# Exploring planetary atmospheres with numerical modeling

Aymeric SPIGA

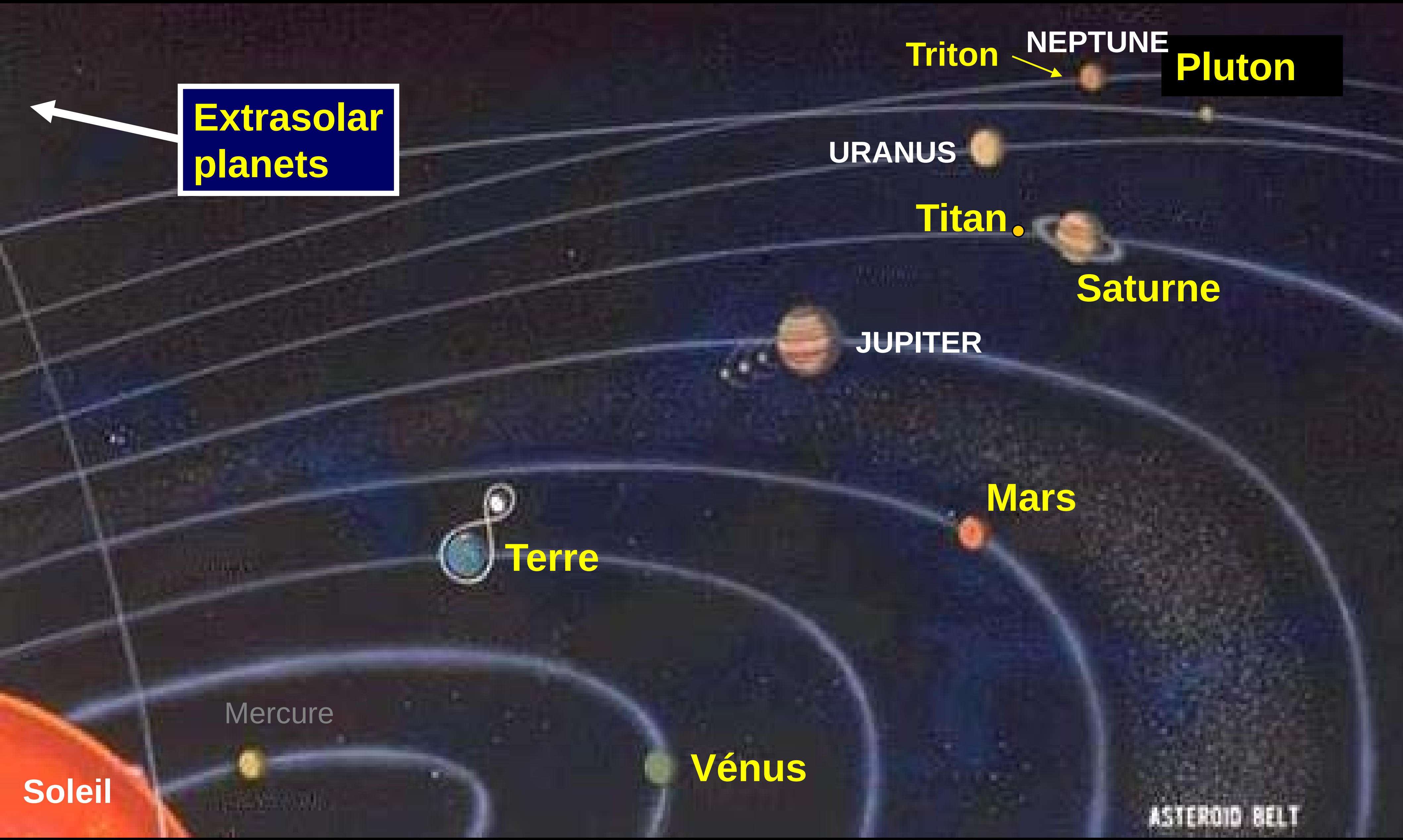
… on behalf of the
LMD planetary group

# Meet the LDM team

102 « peer-reviewed » papers between 2007 and mid-2012

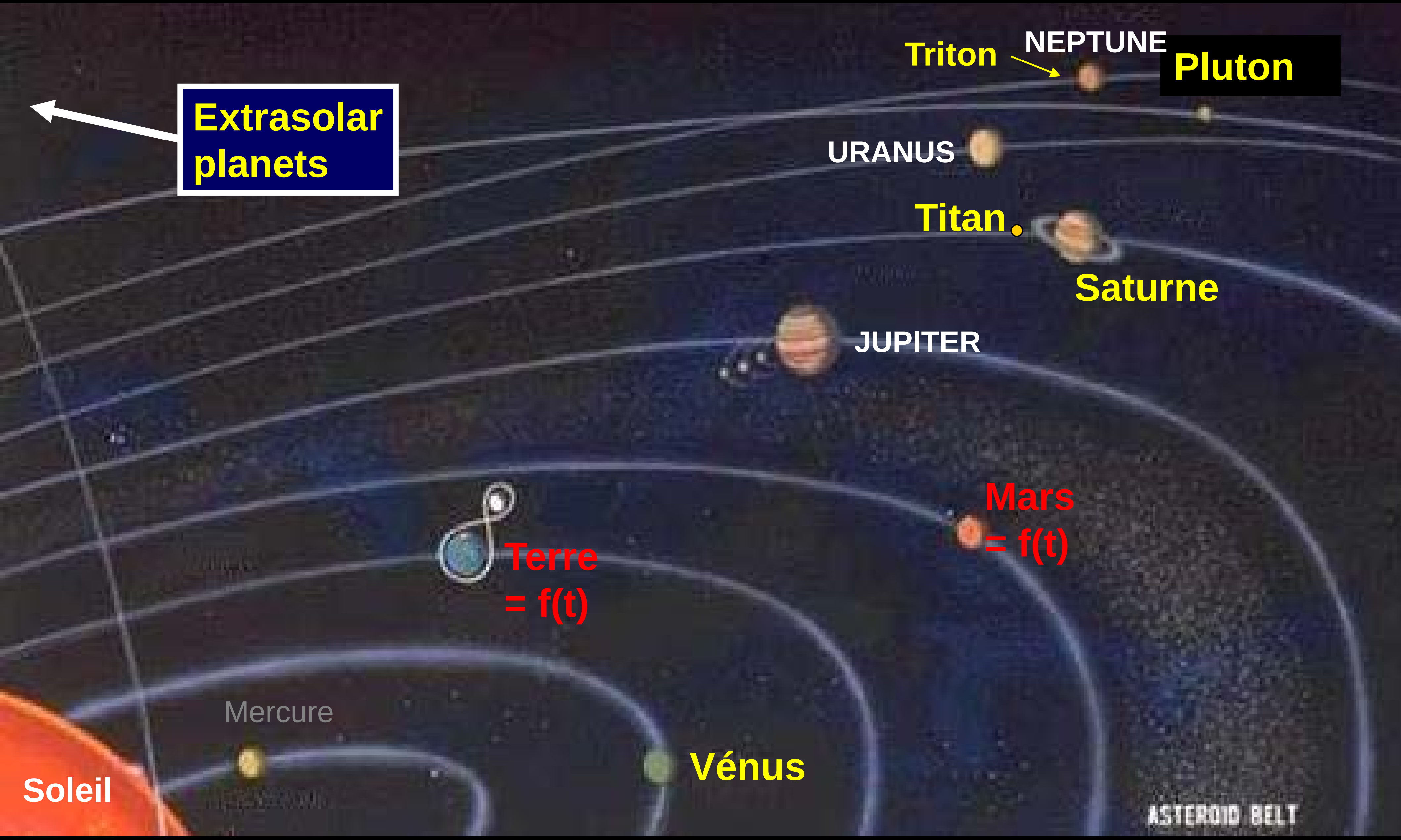
- **4.5 permanent scientists**
  - François Forget (Senior scientist, CNRS)
  - Sébastien Lebonnois (Scientist, CNRS)
  - Ehouarn Millour (Research engineer, CNRS)
  - Aymeric Spiga (Associate Professor, UPMC, recruited 2010)
  - Also: Frédéric Hourdin (Senior scientist, CNRS), Francis Codron (UPMC)
- **6-10 postdoc/PhD/engineer (e.g. right now: 4 + 4 + 1)**
- **Institutions: CNRS, UPMC, ANR, Fondation de France, IPSL, …**
- **Funding from spatial agencies : CNES (FR) ESA (EU) sometime via contracts with industry (Thales-Alenia Space, Astrium)**
- **Many collaborations**
  - France: LATMOS, LESIA, IAS, LERMA, Obs. Bordeaux, LPN, LPG
  - Europe: Oxford, Open University, Instituto de Astrofisica de Andalucia, INAP
  - USA: NASA Ames, GFDL, Brown Univ., Lawrence Livermore, Univ. of Texas
  - In Japan: CPS with Yoshiyuki Takahashi, to be continued!

# A journey in the Solar System… and beyond



# 太陽系で…そして向こう旅

# A journey in the Solar System… and beyond

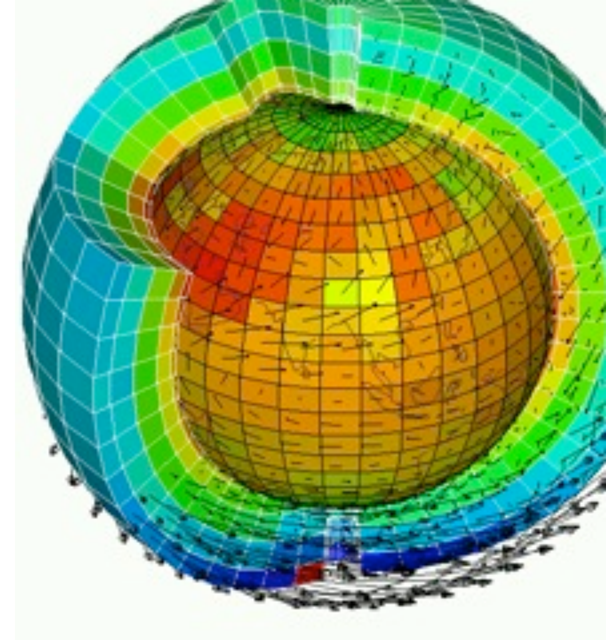


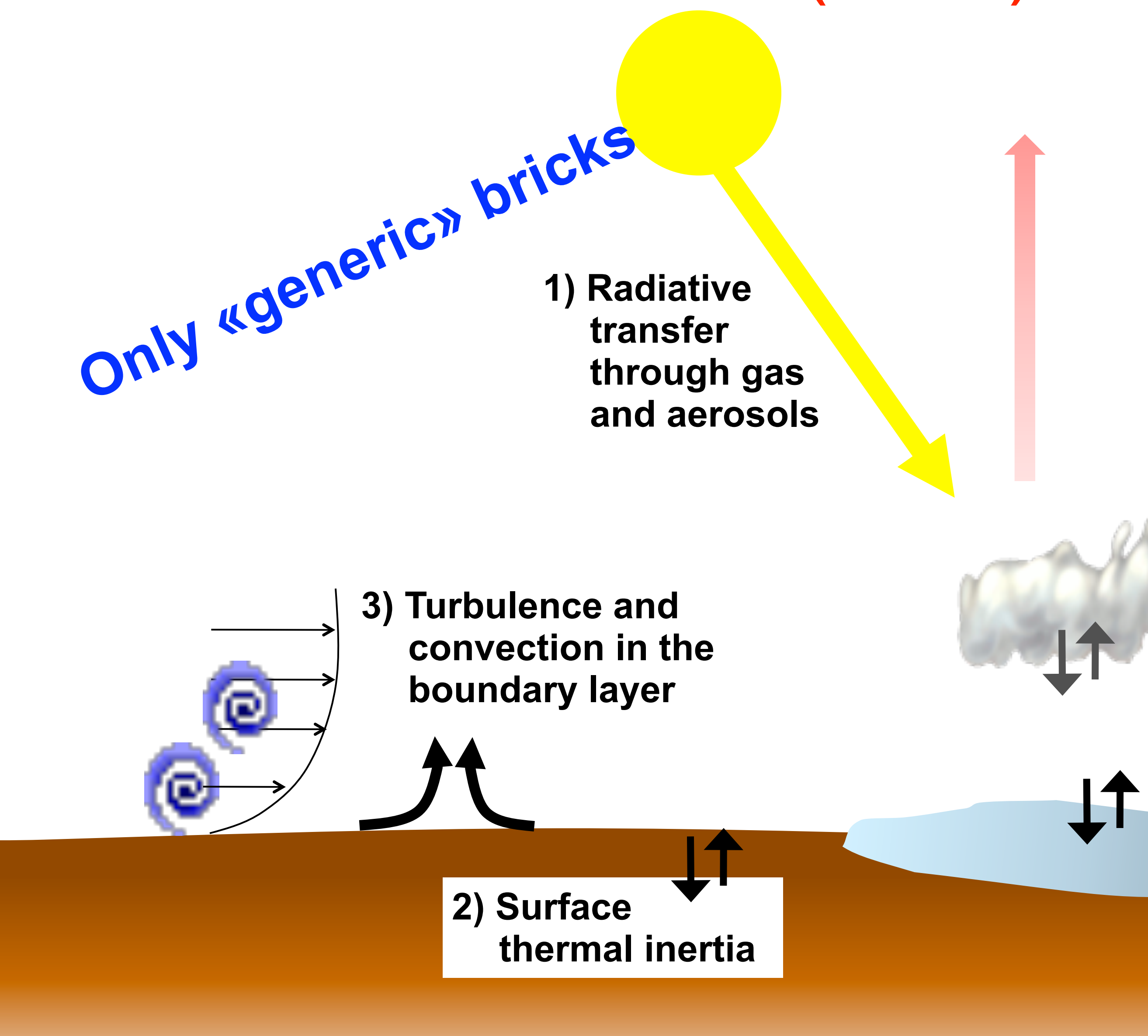
# How GCMs work ? :

1) 3D “Hydrodynamical core”
⇒ ***to compute large scale atmospheric motions and transport***

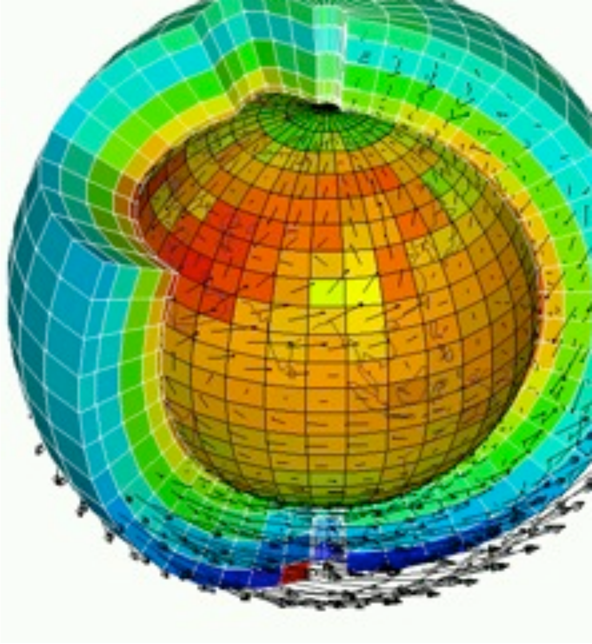
2) At every grid point : Several physical parameterizations
⇒ ***to force the dynamic***
⇒ ***to compute the details of the local climate***

# Toward a “generic” Global climate model (LMD)





# Toward a "generic" Global climate model (LMD)



1) Use parametrisations "universal" for all planets:
   - **Standard dynamical core** (grid point)
   - Surface and subsurface thermal model
   - "Universal" Turbulent boundary layer scheme

2) The key : Versatile, fast and accurate radiative transfer code
   (see next slide)

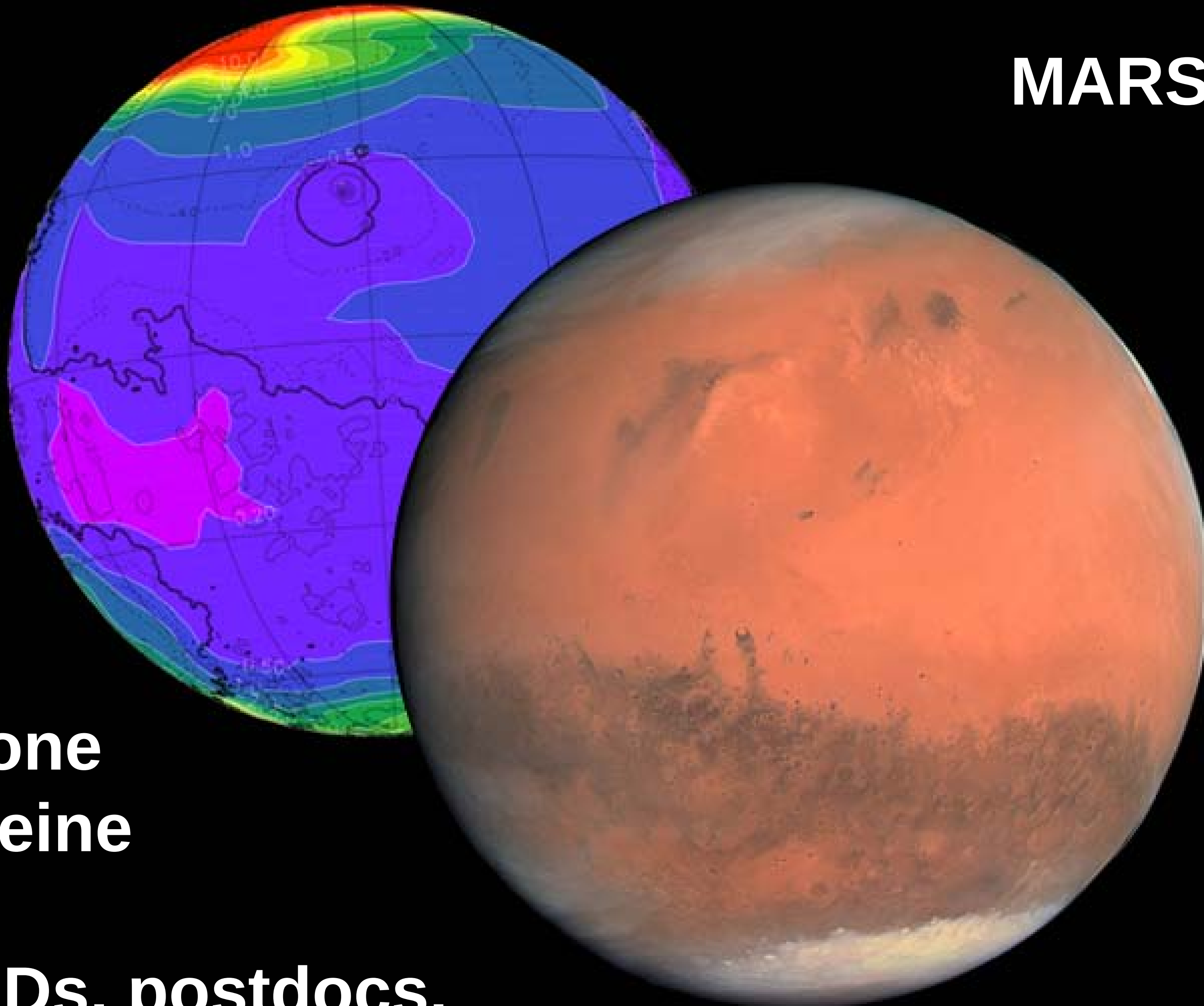
3) **Simple, Robust, physically based parametrisation of volatile phase change processes**
   - Including robust deep convection representation : wet convection
   - Clouds are represented by splitting condensed phase on a prescribed number of Cloud Condensation Nuclei (radii ⇨ scaterring/sedimentation)
   - Precipitation above a threshold mixing ratio.

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 coefficients⇨ 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 : assumptions on the atmosphere!

# MARS

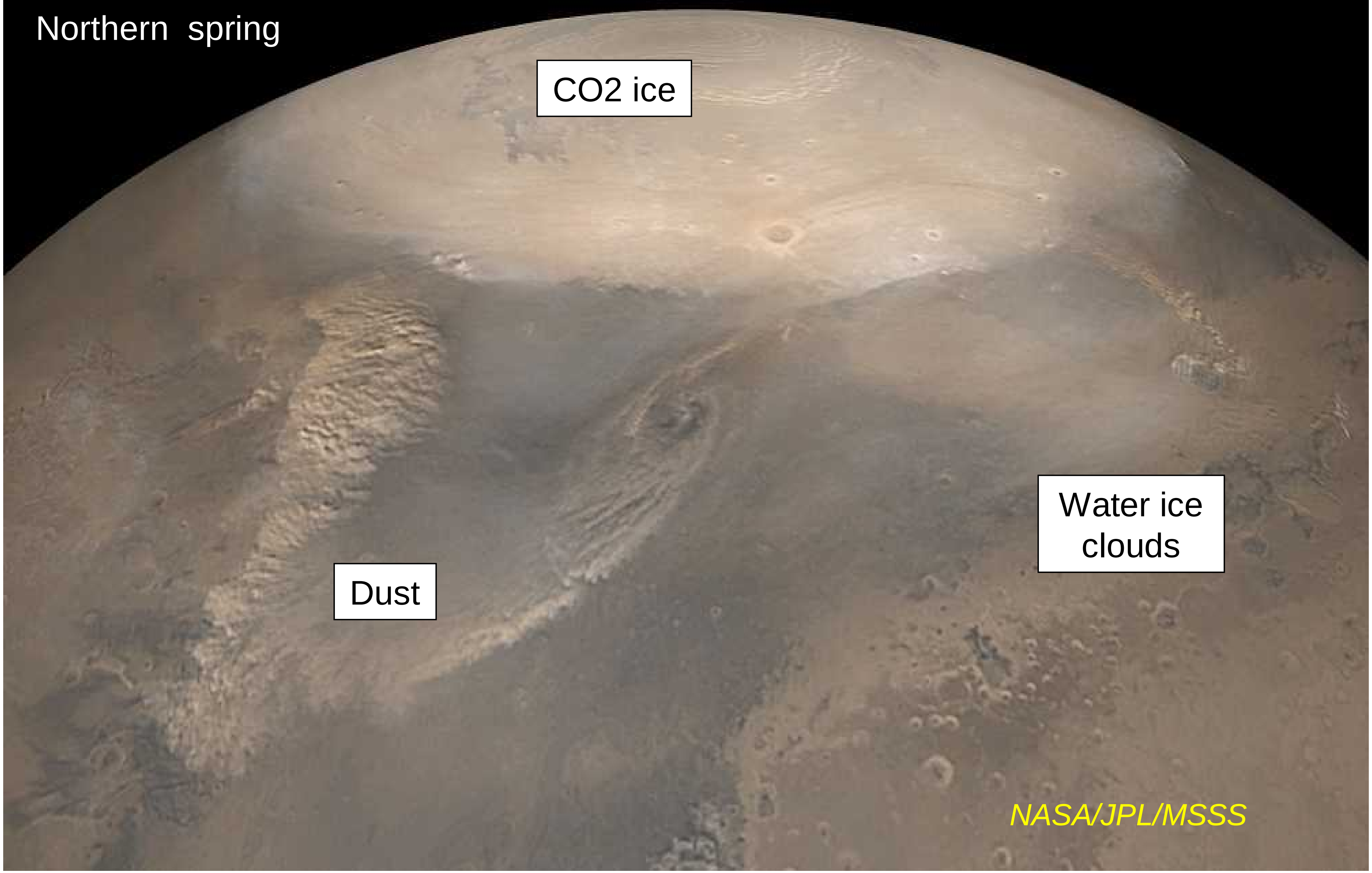


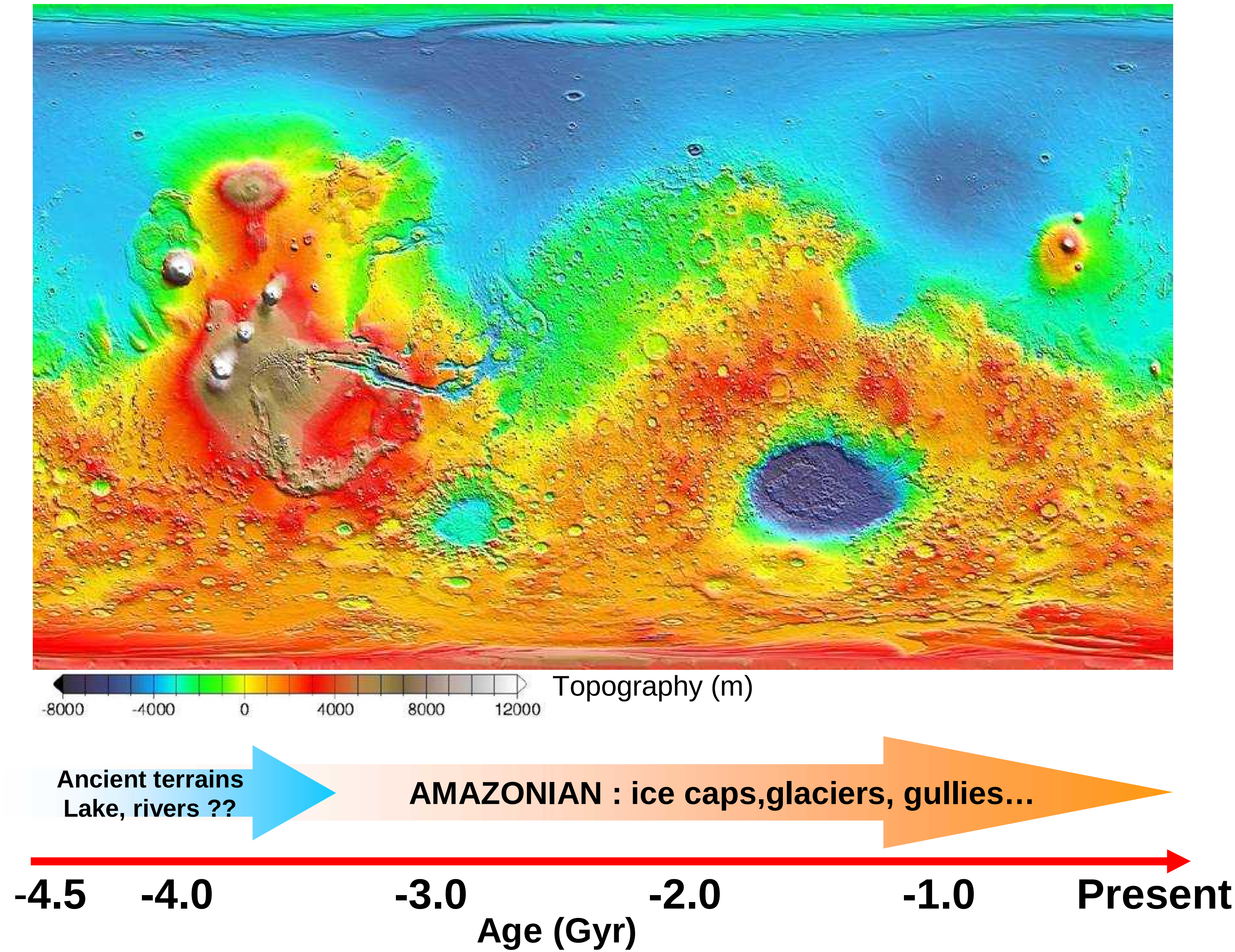
**F. Forget**

**E. Millour**
**A. Spiga**
**L. Montabone**
**J.B. Madeleine**

**+ many PhDs, postdocs, collaborators, …**

**Mars climate now** : atmospheric circulation, dust , $CO_2$ (and some water)

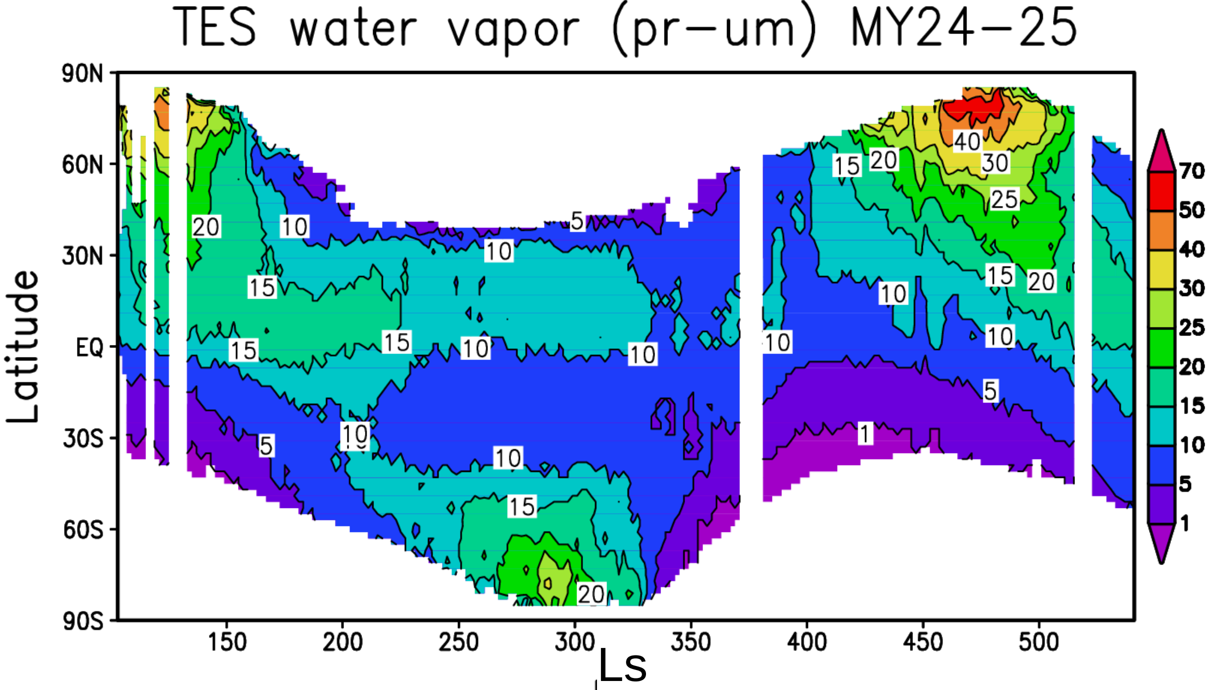



Topography (m)
-8000
-4000
0
4000
8000
12000
Ancient terrains
Lake, rivers ??
AMAZONIAN : ice caps,glaciers, gullies…
-4.5
-4.0
-3.0
-2.0
-1.0
Present
Age (Gyr)

**SEASONAL WATER CYCLE**

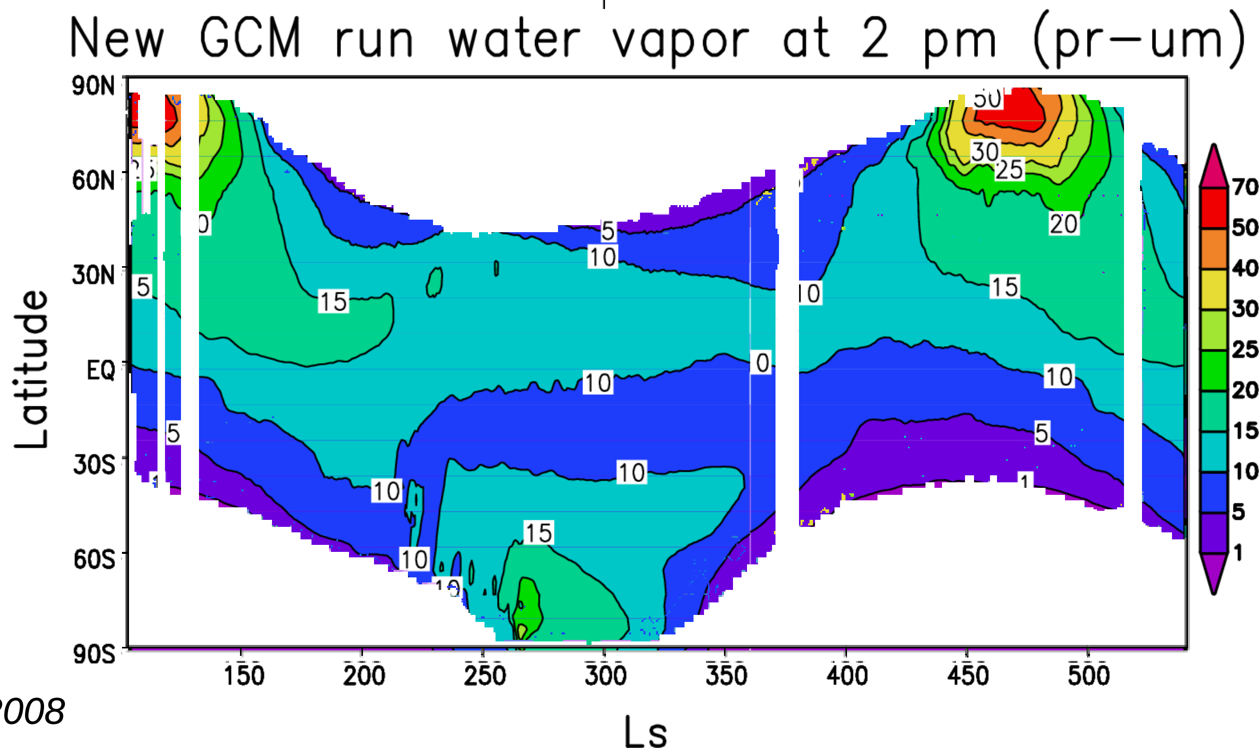
**OBSERVATIONS**

(MGS TES)



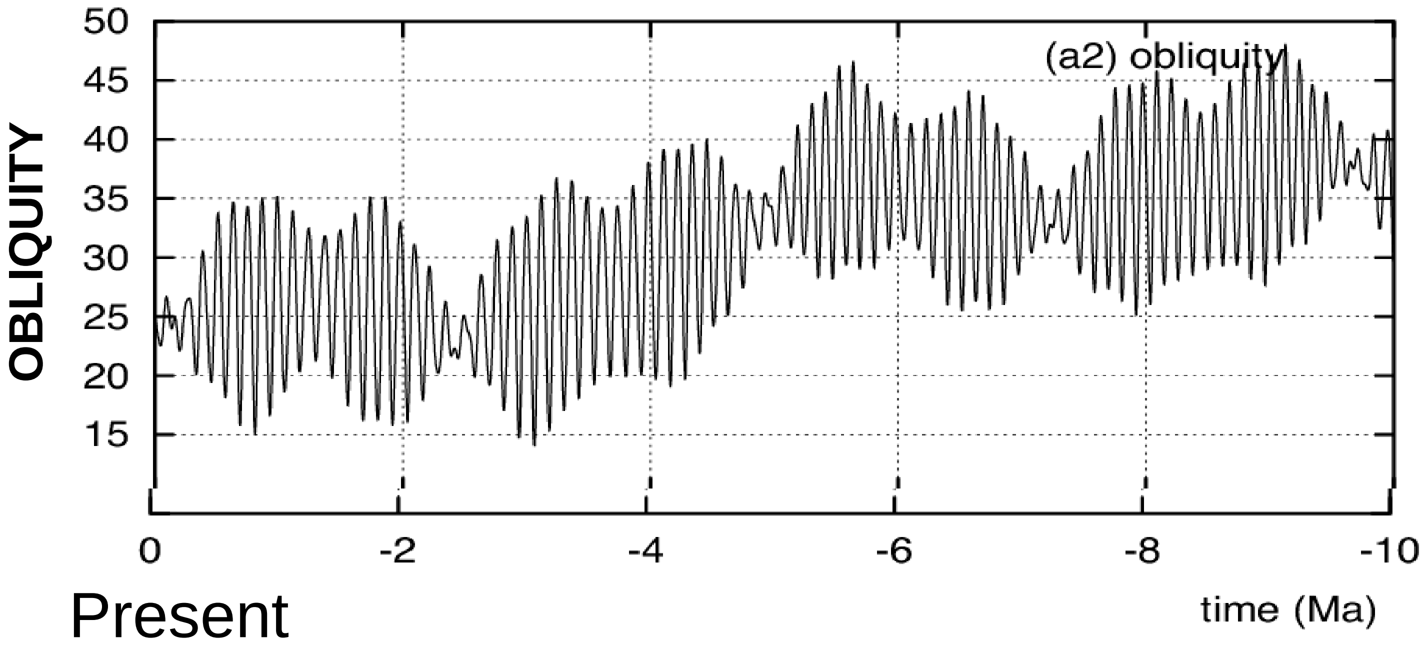

**MODEL**

(LMD GCM)



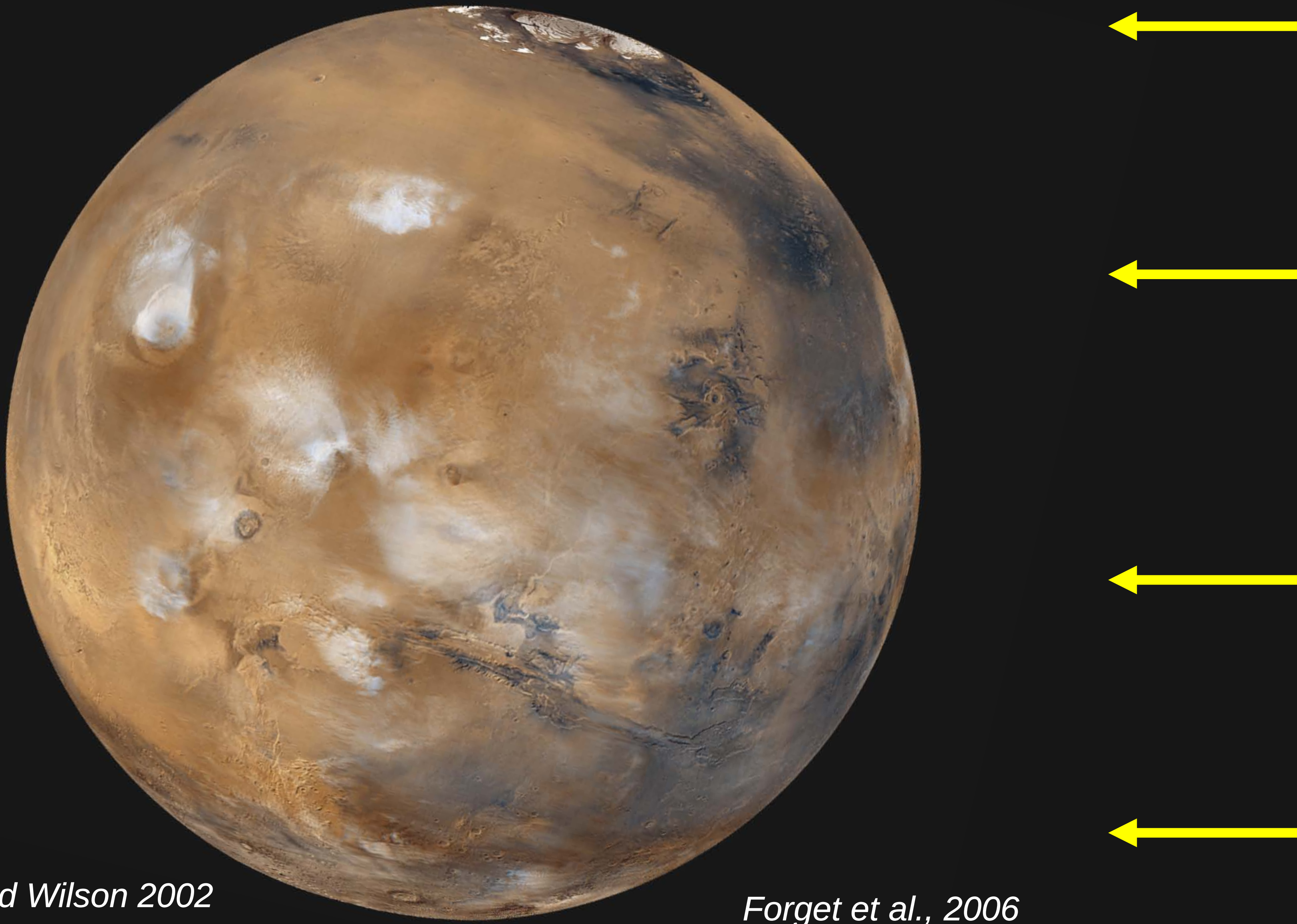

*Montmessin et al. 2004, Forget et al. 2008*

# Climate variation in the recent past: orbit and obliquity variations




During Mars History, most likely obliquity: 41.8° (Laskar et al. 2004)

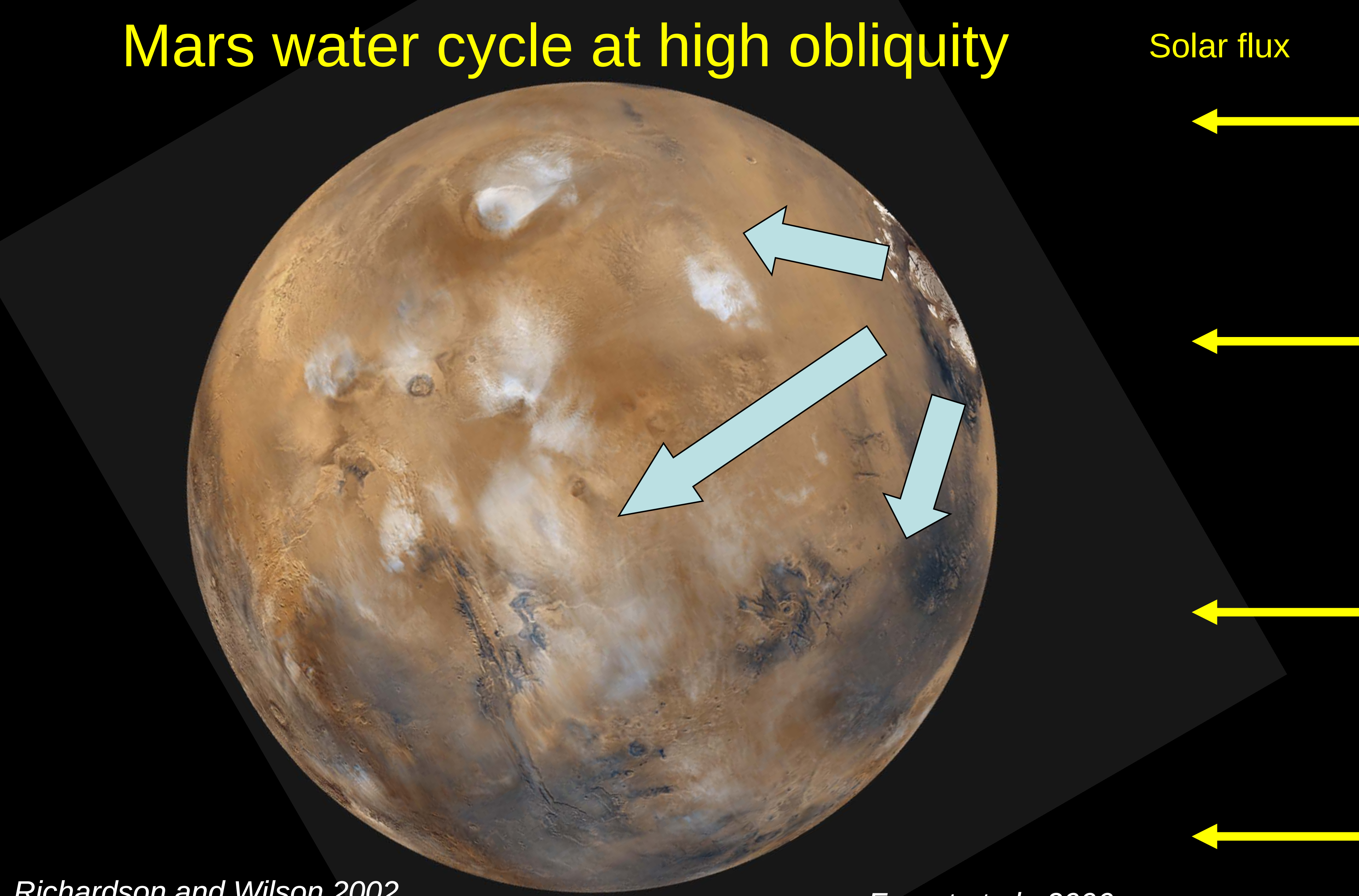
# Mars water cycle at high obliquity




*Richardson and Wilson 2002*
*Mischna et al. 2003*
*Levrard et al., 2004*
*Mischna and Richardson 2005*

*Forget et al., 2006*
*Madeleine et al., 2009*
*Levrard et al. 2007*

# Mars water cycle at high obliquity

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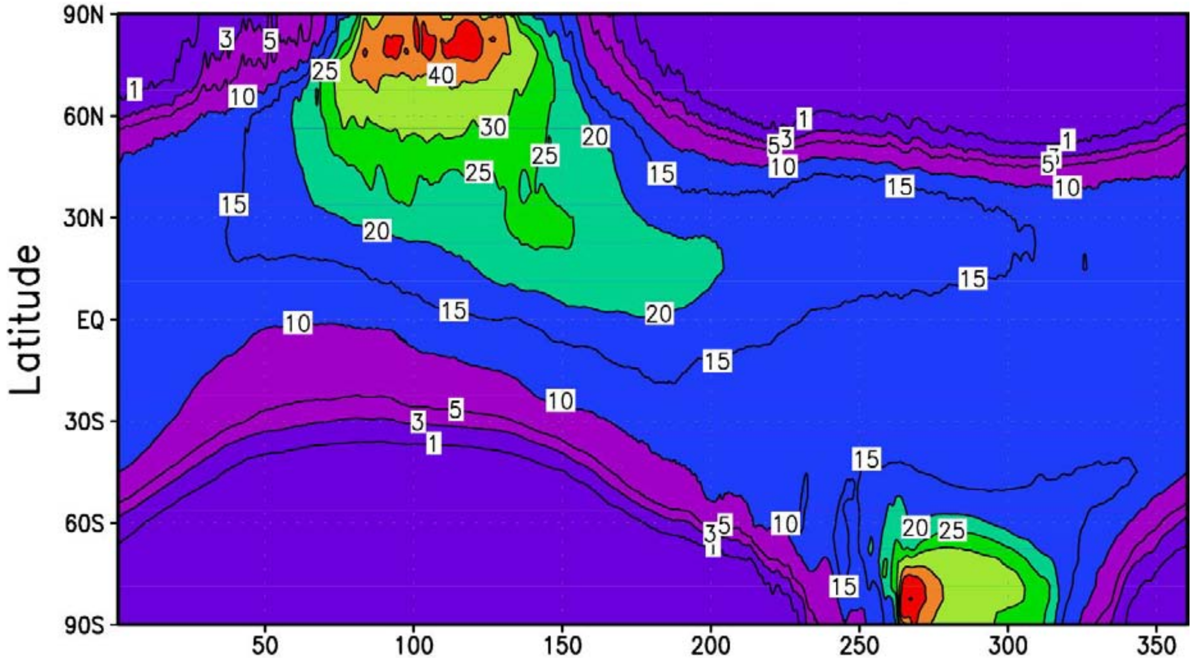
*Madeleine et al., 2009*
*Levrard et al. 2007*

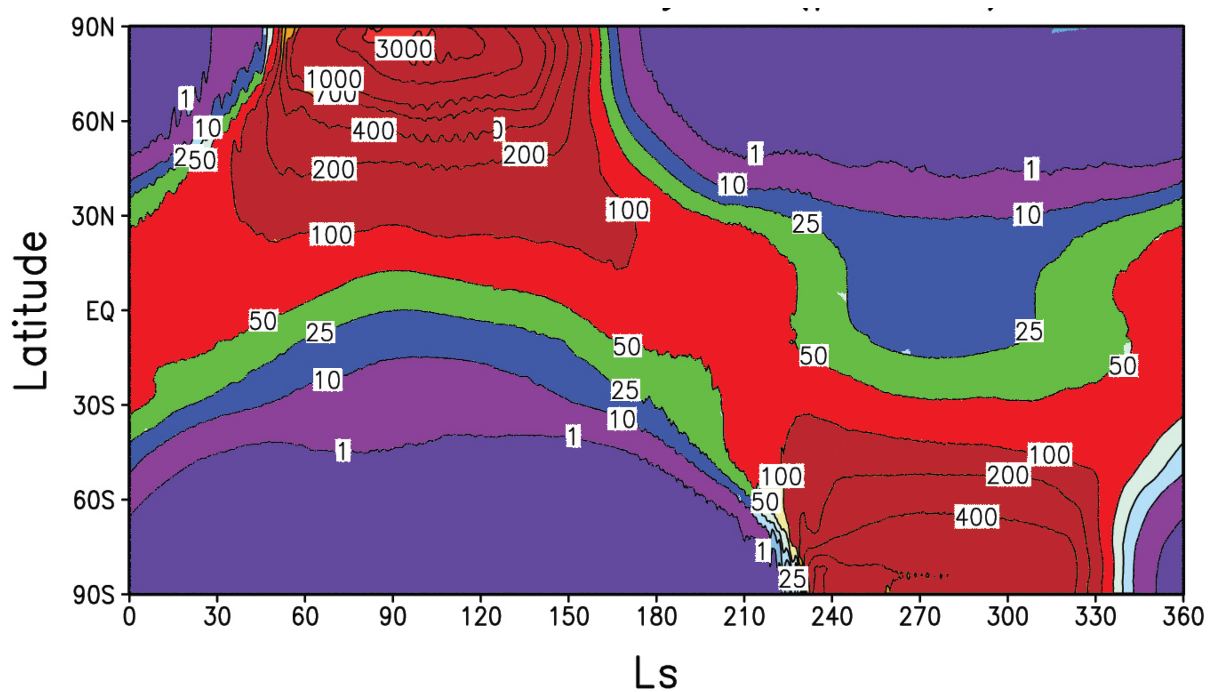
**LMD GCM Simulations**:

Water vapor column

(*precipitable –microns*)




**On present-day Mars :**




**Same, but 45° Obliquity**

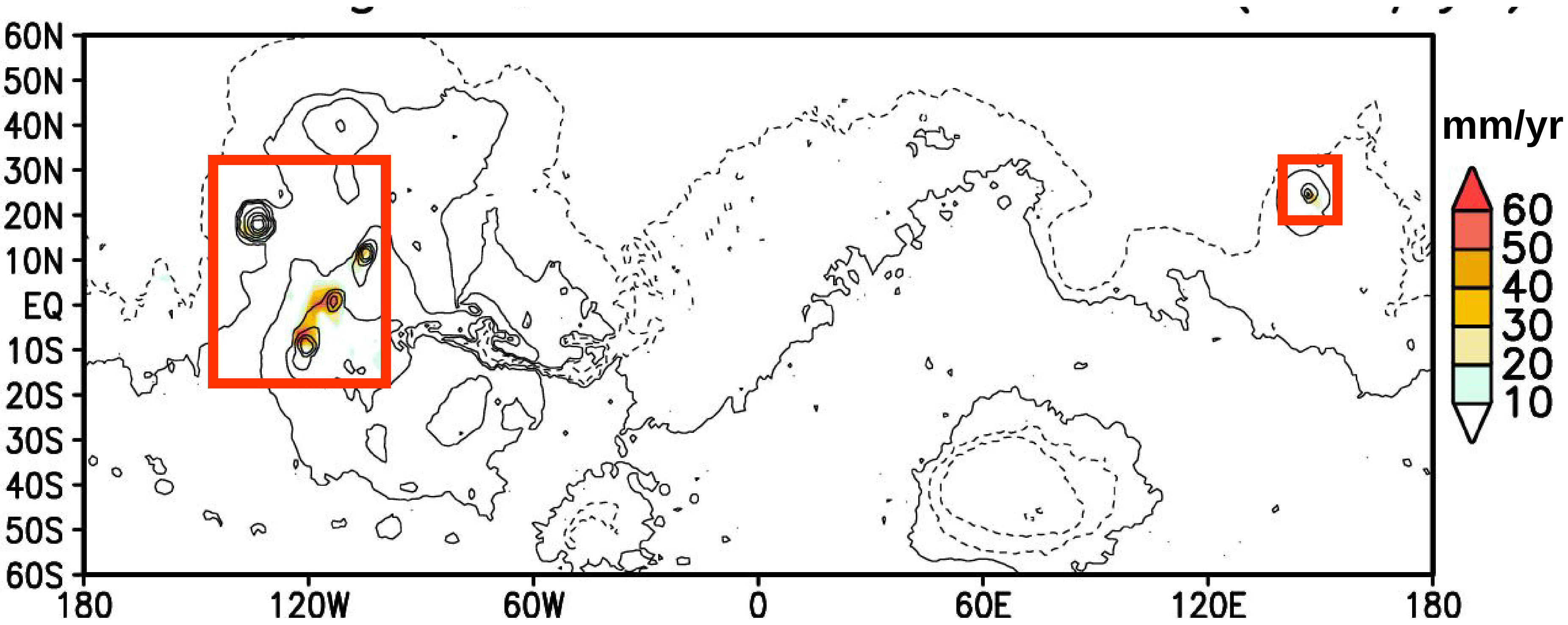
**(Circular orbit )**

# Ice accumulation rate (mm/yr)

**high resolution simulation (2°x2°)**

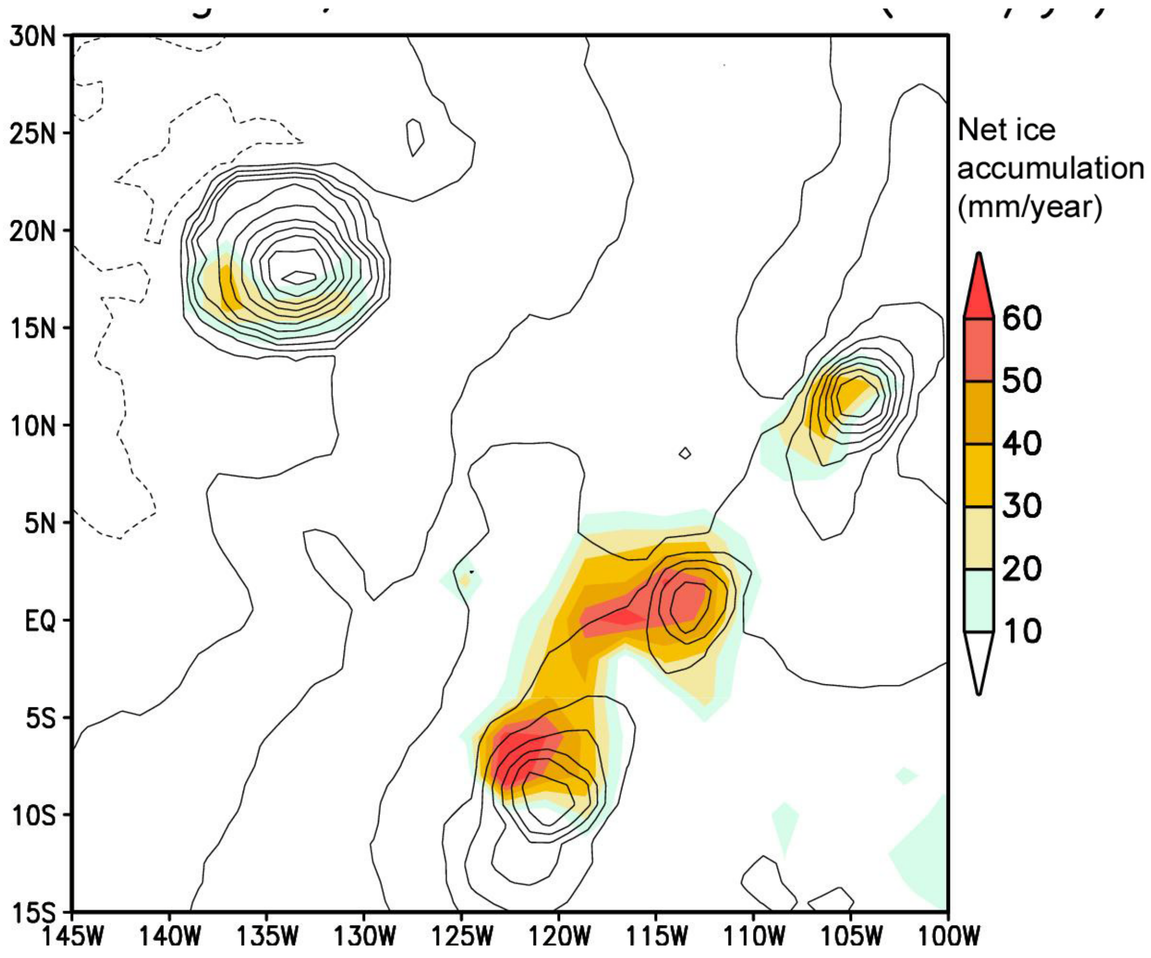
**Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2**

***Forget et al. Science 311, p368, 2006***



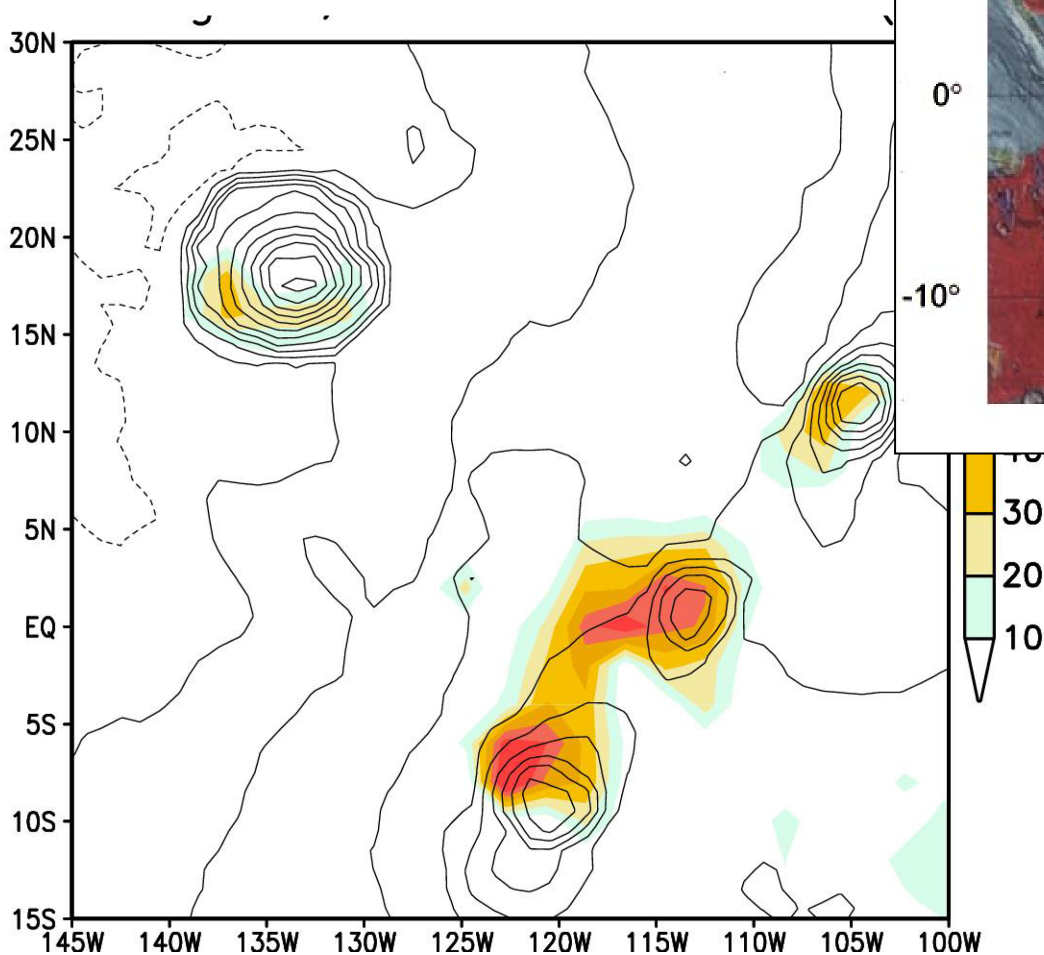
# The formation of glacier : Ice accumulation rate (mm/yr) in a new very high resolution simulation

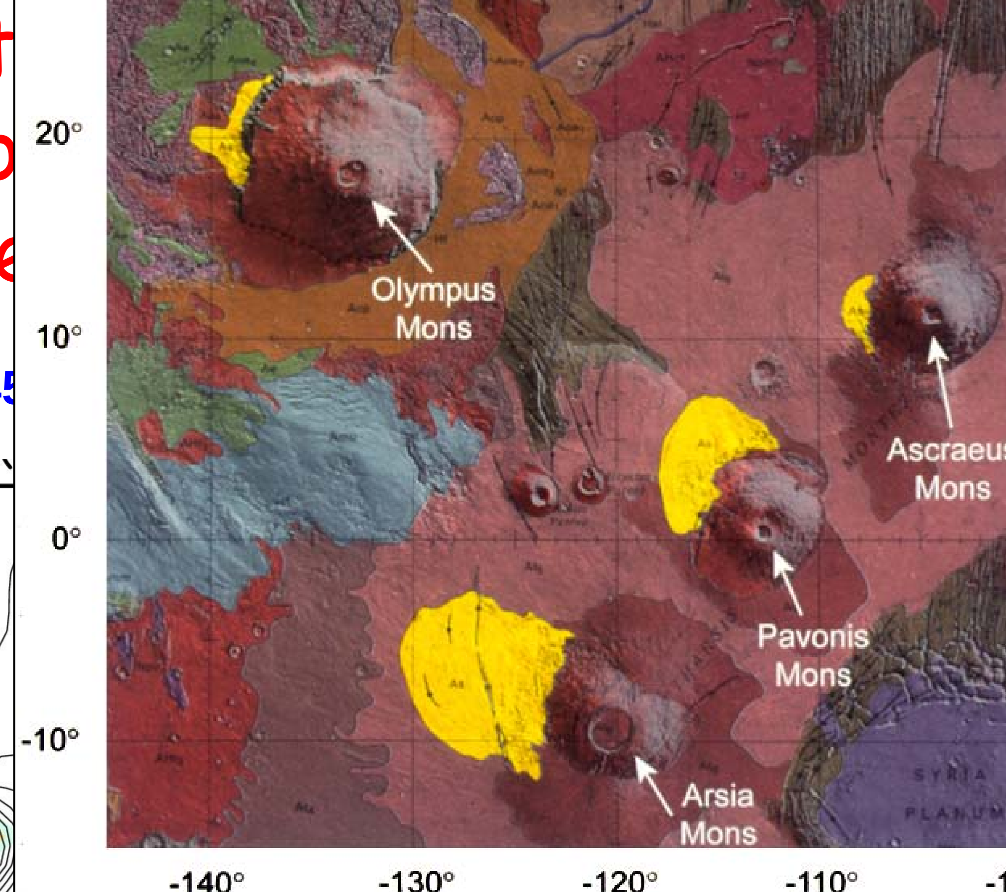
**Forget et al. 2006: Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2**



# The format
# accumulatio
# very high re

**Forget et al. 2006: Obliquity = 45**

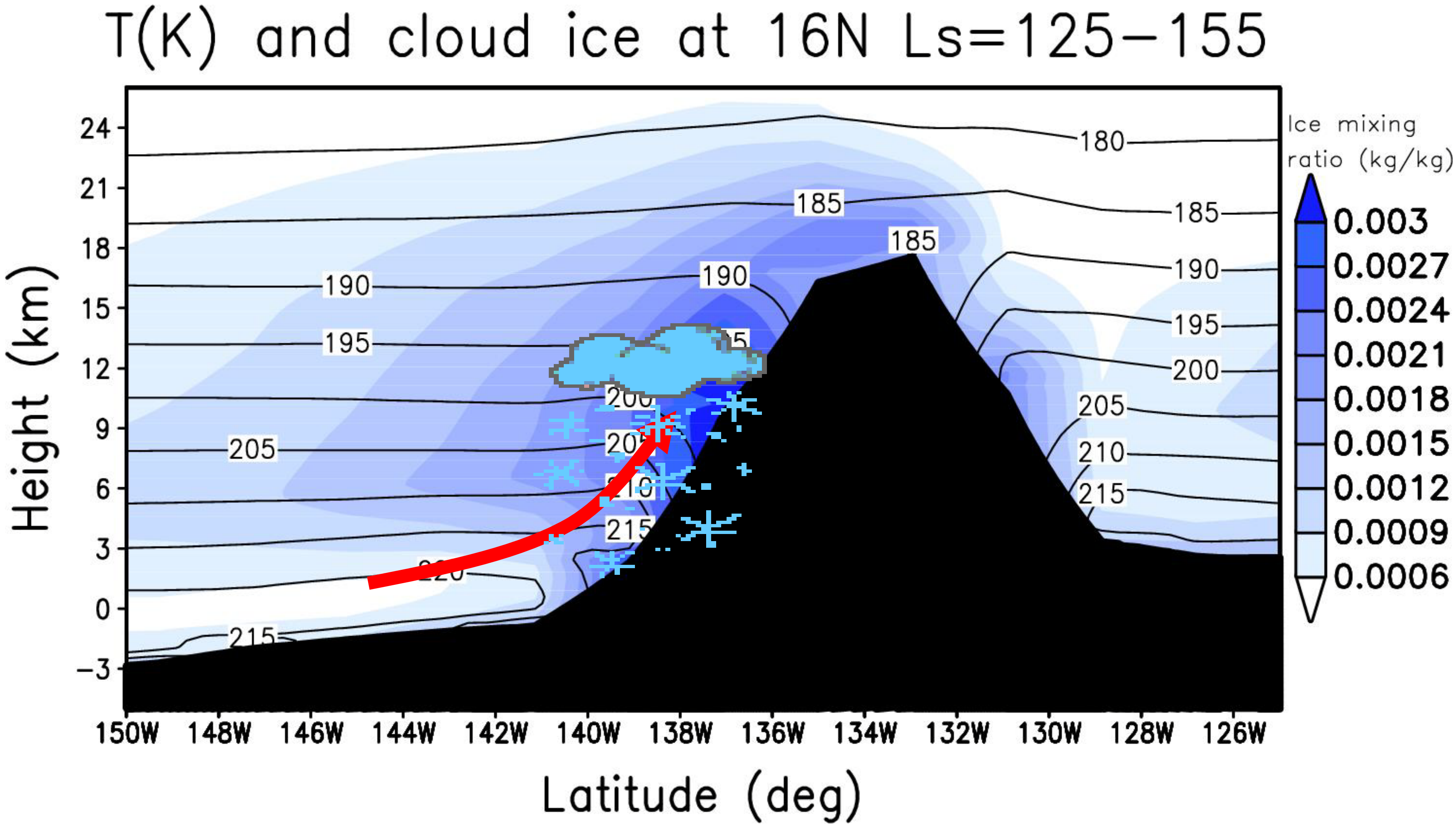



- **Fan shaped deposits, drop moraines characteristic of cold based glaciers.**
- **Rock glaciers**

***Lucchitta 1981, Head et al. 2003, Shean et al. 2005, 2007, Head et al. 2005, Kadish et al. 2008, Schon and Head 2012***

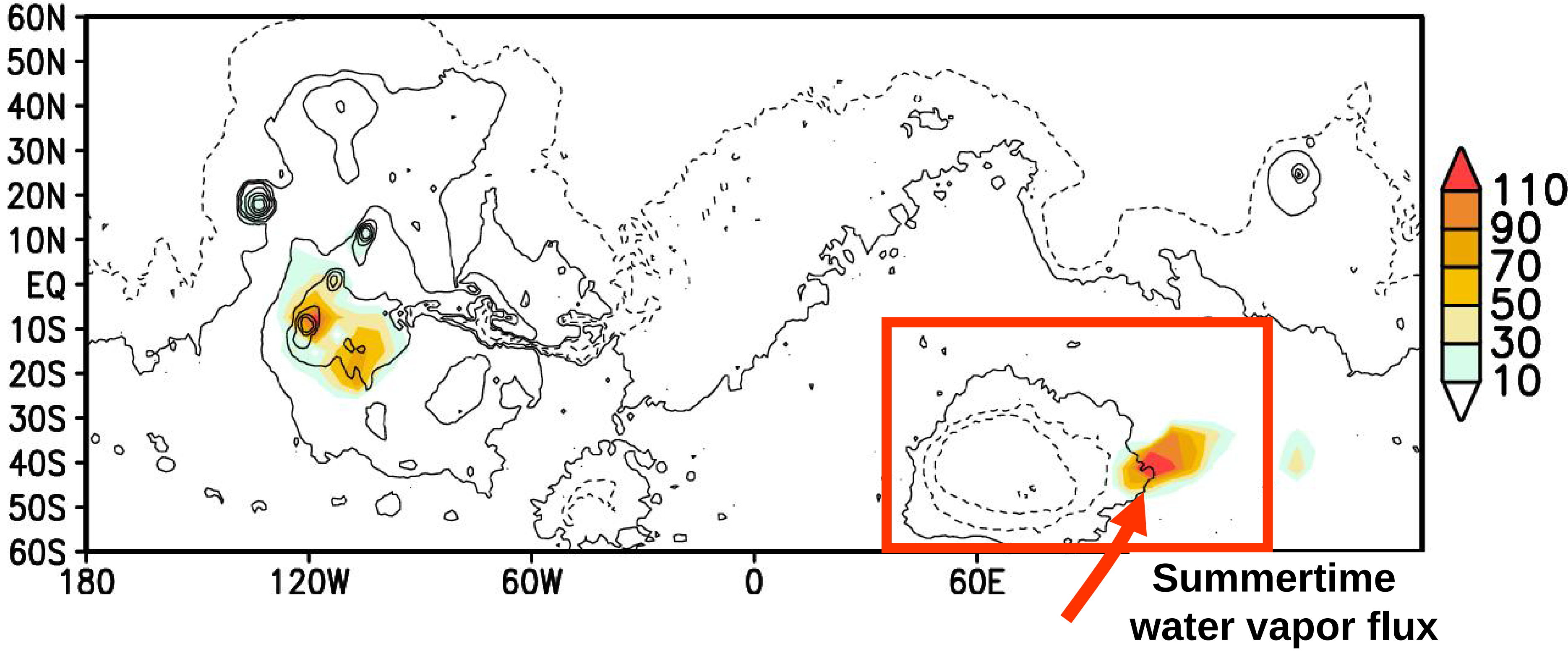
# At high obliquity: Ice accumulation by ice precipitation on windward slope

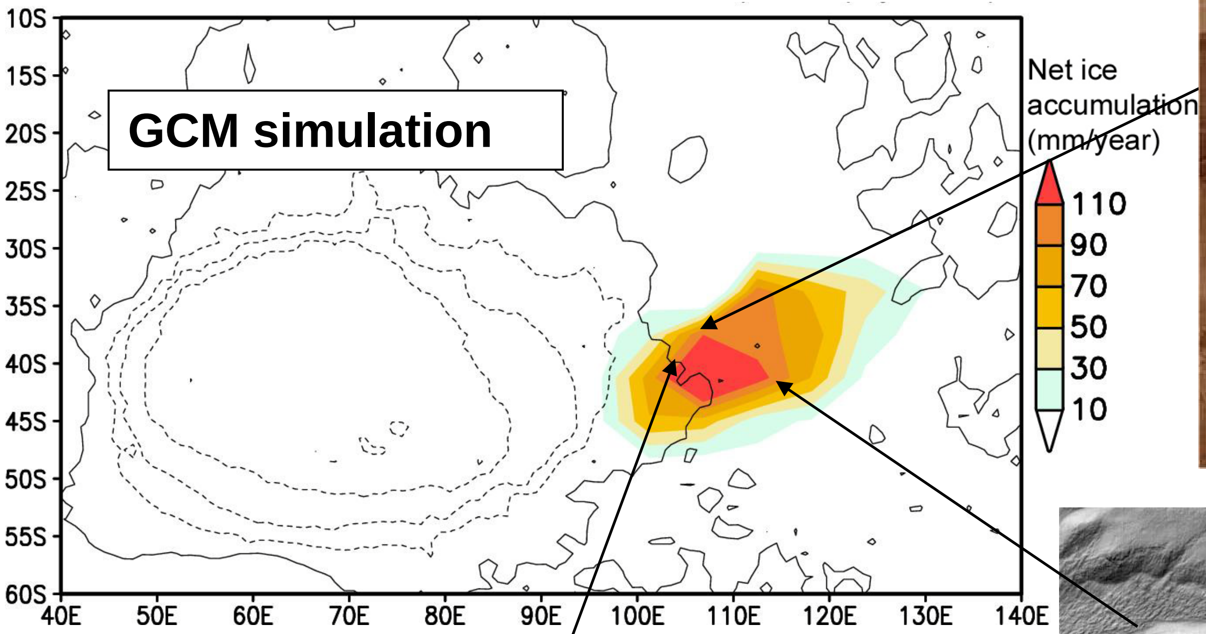


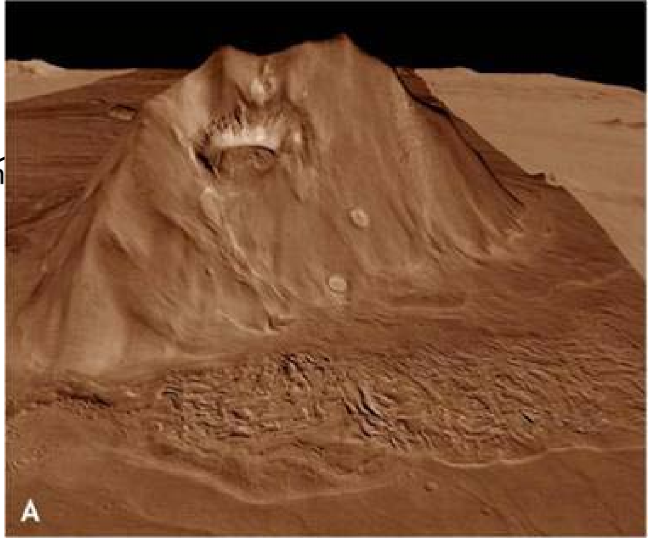
# High Obliquity Simulation with a water ice cap **at the south pole**

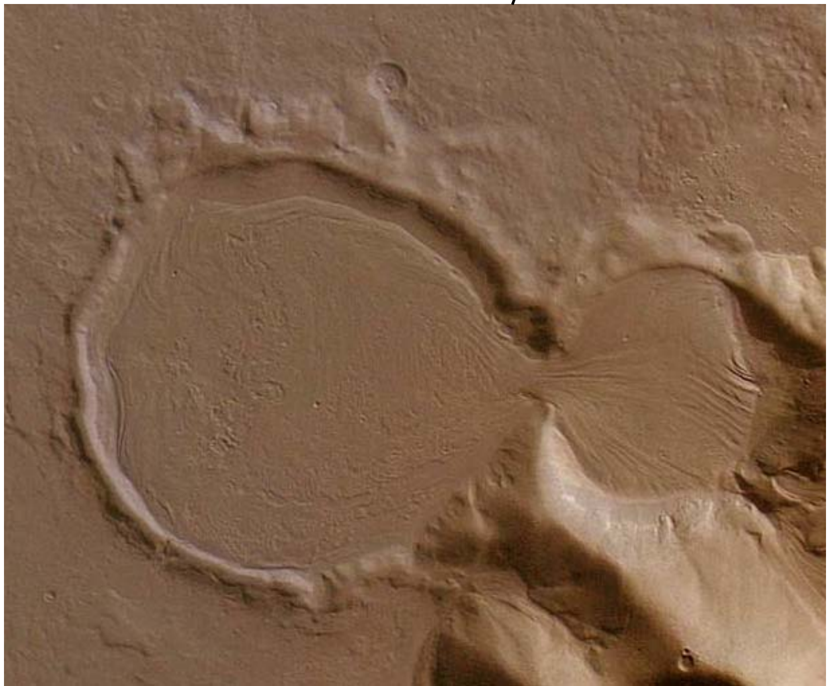
***(Forget et al. 2005)***

**Yearly accumulation rate** (mm/year) (1Oth year simulation)



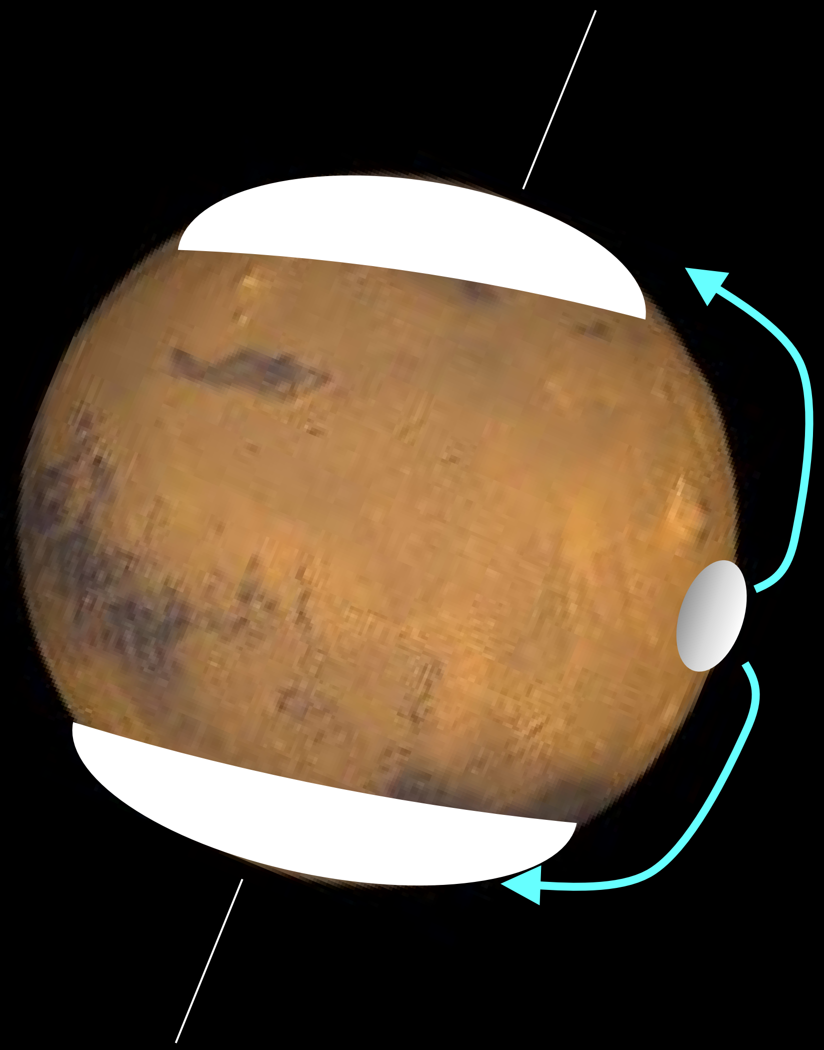


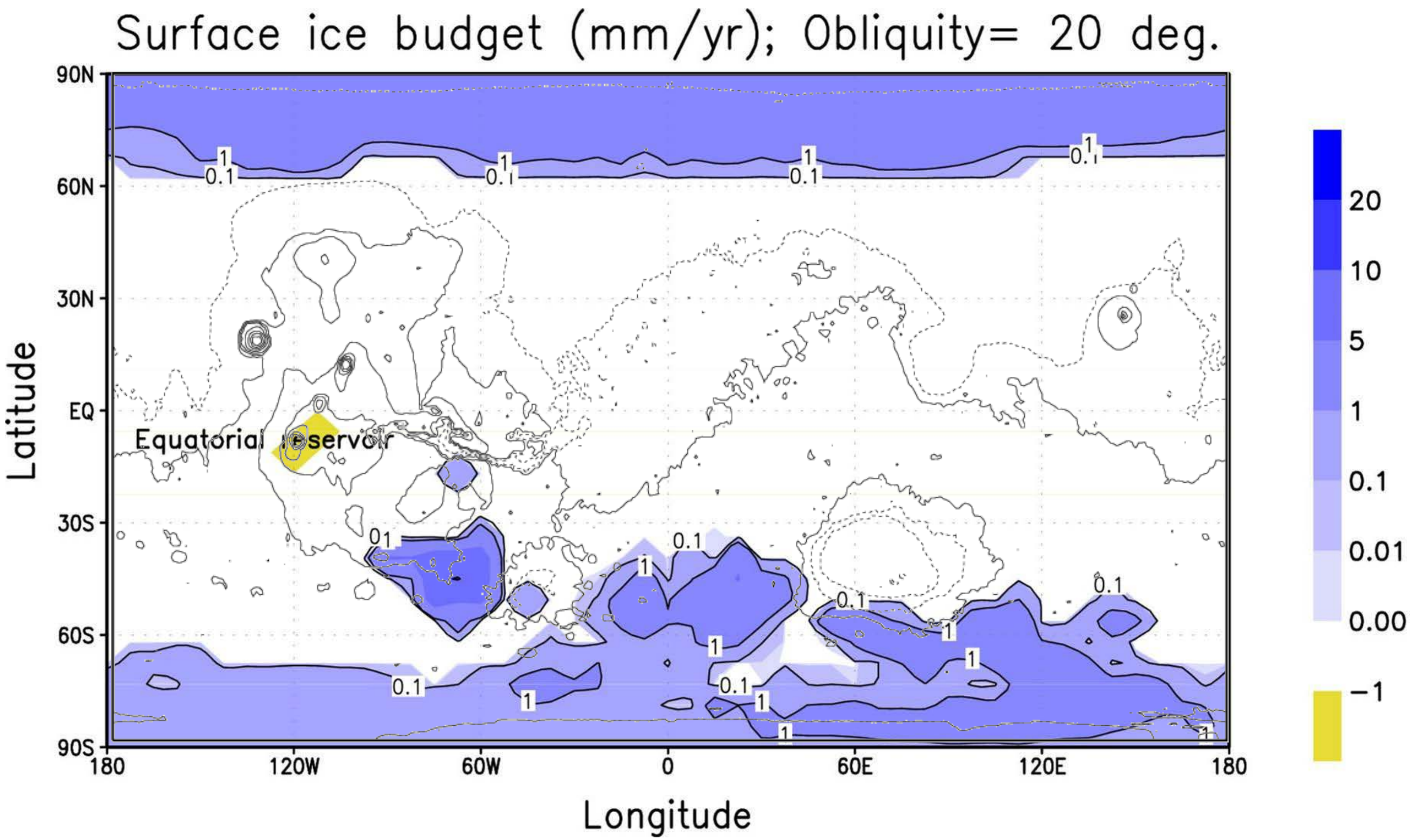



Head et al.
Hartmann et al.
Crown et al.
Etc…

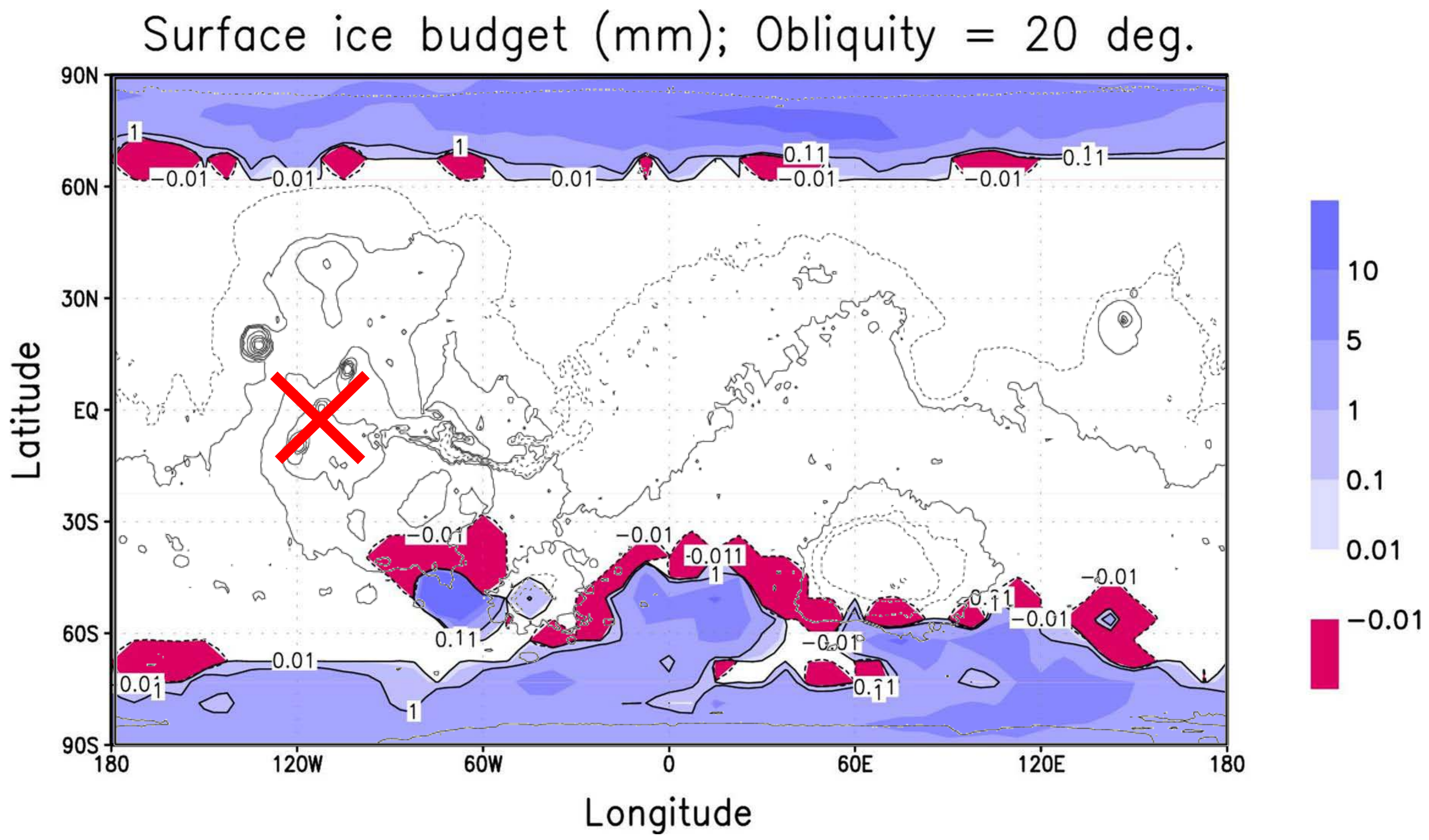
# Back from high obliquity to low obliquity

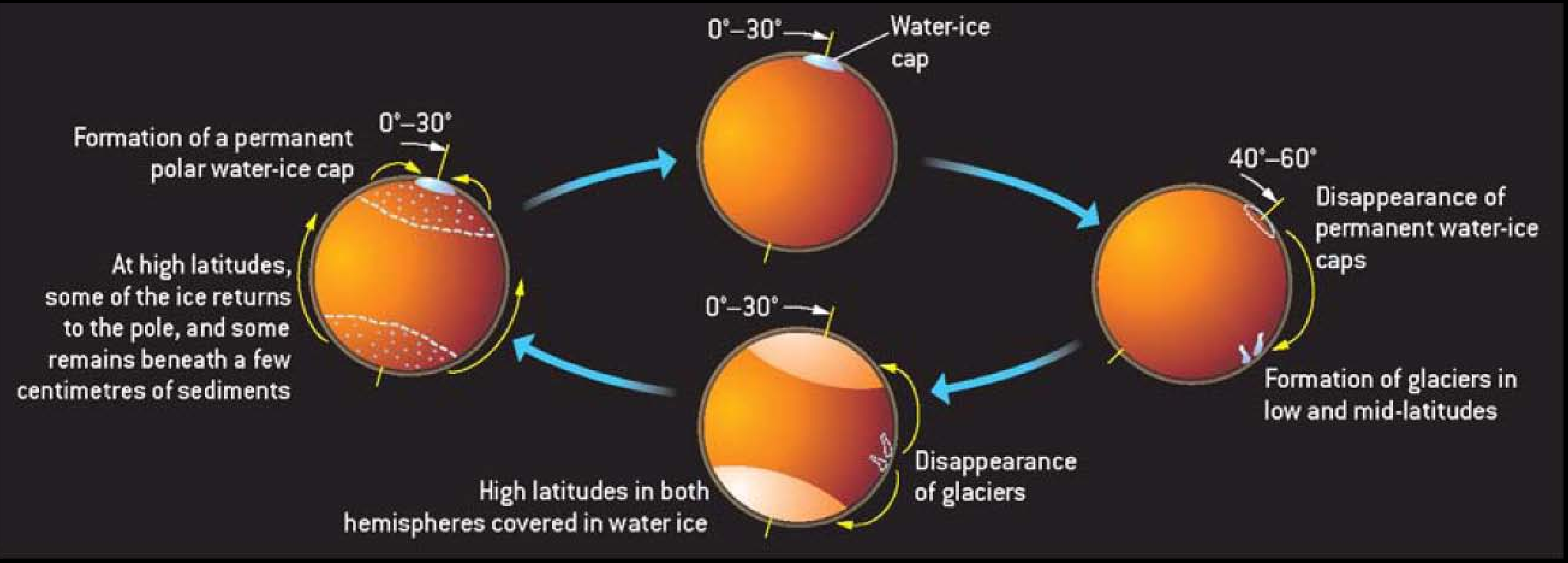


Levrard et al. (2004)



Surface ice budget (mm/yr); Obliquity= 20 deg.
Latitude
Longitude
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
Equatorial reservoir
20
10
5
1
0.1
0.01
0.001
−1

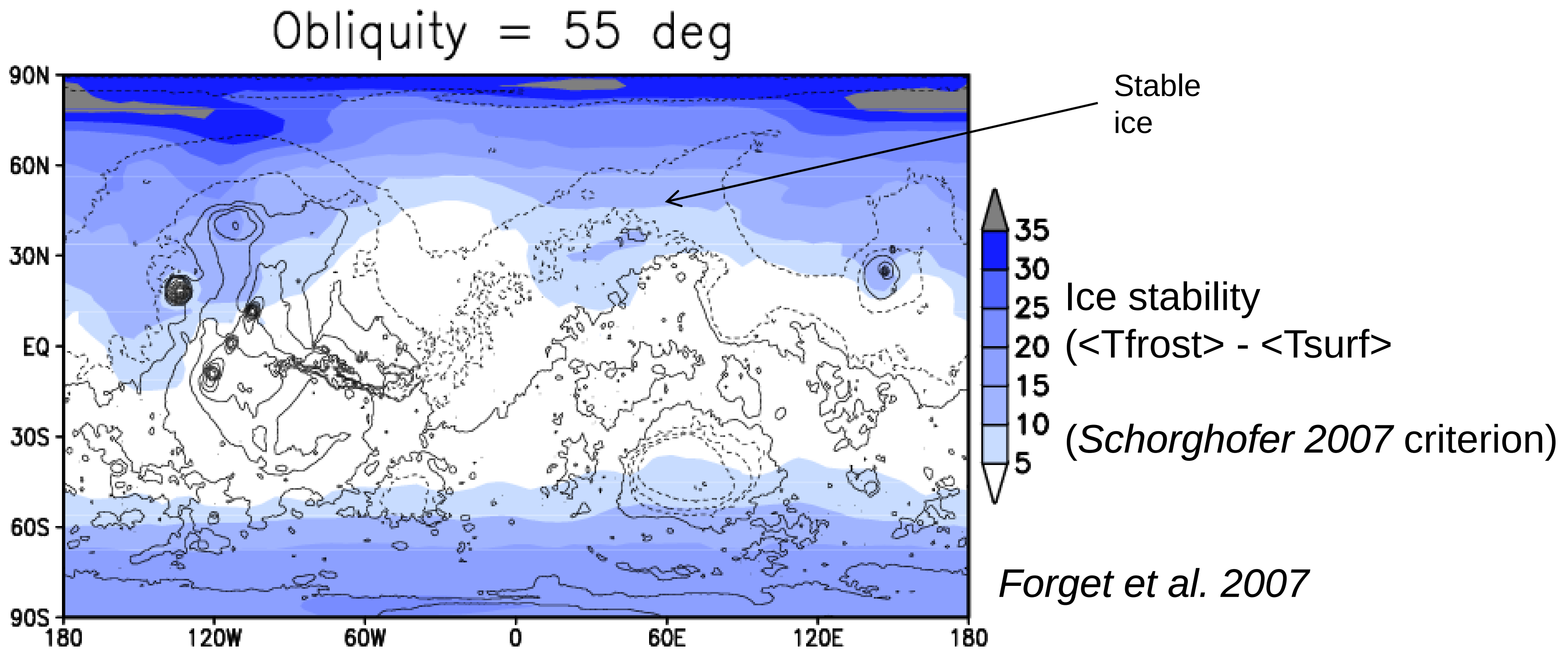

Surface ice budget (mm); Obliquity = 20 deg.
90N
60N
30N
EQ
30S
60S
90S
Latitude
180
120W
60W
0
60E
120E
180
Longitude
10
5
1
0.1
0.01
−0.01


0°–30°
Water-ice cap
0°–30°
Formation of a permanent polar water-ice cap
40°–60°
Disappearance of permanent water-ice caps
At high latitudes, some of the ice returns to the pole, and some remains beneath a few centimetres of sediments
0°–30°
Formation of glaciers in low and mid-latitudes
Disappearance of glaciers
High latitudes in both hemispheres covered in water ice

# Impact of obliquity on SUBSURFACE ice stability

## Obliquity increases :

- ➩ More water vapor : ice more stable
- ➩ Mean temperature and **summer** temperature increase : ice less stable




*Forget et al. 2007*

# Early Mars Climate

**François Forget, Robin Wordsworth, Ehouarn Millour, Jean-Baptiste Madeleine, Benjamin Charnay, Vincent Eymet and Bob Haberle**

# More and more observations suggesting that « early Mars » was different, with flowing liquid water, possibly precipitation:

## Only in ancient terrains:

- **Valley networks**
- **High Erosion rate in very ancient terrains**
- **Layers, « Lacustrine » deposits, deltas**
- **Mineralogy related to water alteration :**
- **Clays** ***(****detected by Mars Express Omega): in very ancient terrains*
- **Sulfate** ***(****detected by Omega & MER): less ancient terrains*
- Hematite ***(****detected by MGS TES)*
- Silica (Opal) *(Spirit)*

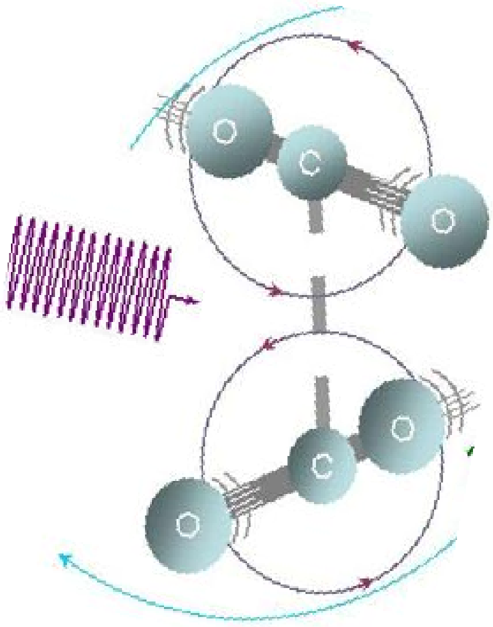
# Early Mars: a completely different world!

$CO_2$-$CO_2$ collision-induced absorption was overestimated

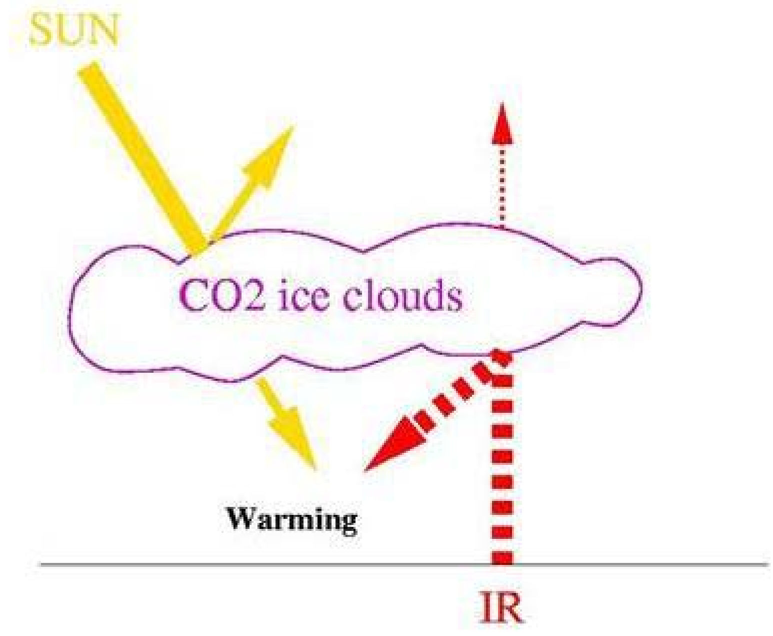
**New parametrisation**

⇨ Reduced $CO_2$ greenhouse effect !

**(*Wordsworth et al.* Icarus 2010)**



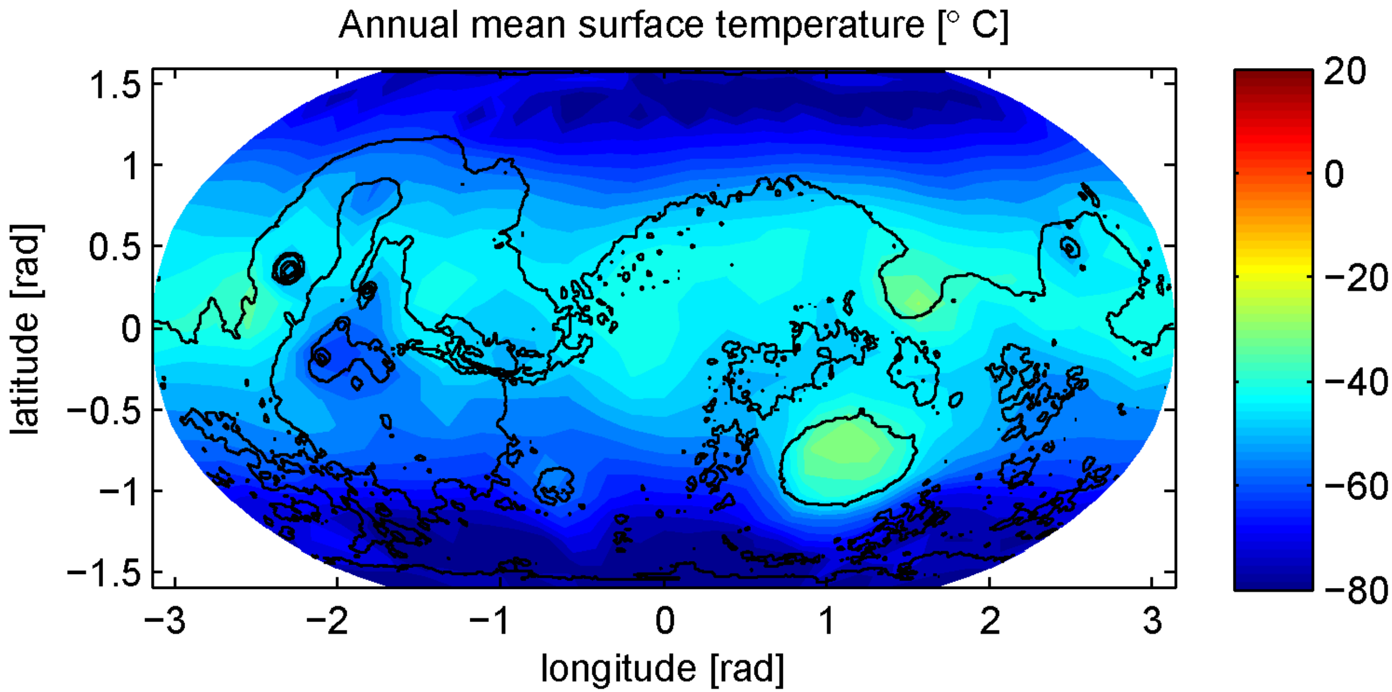
**CO2 ice clouds warming**
**15 to 20K**

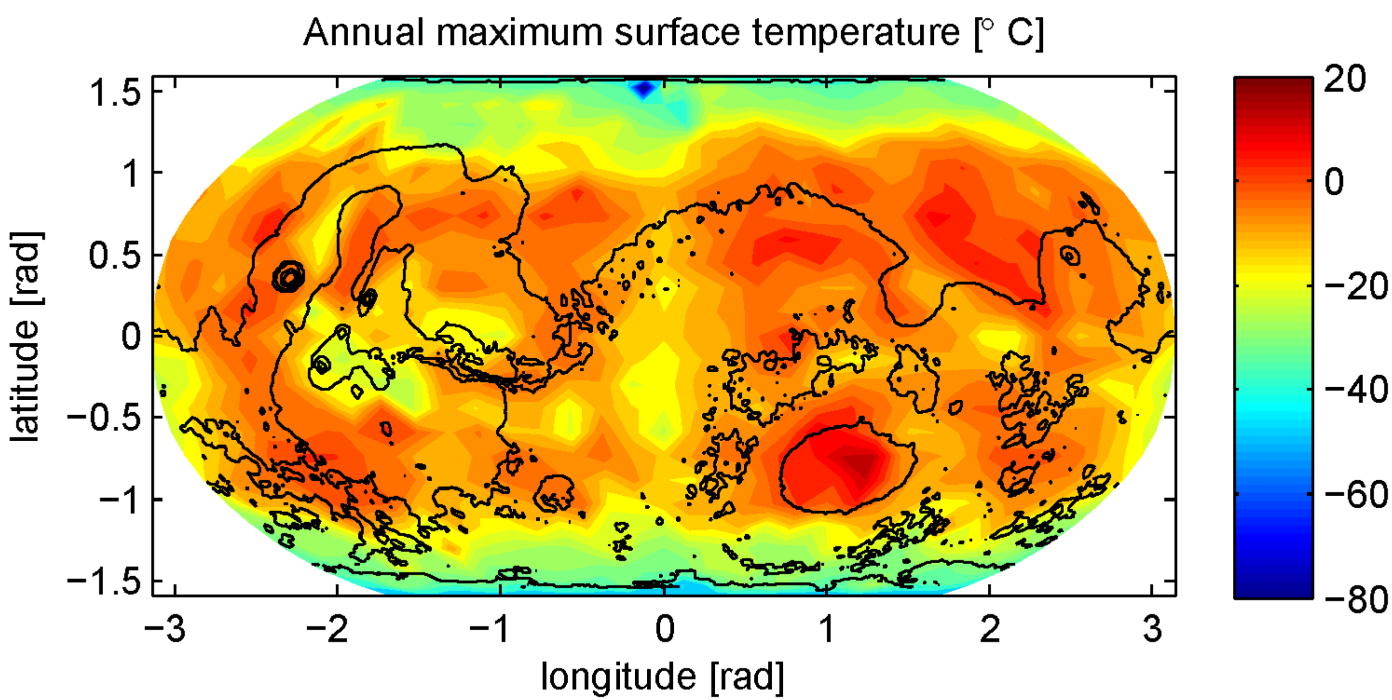



***Forget and Pierrehumbert 1997***

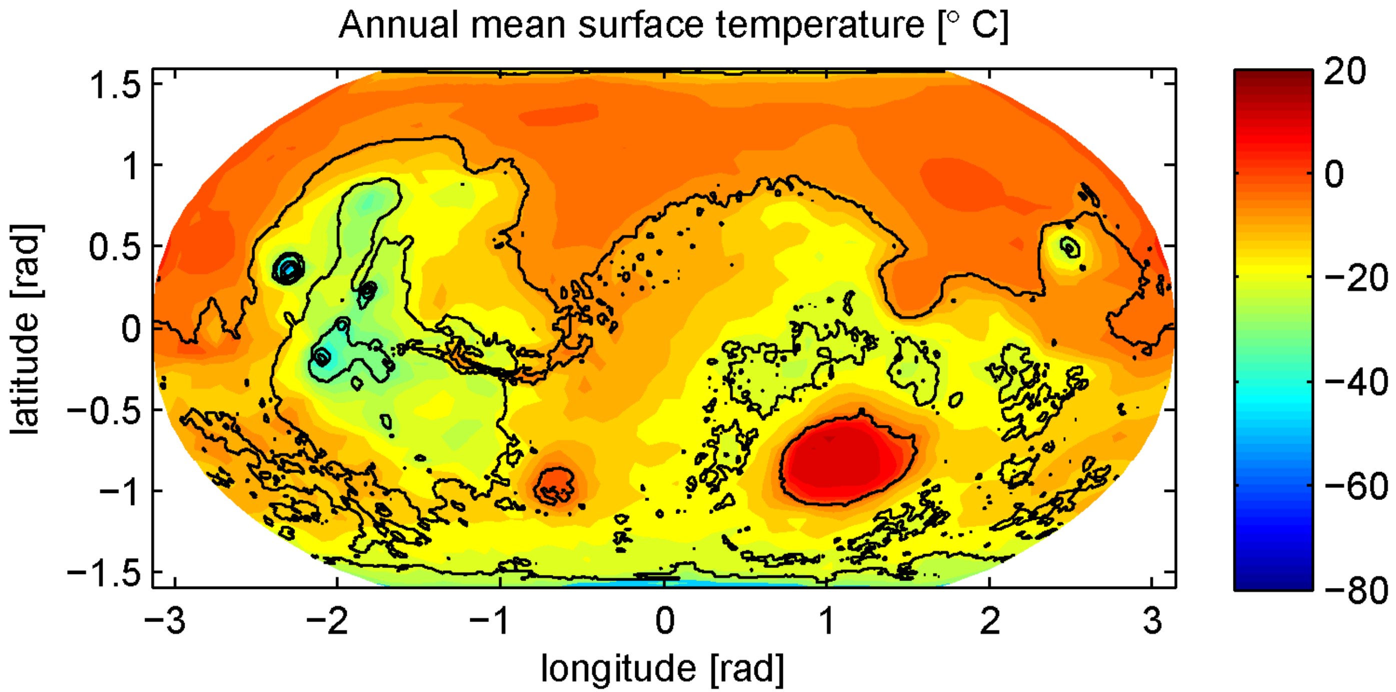
# 0.5 bar

Surface
$CO_2$ ice

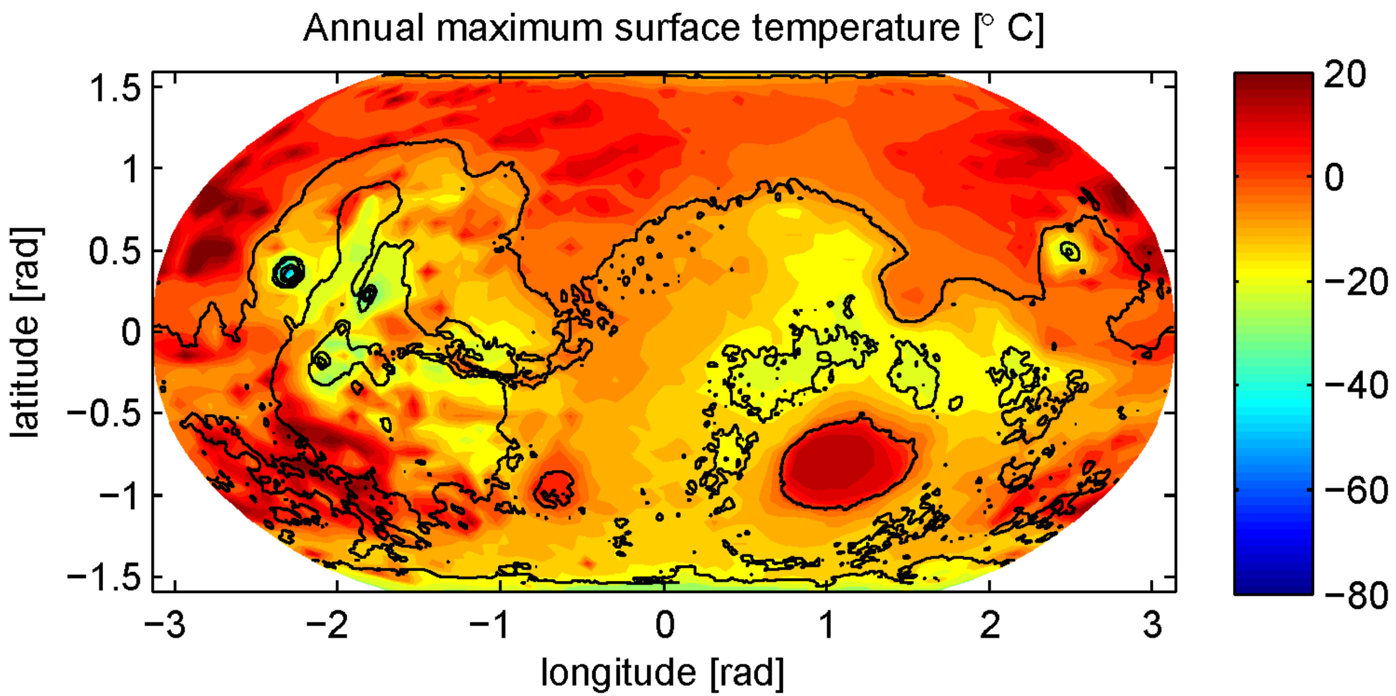


# 5 bar

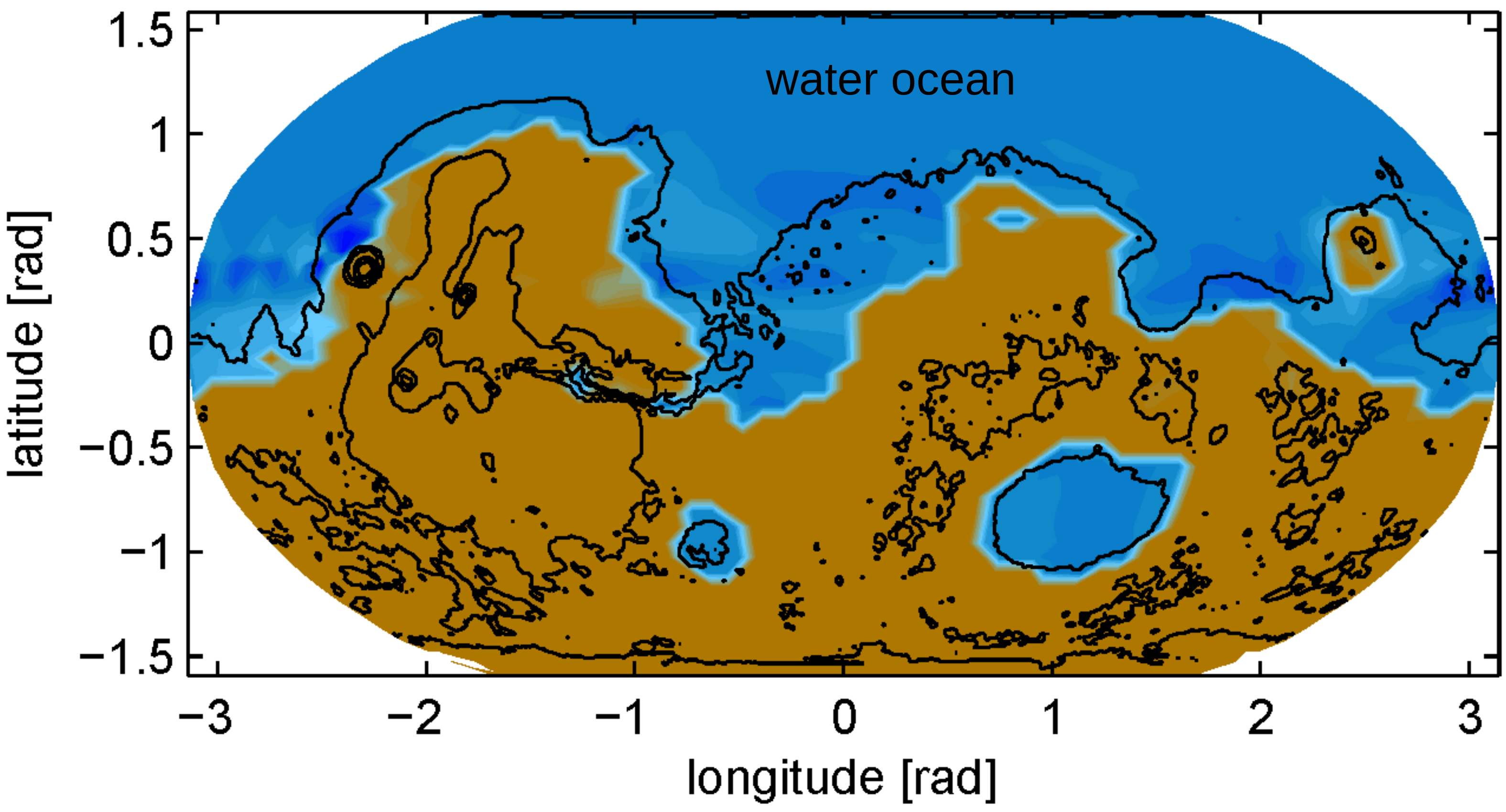


Annual mean surface temperature [° C]
1.5
1
0.5
0
−0.5
−1
−1.5
latitude [rad]
−3
−2
−1
0
1
2
3
longitude [rad]
20
0
−20
−40
−60
−80

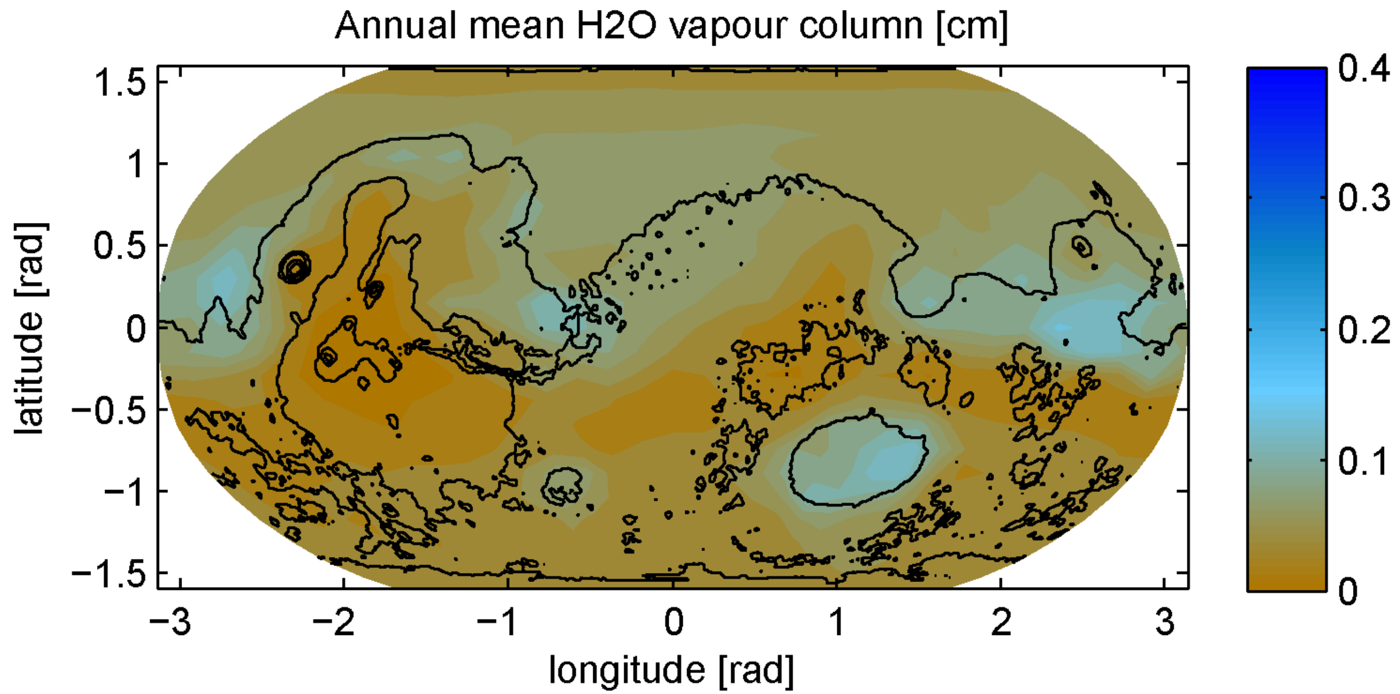



Annual maximum surface temperature [° C]
1.5
1
0.5
0
−0.5
−1
−1.5
latitude [rad]
−3
−2
−1
0
1
2
3
longitude [rad]
20
0
−20
−40
−60
−80

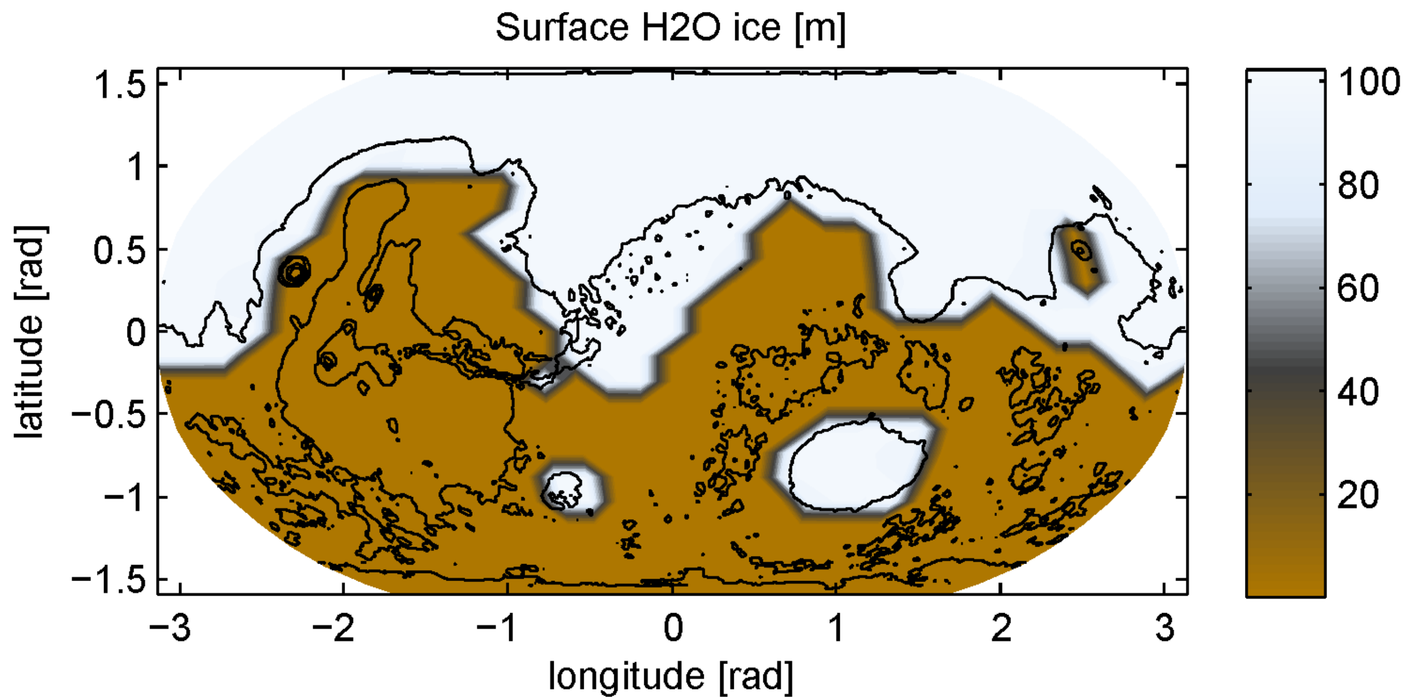
# 3D initial conditions for $H_2O$



# 2 bar, ocean

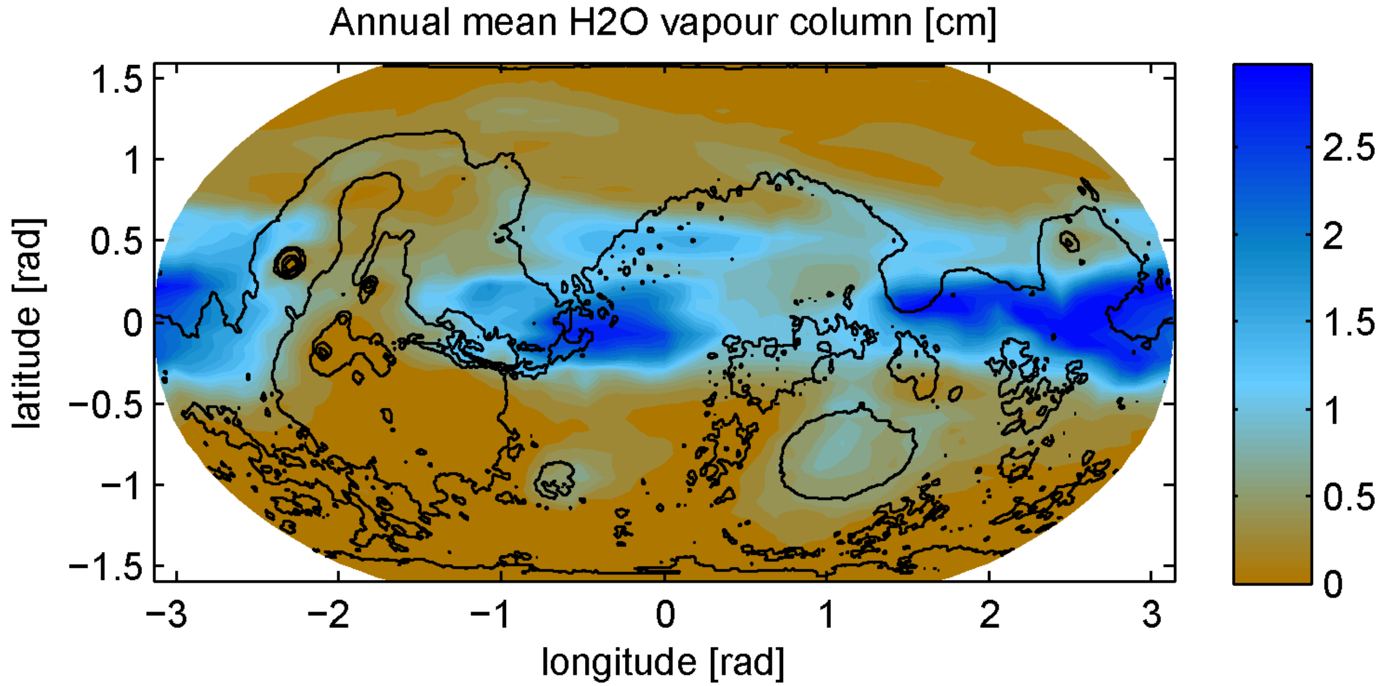


Annual mean H2O vapour column [cm]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
0.4
0.3
0.2
0.1
0

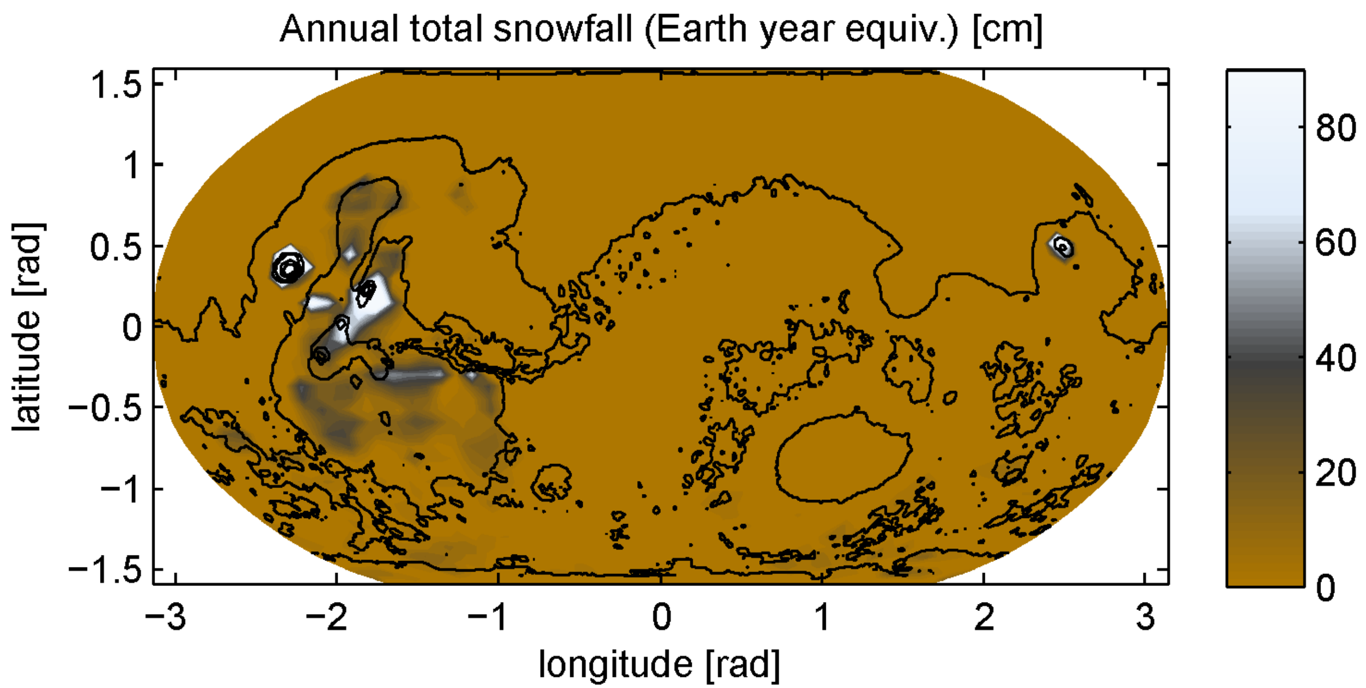



Surface H2O ice [m]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
100
80
60
40
20

# 5 bar, ocean



Annual mean H2O vapour column [cm]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
2.5
2
1.5
1
0.5
0

Annual total snowfall (Earth year equiv.) [cm]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
80
60
40
20
0

# 5 bars of $CO_2$ ???

**Initial Mars inventory > 10 bars (probably)**

**BUT recent studies suggest a much thinner inventory for the Noachian Martian atmosphere:**

- **Primordial atmosphere maybe removed quickly (*Tian et al., 2009)***
- **Tharsis outgassing probably overestimated. *Morschhauser 2011***
- **After heavy bombardment, weak atm. escape (*Lammer et al.* 2011)**

**⇨ 500 mbar of $CO_2$ may be an upper limit on ancient Mars ? . It will still be very different than today :**

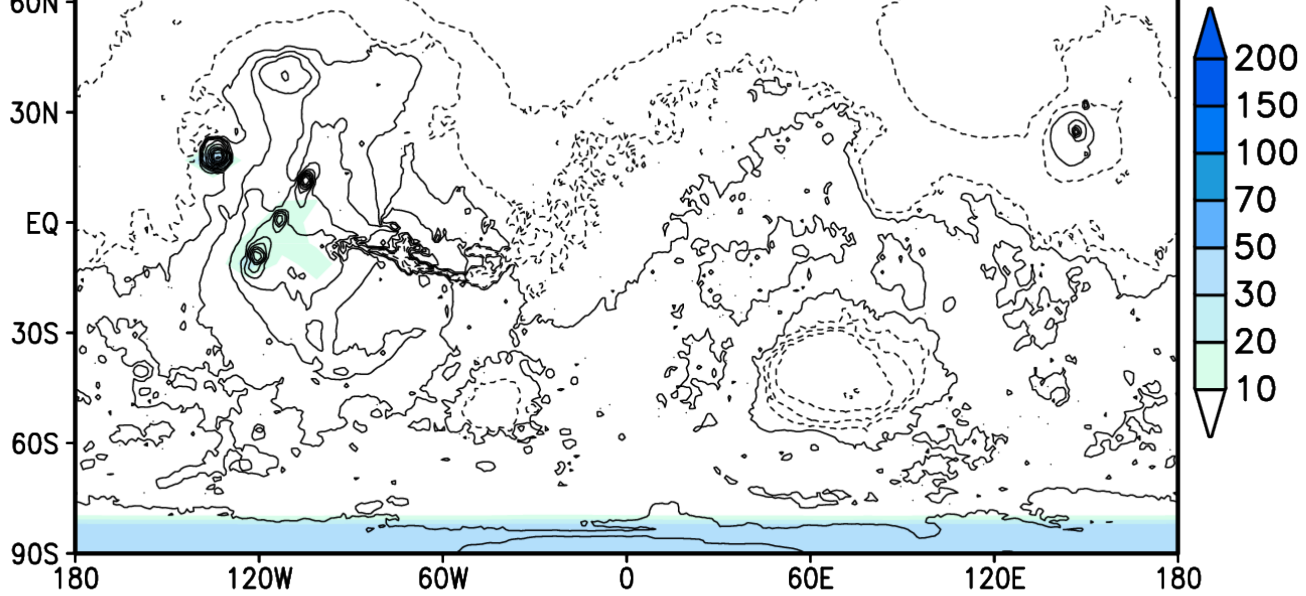
- **Cold traps in the mountains (like on Earth)**
- **Liquid water much more stable**
- **Larger ice inventory ? (less ice sequestered?)**
- **Some greenhouse effect**

# Mars with ~500 mbar of $CO_2$

Starting with limited polar caps:

Surface ice (kg/m2) : initial state → same after 50 years

Ps = 0.5 bar  obliquity=25°

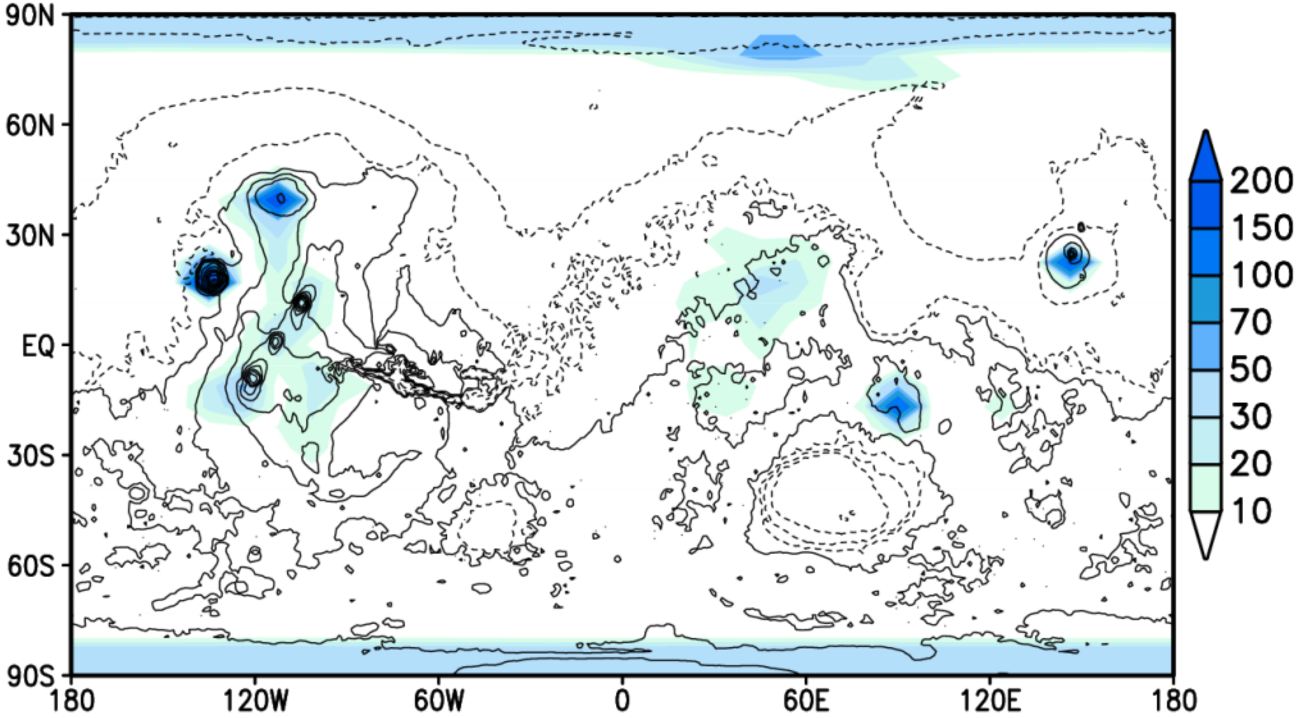


# Mars with ~500 mbar of $CO_2$

Starting with limited polar caps: HIGHER obliquity (45°)

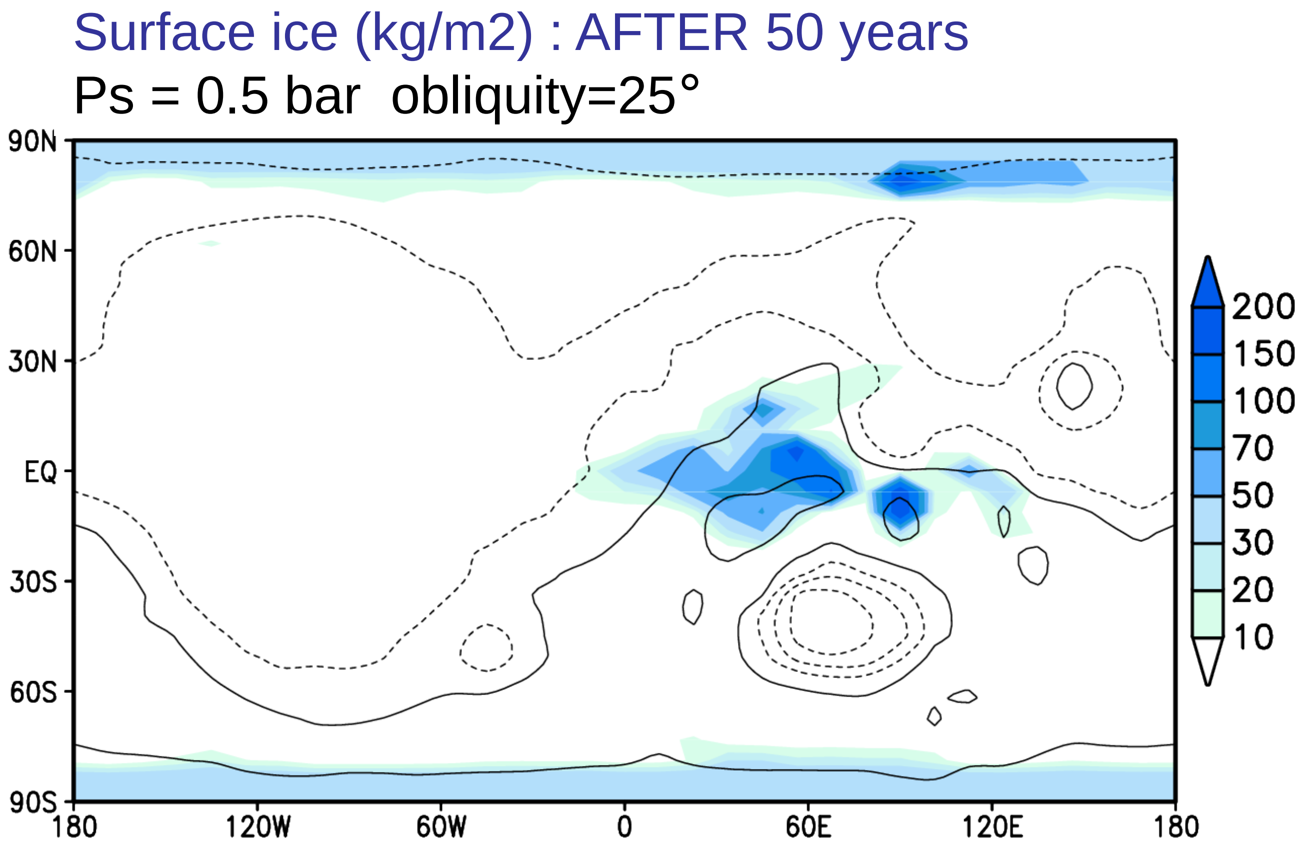
Surface ice (kg/m2) : AFTER 50 years

Ps = 0.5 bar  obliquity=45°



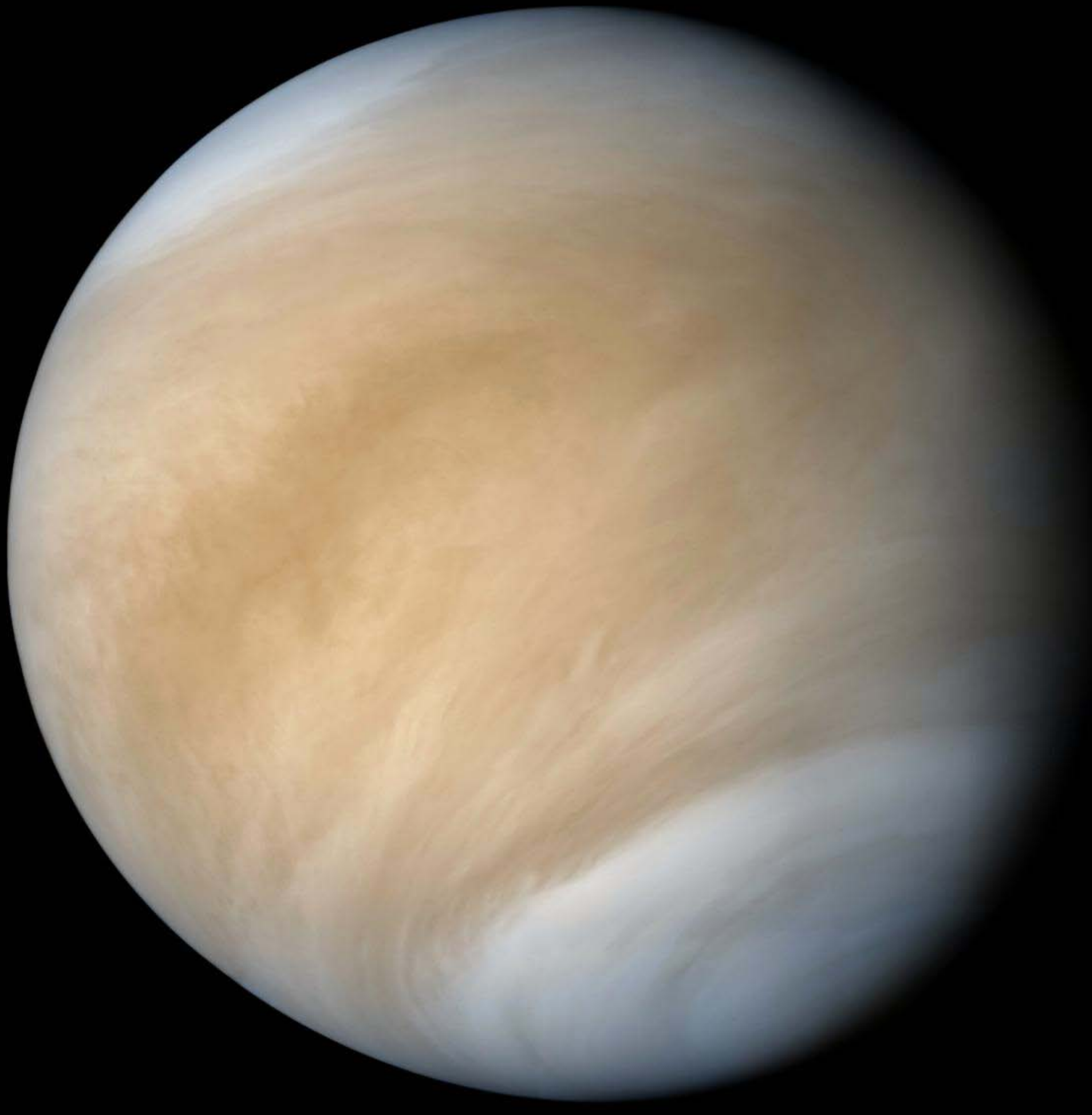
Starting with limited polar caps: REMOVING THARSIS

**Next step: remove the LHB basin**



# VENUS

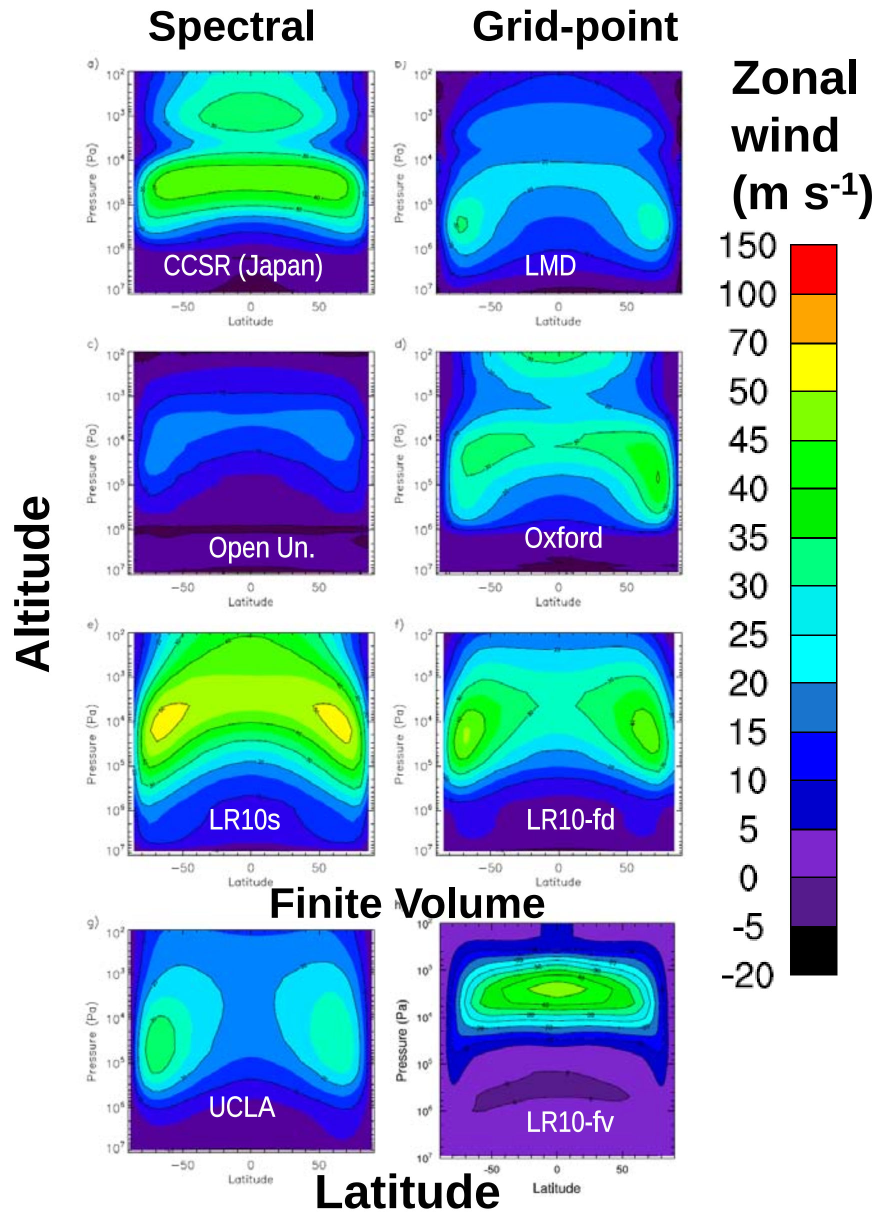
S. Lebonnois
+
Many
collaborators



# Venus is an extreme case for dynamical cores given its slow forcings

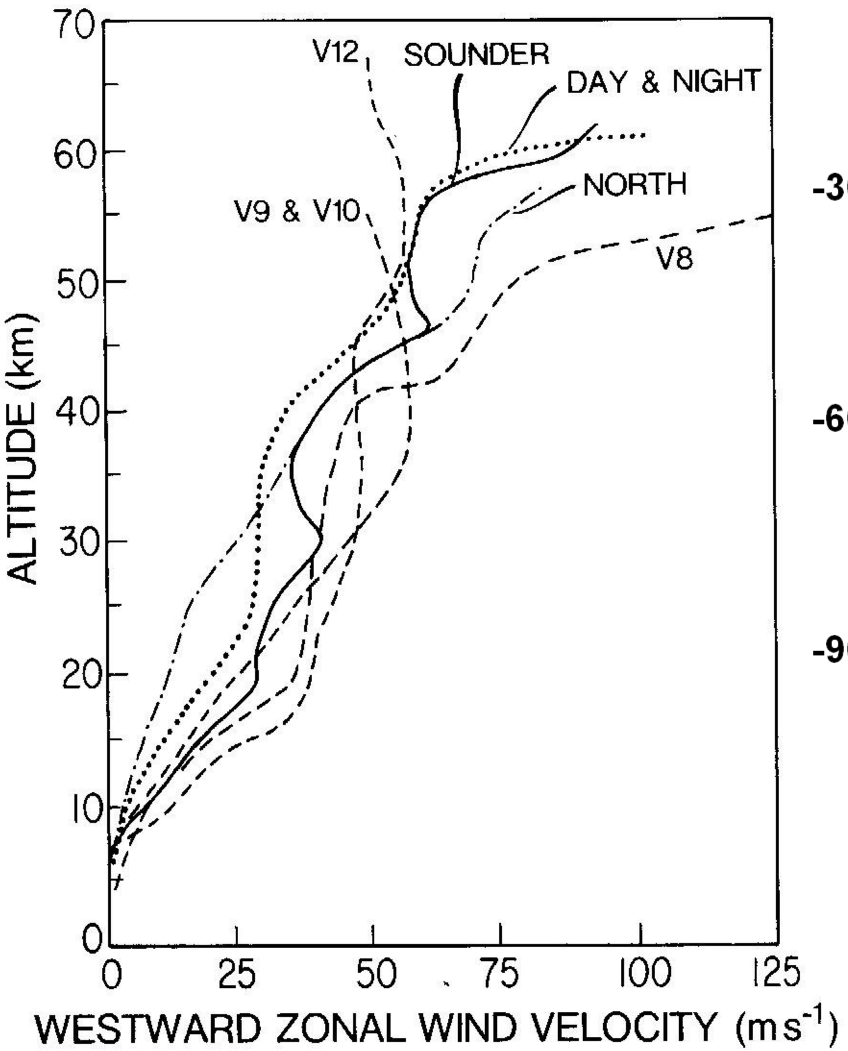
Intercomparison
Lebonnois et al. 2012

All models are run with a simple Newtonian relaxation!

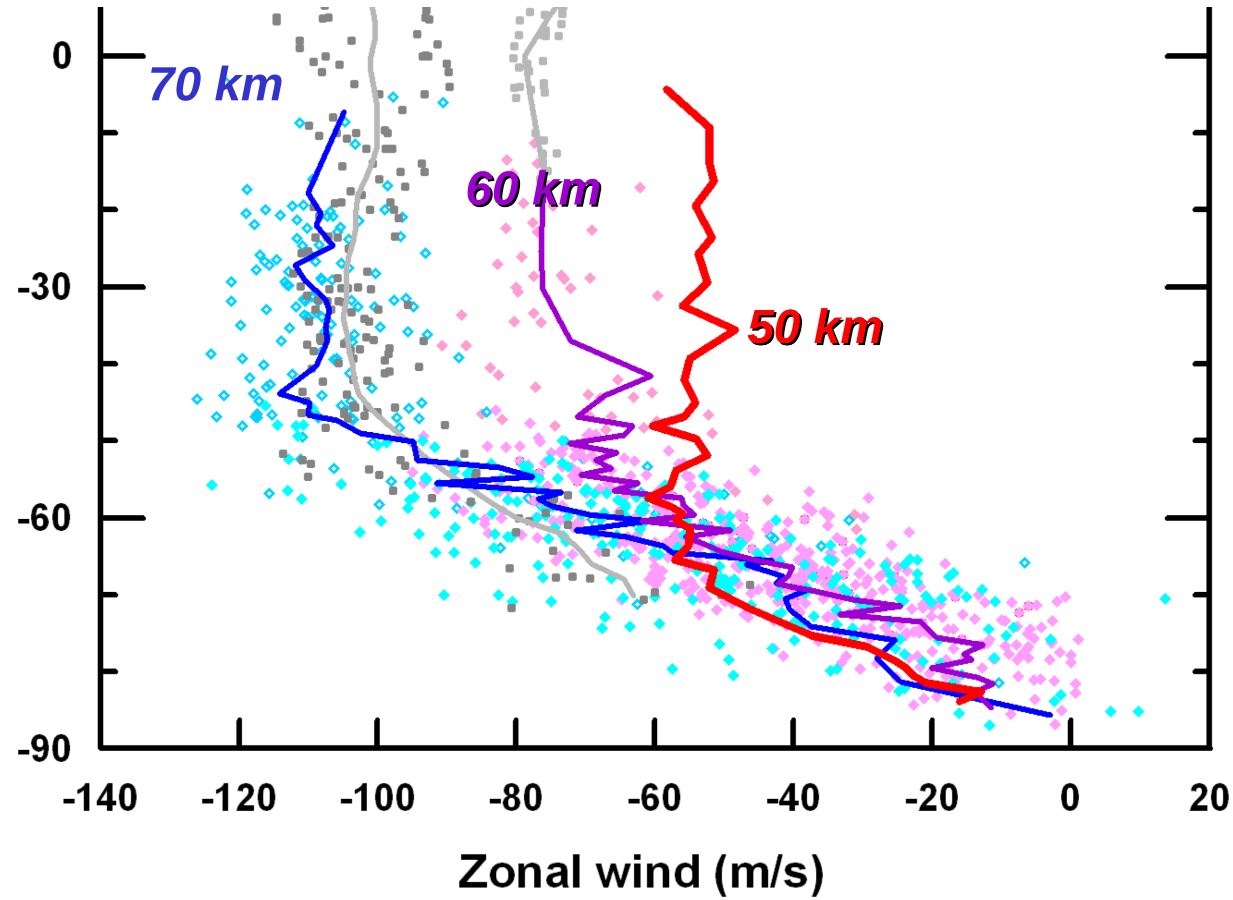


# Observations of superrotation

## Pioneer Venus and Venera probes




## VENUS

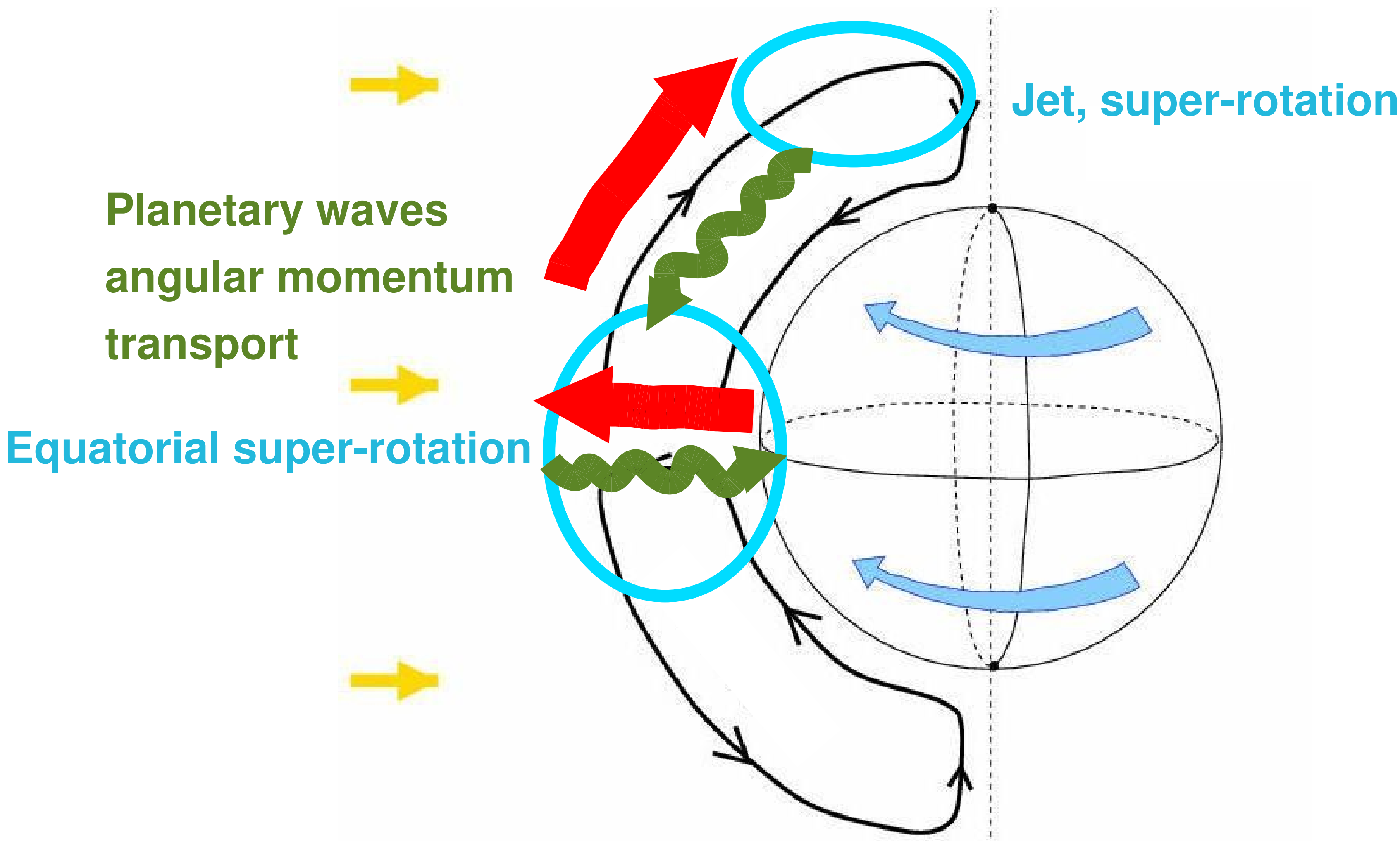



## Venus Express/VIRTIS cloud tracking

# The superrotation question

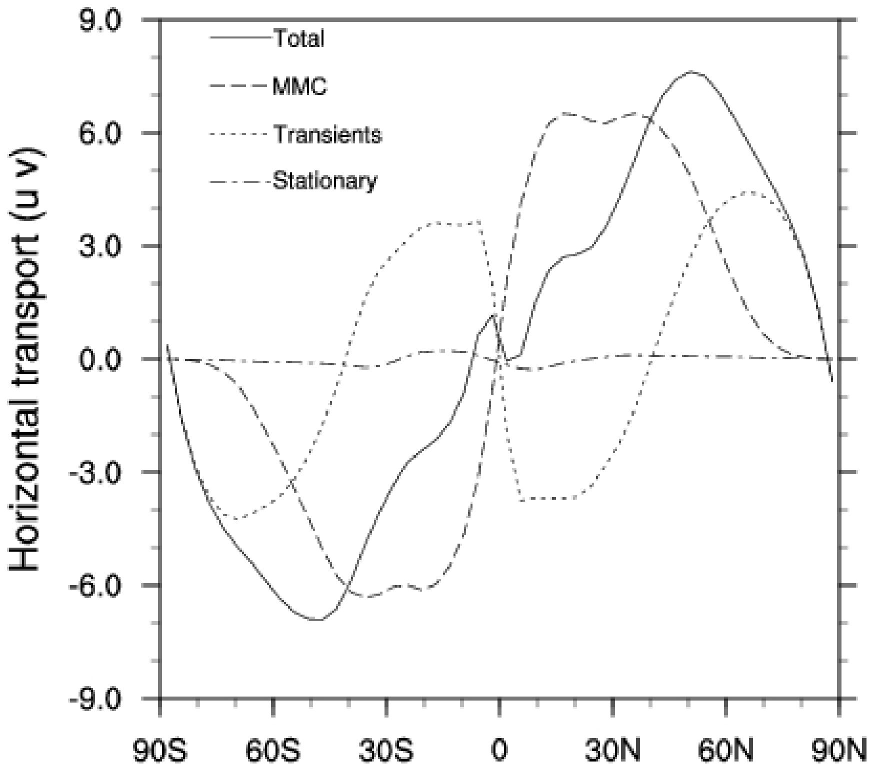
**Superrotation at the equator:**

**need for non-axisymmetric planetary waves**

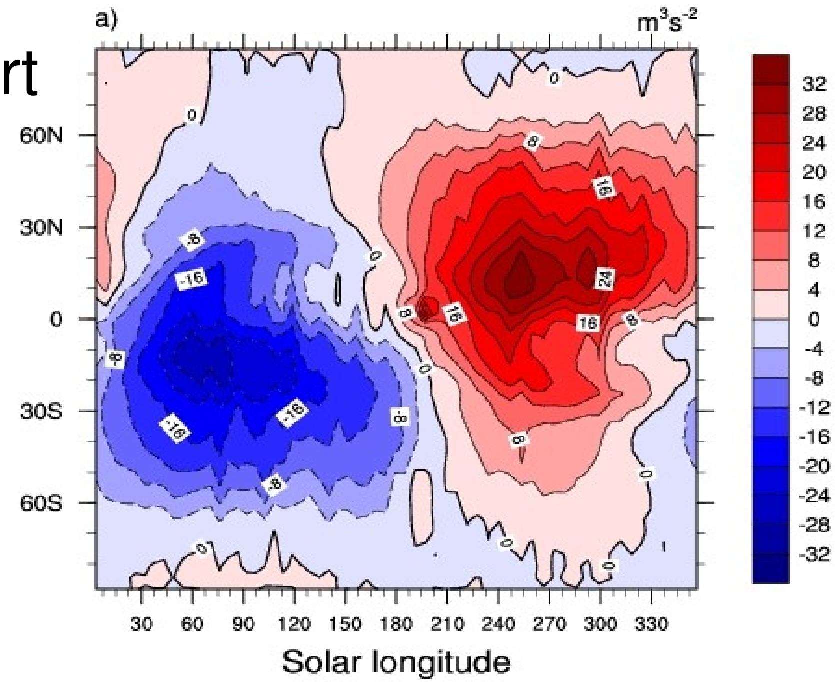


# Angular momentum transport

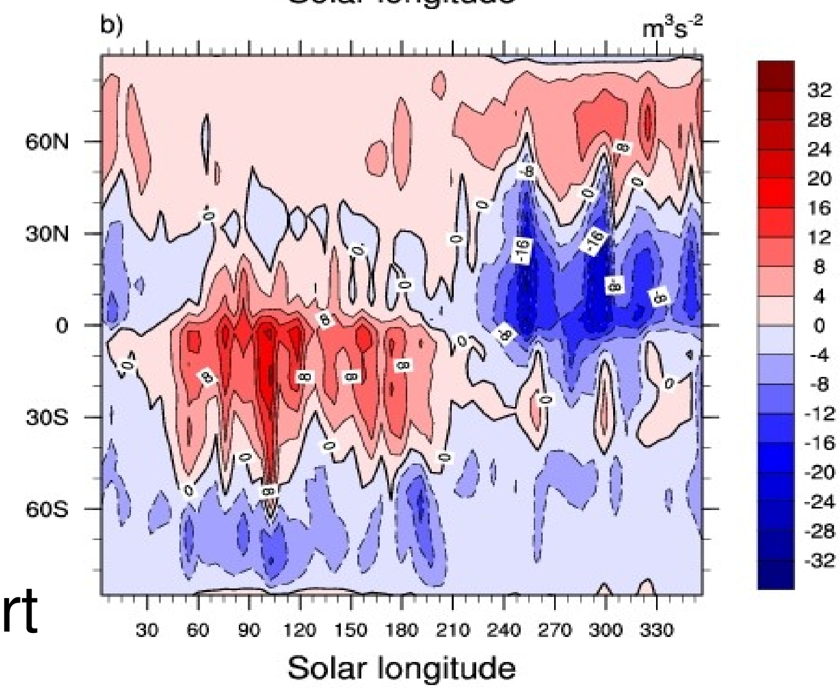
Annual mean



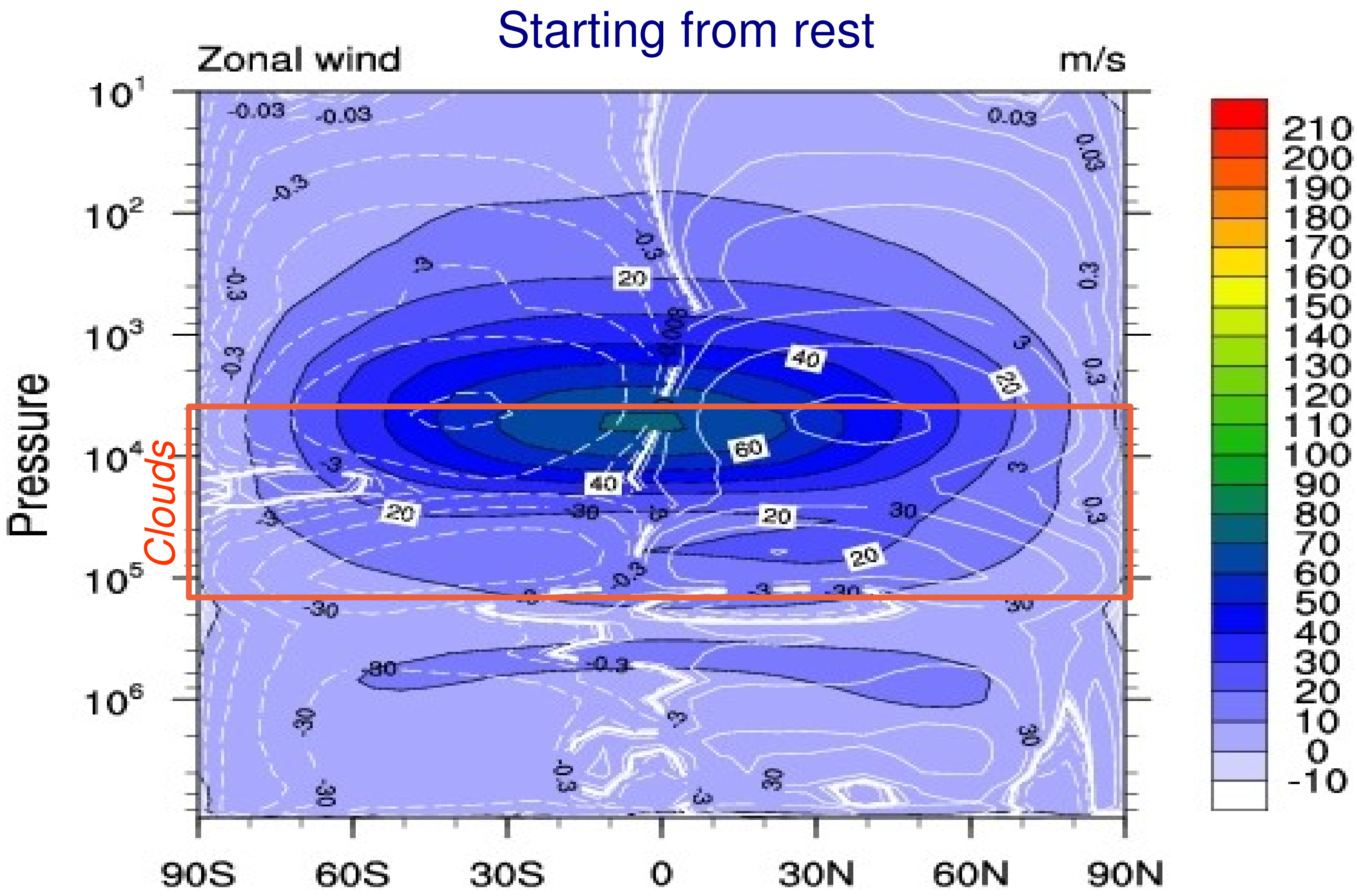

MMC transport




Transients transport

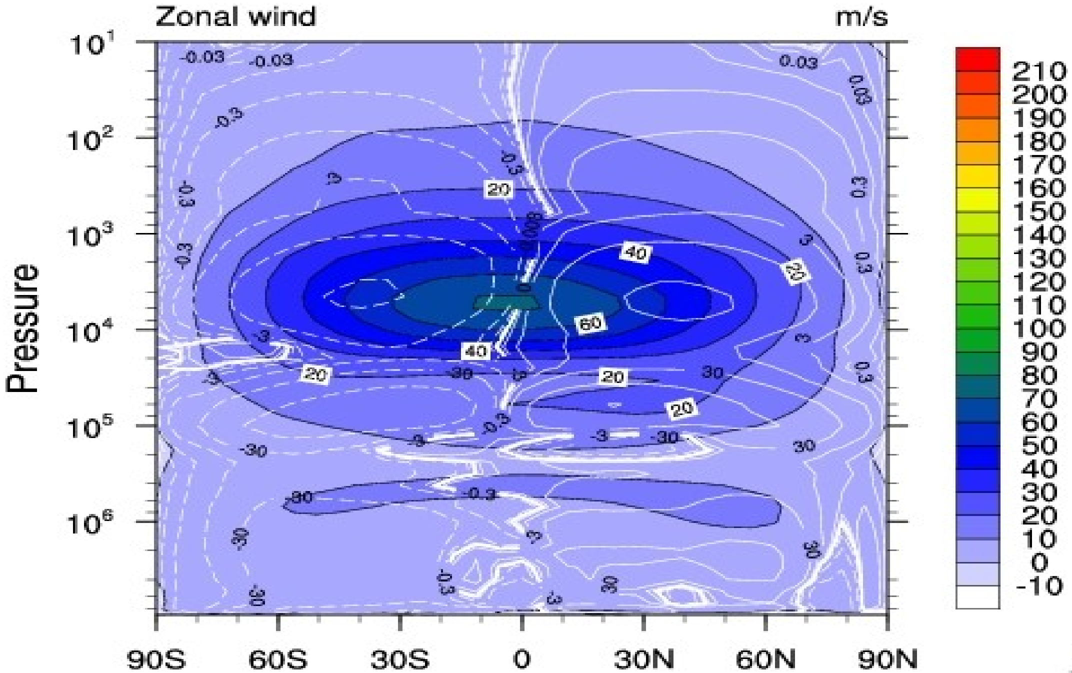


# Venus Superrotation

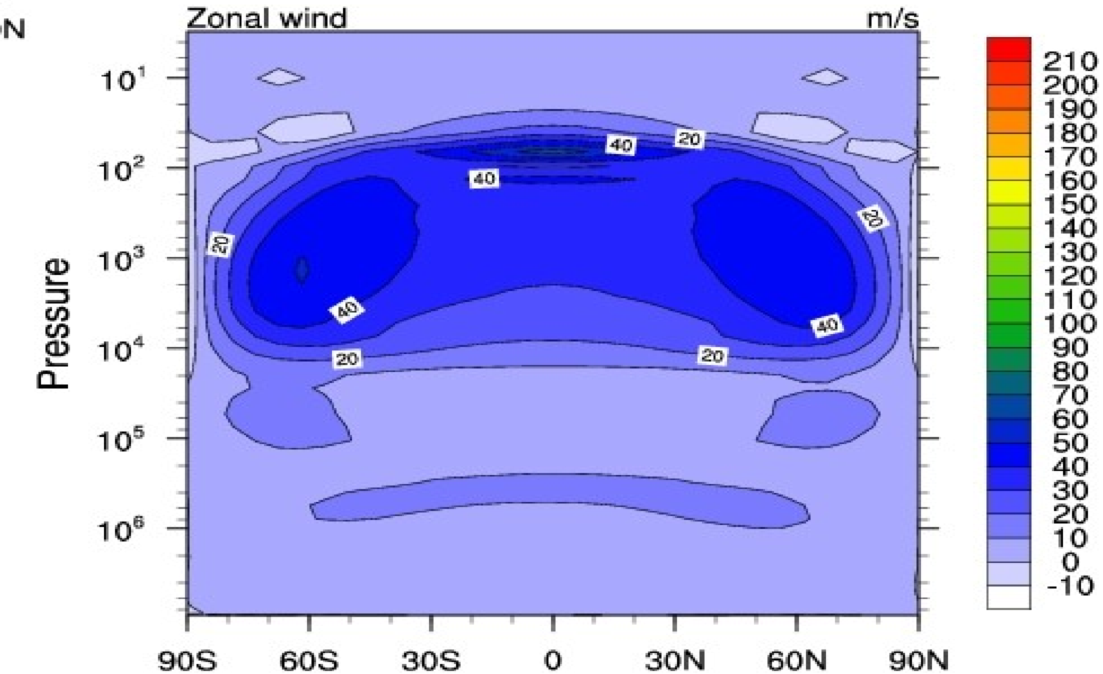



Mean zonal wind and stream function after 1000+ Vdays
(Topography, diurnal cycle)

# Role of the diurnal cycle




With diurnal cycle

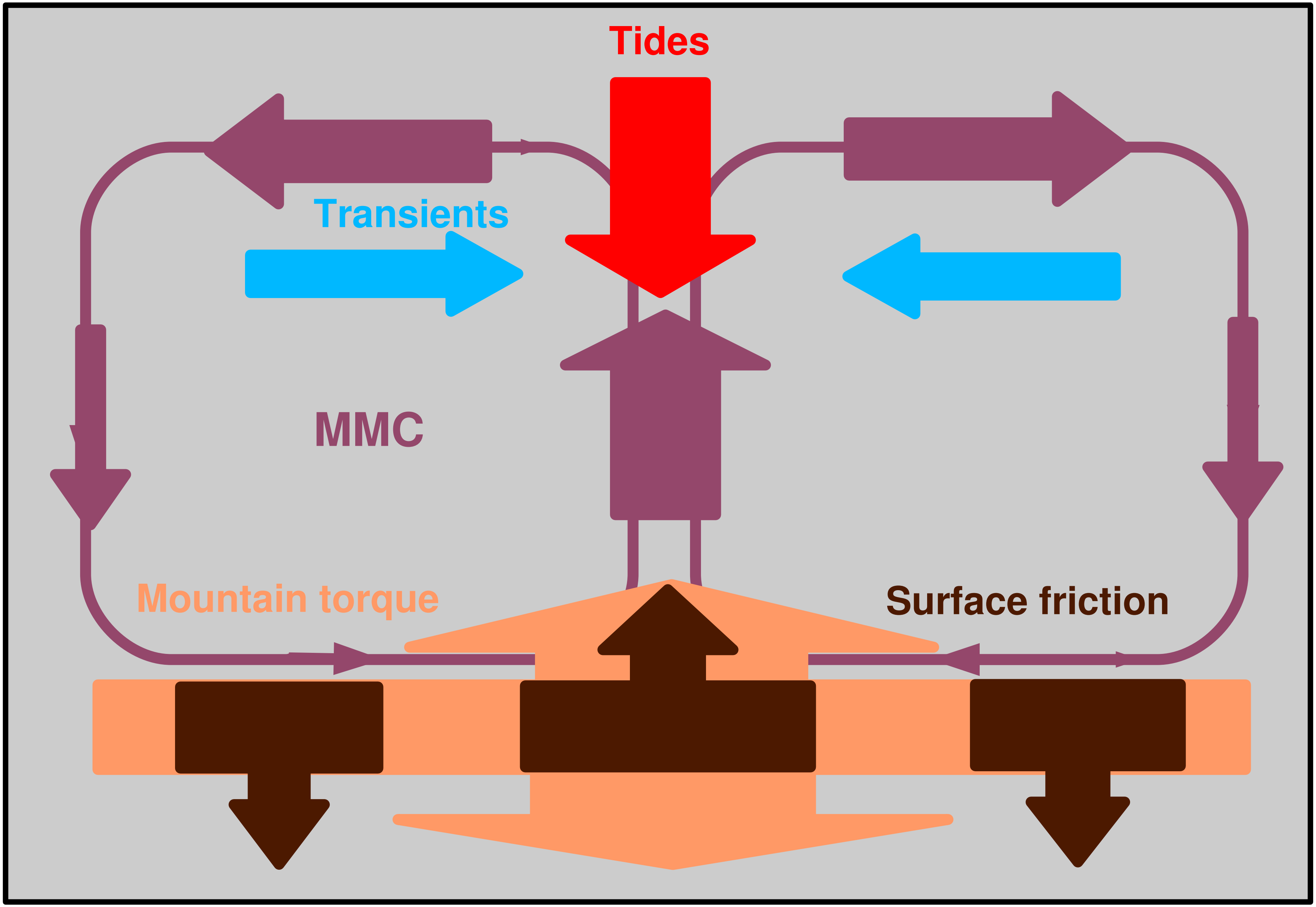



Without diurnal cycle

Influence of thermal tides in angular momentum transport:

downward transport in the equatorial 64-90 km region.

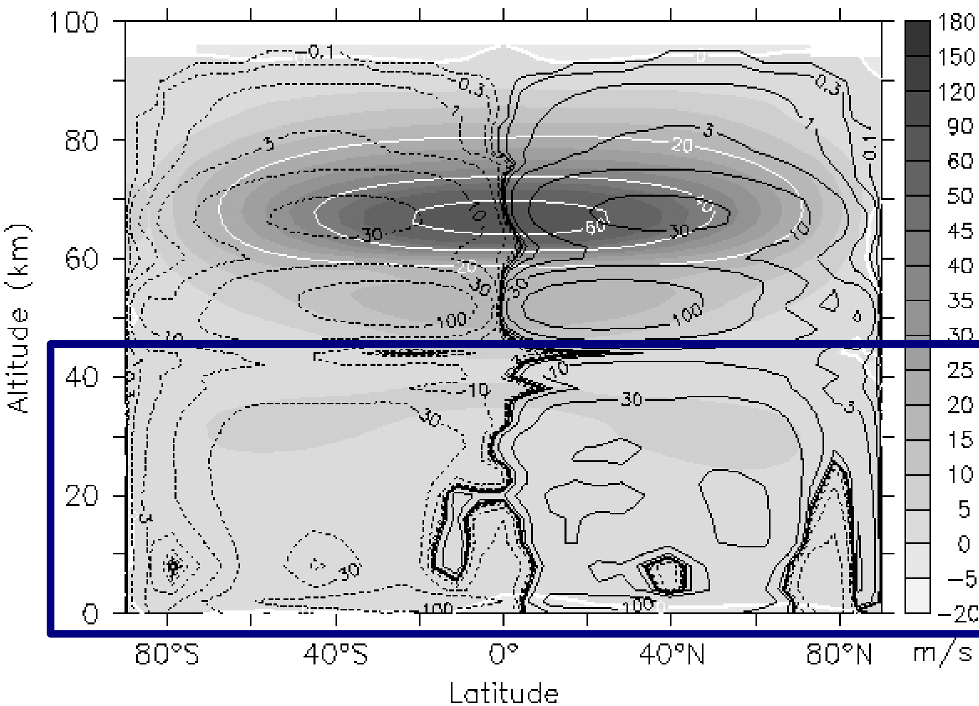
# Discussion

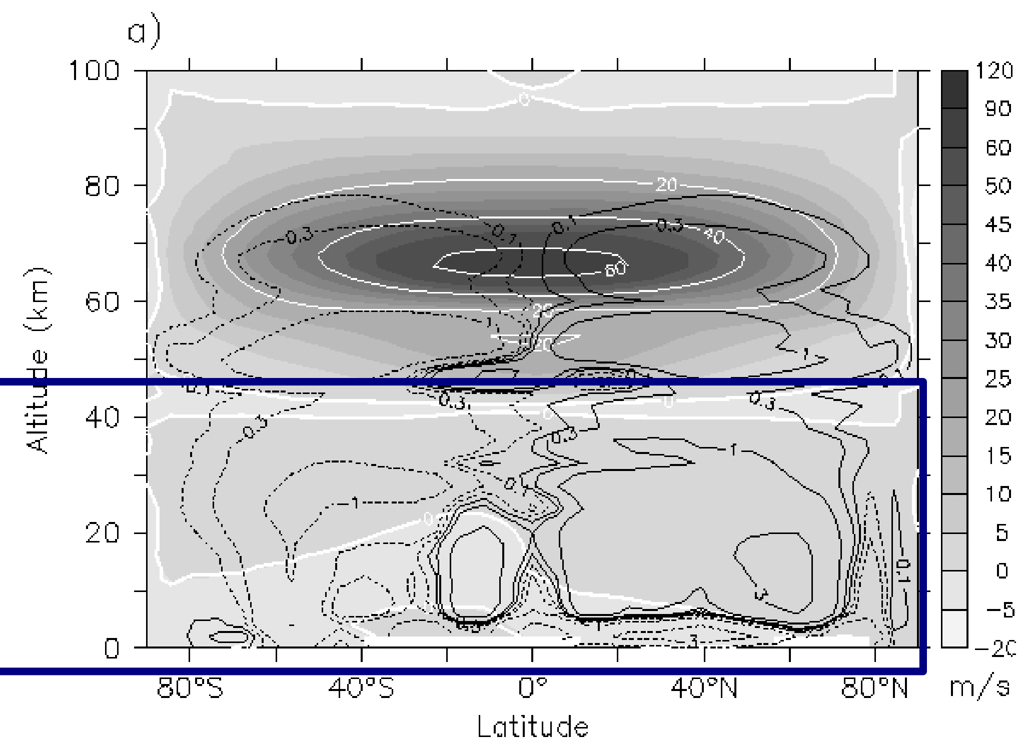



Additional aspect: Titan vs Venus: the influence of seasonal variations.

# Examples of such impacts

PBL scheme in Venus simulations :



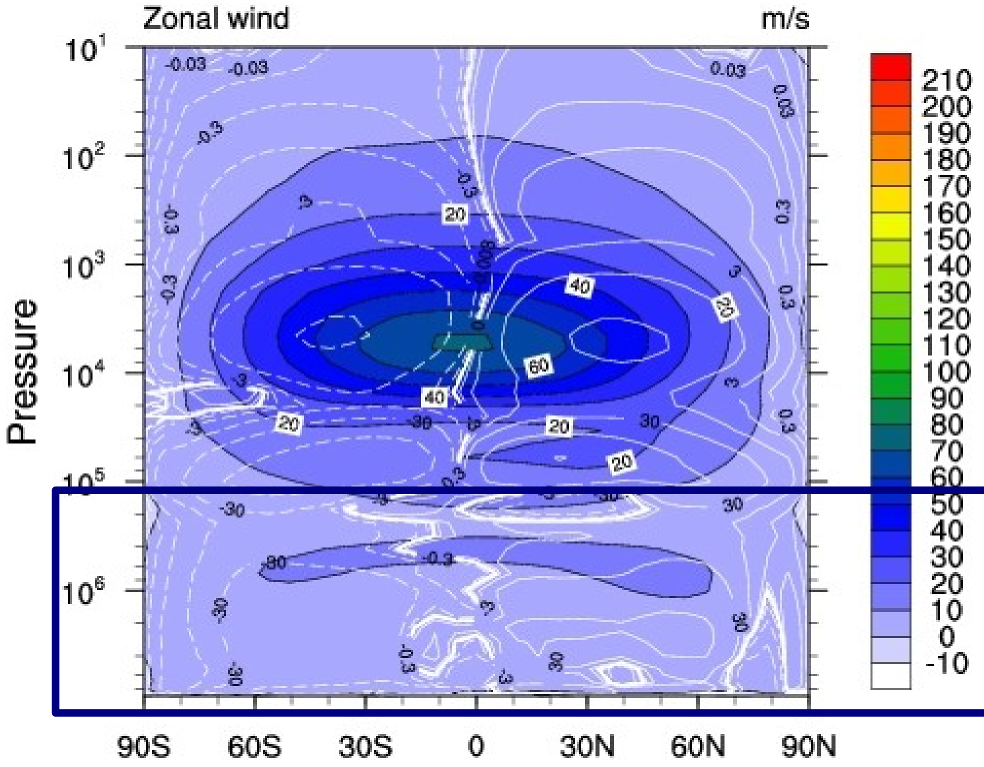



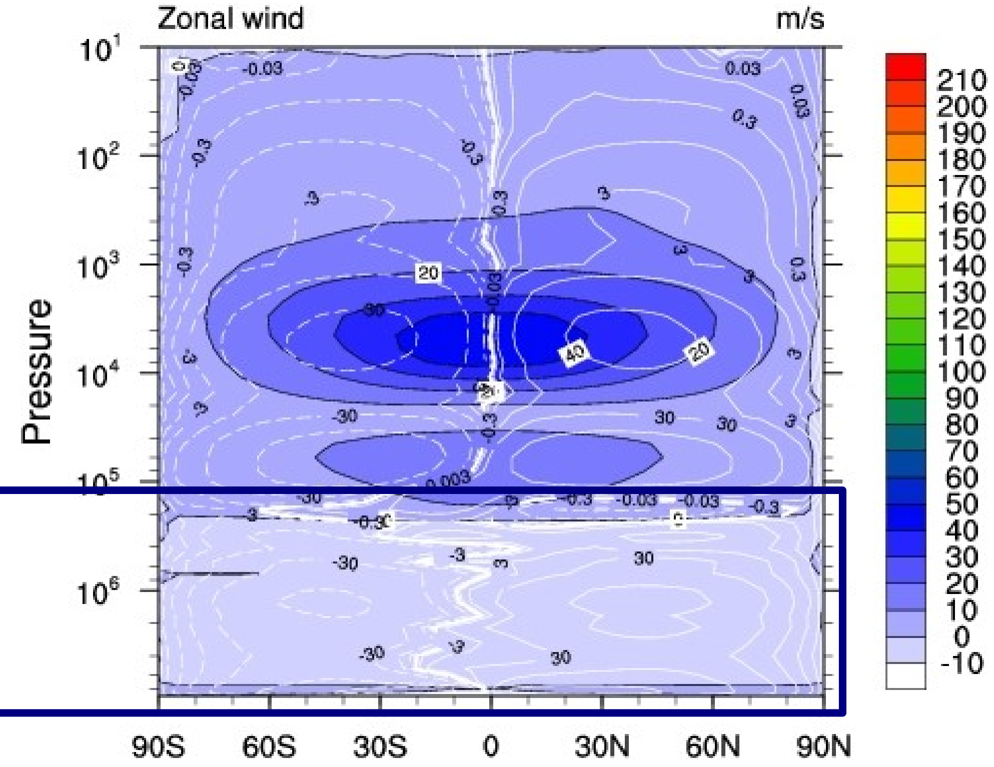

Mellor & Yamada (1982) scheme

Previous scheme (Lebonnois et al 2010)

# Examples of such impacts

Topography in Venus simulations :



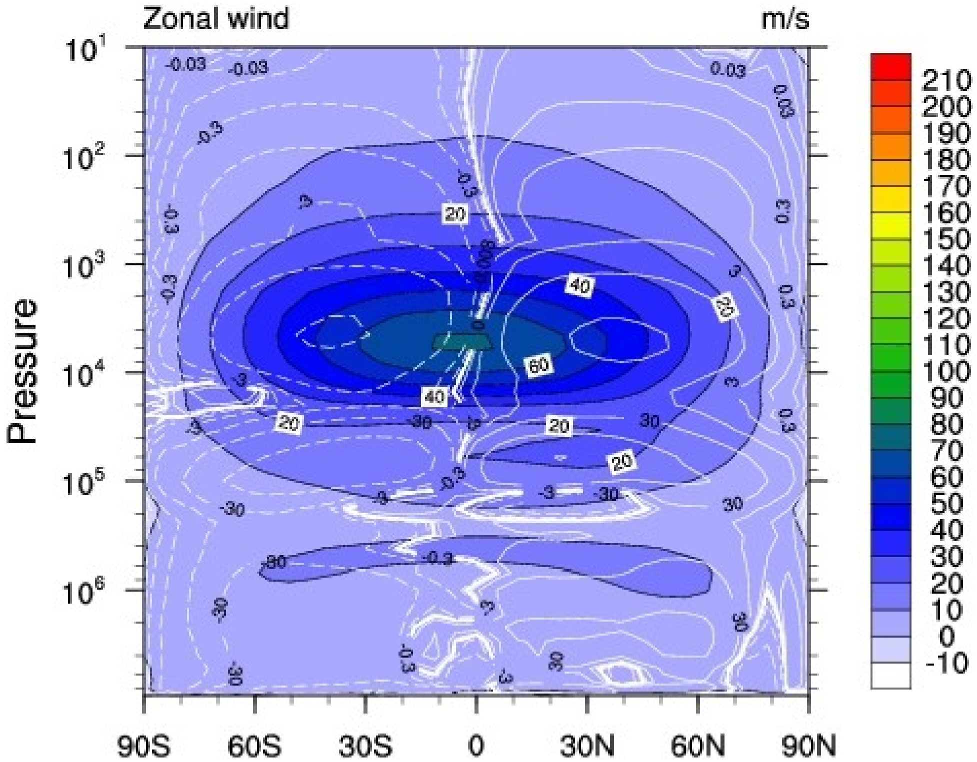




With topography

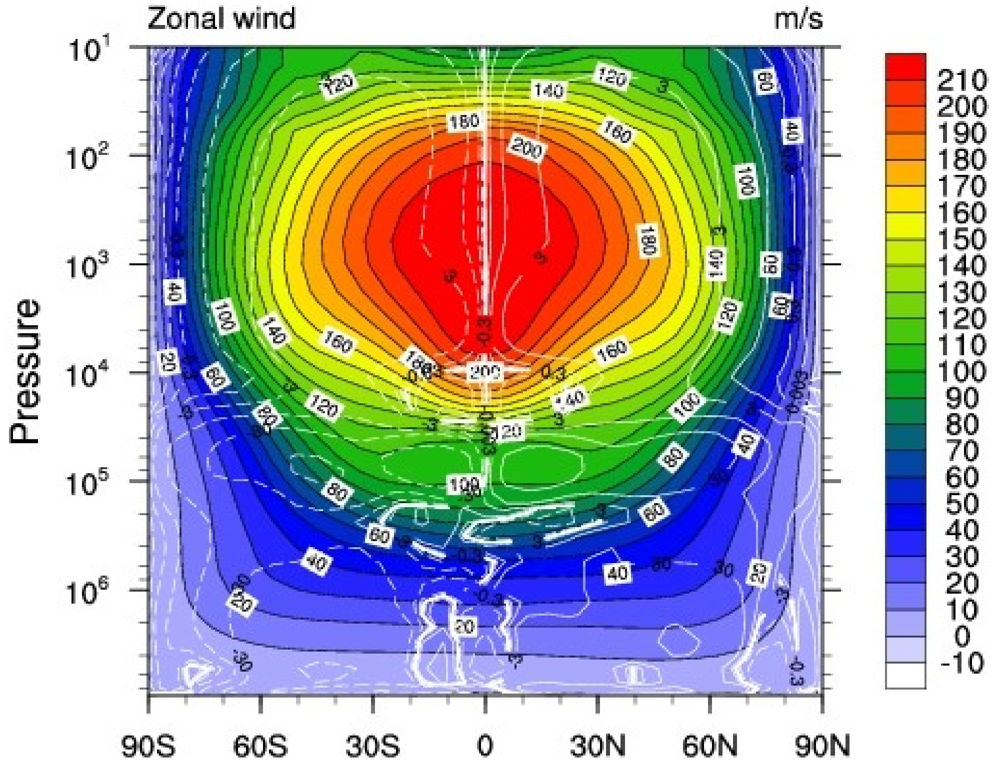
Without topography

# Examples of such impacts

Initial conditions in Venus simulations :



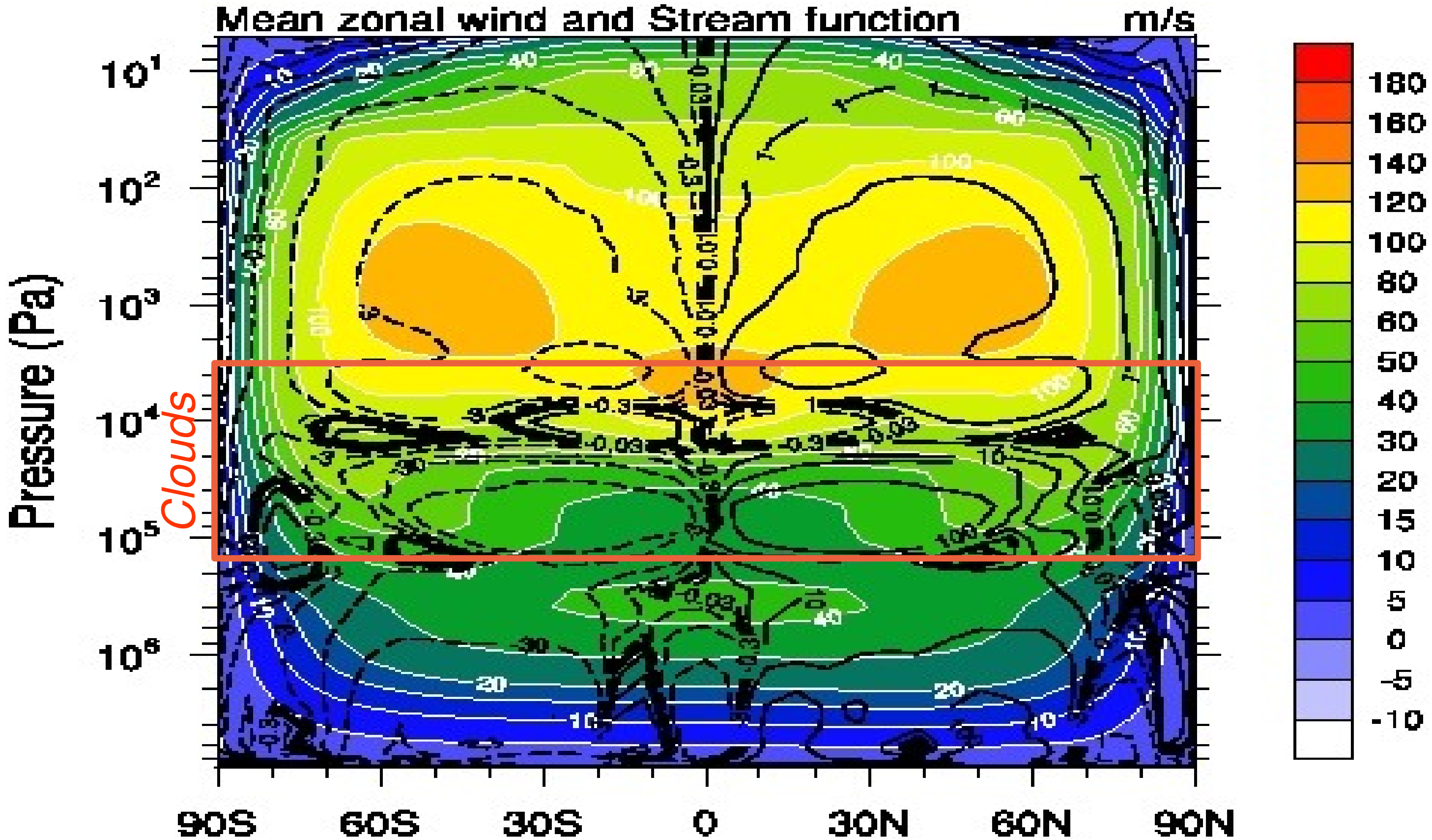

Started from rest




Started from realistic wind profile

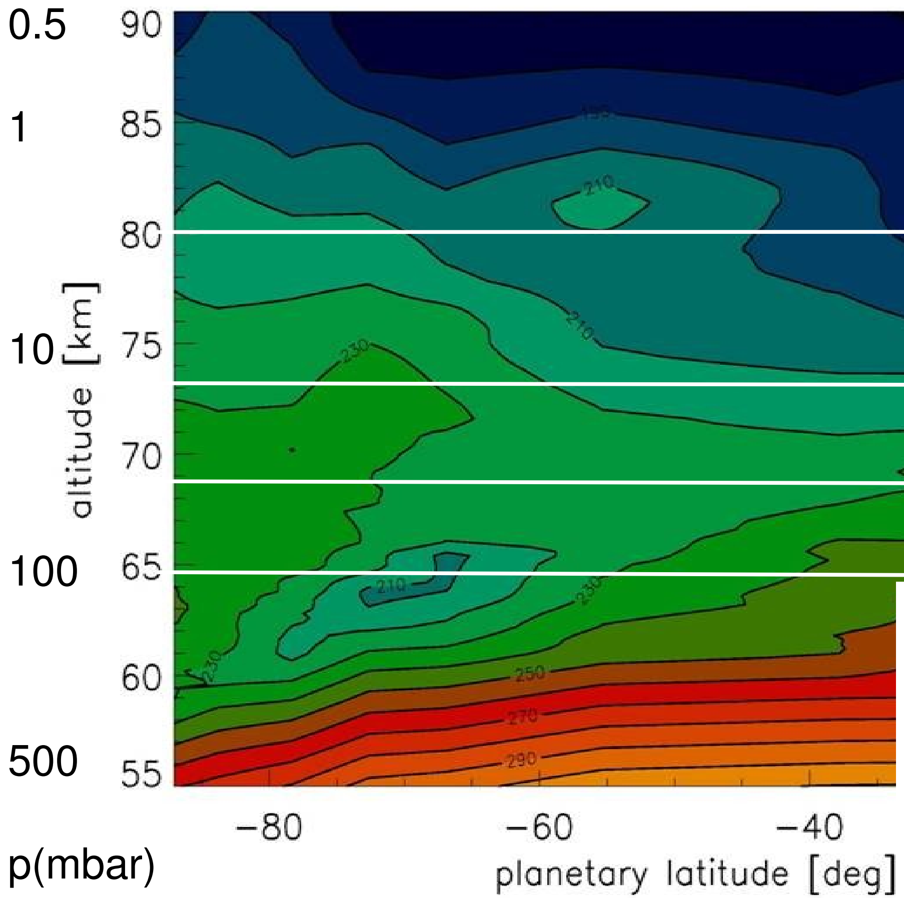
# Gravity waves

Impact on the simulation started from superrotation



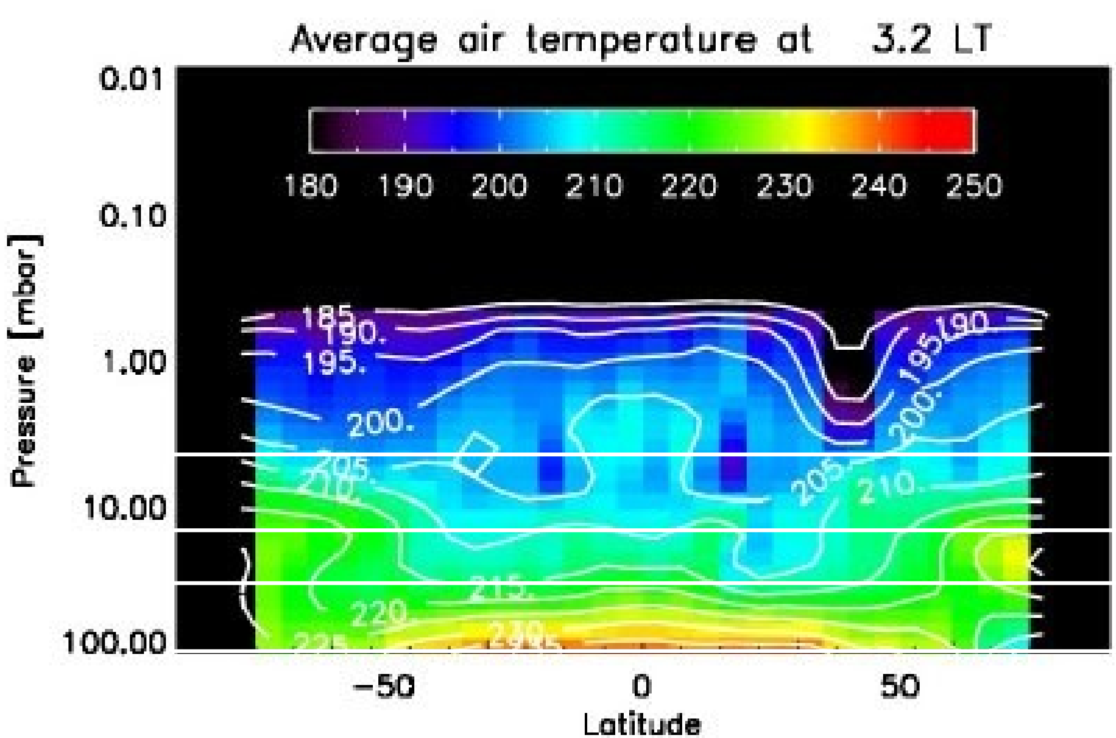

Closer to observations, though cloud-bottom to cloud-top gradient still too strong.

# Temperature meridional distribution

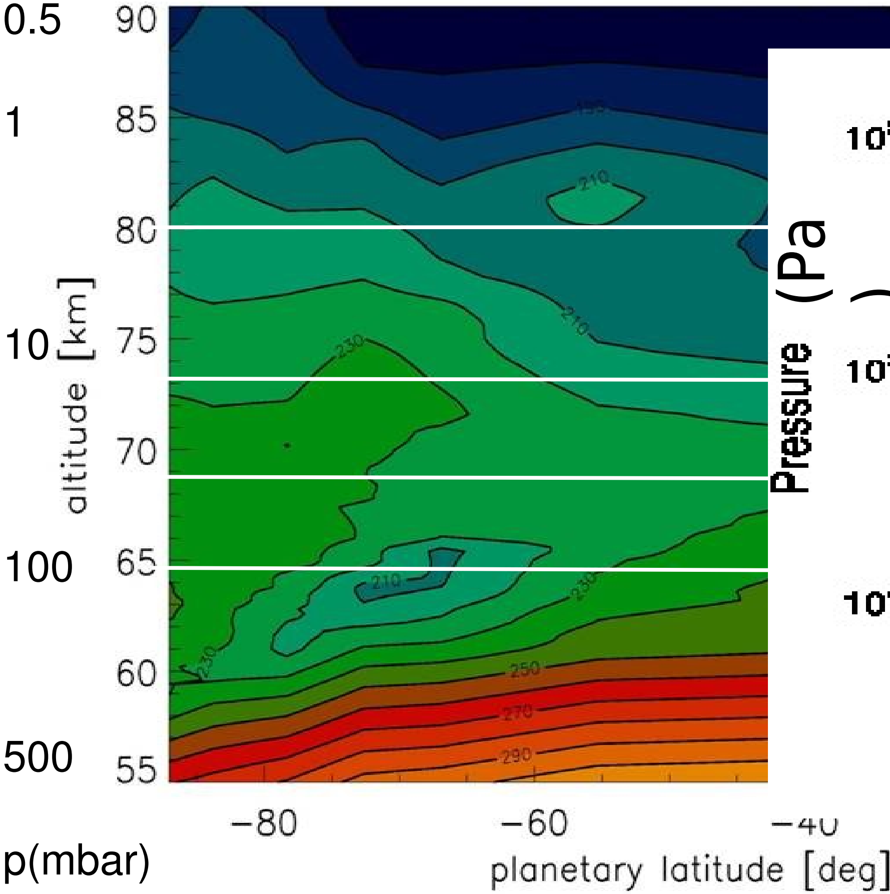



VeRa, Venus Express

VIRTIS, Venus Express

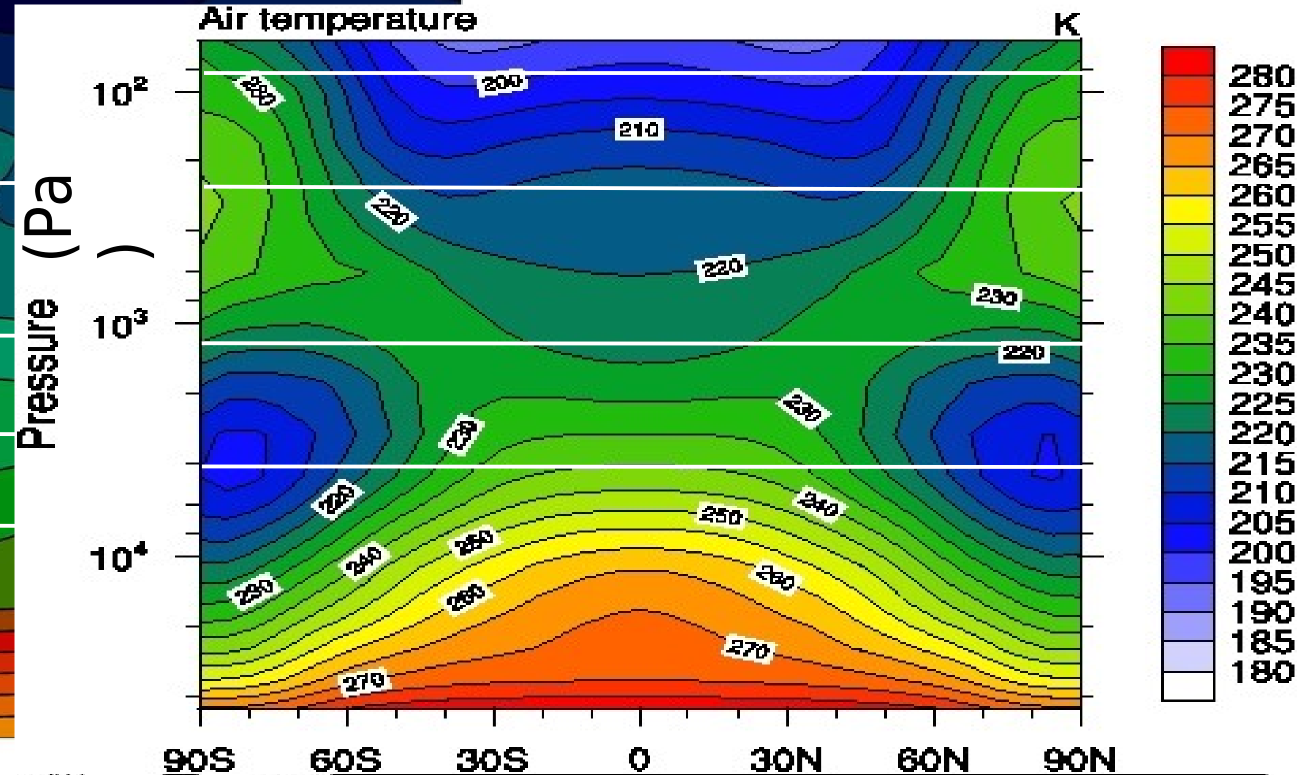


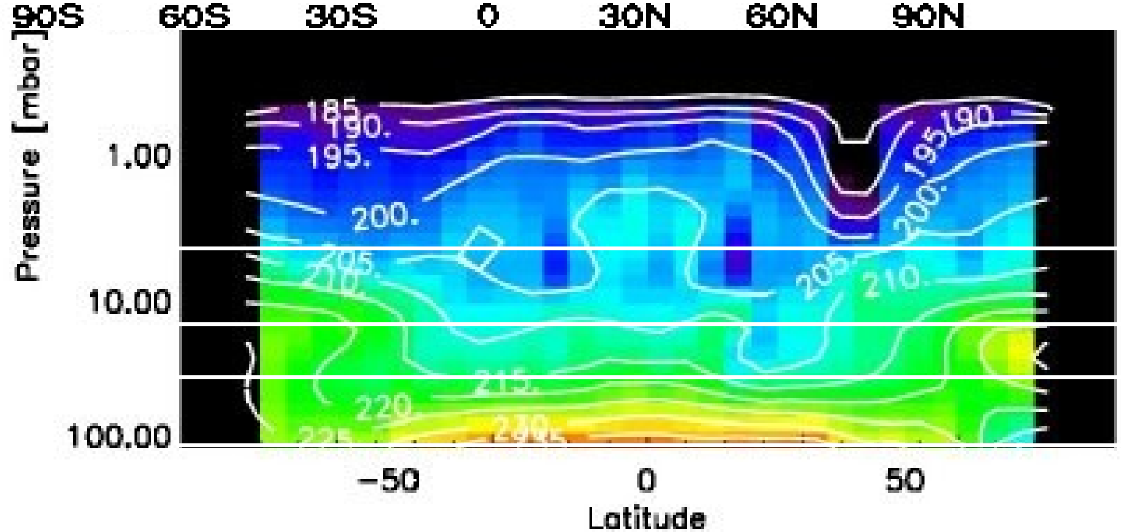
# Temperature meridional distribution




VeRa, Venus Express

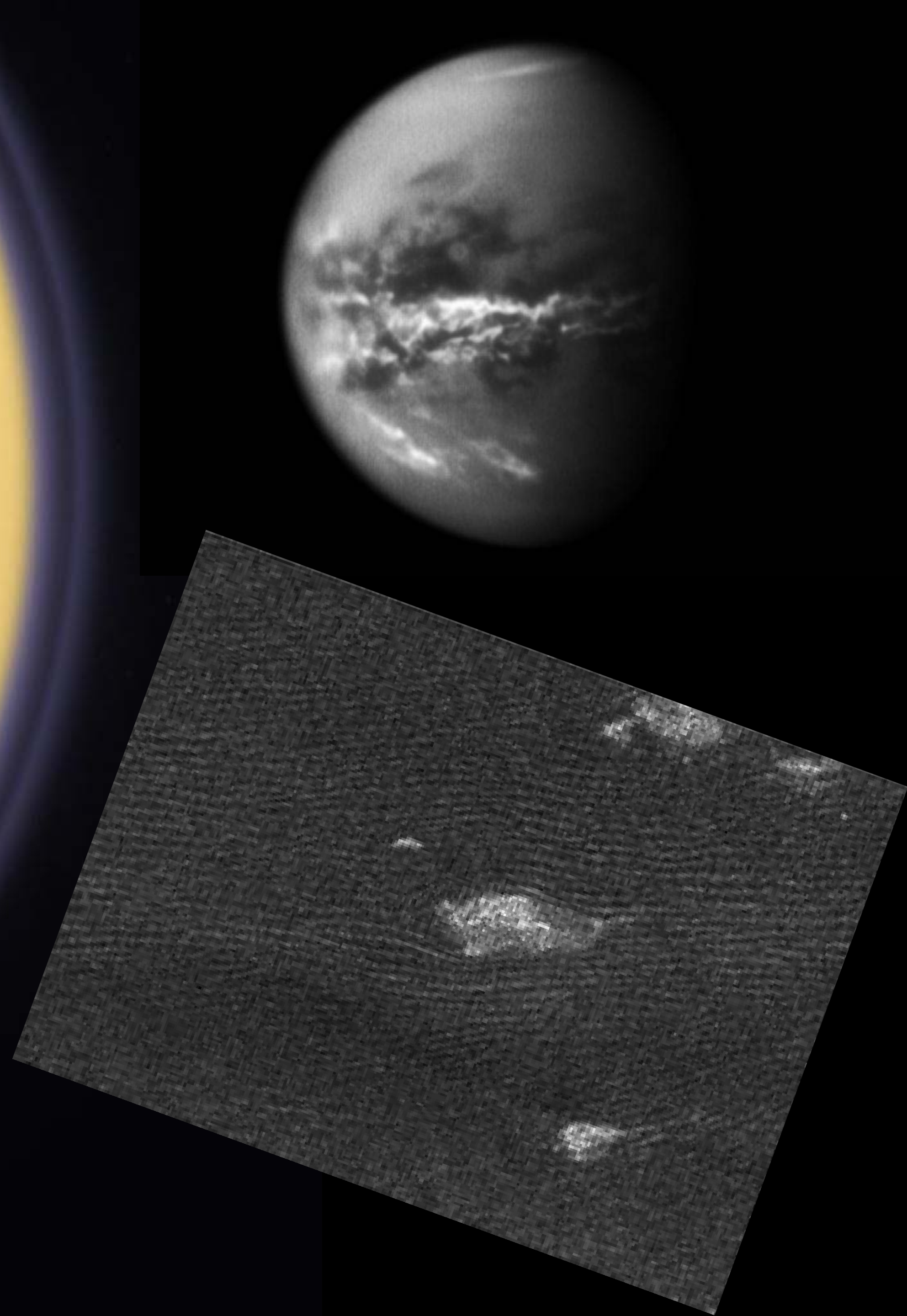
LMDZ-Venus



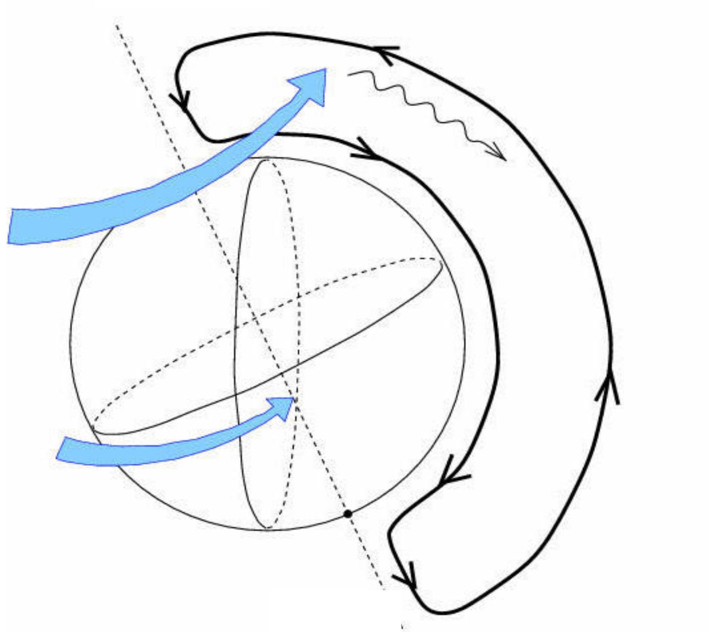
# Titan

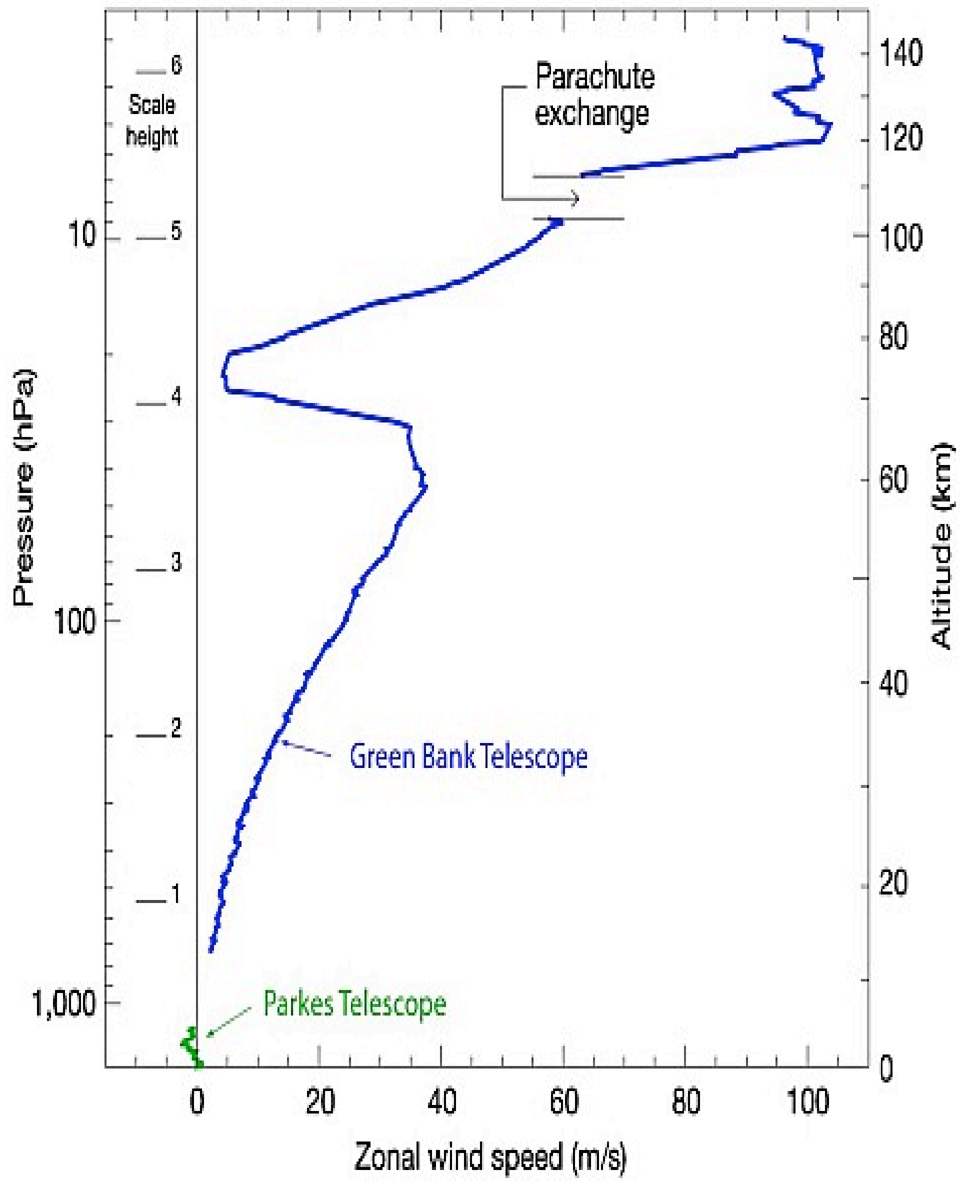
S. Lebonnois
B. Charnay
F. Hourdin
P. Rannou
…



# Main characteristics of Titan's atmosphere

- Super-rotation
- Methane cycle
- One Hadley cell. Equinox reversal
- Radiative time scale ~ 2.5 Titan years
    - Weak diurnal cycle (ΔTs < 1 K)
    - Circulation ~ Mean circulation
- Pressure influenced by gravitational tides induced by Saturn



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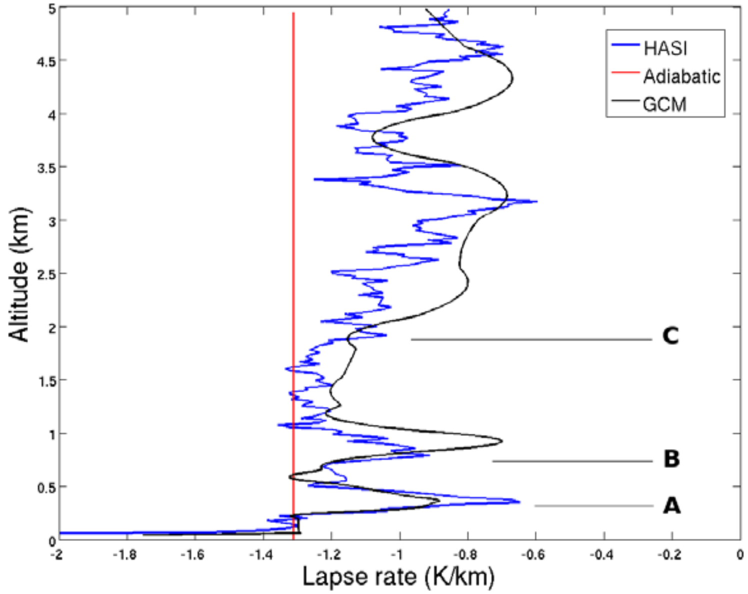
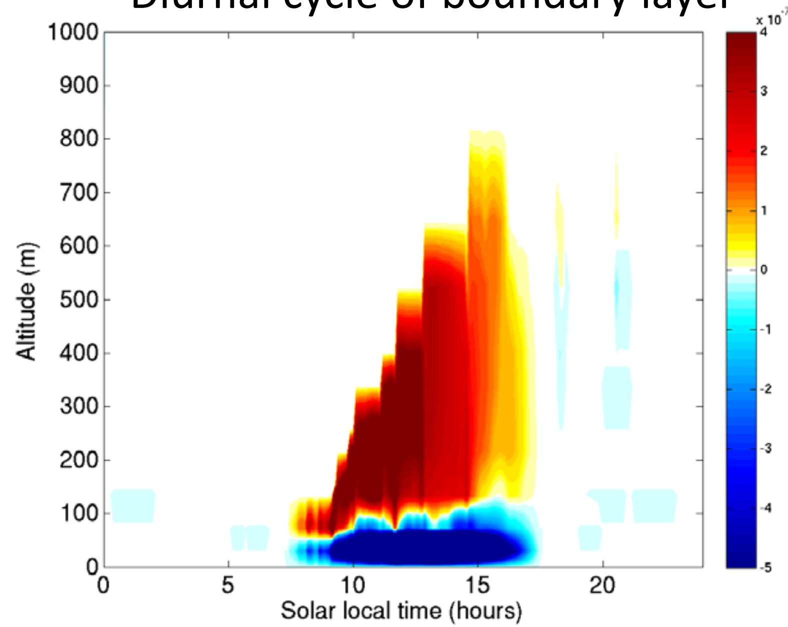
# Lower troposphere and boundary layer of Titan

Charnay & Lebonnois, *Nature Geoscience* (2012)

Thermal structure




Diurnal cycle of boundary layer

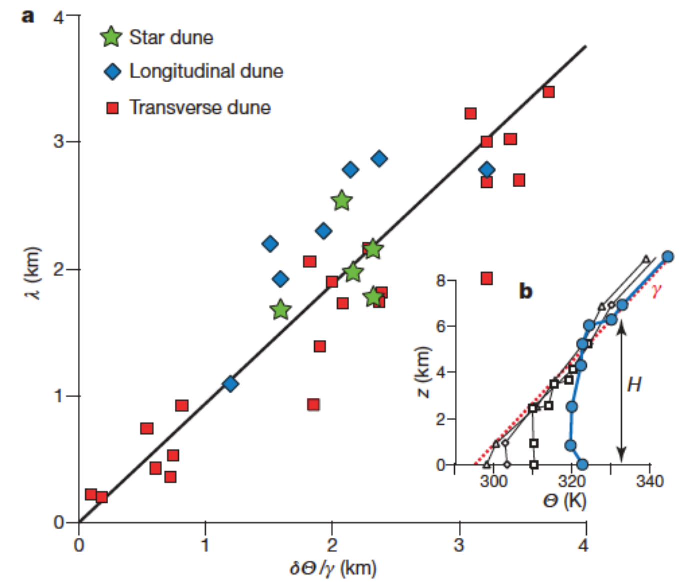



- Boundary layer forced by diurnal cycle, up to 2 km @ ITCZ
- Hadley cell confined in the lowermost 2 km
  - → additional boundary layer circulation

# Formation of giant dunes

Andreotti et al., *Nature* (2009)

PBL controls size & spacing of giant dunes: λ≈H

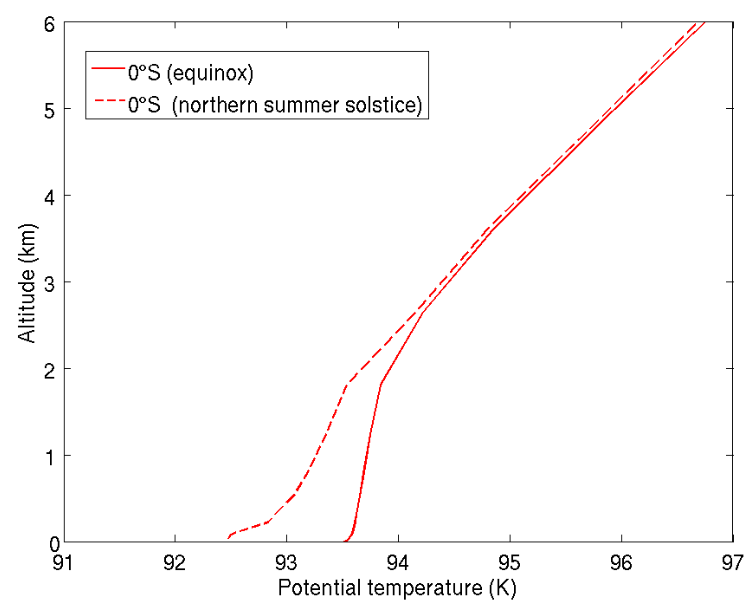



## Dune spacing on Titan ≈ 3 km

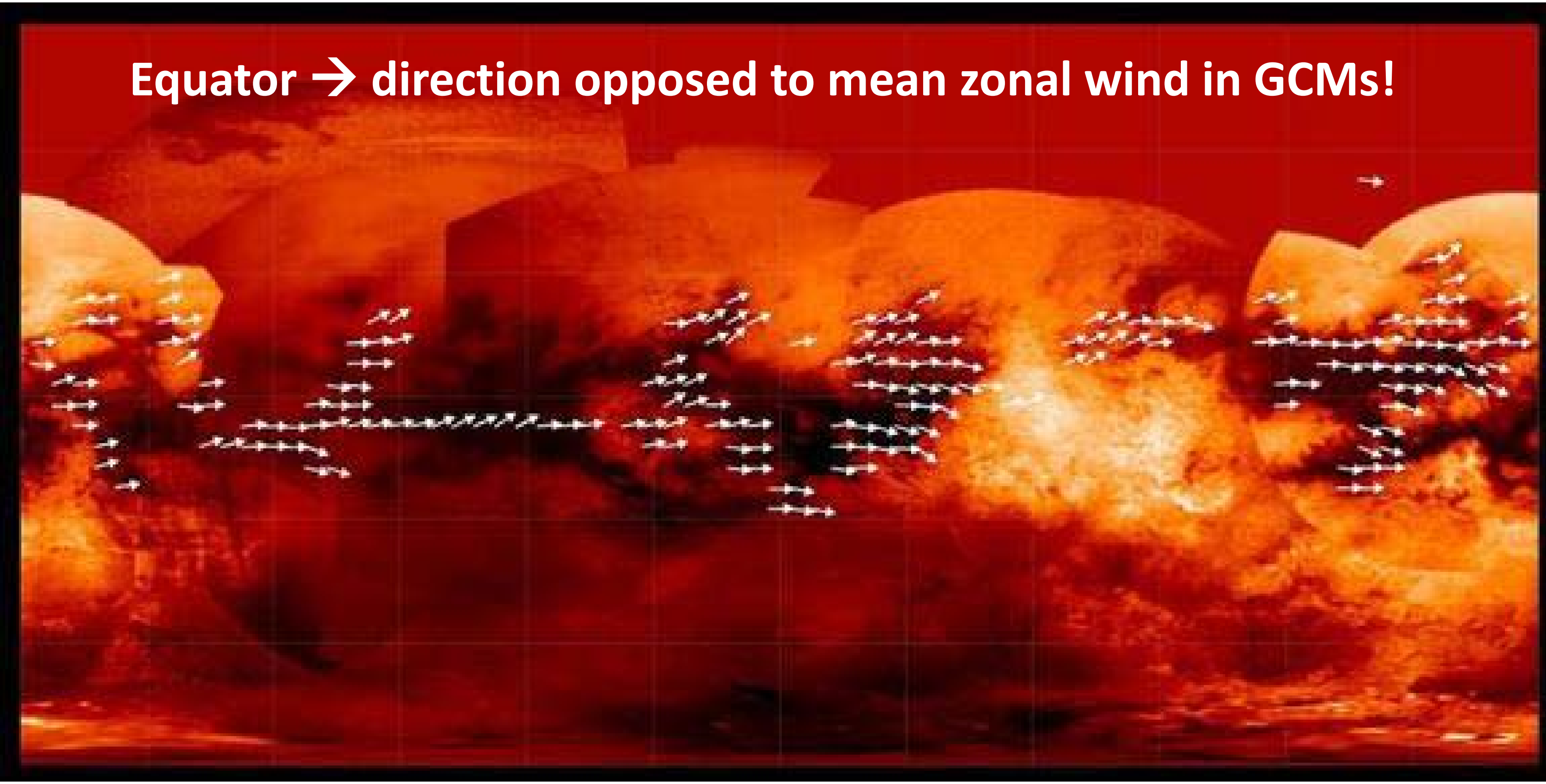
➡ Agreement with a PBL 2-3 km deep (Lorenz et al, 2010)

Thermal structure compatible with 2 km-deep PBL → explains dune size and spacing.

Charnay & Lebonnois (2012)



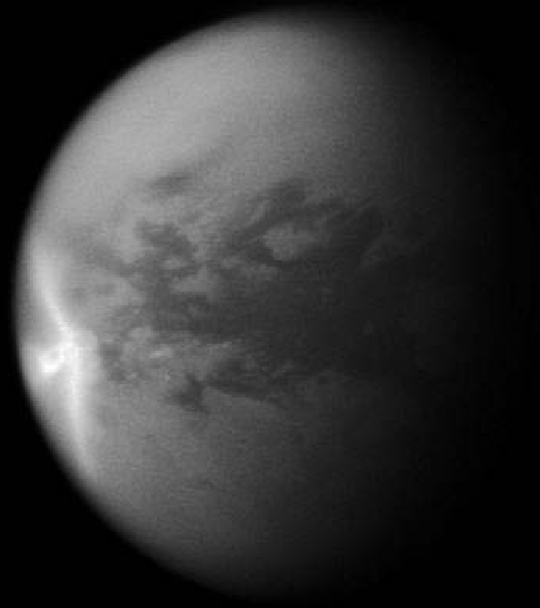
# Dune orientation

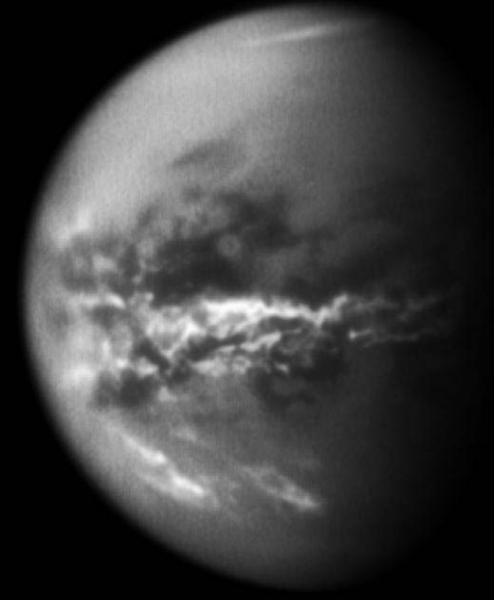


# Why
# GCM winds
# are opposed to
# dune winds?

- Either: an important atmospheric process is missing (topography, methane cycle, …)

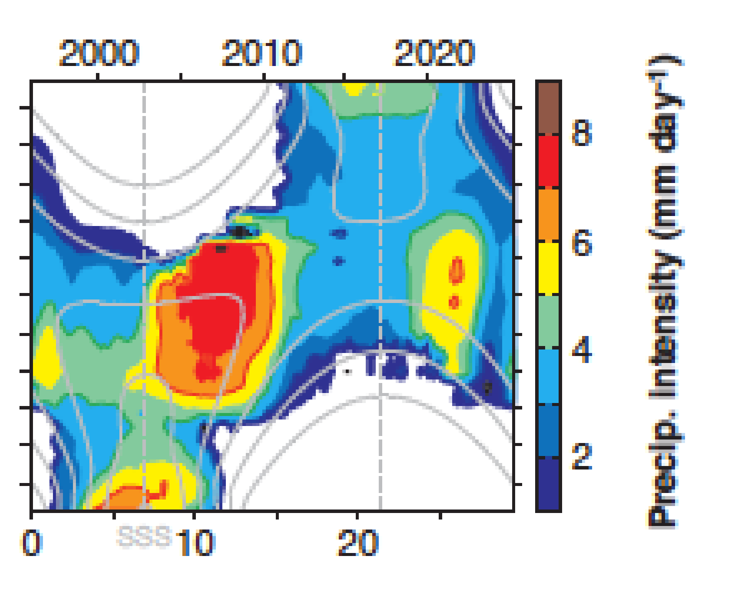
- Or: dunes do not form by saltation; dunes are paleo-dunes (different climate) ; …



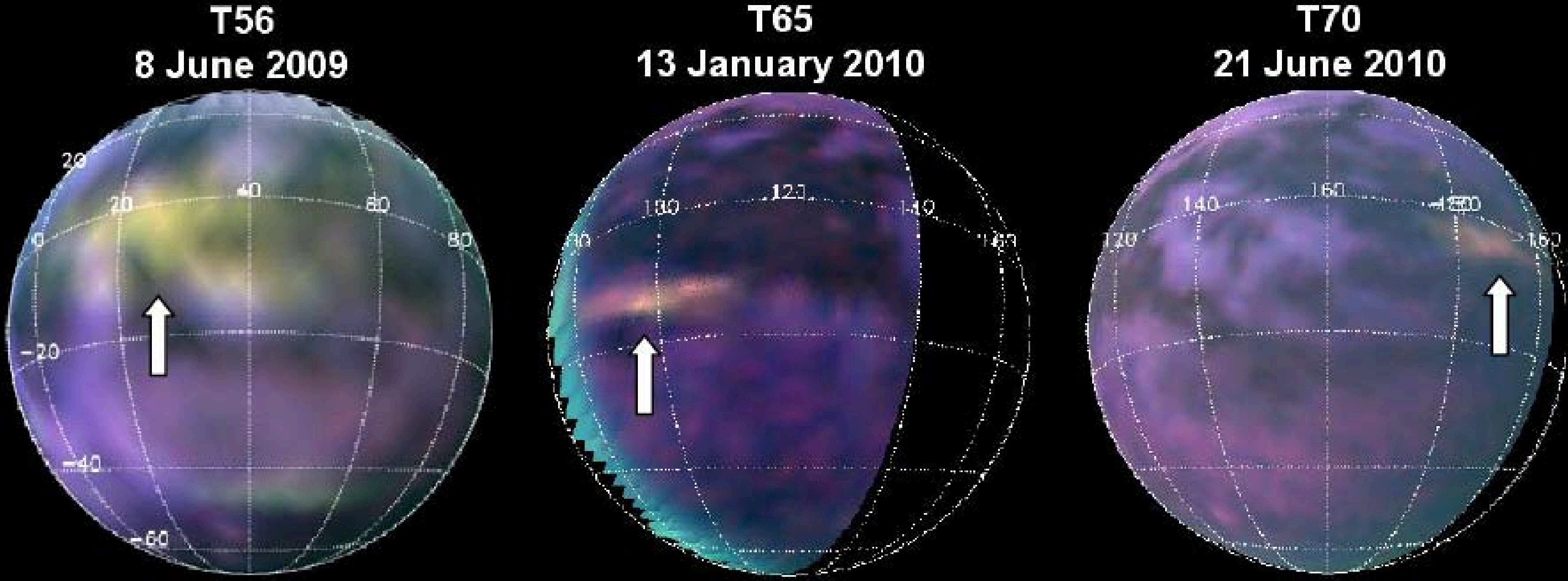


Convective storms at the equator at equinoxes
Turtle et al (2010,2011)

Could be reproduced by GCMs
Schneider et al (2011)



# Possible dust storms on Titan

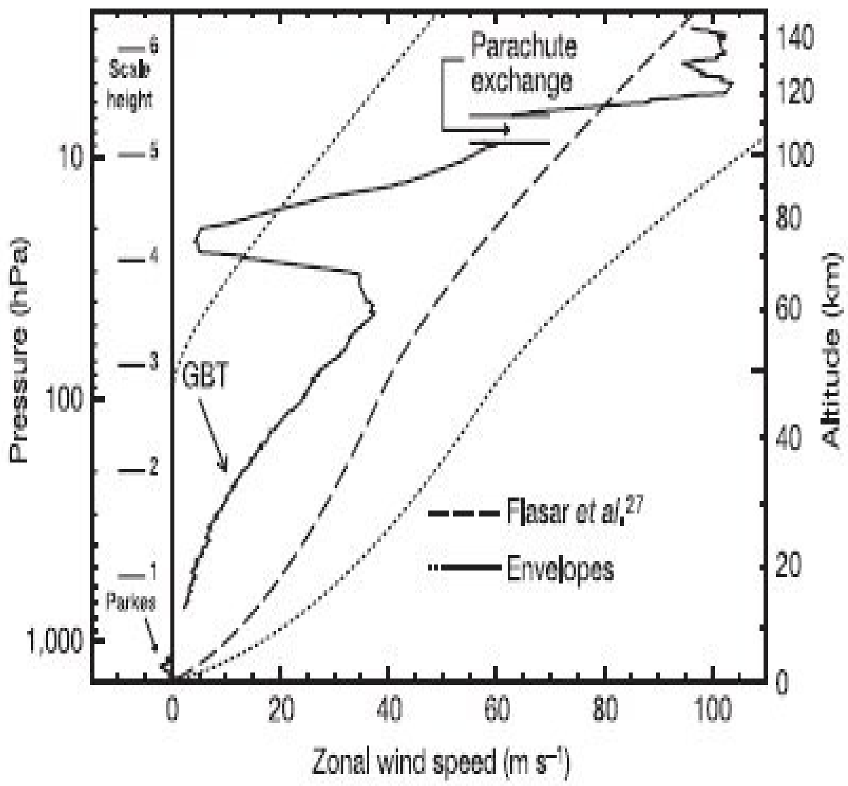


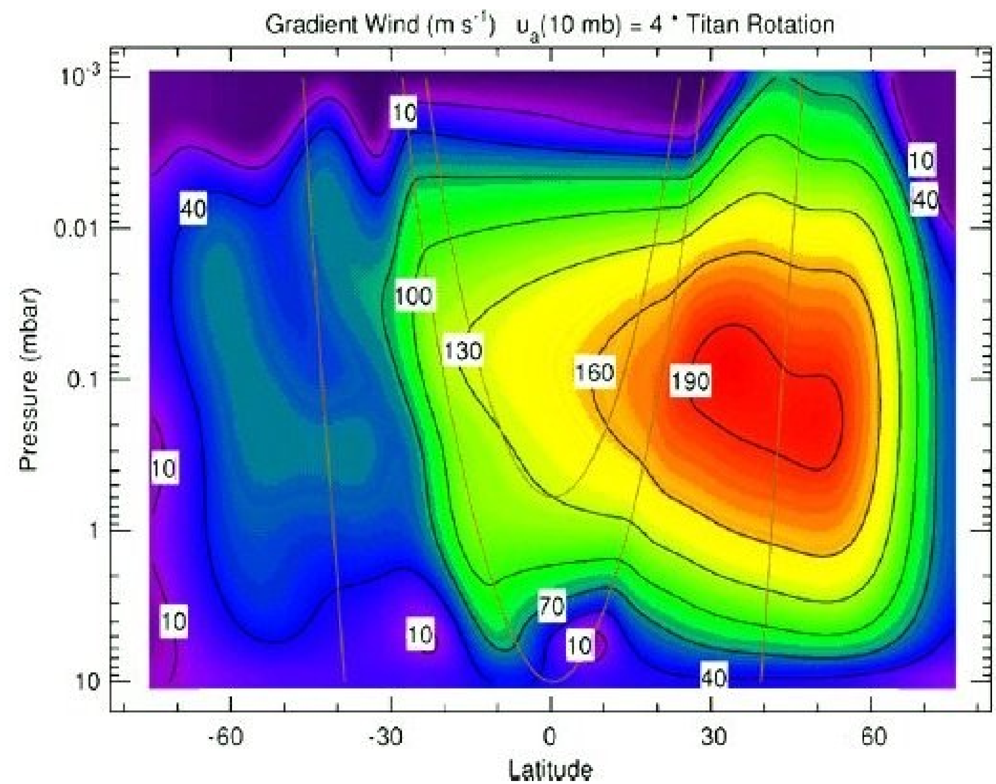

Rodriguez et al, LPI 2012

# Observations of superrotation

## TITAN

**Huygens/DWE vertical profile at 10°S (Ls ~ 300°)**

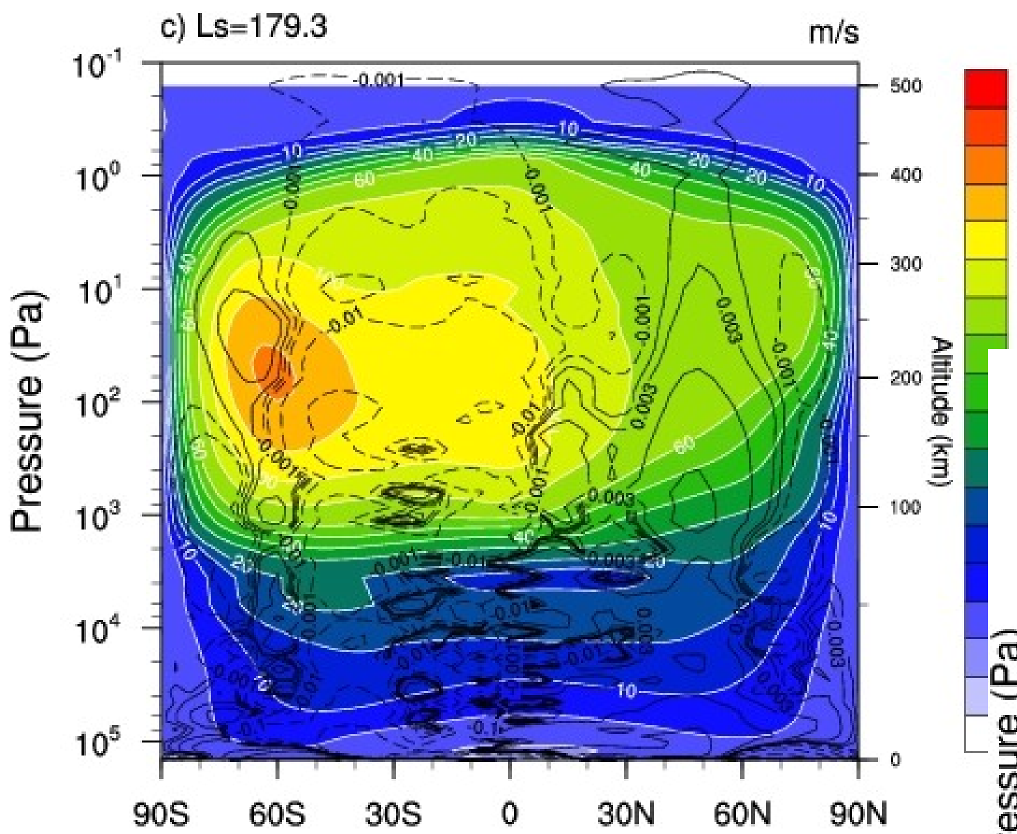


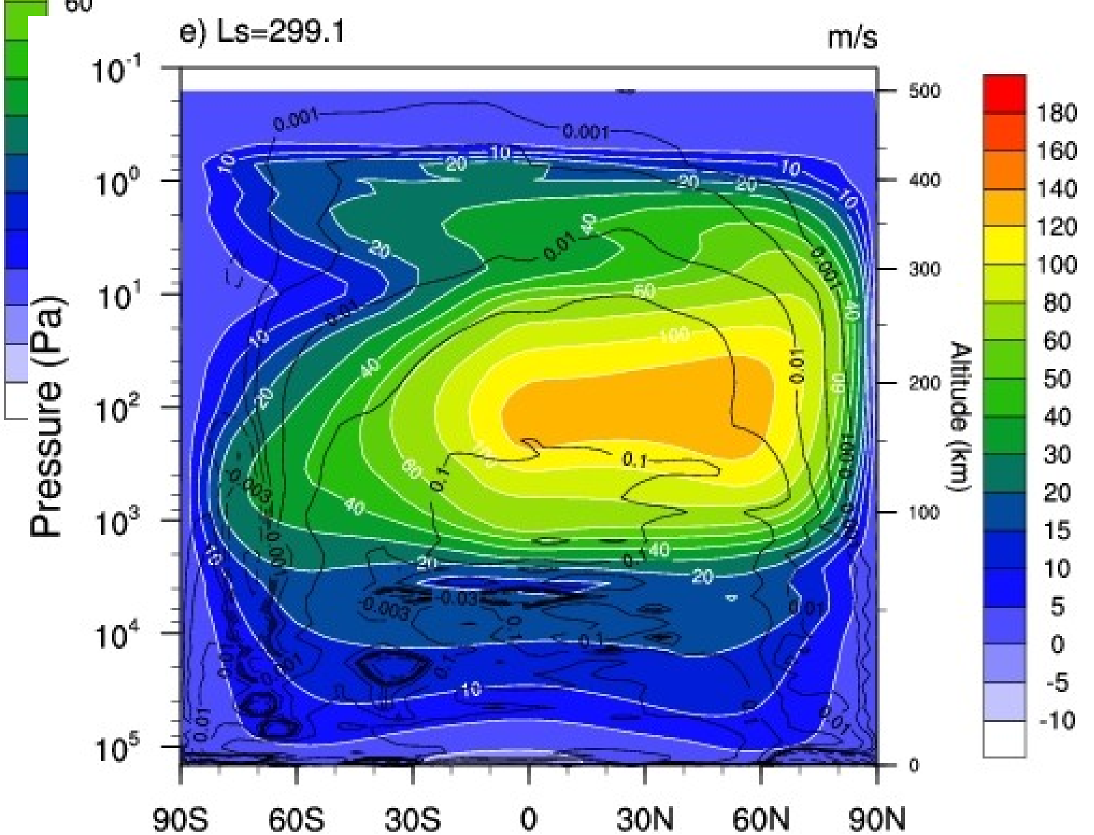




**Cassini/CIRS thermal winds retrieval (Ls ~ 300°)**

# Titan Superrotation

Started from 2D-CM simulations, interactive haze




Mean zonal wind and stream function after 12 Titan years

# Pluto and Triton

**Triton Ps=1.4 Pa ($N_2$)** *observed by Voyager 2 (1989)*

First GCM : retro-super-rotation; observed winds explained

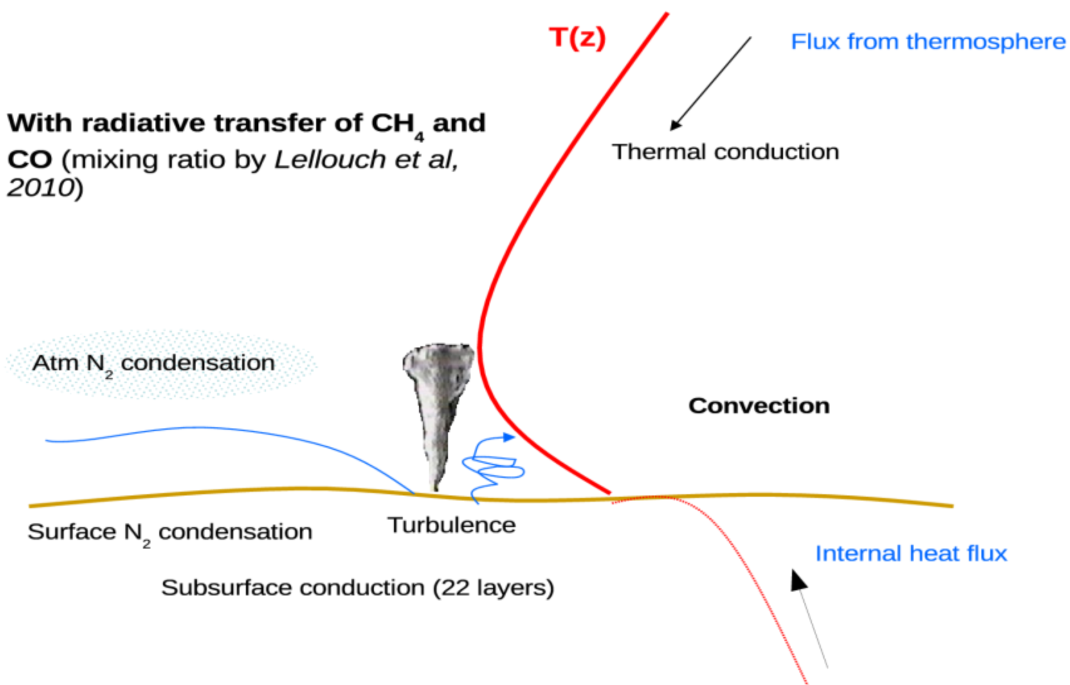
Seasonal model for ices (run over 3000 years!)

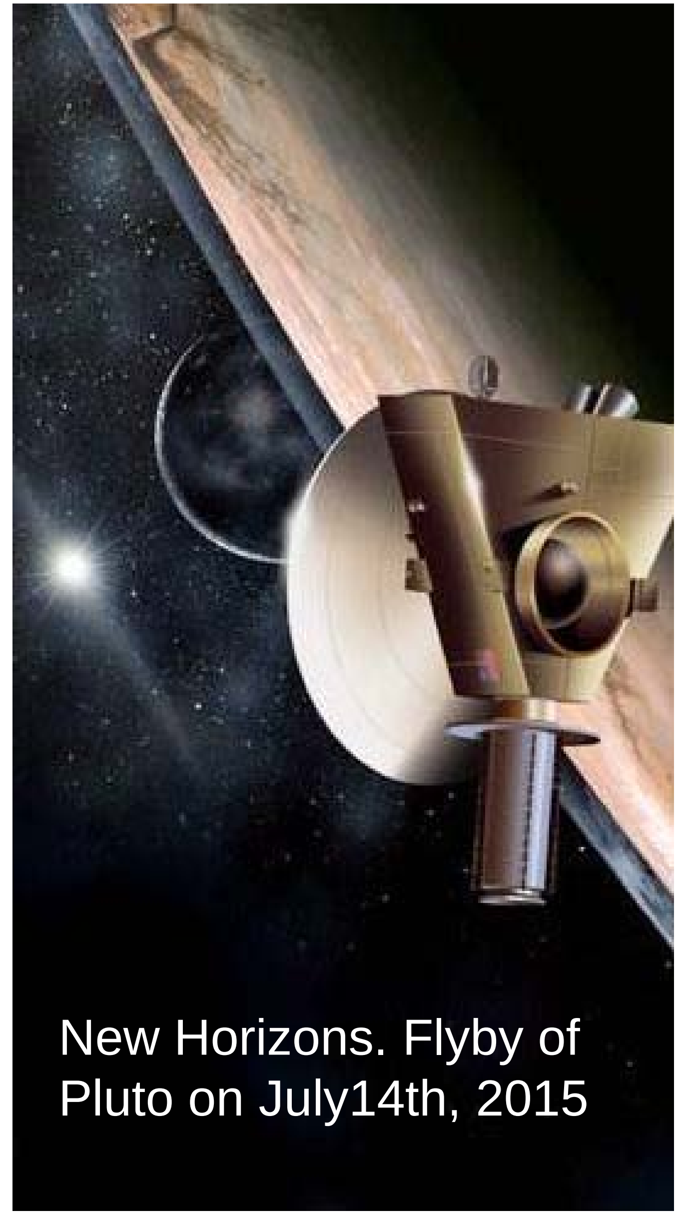
**Pluton Ps= 2Pa ($N_2$ + 0,5% $CH_4$)**

First complete GCM

Circulation , methane cycle, organic haze

**Preparation of the NASA New Horizons mission→**



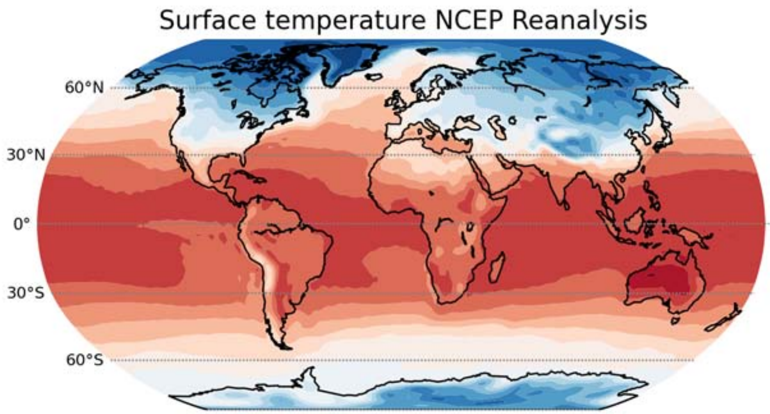



# Archean Earth

Benjamin Charnay, François Forget, Robin Wordsworth, Jérémy Leconte, Ehouarn Millour, Francis Codron and Aymeric Spiga

# Observations (Reanalysis)

# LMDZ Generic

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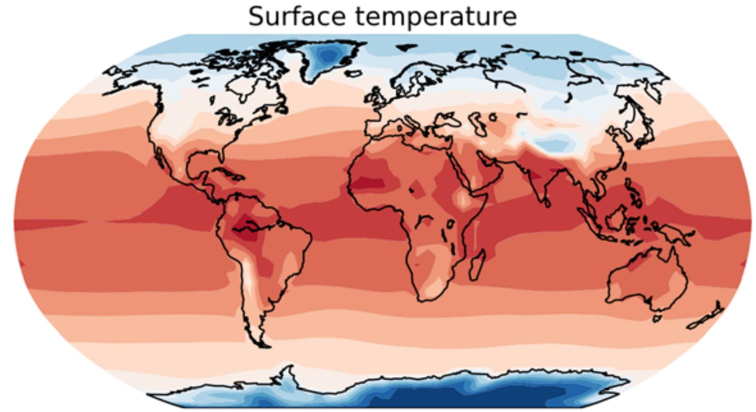
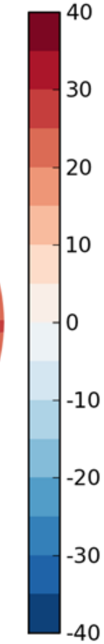
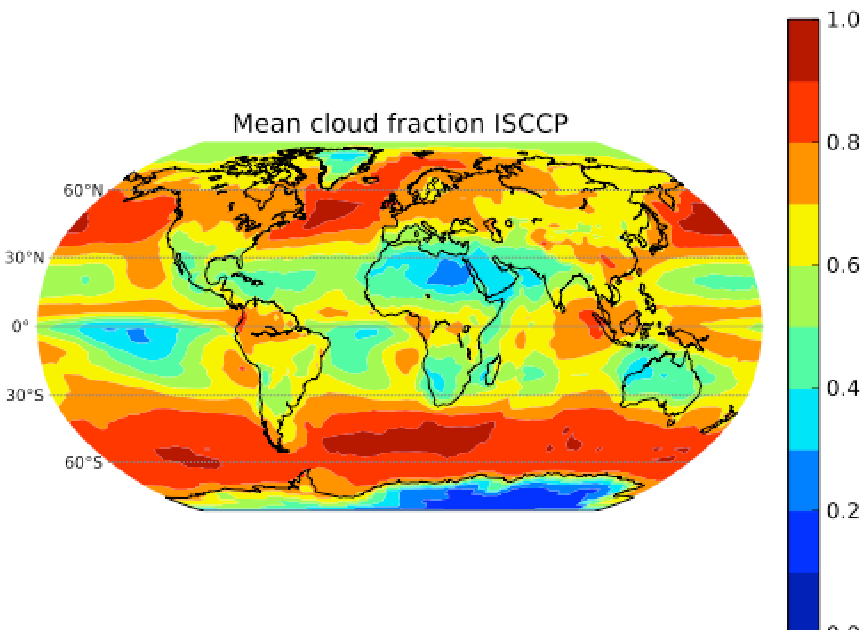
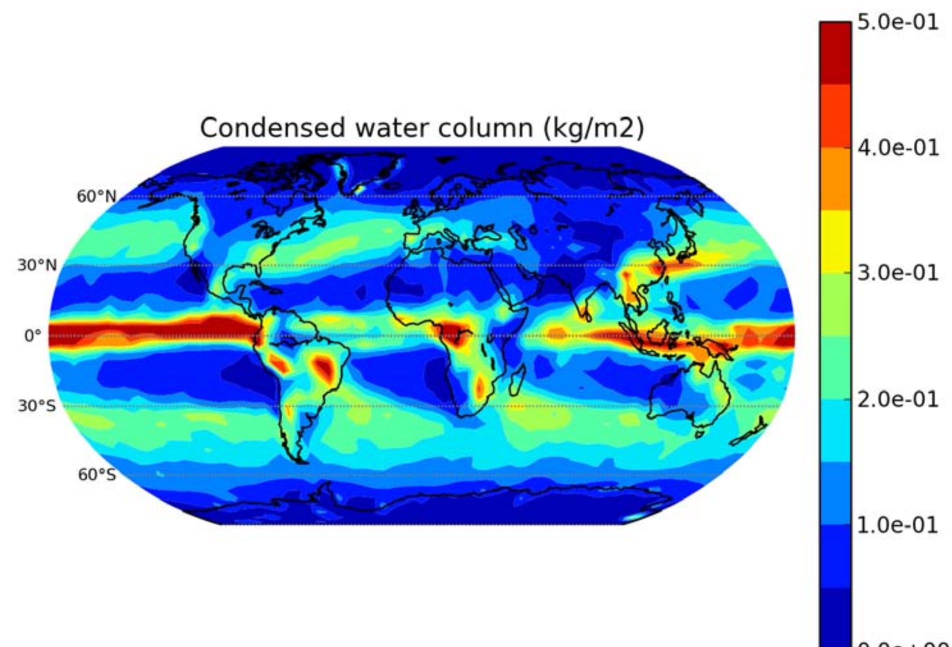



<Tsurf>=14.7°C



## The faint young Sun paradox:

- Sun 20-25% weaker during the Archean
- Geological evidence for liquid water and primitive life
- Need for warming processes

## Solutions:

**Greenhouse gases**
- $CO_2$
- $CH_4$
- $NH_3$
- …

**A reduced planetary albedo**
- less lands
- larger cloud droplet

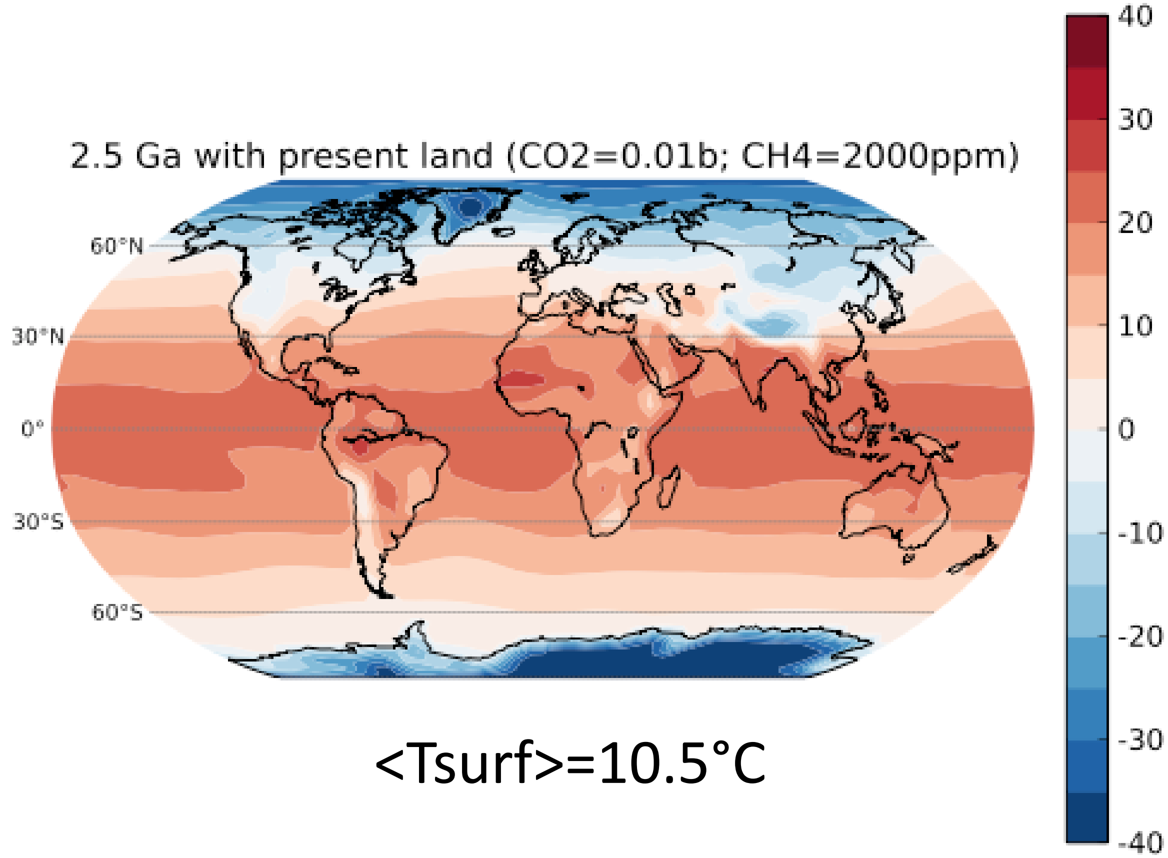
**Other effects**
- higher atmospheric pressure
- faster rotation

# Can we get a temperate early Earth with the geological constraints?

Maximal partial pressure of $CO_2$ at 2.5 Ga: 0.01-0.02 bar
Maximal haze free $CH_4/CO_2$ ratio: 0.1-0.3

# Climate obtained with present day lands

(simulations at 2.5 Ga with $C0_2$=0.01 bar; $CH_4$=2 mb)

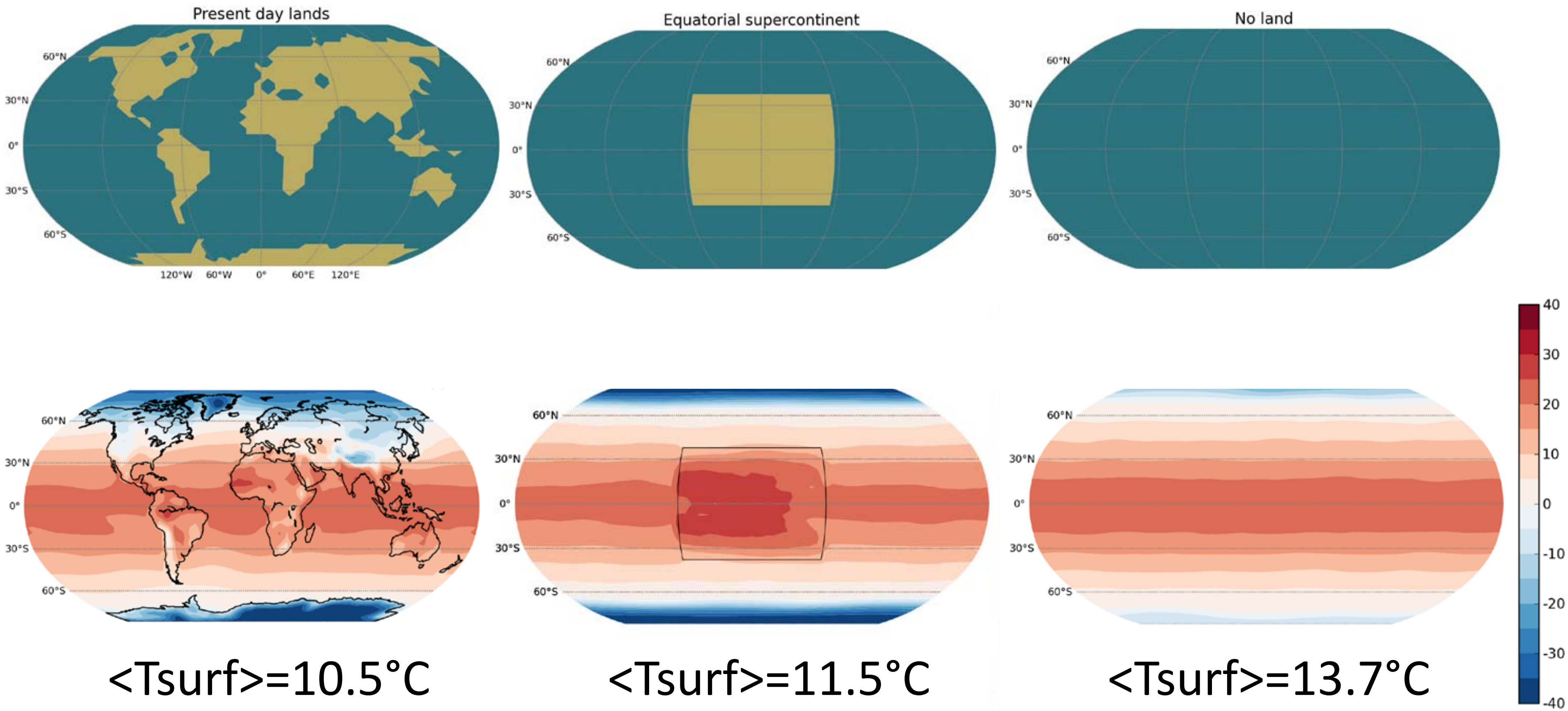



<Tsurf>=10.5°C

- Colder climate than today
- Continental ices at high latitudes
- Maybe acceptable with geological constraints

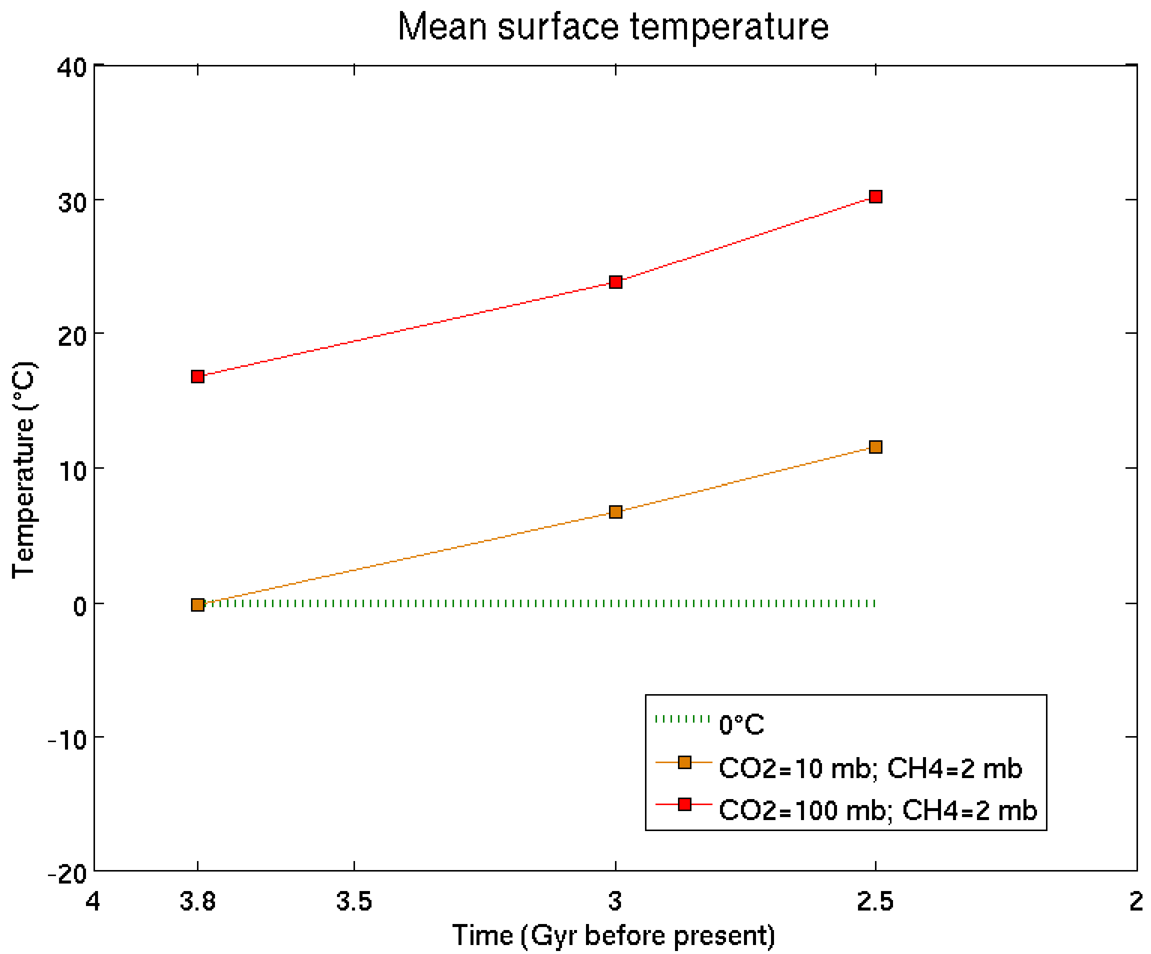
# Climates obtained with different lands

(simulations at 2.5 Ga with C02=0.01 bar; CH4=2 mb)




- ΔTsurf=0-3°C
- Case with supercontinent fully acceptable

# Effect of greenhouse gases

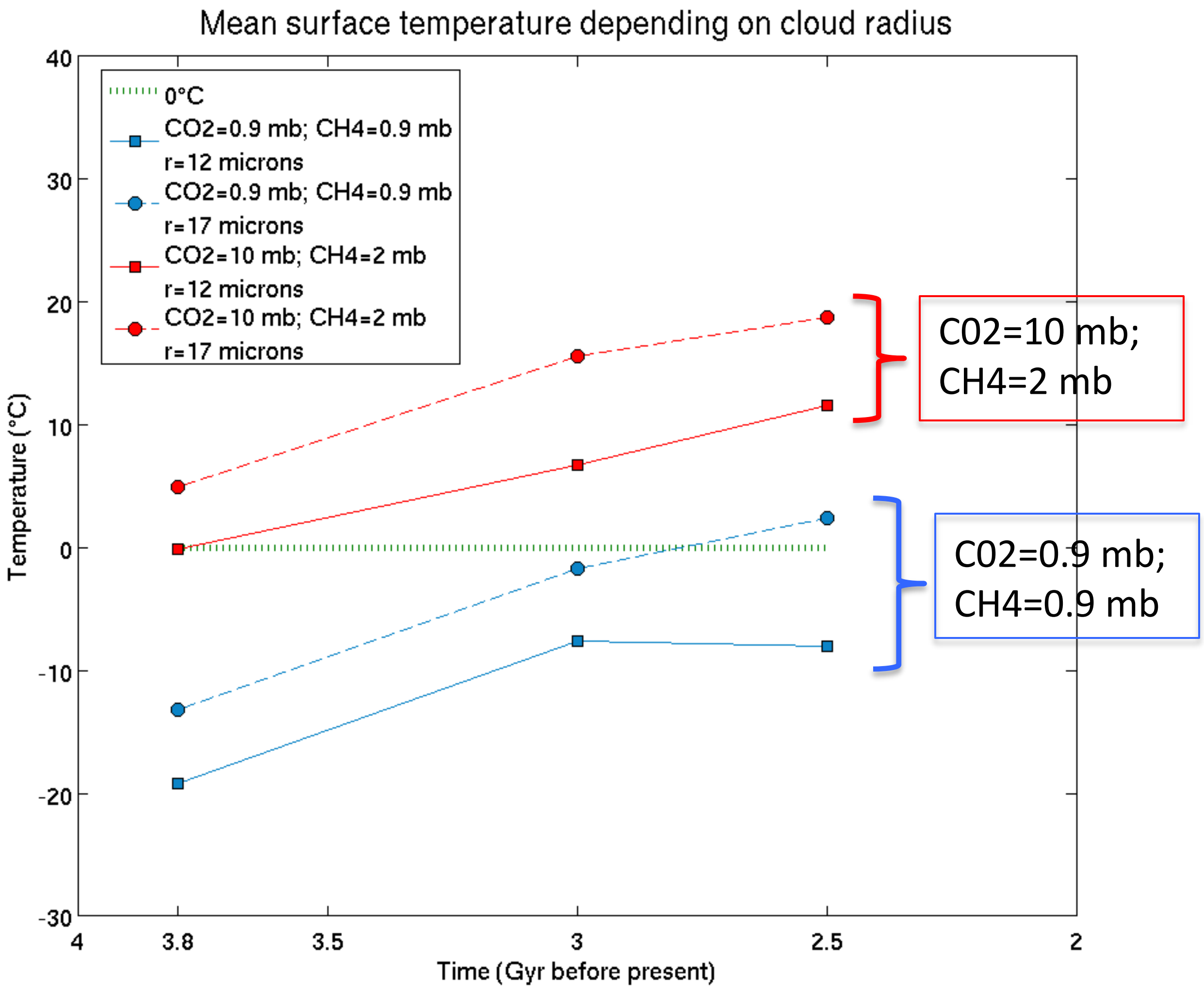



<u>Conditions for temperate climates:</u>

Late-Archean: $CO_2$=0.01 b and $CH_4$=2 mb

Earlier Archean: $CO_2$=0.1 b and $CH_4$=2 mb

# Effect of cloud droplet size on surface temperature

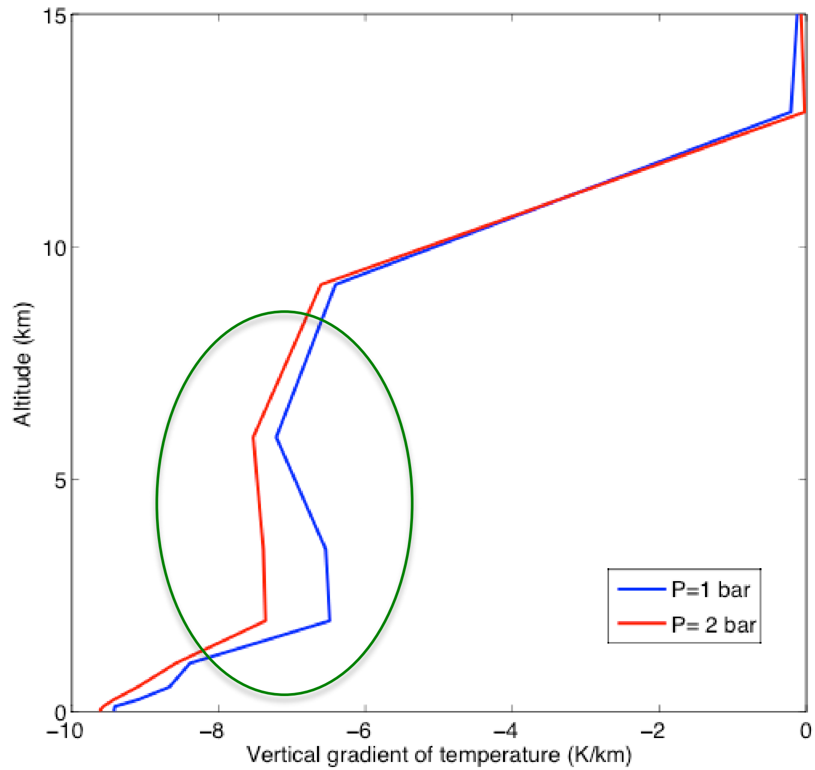



ΔTsurf=5-10°C

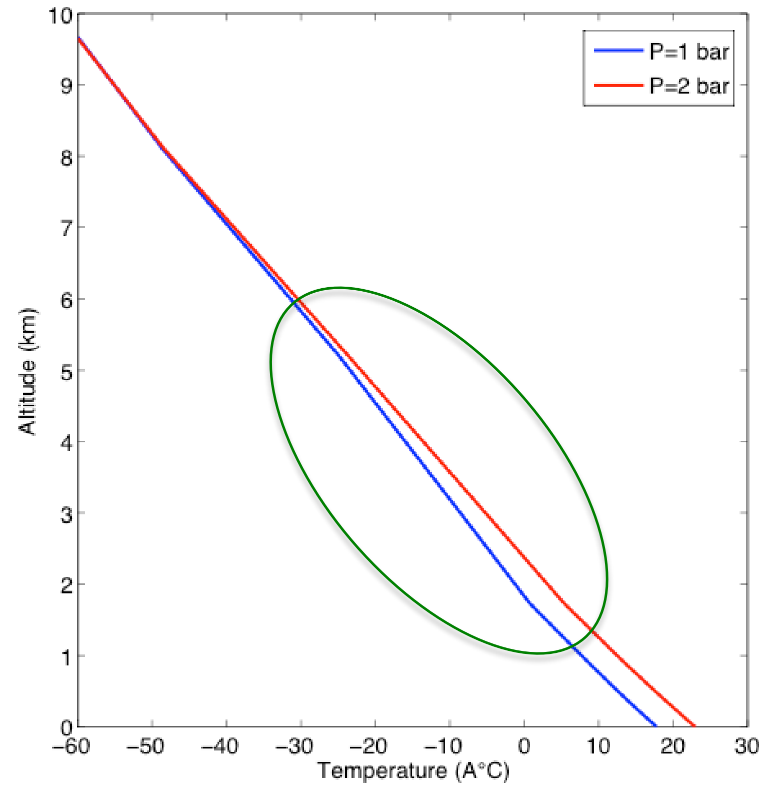
# Effect of atmospheric pressure

(simulations at 3 Ga with C02=0.01 bar; CH4=2 mb; N2=1-2 bar)

Temperature lapse rate




Temperature profile




ΔTsurf=4-8°C

# Effect of the rotation period

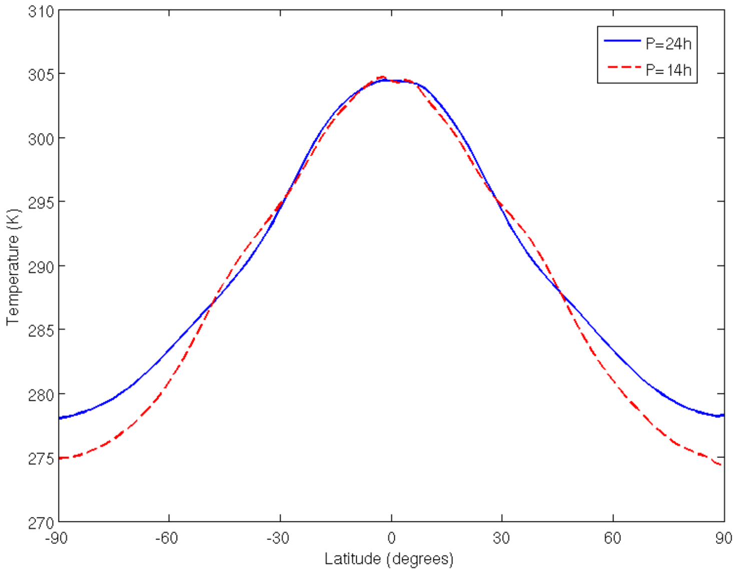
Earth's rotation period at 4 Ga ≈ 14h
Tidal friction rised it to 24h now.

Meridional transport $\propto \frac{1}{\Omega^2}$
(Stones 1972)

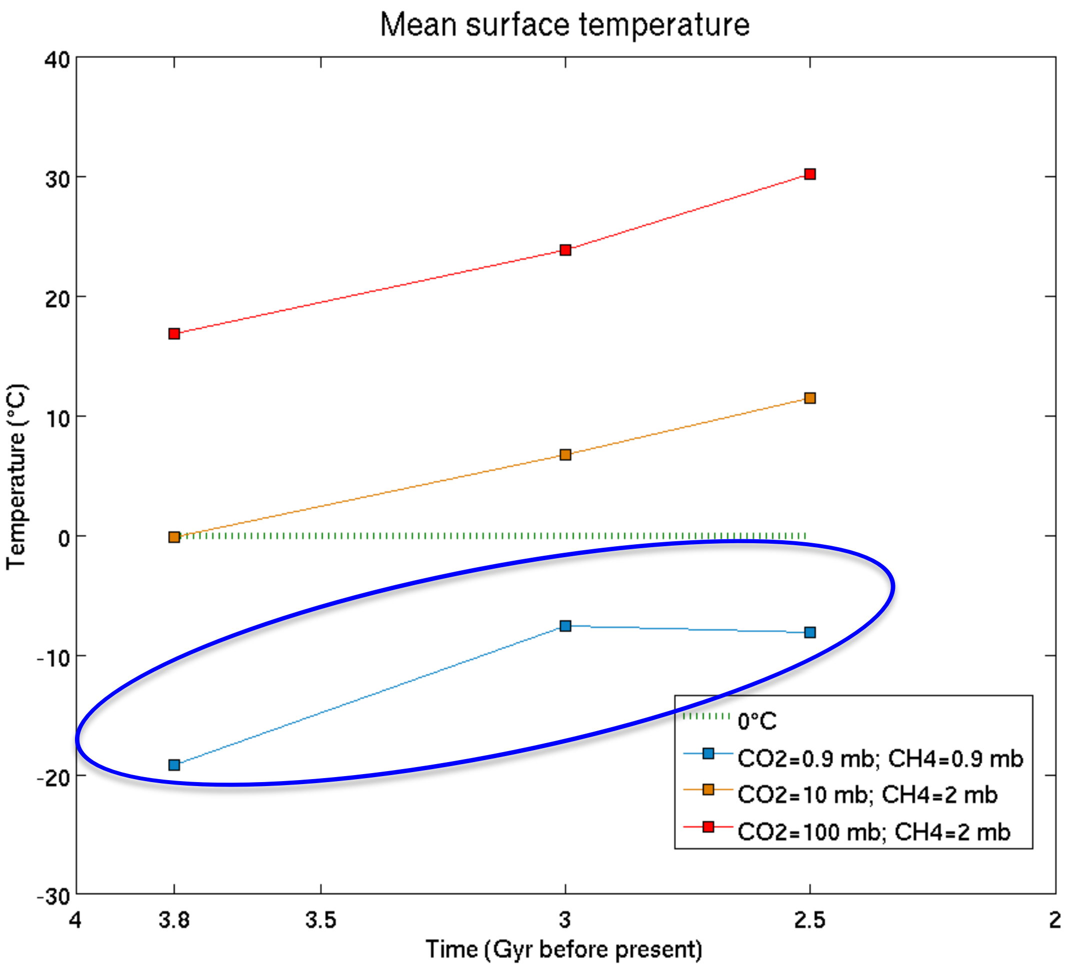
- Colder poles/warmer equator
- Possible effects on cloud covering (Jenkins 1995)

**With our GCM:**

- Cooling of less than 1 K for temperate climates
- Warming for cold climates



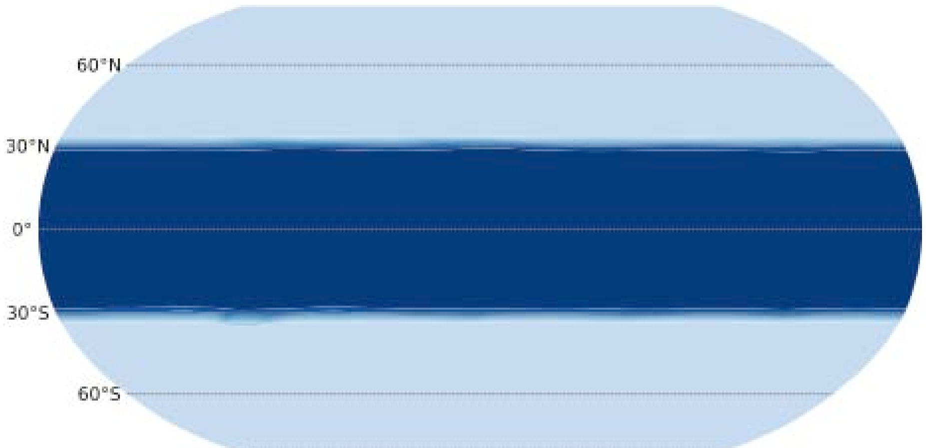
# Case of a cold early Earth



# Cold climates and waterbelts

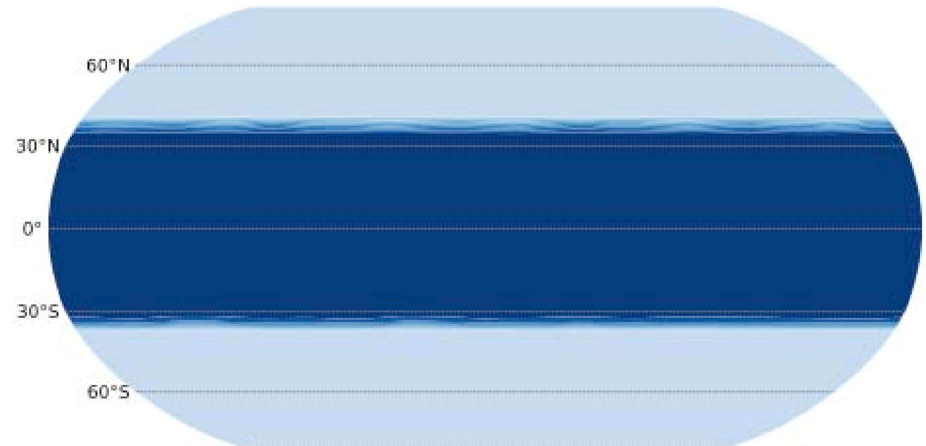
(simulations at 3.8 Ga with C02=0.9 mb; $CH_4$=0.9 mb; no land)

P=24h




<Tsurf> = -18°C

P=14h

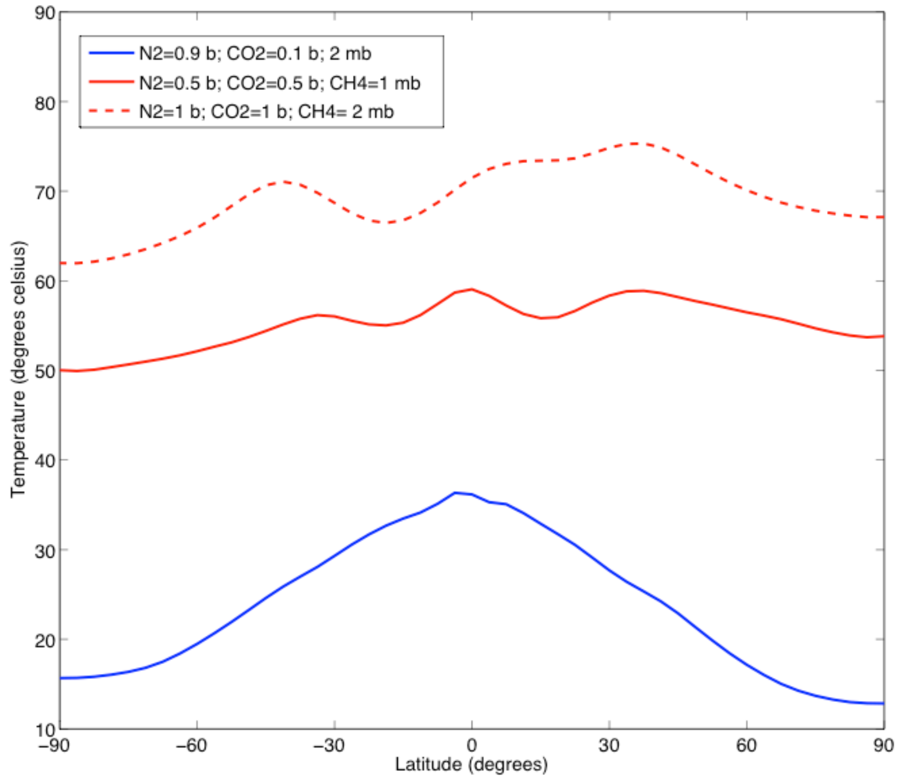



<Tsurf> = -15°C

# Hot climates

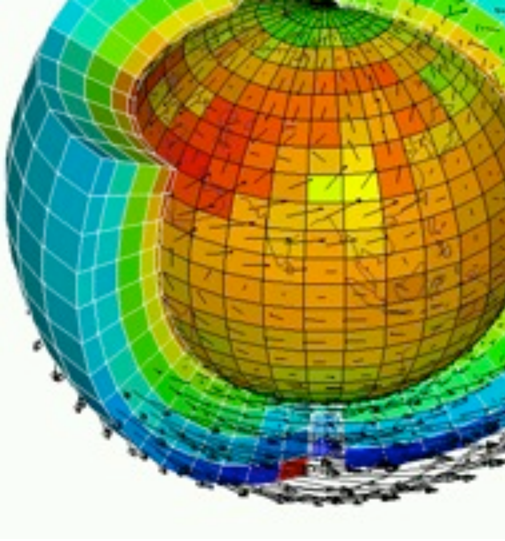
(simulations at 3.8 Ga with r=17 microns and no land)

Preliminary results




| Composition | <Tsurf> | Precipitable water | Albedo |
|---|---|---|---|
| N2=0.9 b; CO2=0.1 b; CH4=2 mb | 27.5 °C | 40 $kg/m^2$ | 0.25 |
| N2=0.5 b; CO2=0.5 b; CH4=1 mb | 56 °C | 280 $kg/m^2$ | 0.24 |
| N2=1 b; CO2=1 b; CH4=2 mb | 70.5 °C | 470 $kg/m^2$ | 0.22 |

# Simulating exoplanetary atmospheres: Living beyond the runaway greenhouse limit



Jeremy Leconte

Francois Forget, Robin Wordsworth, B. Charnay, E. Millour, F. Codron, A. Spiga, F Selsis, V. Eymet

*LMD, Institut Pierre Simon Laplace, Université Pierre et Marie Curie, BP 99, 75005 Paris, France*

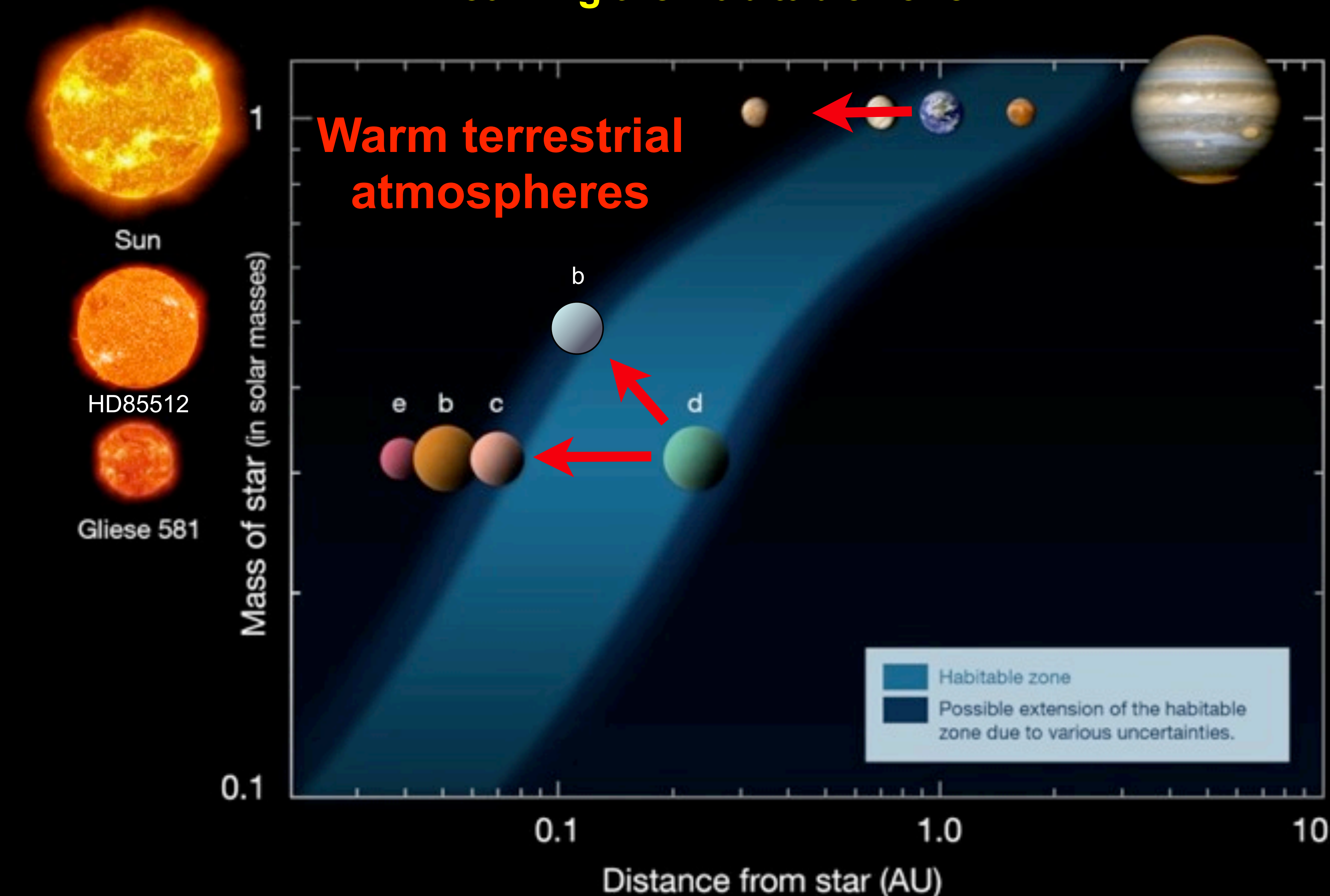
# What we have learned from solar system GCMs

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

- **However Problems with :**
  - Missing physical processes (*e.g. radiative effects of Martian clouds*)
  - Positive feedbacks and unstability *(e.g. ice albedo feedback on the Earth)*
  - Non linear behaviour and threshold effect *(e.g. dust storms on Mars)*
  - Complex, large System with small forcing *(e.g. Venus circulation).* /Sensitivity to initial state
  - Complex subgrid scale process and poorly known physics *(e.g. clouds on the Earth, Gravity waves on Venus)*

=> whatever the quality of the model, heavy study of model sensitivity to parameters will always be necessary.

# Roaming the Habitable zone

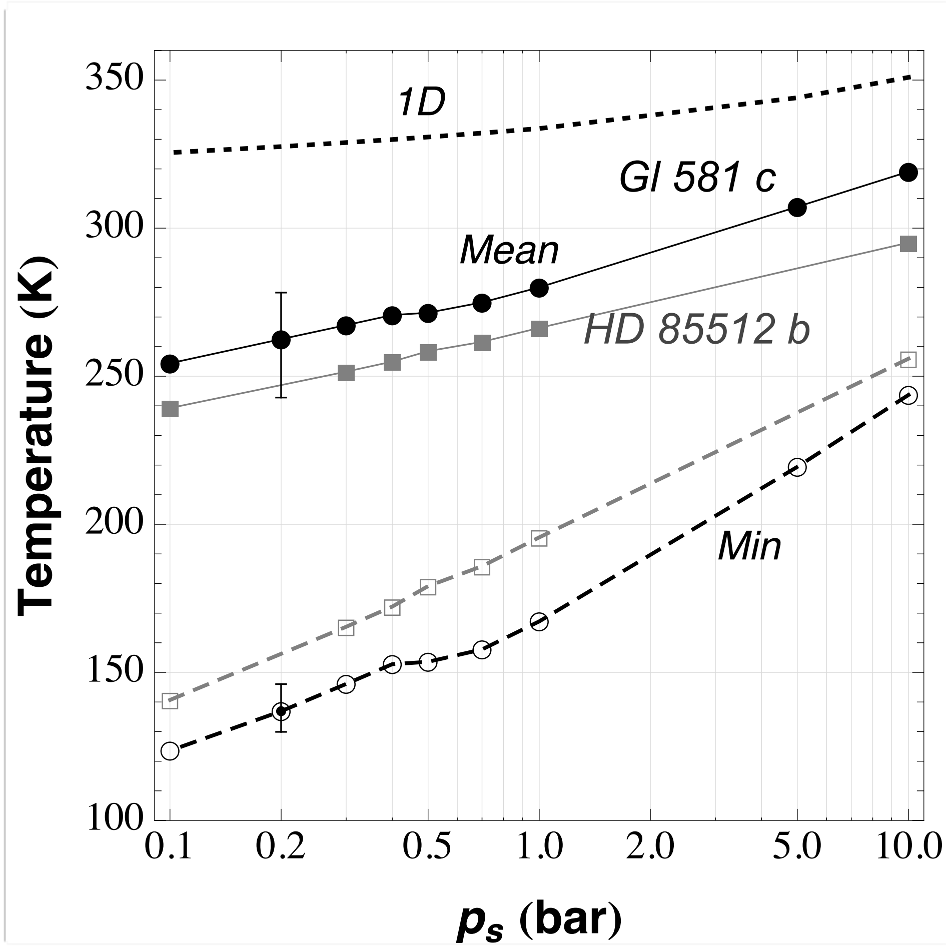



**The goal is not only to model a given planet climate!**

*Selsis et al. 2007*

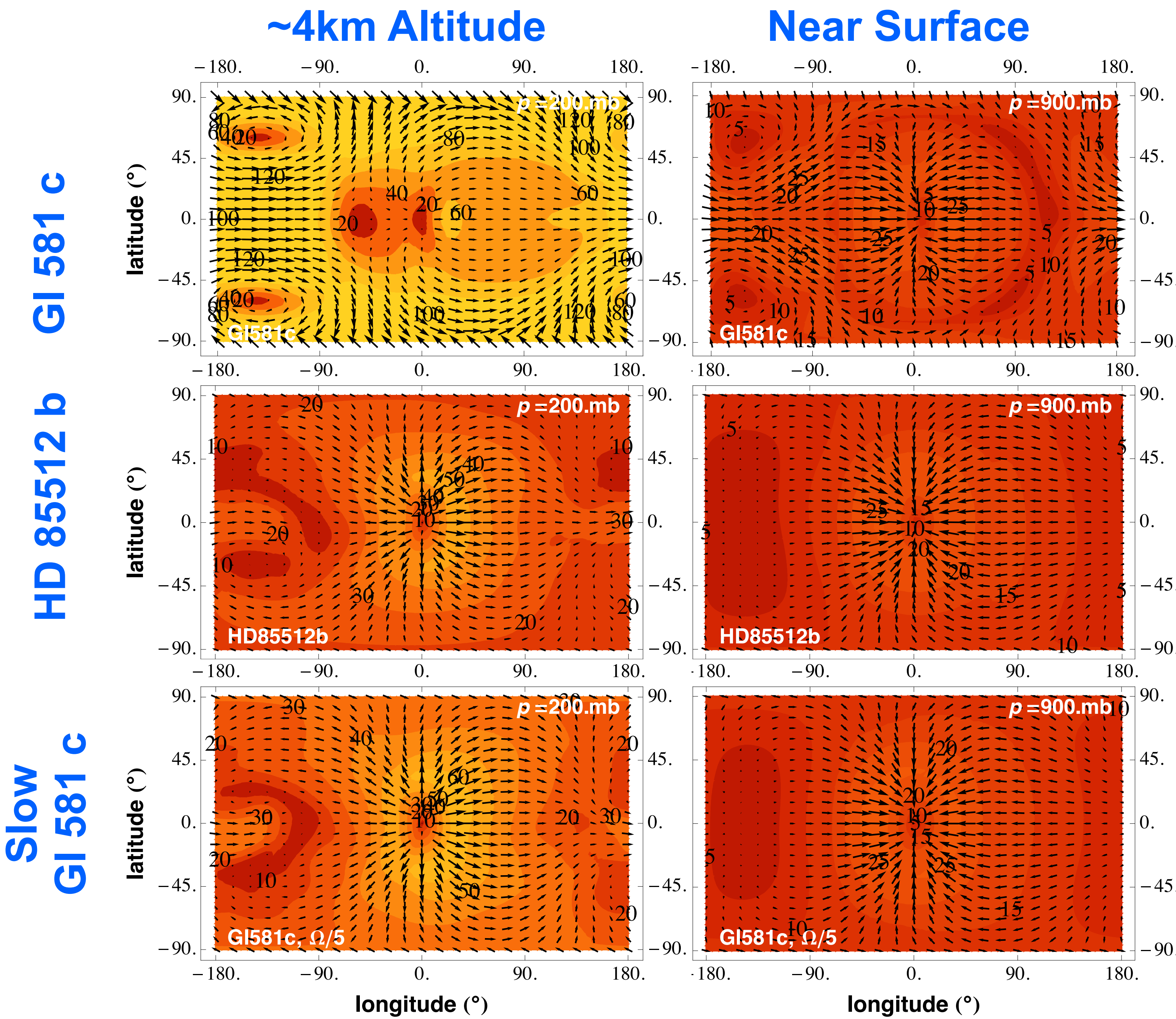
# 1D vs D3: systematic biases

Systematic 1D/3D discrepancy

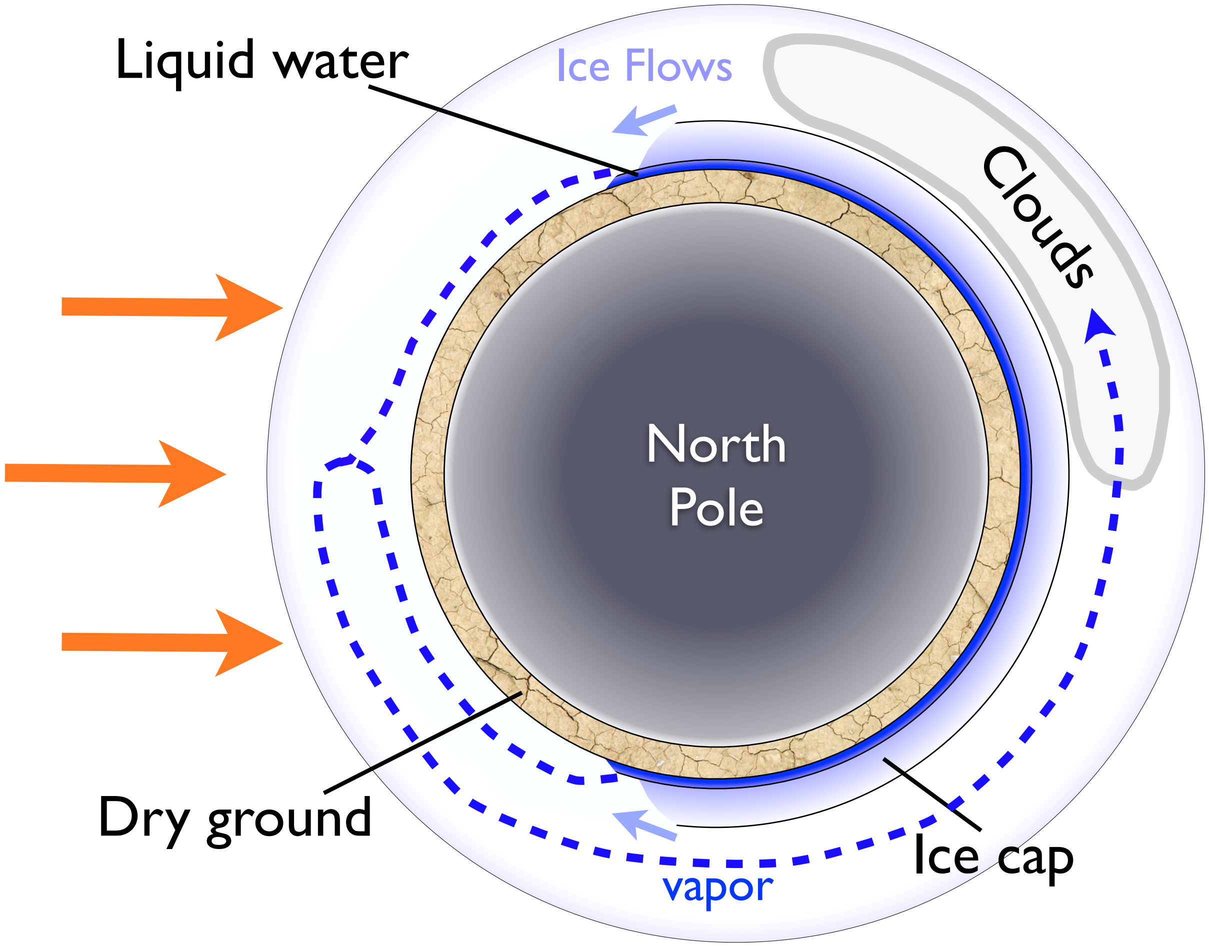



$$\bar{T}_s = \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_0^1 d\cos\theta_\star \left( \frac{(1-A)\, F_\star\, \cos\theta_\star}{\sigma_{SB}} \right)^{1/4} = \frac{2\sqrt{2}}{5}\, \bar{T}_{equ}$$

# wind maps (m/s)


~4km Altitude
Near Surface
Gl 581 c
HD 85512 b
Slow
Gl 581 c
p =200.mb
p =900.mb
Gl581c
HD85512b
Gl581c, Ω/5
latitude (°)
longitude (°)

# Can these planet bear liquid water?




*Like on Earth, if a thick ice cap is present (a few km), Ice flows and subsurface water could exist.*

# Gliese 581d is the first discovered terrestrial-mass exoplanet in the habitable zone

Robin D. Wordsworth,[1*] François Forget,[1] Franck Selsis,[2,3]
Ehouarn Millour,[1] Benjamin Charnay,[1] Jean-Baptiste Madeleine[1]

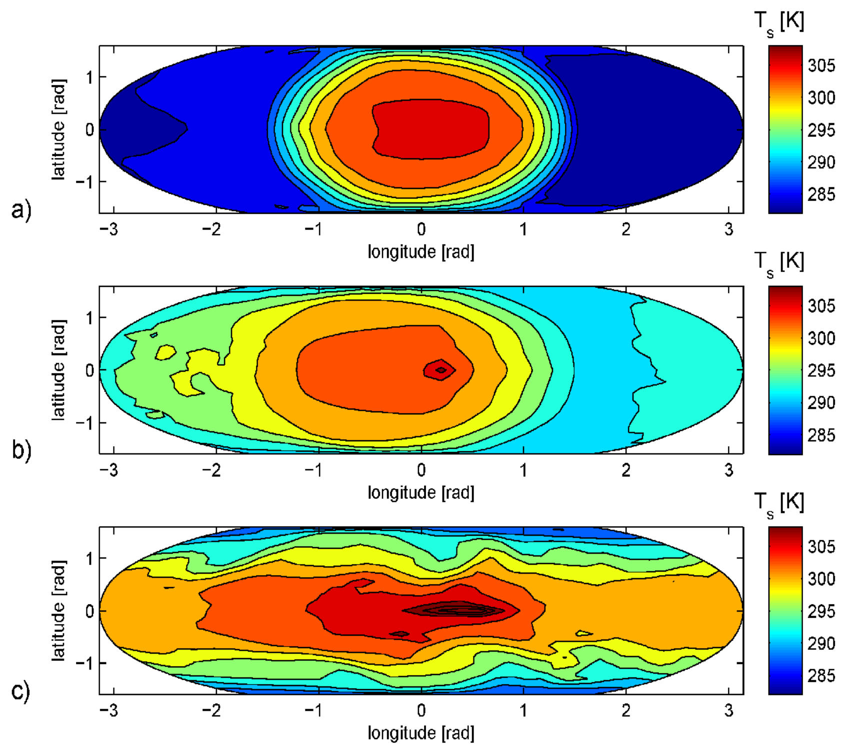



Fig. 1.— Surface temperature snapshots after 60 orbits integration time for rocky planet simulations with a) 1:1, b) 1:2 and c) 1:10 tidal resonance and a 20-bar $CO_2$ atmosphere.

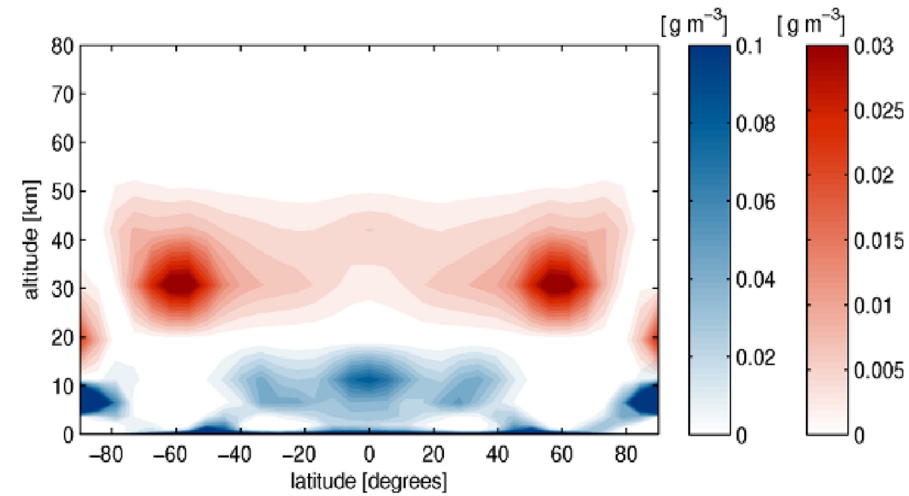
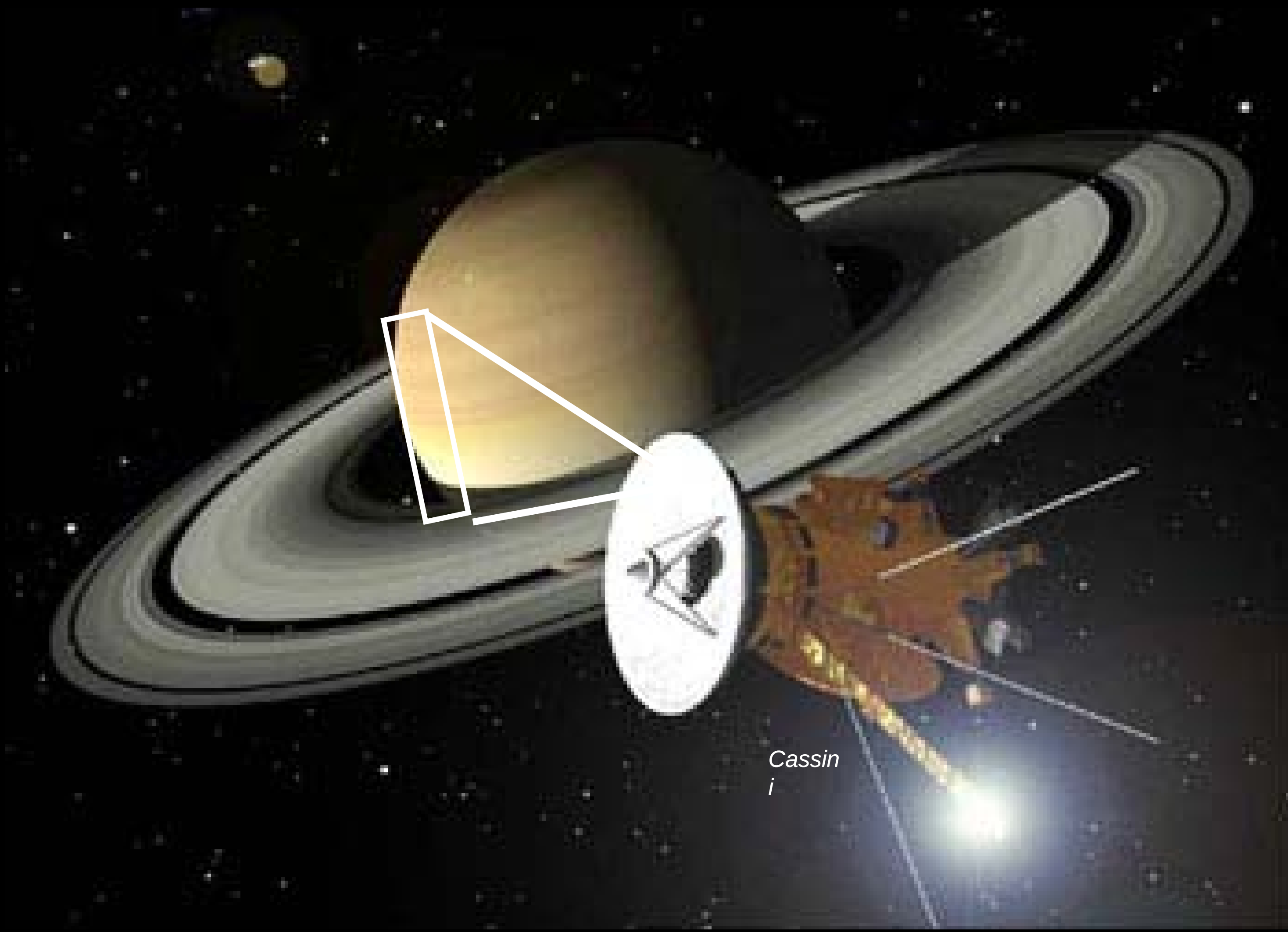



Fig. 3.— Latitude-altitude map of $H_2O$ (blue) and $CO_2$ (red) cloud coverage for a 20-bar ocean simulation with 1:2 resonance, averaged in longitude and over one orbit. While the cloud deck altitudes were similar for all simulations, the latitudinal distribution depended strongly on the atmospheric dynamics and hence on the rotation rate and total pressure.

# SATURN and GIANT PLANETS



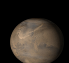

A. Spiga
with
T. Fouchet
S. Guerlet
M. Sylvestre
E. Millour

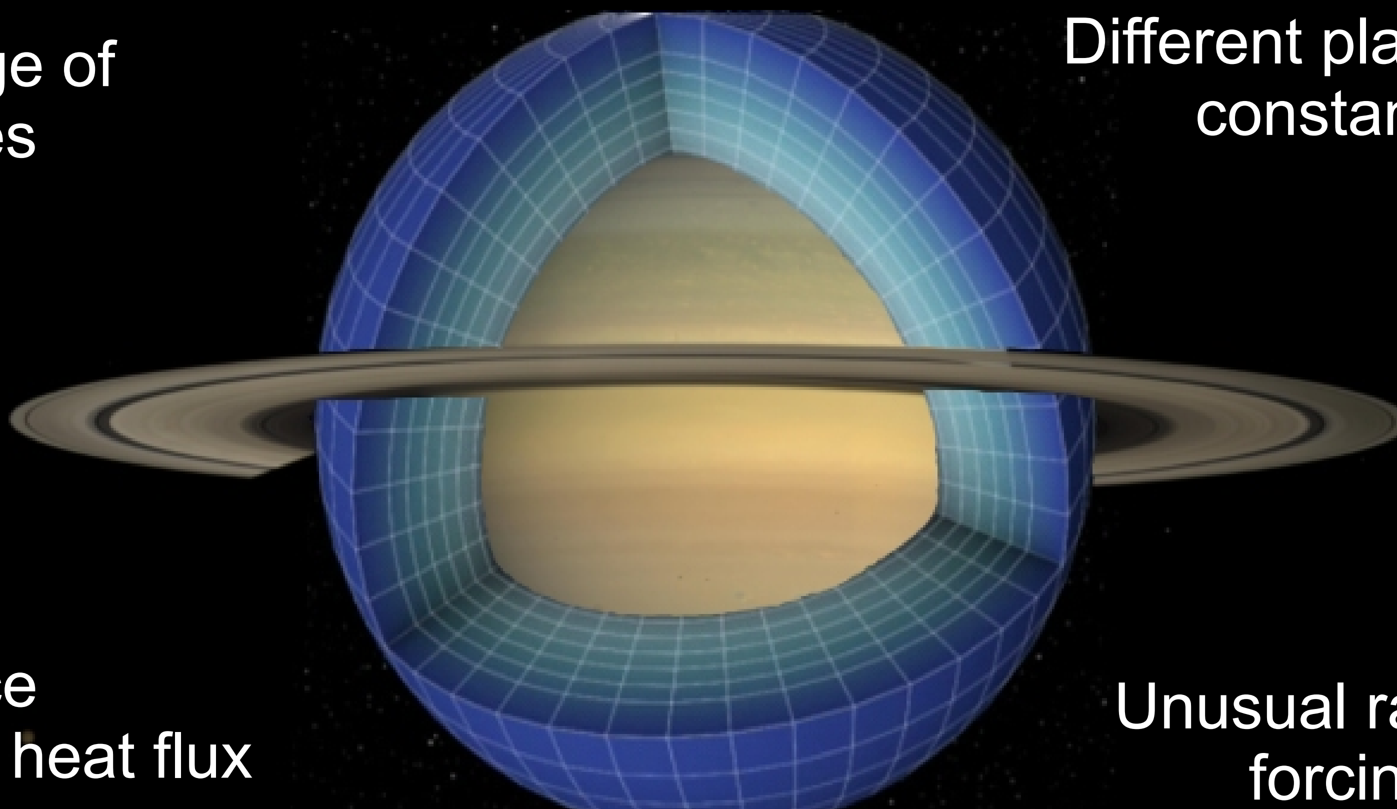
# EmerGéantes : a new Saturn GCM

## A lot of challenges!

A change of scales

Different planetary constants

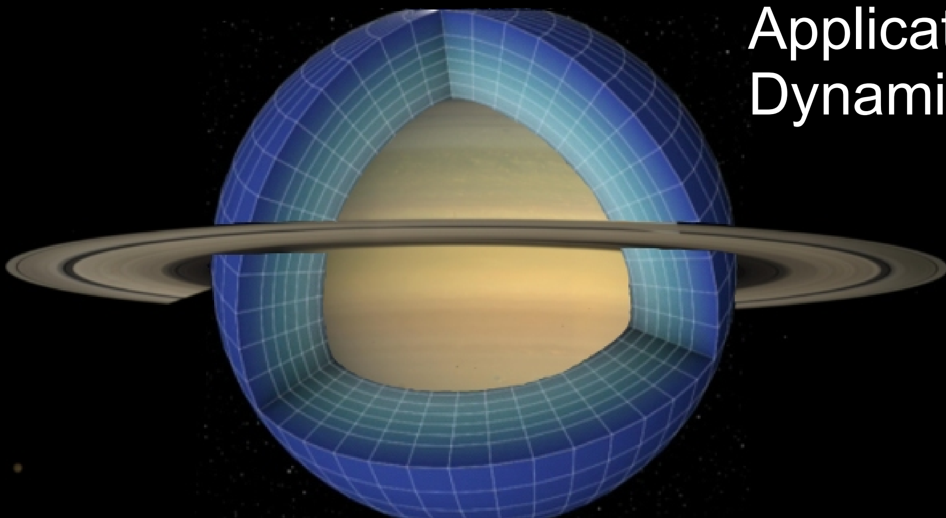




No surface
+ internal heat flux

Unusual radiative forcings

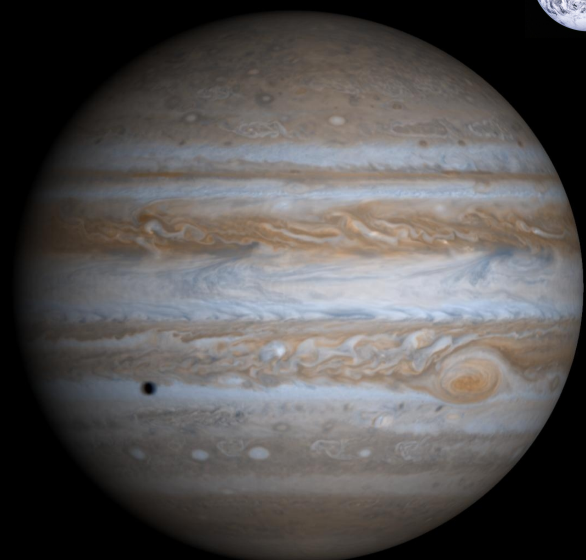
# Numerous applications

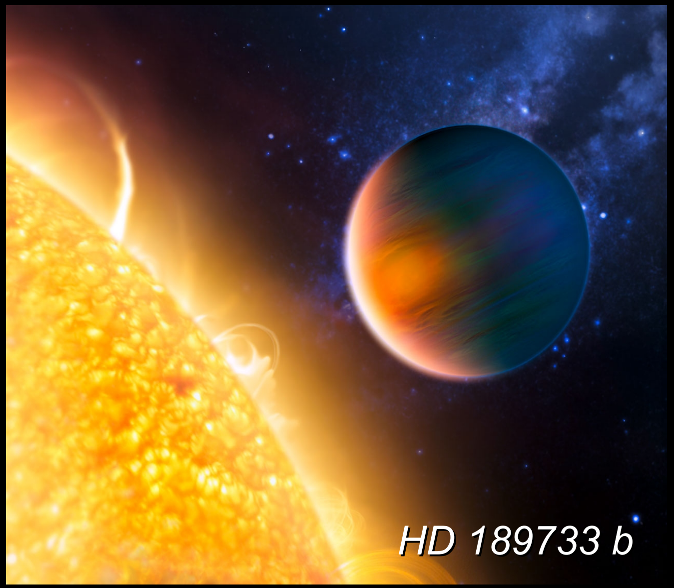


Application 1
Dynamical enigma in the Saturn stratosphere

Application 2
Comparative planetology

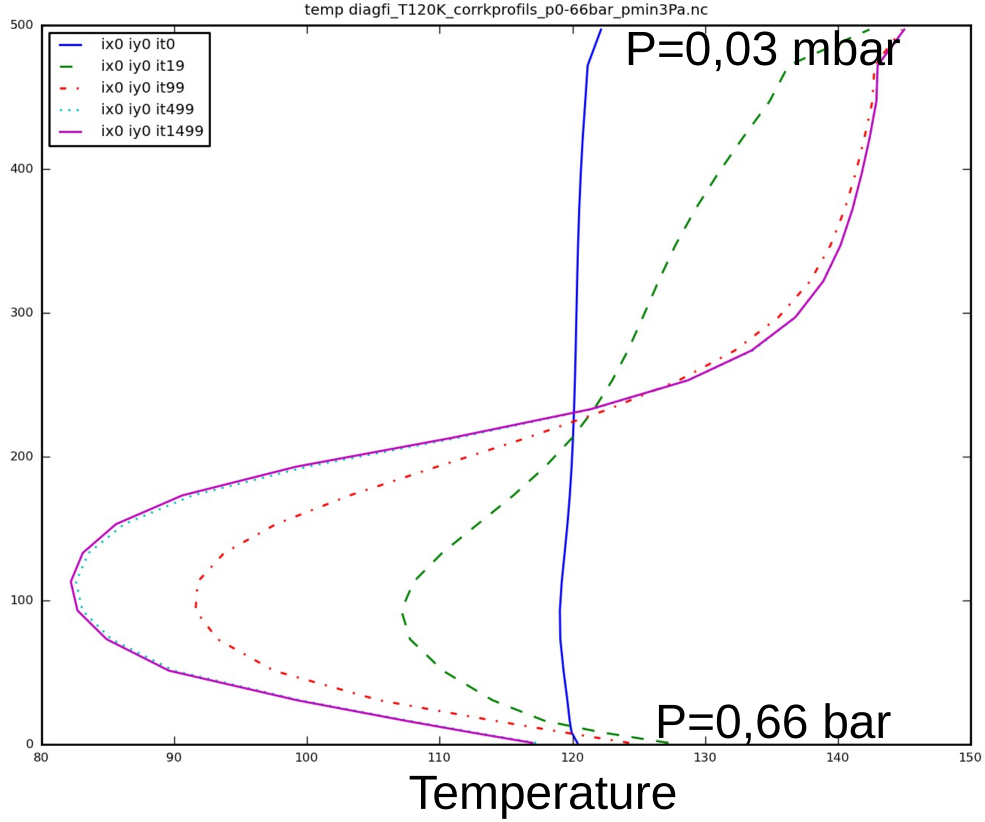
Application 3
Exoplanets : hot Jupiters





# Development of a first prototype

- Main ingredients: absorption by $CH_4$, thermal emission by $CH_4$, $C_2H_6$, $C_2H_2$, $H_2$/He continuum.
  We use correlated-k distributions.
- Radiative transfer tested in a 1D set-up of the GCM: typical temperature profile well reproduced
- First 3D test runs in progress




Goal: Present first results at EPSC and DPS 2013 !

# A recipe for our work

1. Exploration and fun (but we are very serious about our work)
2. New models adapted from existing « bricks » from past projects
3. Benefit from Earth climate modeling at LMD
4. Excellent young students, post-docs, engineers…
5. LOTS of collaborations, and not only atmospheric scientists
6. Strong link to spatial programs, missions, instruments

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7. French wine

あなたの温かいおもてなしとご関心をお寄せいただきありがとうござい

**Aymeric SPIGA**
えめりく すぴが