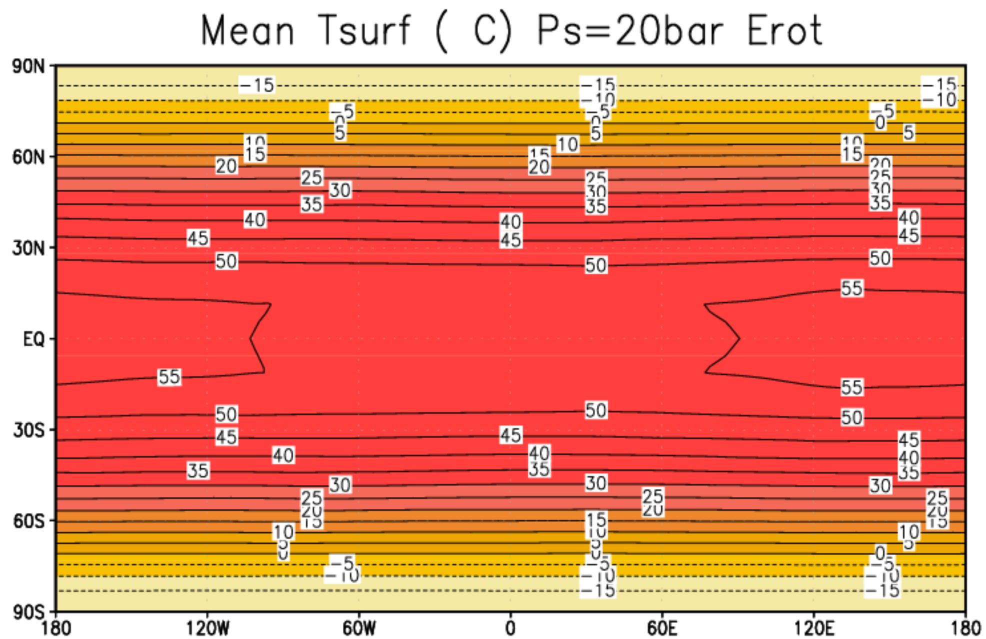


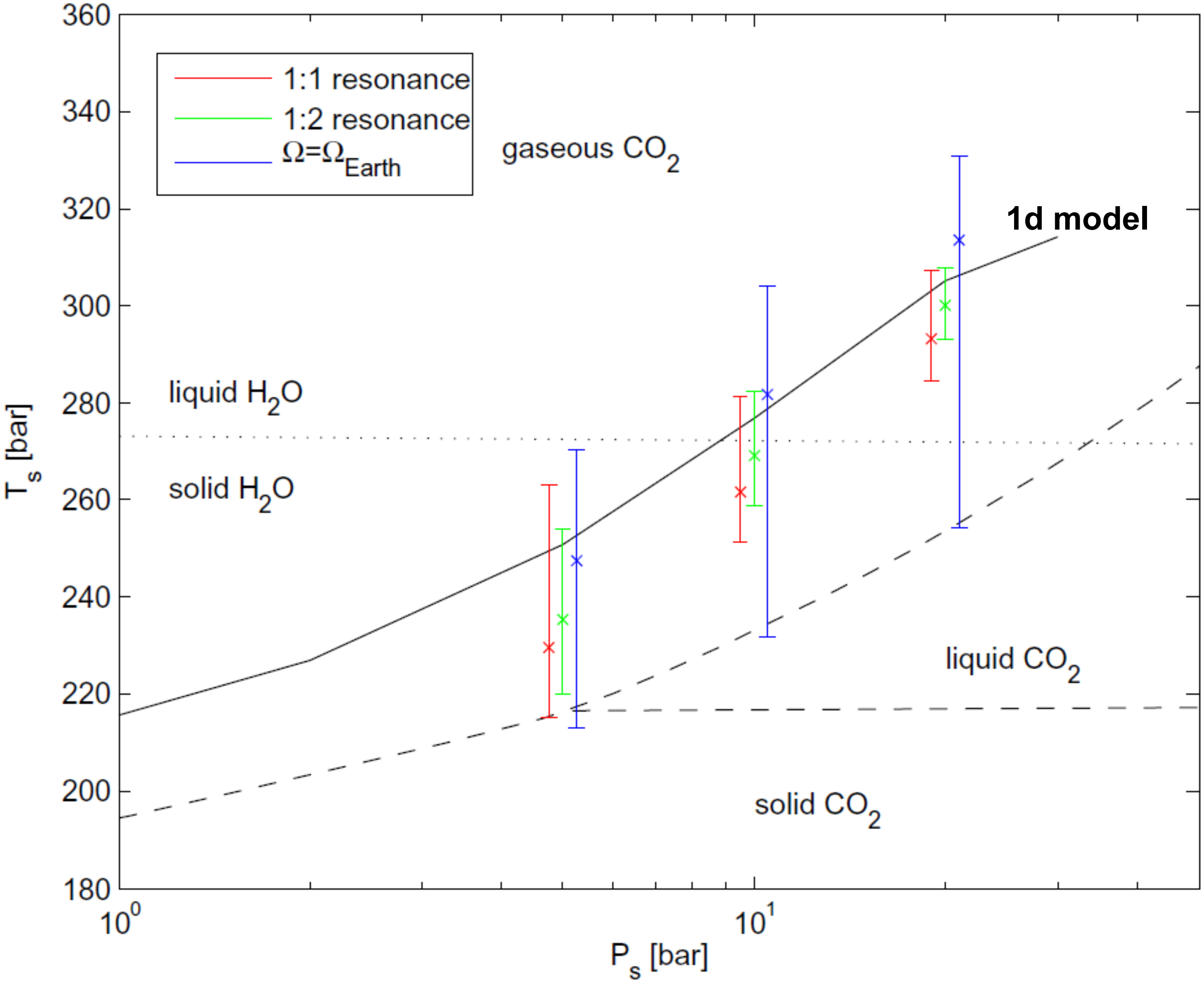
Mean surface temperature (No atmospheric CO_2 collapse)

20 bars





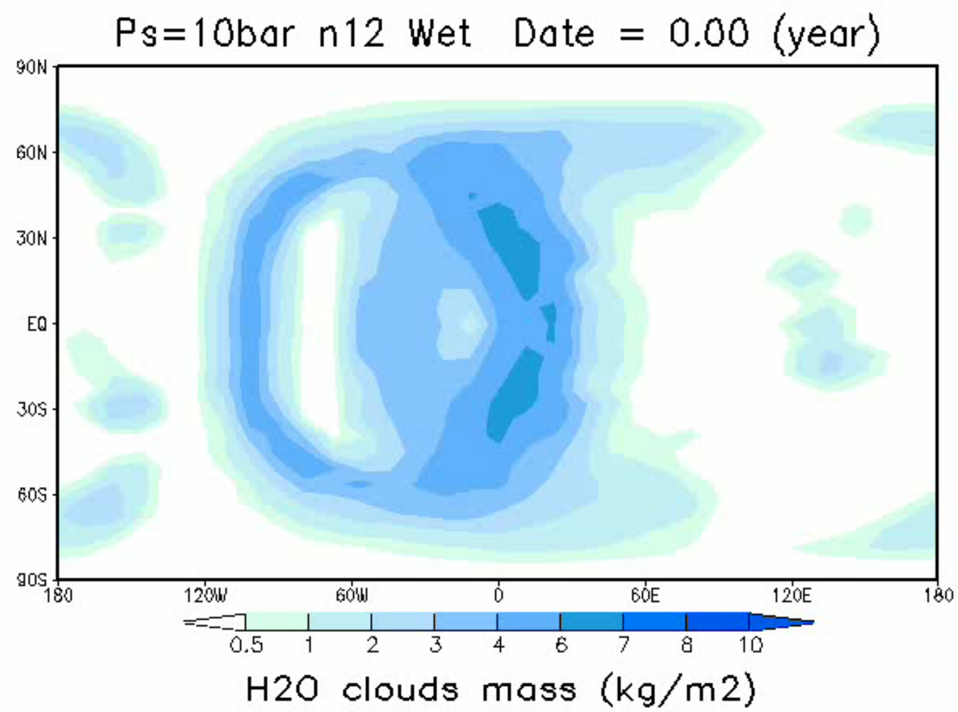


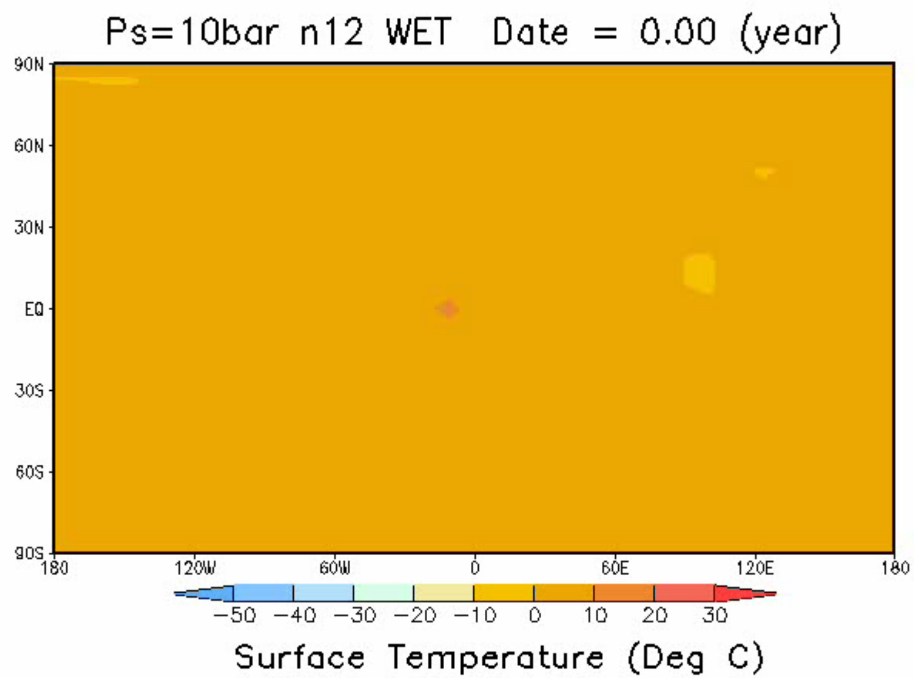


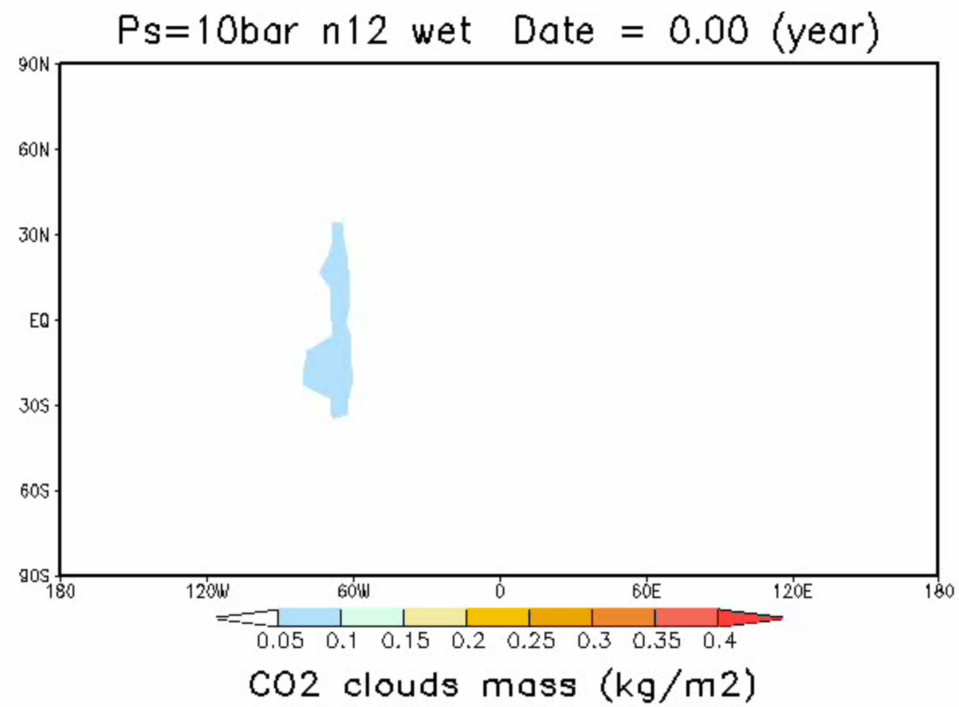
1:1 resonance
1:2 resonance
Ω=Ω_Earth
gaseous CO2
1d model
liquid H2O
solid H2O
liquid CO2
solid CO2
T_s [bar]
P_s [bar]
360
340
320
300
280
260
240
220
200
180
10^0
10^1

Including the water cycle: Preliminary results

(assuming an ocean planet)

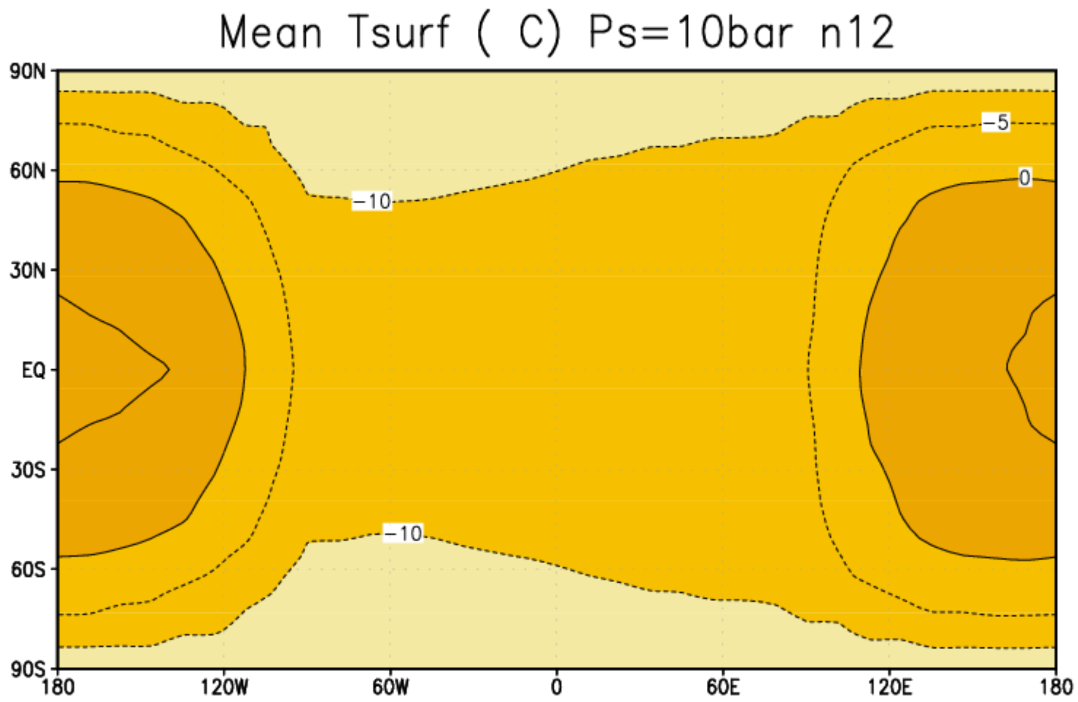




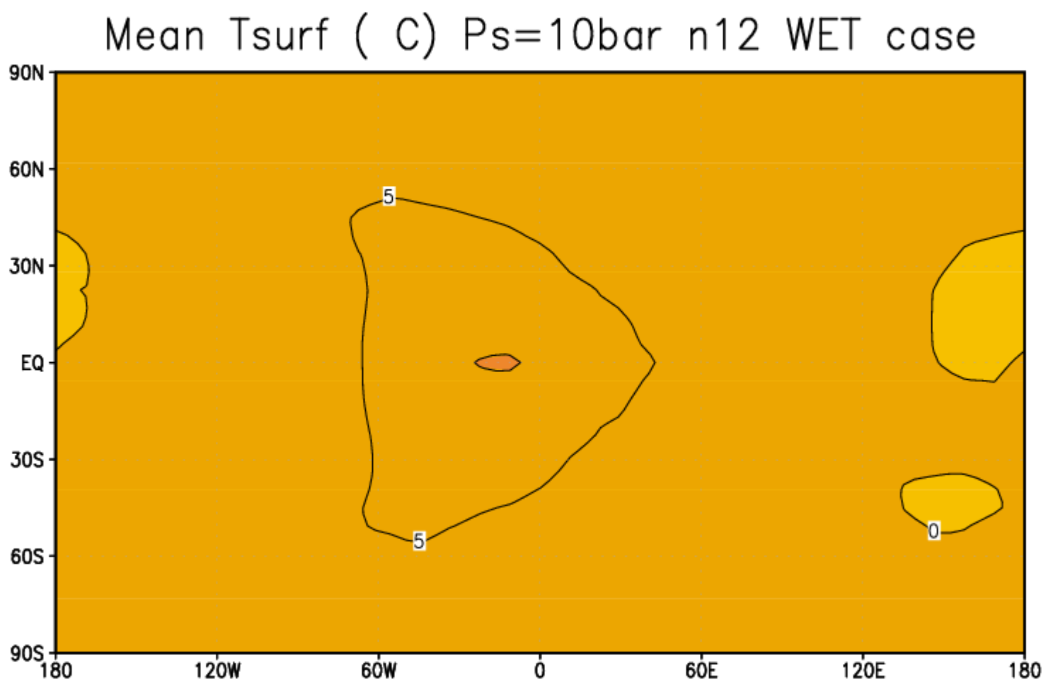


Including the water cycle: Preliminary results

Dry case



Water cycle case

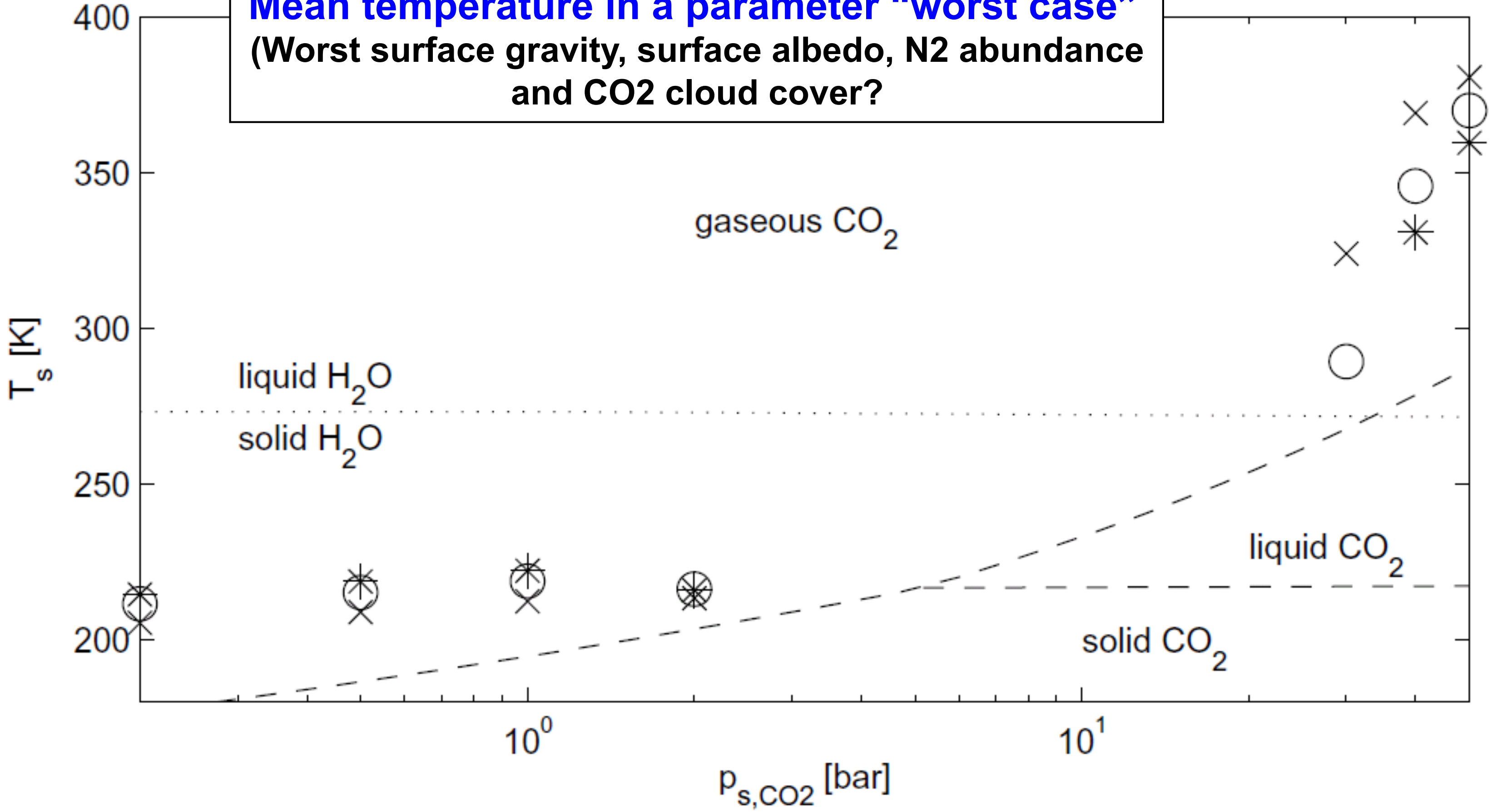


- Net warming
- No glaciation with Ps > 10 bars

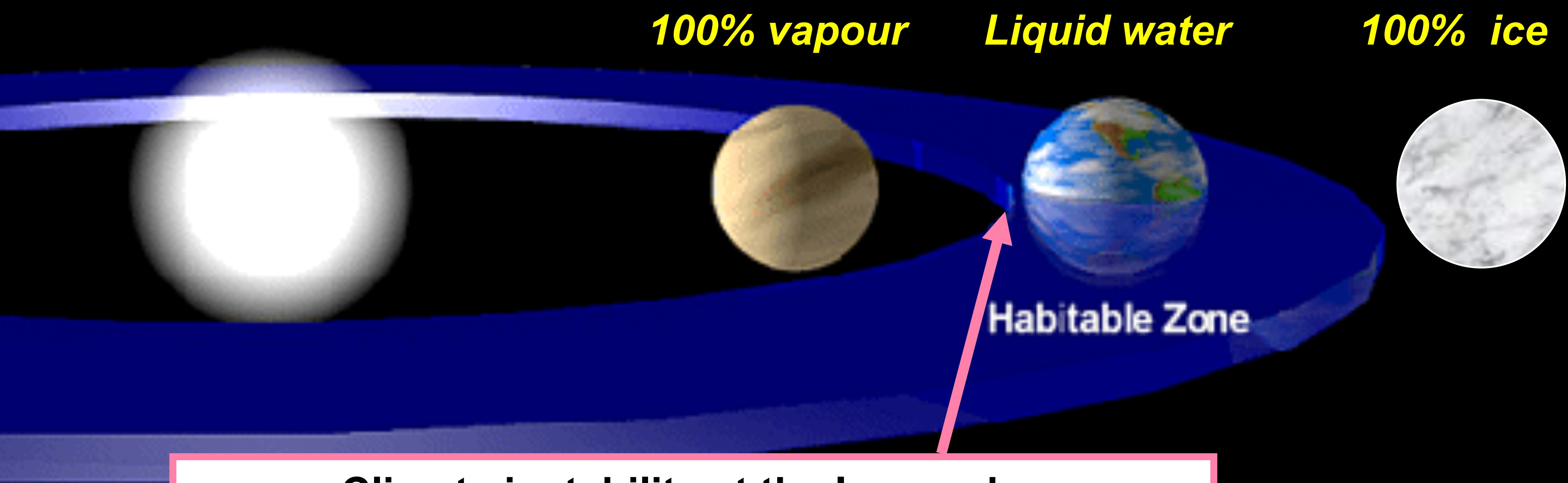
Gliese 581d: conclusions

We may be able to demonstrate that, assuming enough CO2 and H2O (which is not unlikely), the planet WOULD be habitable.

Mean temperature in a parameter "worst case"
(Worst surface gravity, surface albedo, N2 abundance and CO2 cloud cover?



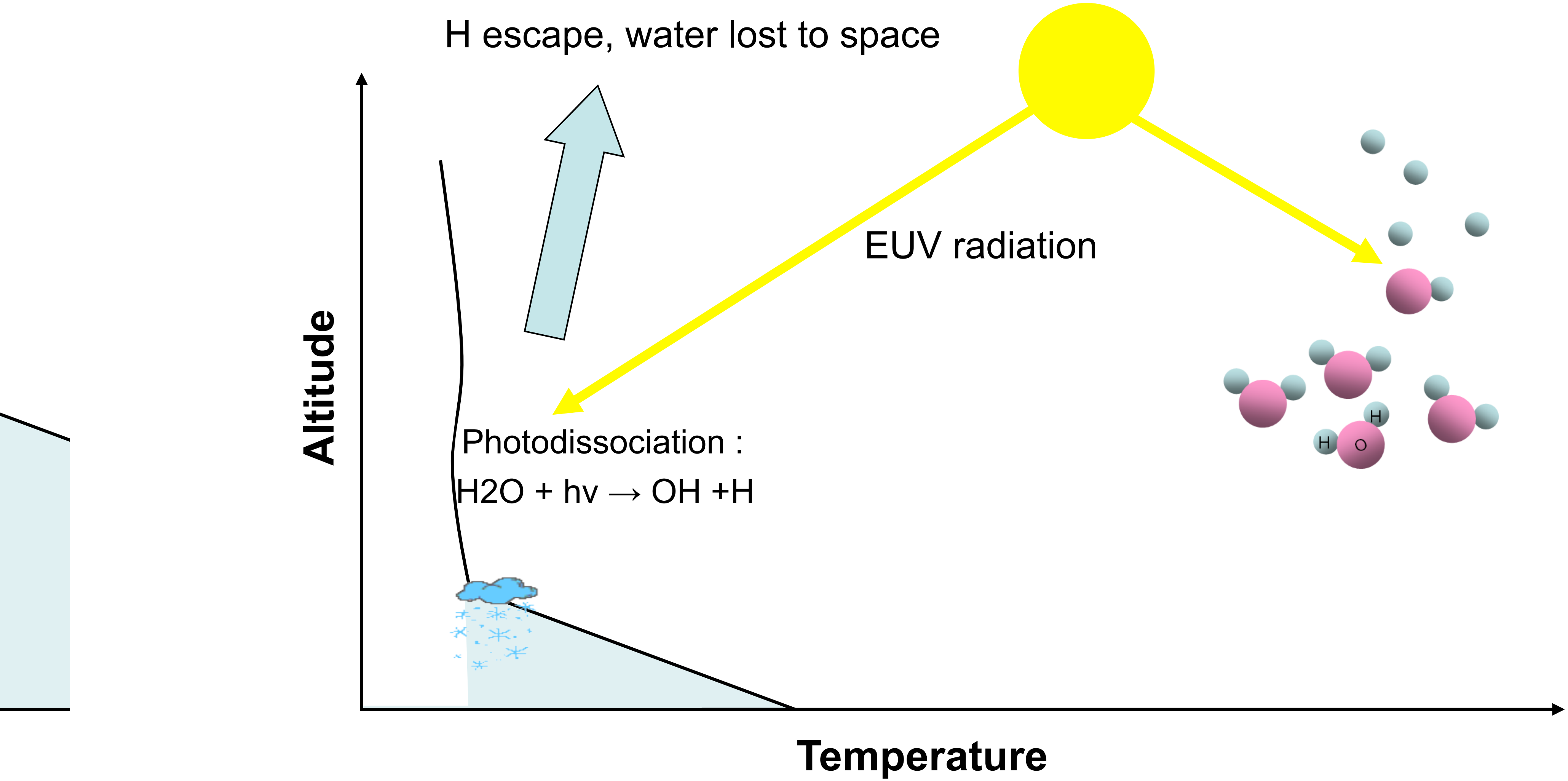
3D GCM on the hot side



Climate instability at the Inner edge

Solar flux ↑ → **Temperature ↑** → **Evaporation ↑** → **Greenhouse effect ↑** → **Temperature ↑**

Impact of temperature increase on water vapor distribution and escape



Inner Edge of the Habitable zone from 1D model

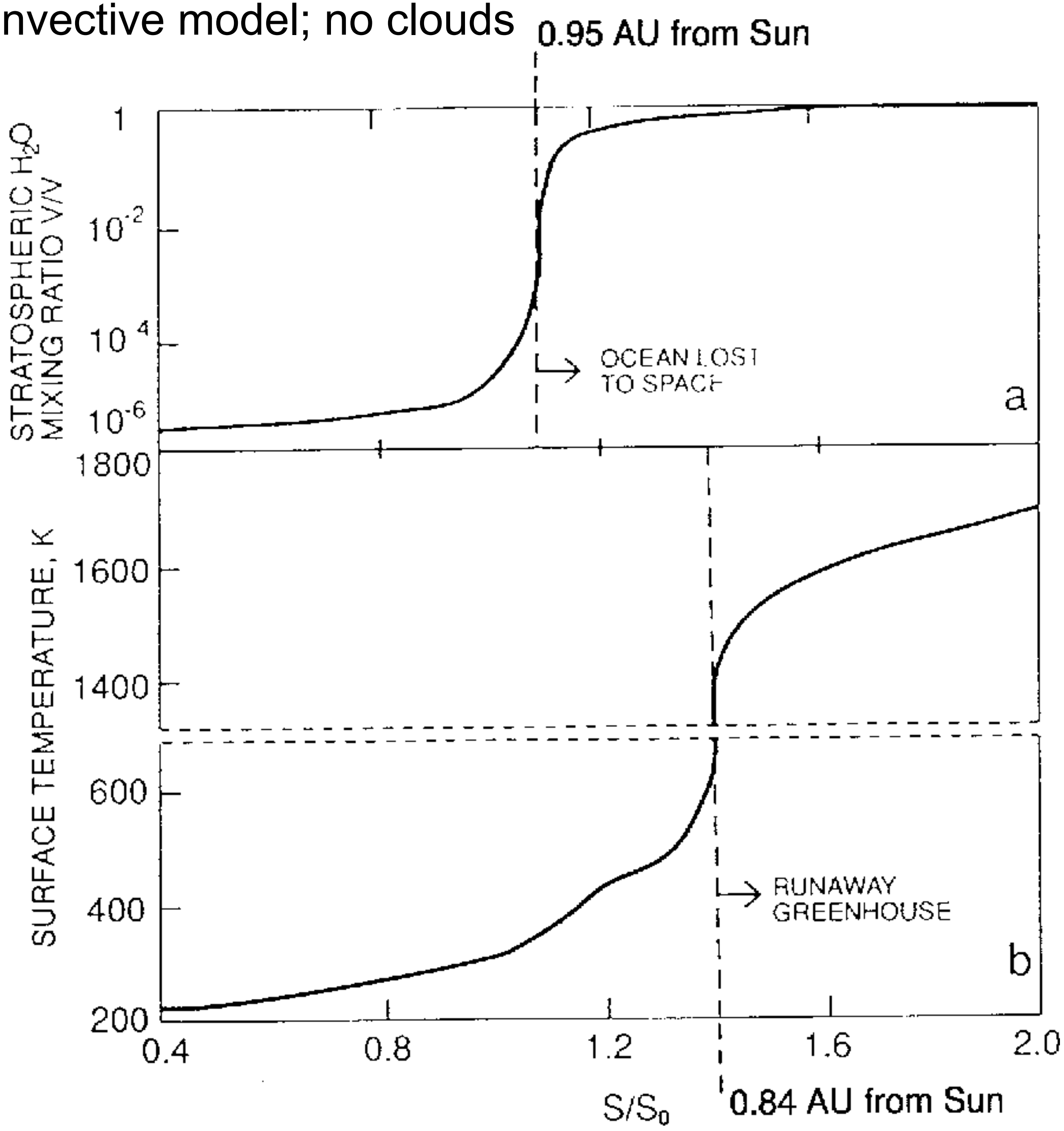
Kasting et al. 1D radiative convective model; no clouds

Water loss limit

Runaway greenhouse limit

H2O critical point of water reached at Ps=220 bar, 647K

protection by clouds:
Can reach 0.5 UA assuming 100% cloud cover with albedo =0.8 ?



Hot *dry* planets modeled with a 3D GCM

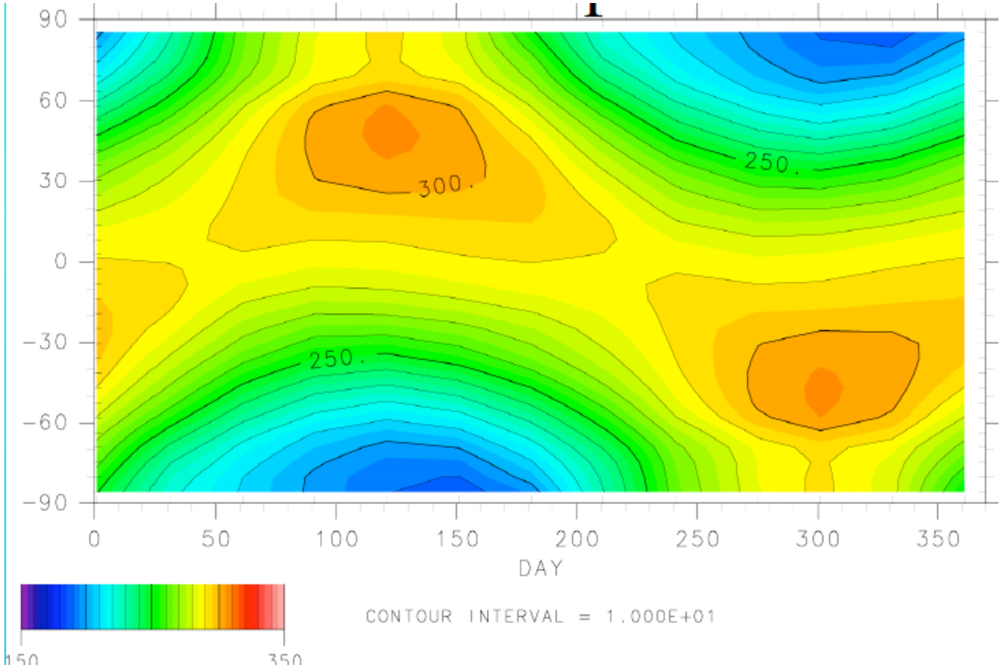
Stolen from Pr. Yutaka Abe, A. Abe-Ouchi, and K. Zahnle

Ocean planet and Land planet

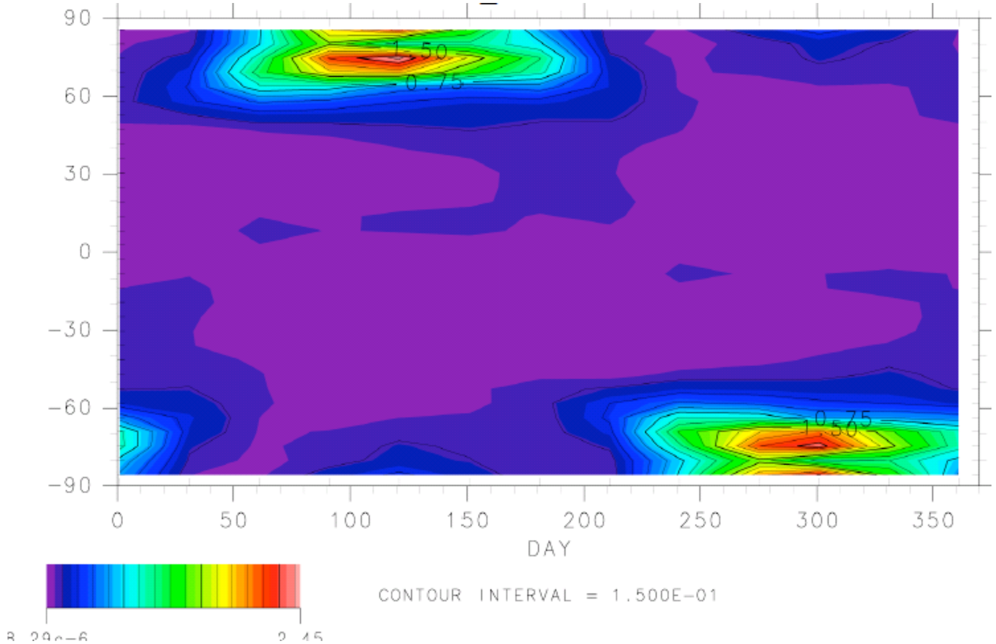
Aqua Planet (ocean planet):
A planet with a globally wet surface.
Precipitation and evaporation are not in balance
Earth like
Land Planet:
A planet on which the surface water distribution is dominated by the atmospheric circulation (Abe et al., 2005).
Precipitation and evaporation are in balance
Scattered lake, large desert
Dune planet (Herbert, F. (1965) *Dune,)*
Titan, ancient Mars?

Example of dry land planet (at 1AU)

Surface Temperature

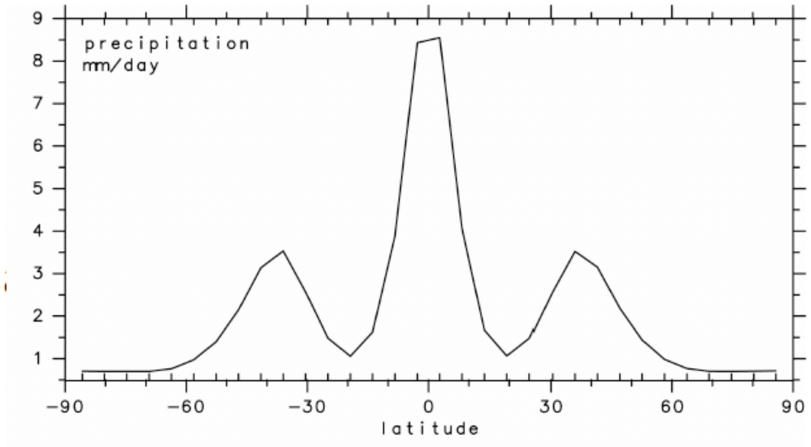


Precipitation

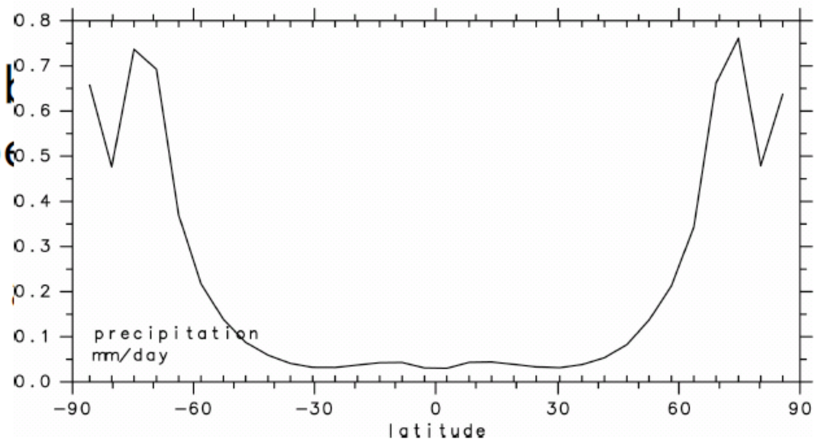


Ocean planet and Land planet

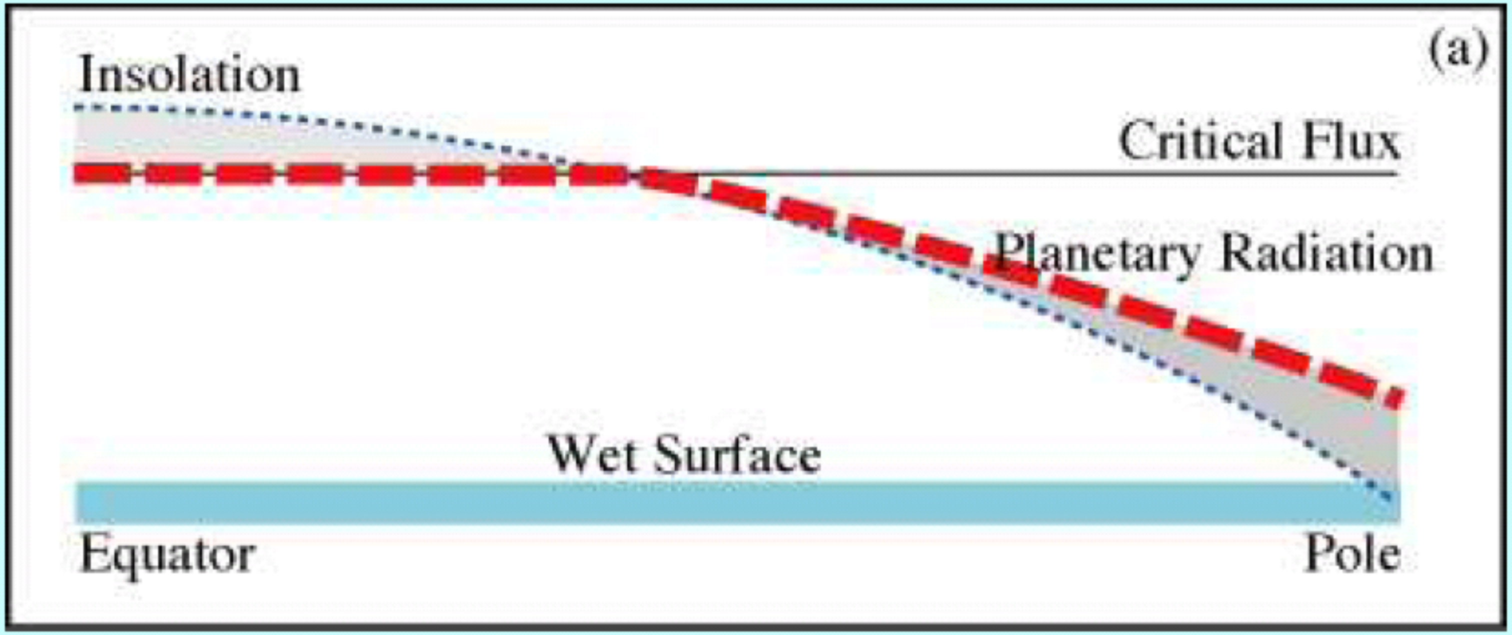
- Water Planet (ocean planet):
- A planet with a globally wet surface.
- Precipitation and evaporation not in balance



- Land Planet:
- A planet on which the surface water distribution is dominated b the atmospheric circulation (Abe al., 2005).
- Precipitation and evaporation in balance



Runaway greenhouse of an ocean planet

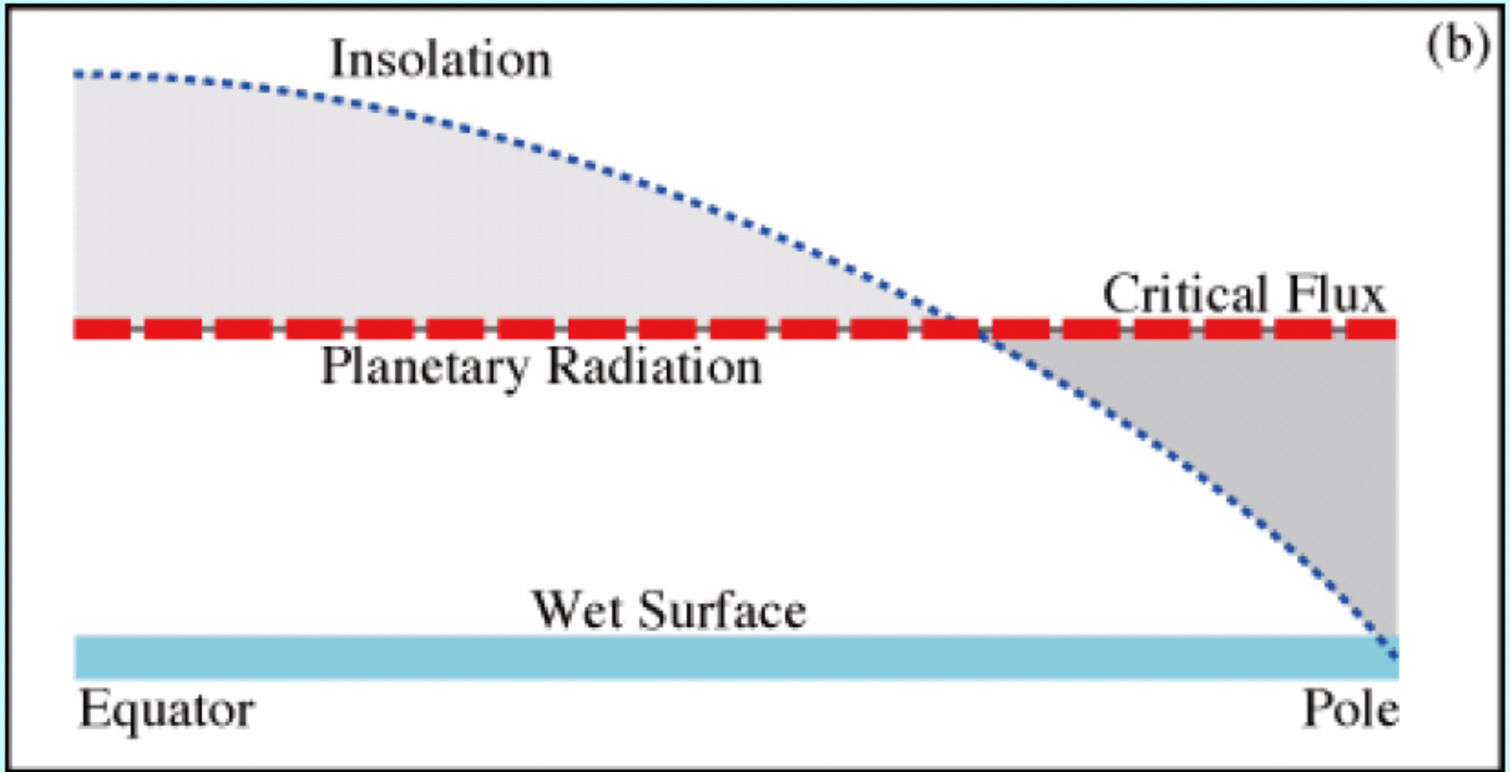


Global average insolation below the critical flux

Even if the insolation at the low latitude is above the critical ,
High latitude emits the excess

Present Earth is in this state

Runaway greenhouse of an ocean planet

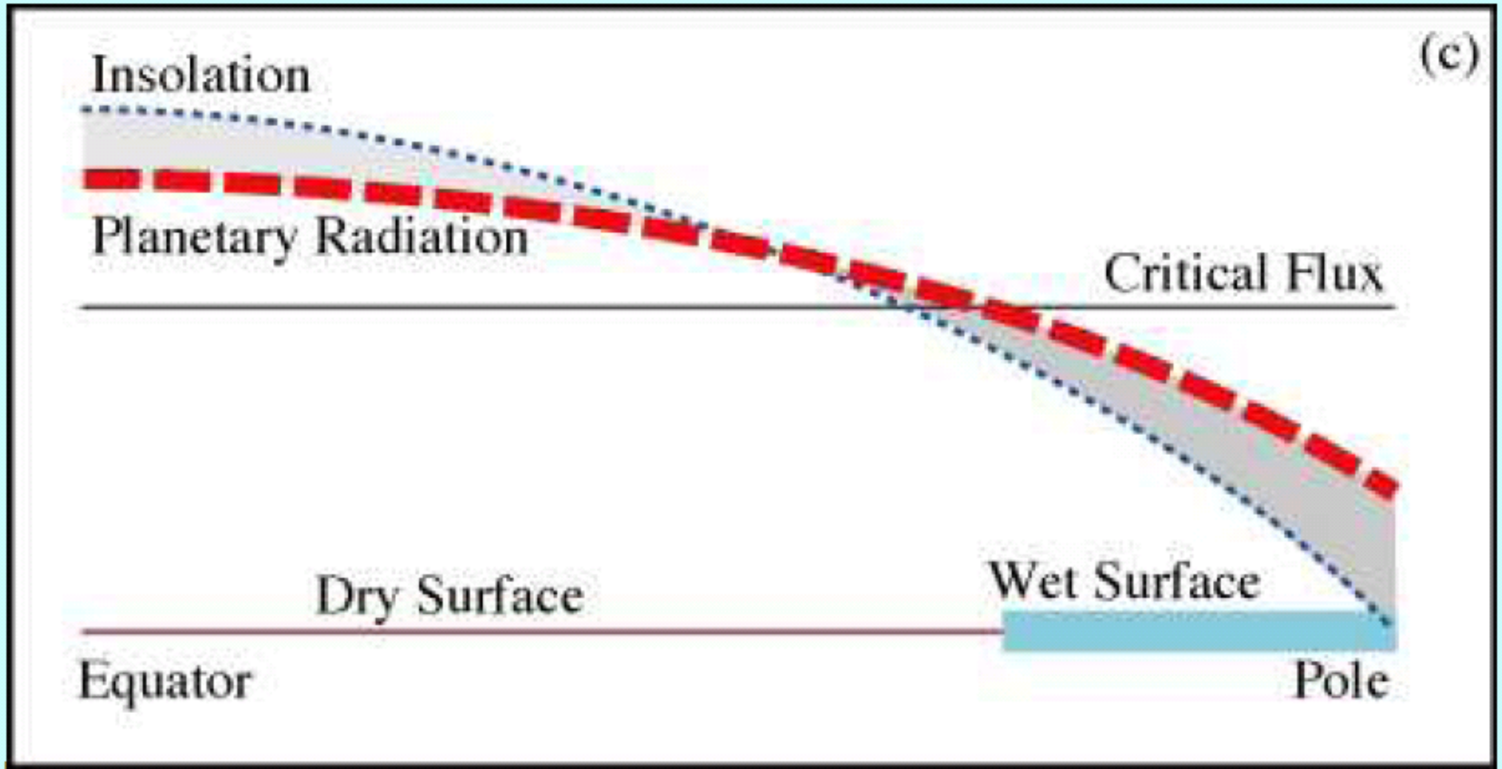


Global average insolation above the critical flux

Planetary radiation cannot exceed the critical
Energy balance cannot be achieved

Runaway

Runaway greenhouse of a land planet



Global average insolation above the critical flux

Dry low latitude can emit above the critical ,
High latitude is below the critical

Water can exist at high latitude

Some idealized GCM experiments by Professor Abe

Model

A general circulation model, CCSR/NIES AGCM 5.4g (T21L11 and T21L20) (Numaguti, 1999)

An Earth-sized planet with 1 bar air atmosphere on a circular orbit.

Fixed CO_2 concentration. (345 ppm)

Spin period (= a "day") is 24 hours

Revolution period around the Sun (= a "year") is 360 days.

Obliquity =0 °

Land Planet:

Surface paremters of desert (ground albedo 0.3), No topography.

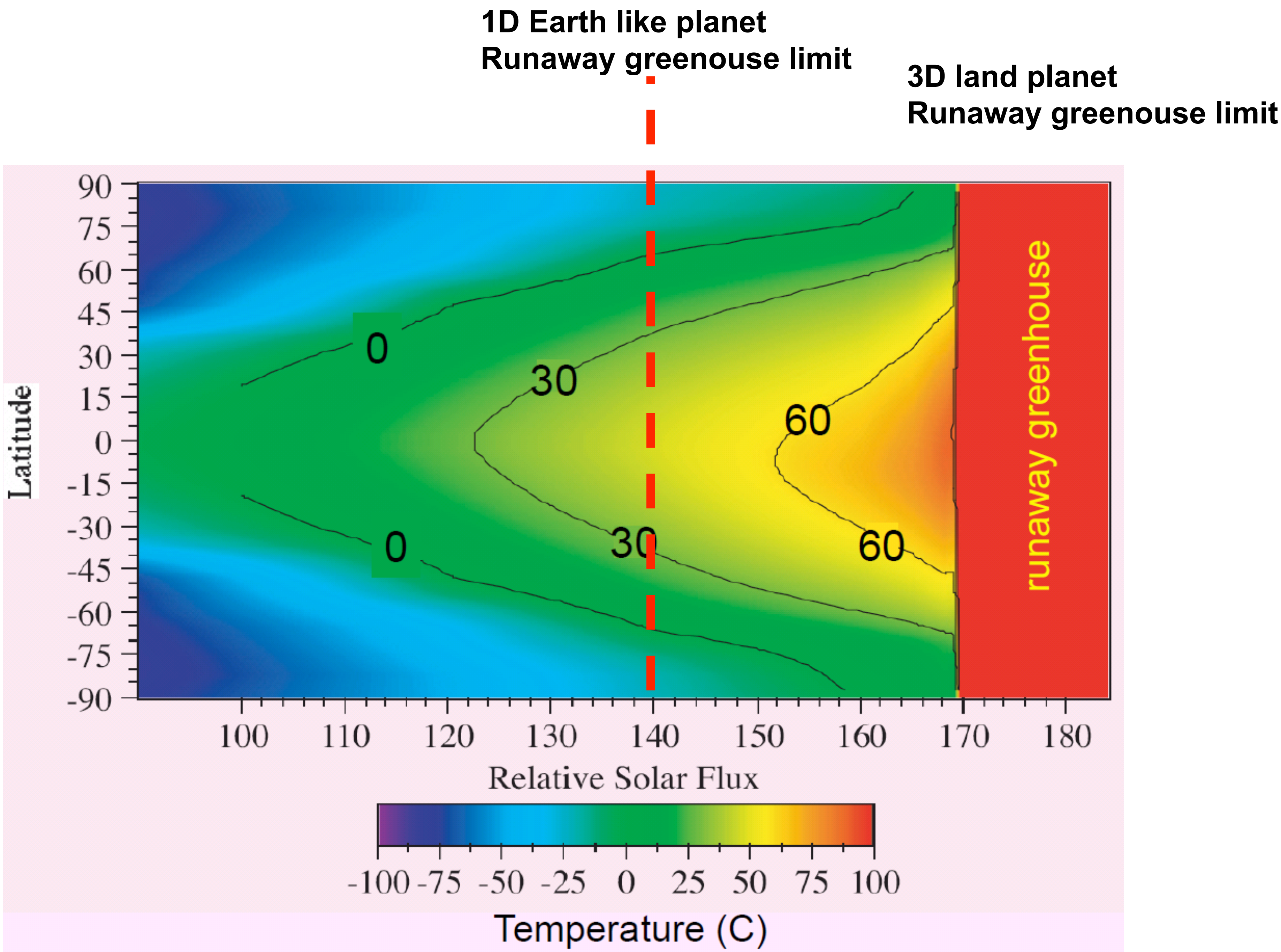
A bucket model with the saturation depth of 10 cm

No ground water transport: atmospheric controll of water distribution

Ocean Planet:

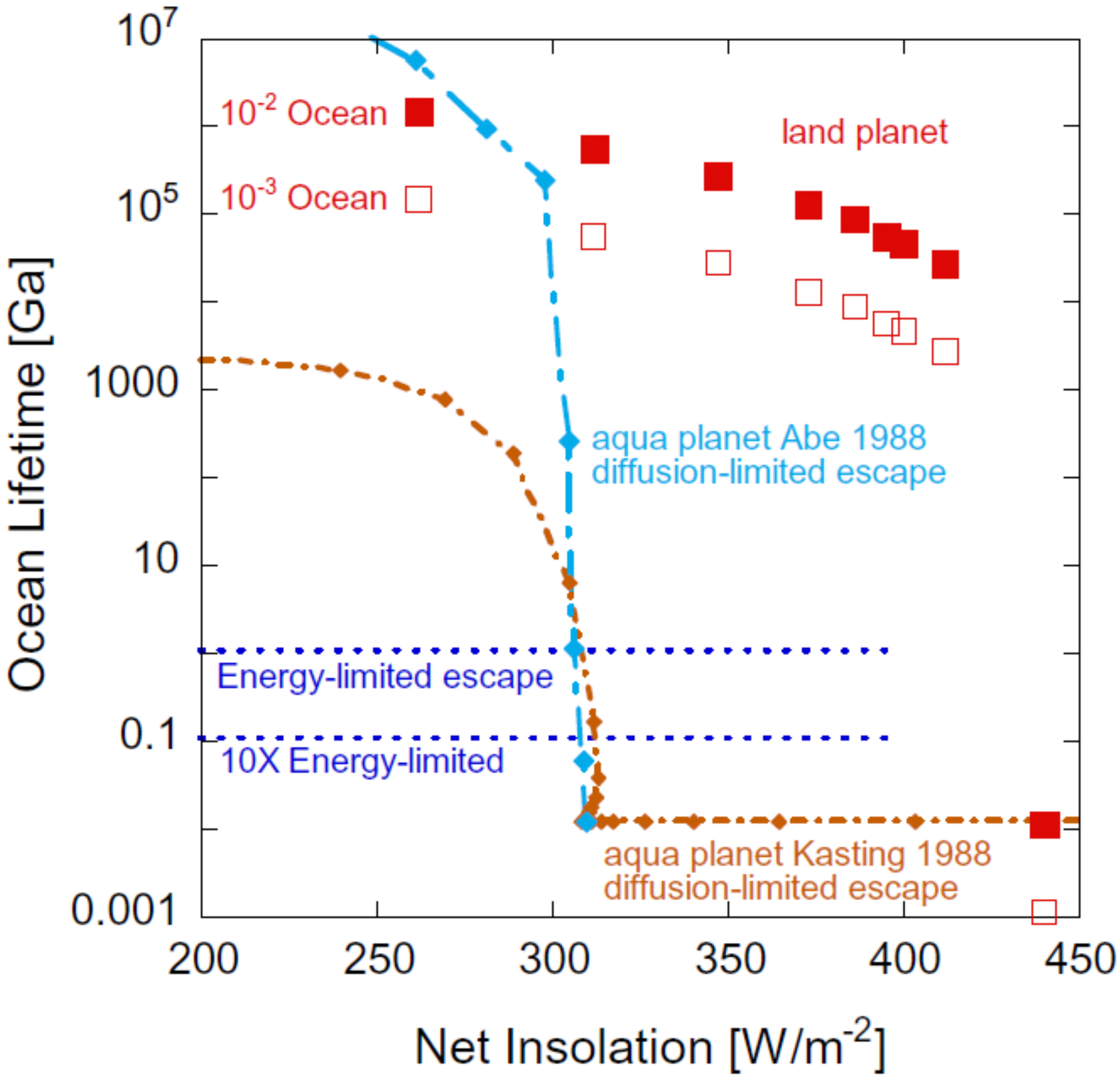
50m slab ocean

More than 100 cases are examined with various solar flux.



1D Earth like planet
Runaway greenouse limit
3D land planet
Runaway greenouse limit
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
Latitude
0
30
60
0
30
60
runaway greenhouse
100
110
120
130
140
150
160
170
180
Relative Solar Flux
-100 -75 -50 -25 0 25 50 75 100
Temperature (C)

Water loss limit:



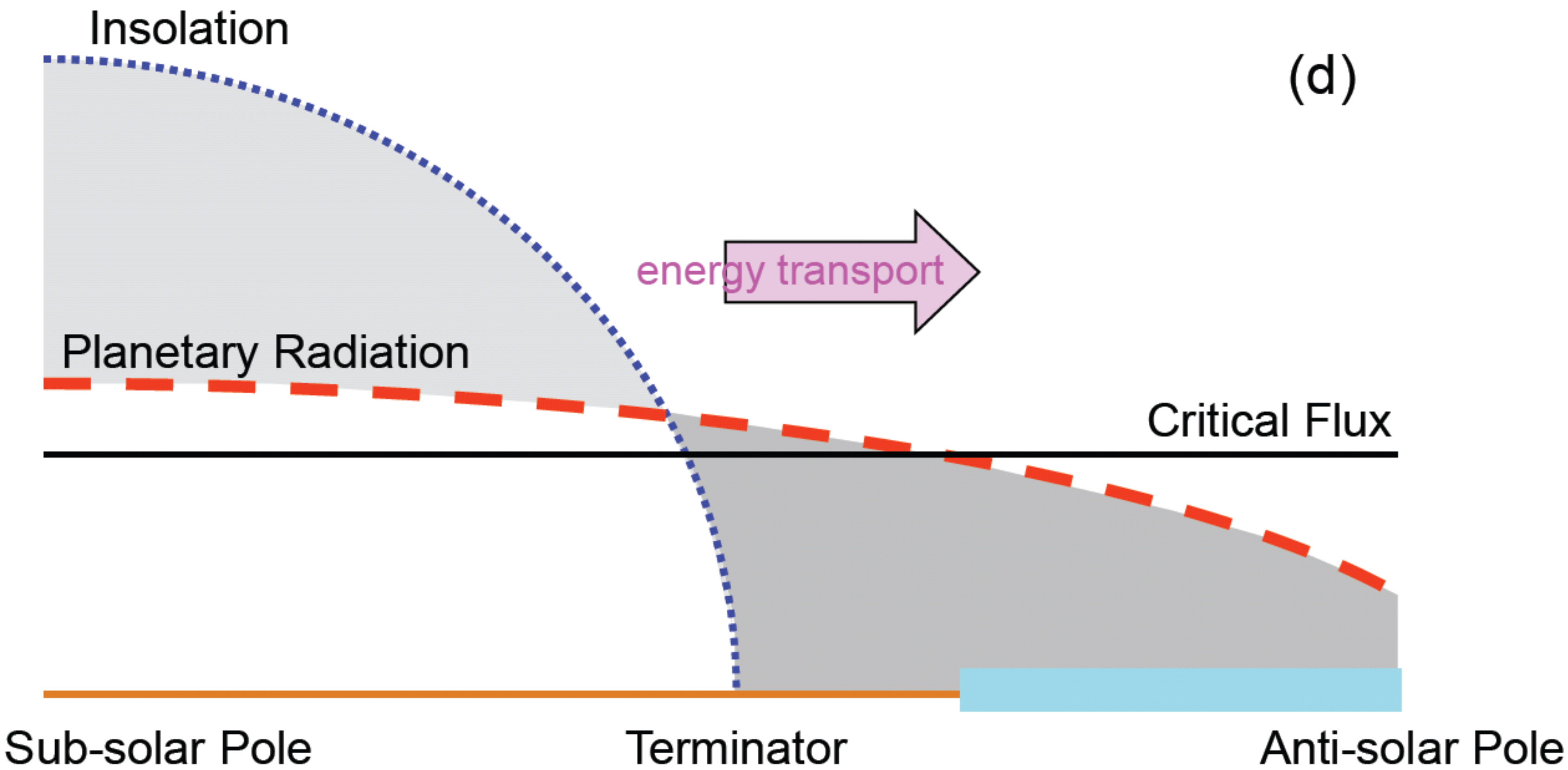
Upper atmosphere of land planet remains dry

H escape is inhibited

The lifetime of water on the surface of the land planet is longer than that of the aqua planet

⇨Stabilizing feedback

Early Venus ?



A dry synchronous M-dwarf planet is another form of land planet: the dry hemisphere radiates away most of the sunlight

Some Conclusions

- ***Assuming atmosphere/ocean compositions***, robust, "complete" GCMs/Planet simulators may be developed to address major scientic questions related to extrasolar planets :
  - Limits of habitability
  - Could such and such planet be habitable. Example: Gliese 581b
  - Prepare observations (e.g. F. Selsis today)
- However, whatever the quality of the model, heavy study of model sensitivity to parameters will always be necessary.
- **The key scientific problem may be to understand the zoology of atmospheric composition and long term evolution…**
- **To be continued…**