Evolution of the Martian Climate *and atmospheric escape*

François Forget

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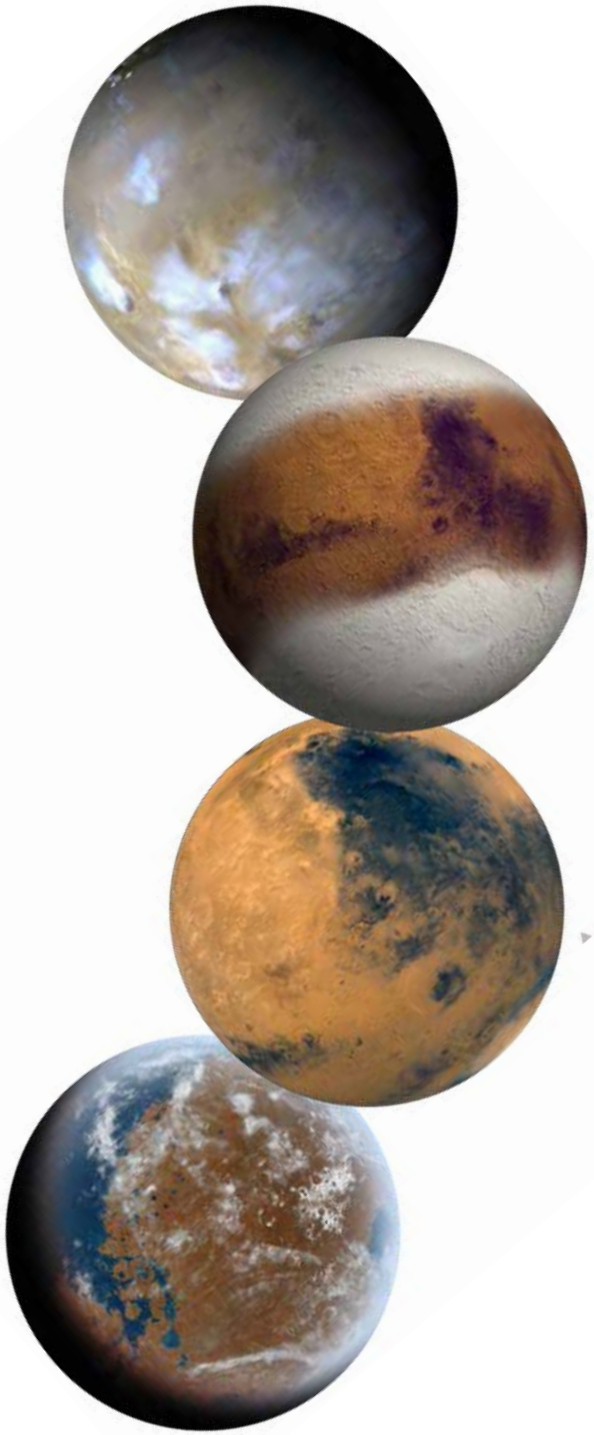
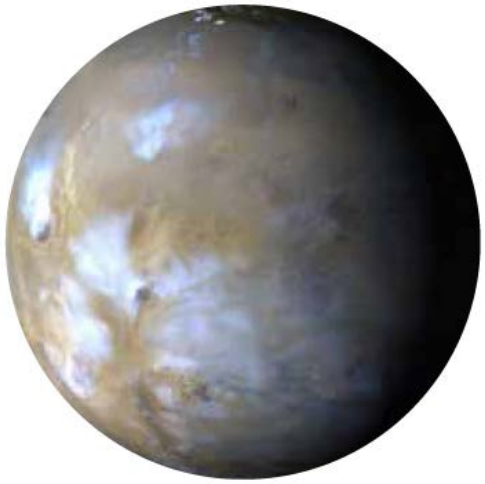
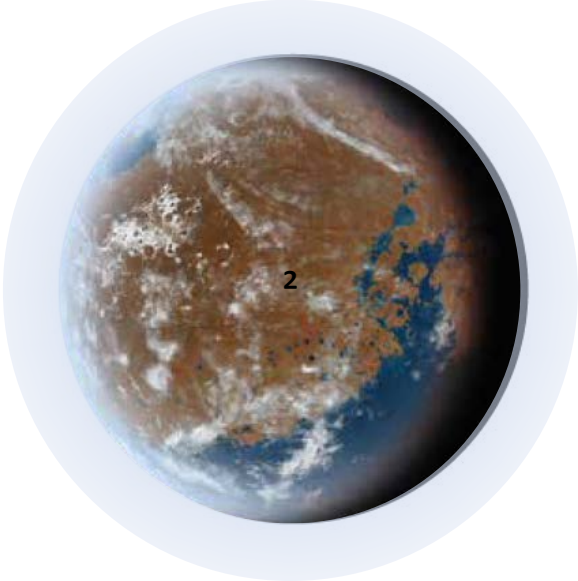
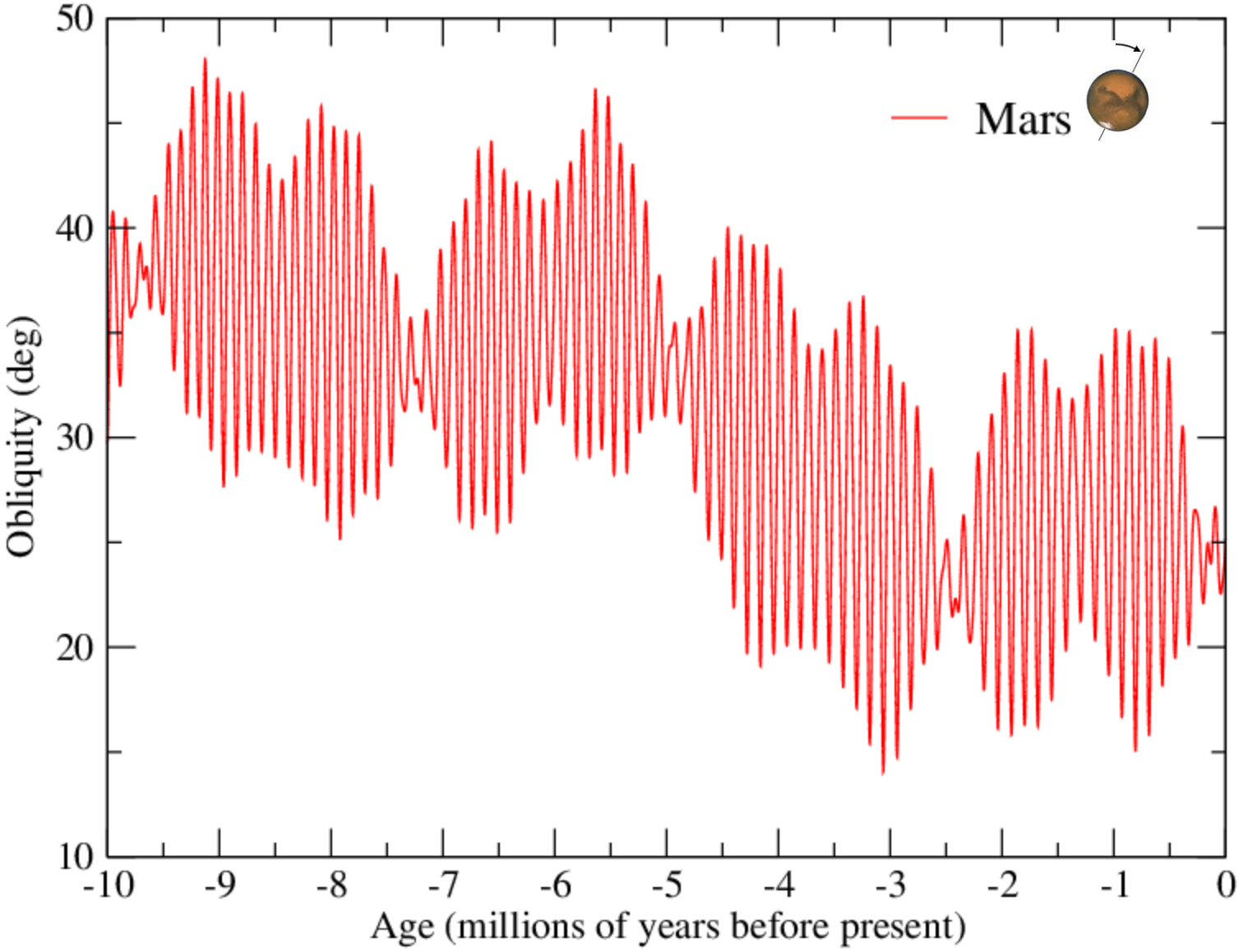


Why the Mars Climate evolves ?

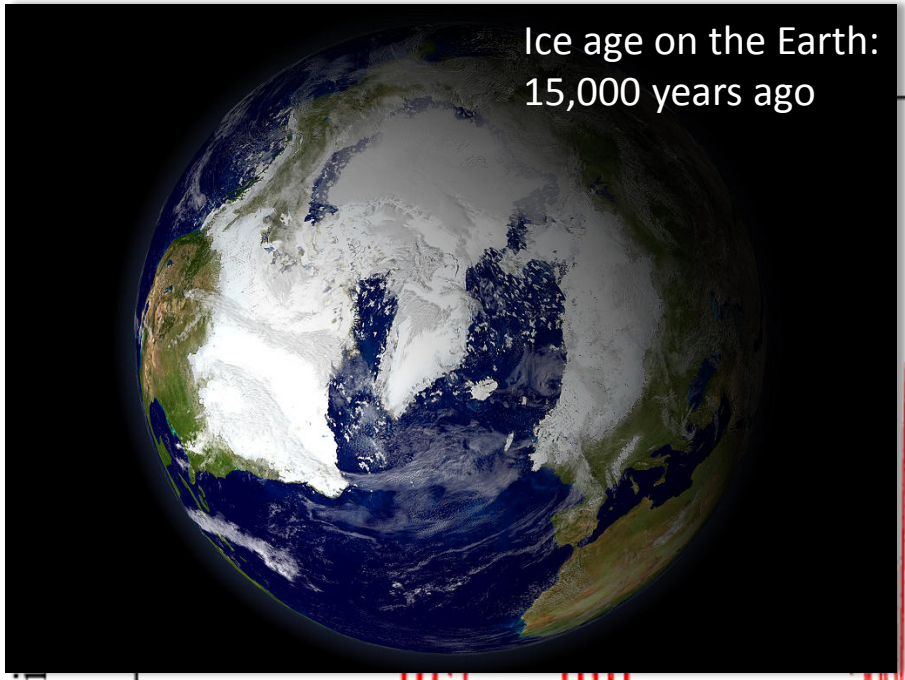
- Throughout Mars History : Variations of the obliquity and orbital parameters
- On Early Mars (Noachian, Hesperian): major changes in the Martian atmosphere
- *Not discussed today: impacts, effect of solar wind and EUV variations, etc…*

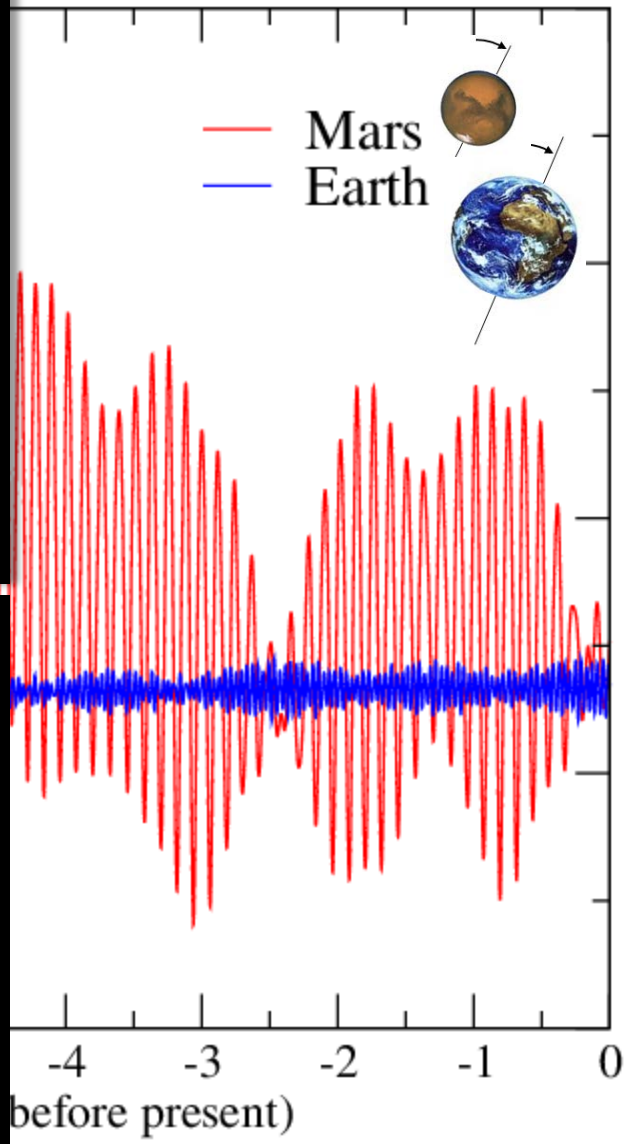






Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)

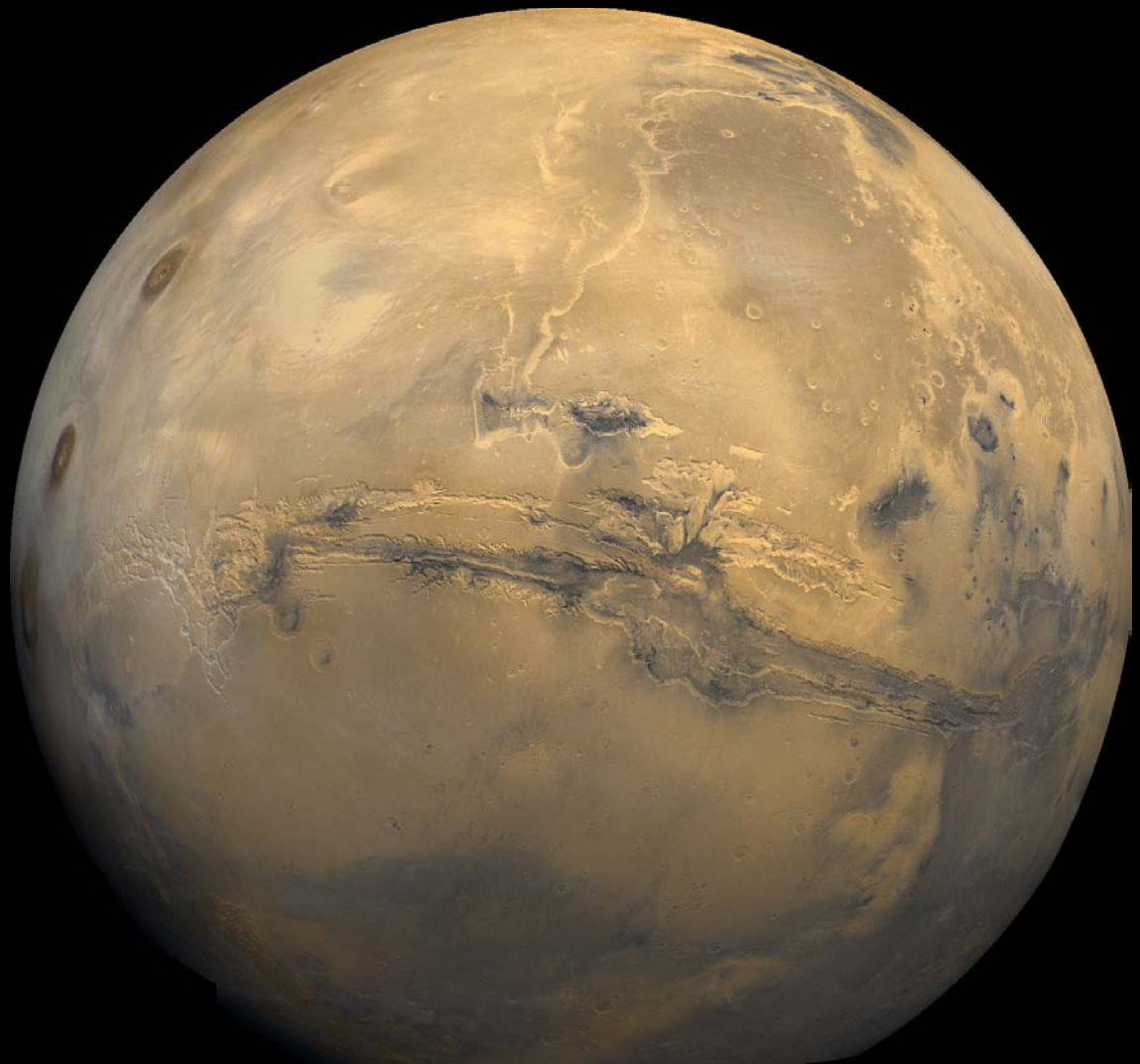




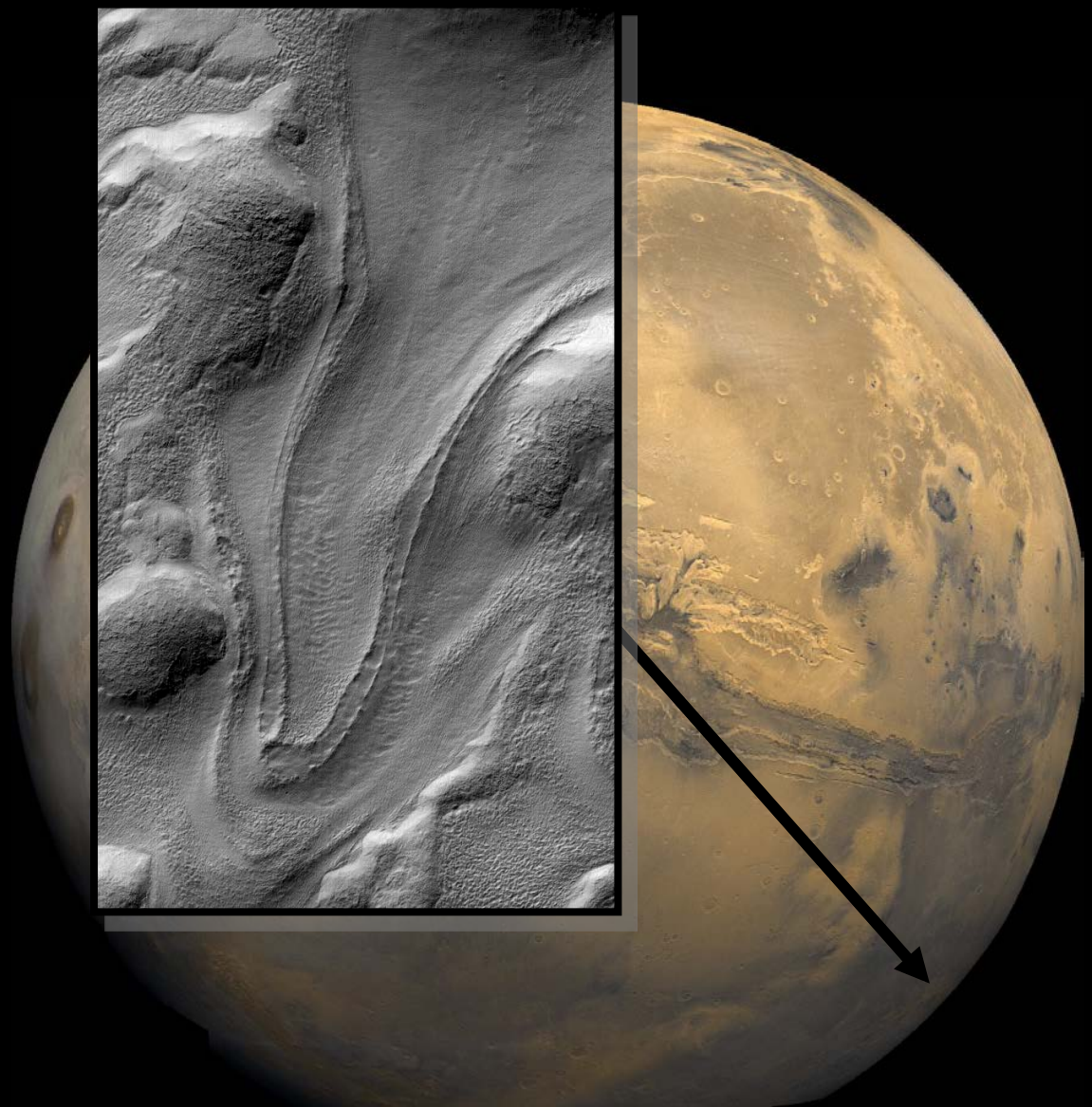
Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)

Mars Today: no permanent ice outside the polar regions

No detection by spectrometer (Omega, Crism , etc), as confirmed by climate models



Mid-latitudes: Burried geolofically recent rock glaciers in specific locations



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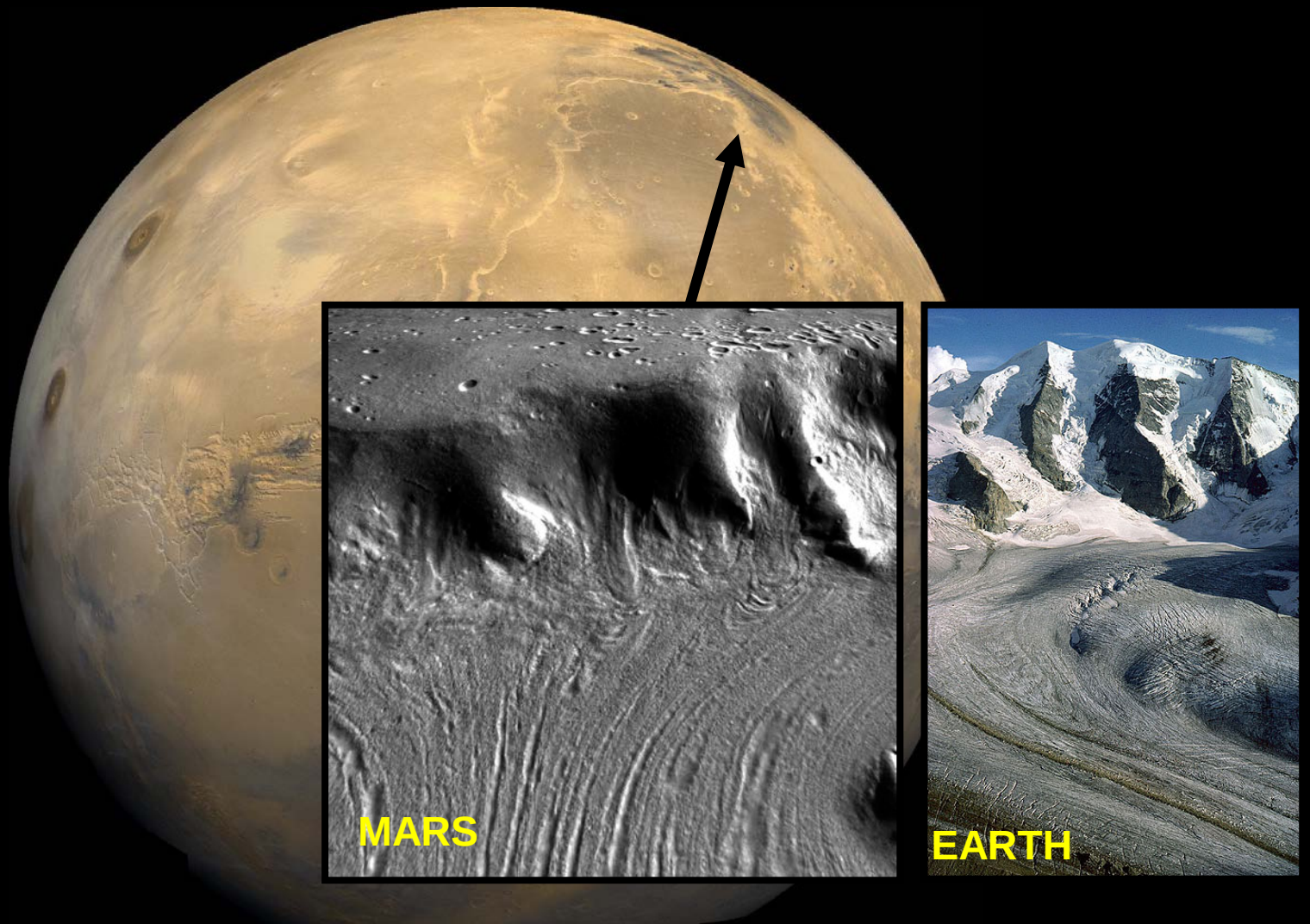

Tropics: Glaciers remnants on the western flanks of the giant Tharsis volcanoes

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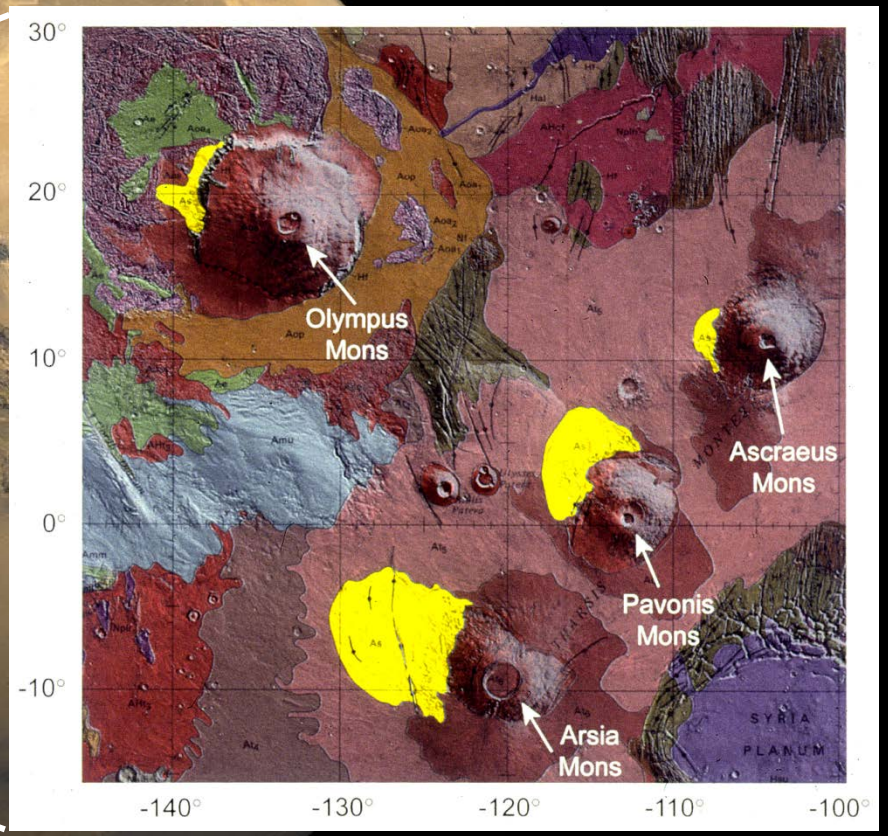


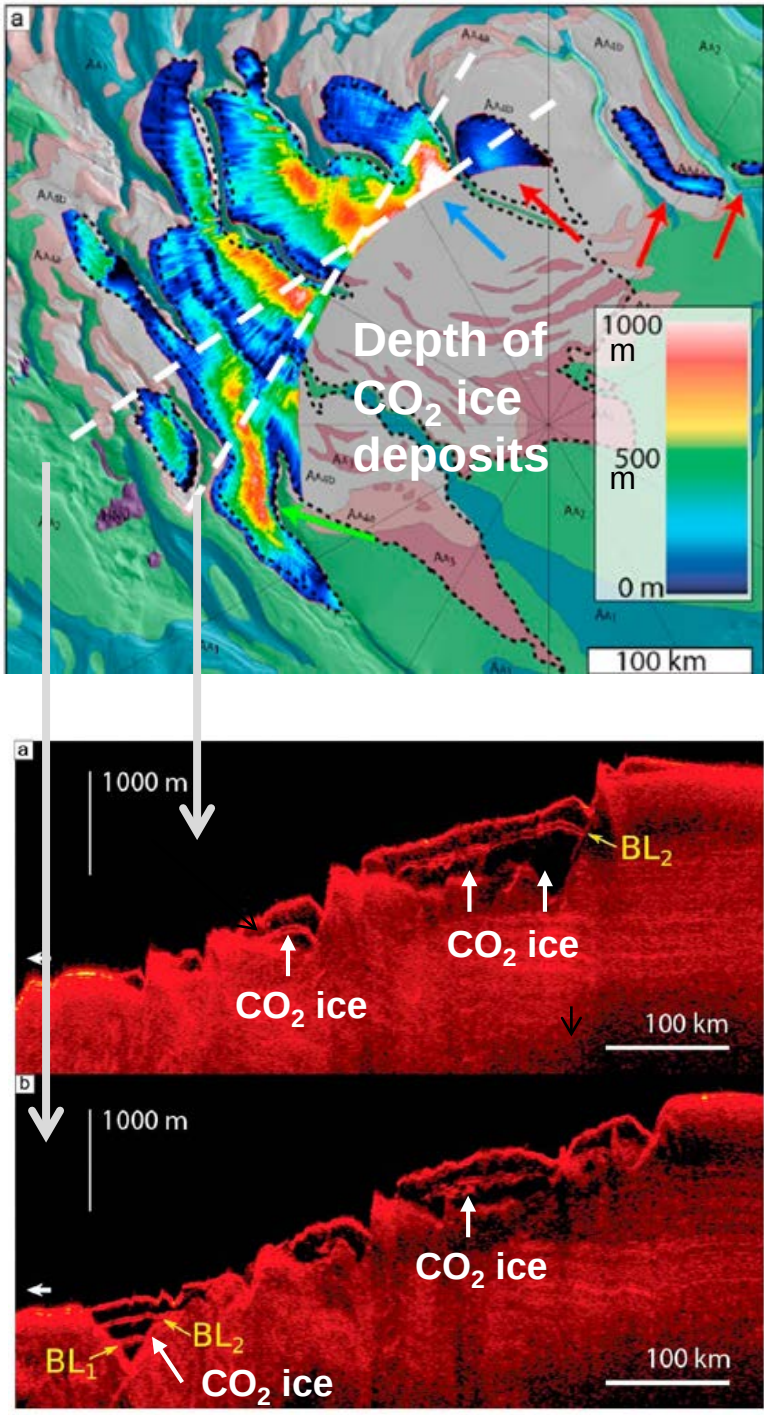
<u>High latitudes</u> (> 50°): covered by a mantle of ice isolated from the atmospheres by a few centimers of dry sand..

Impact on upper atmosphere and atmospheric escape ?

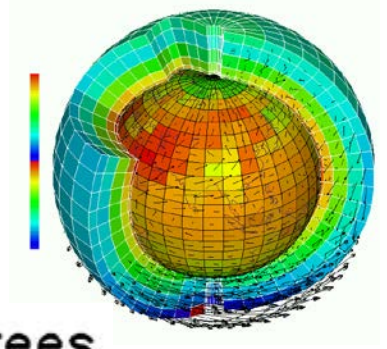
Head et al. 2003

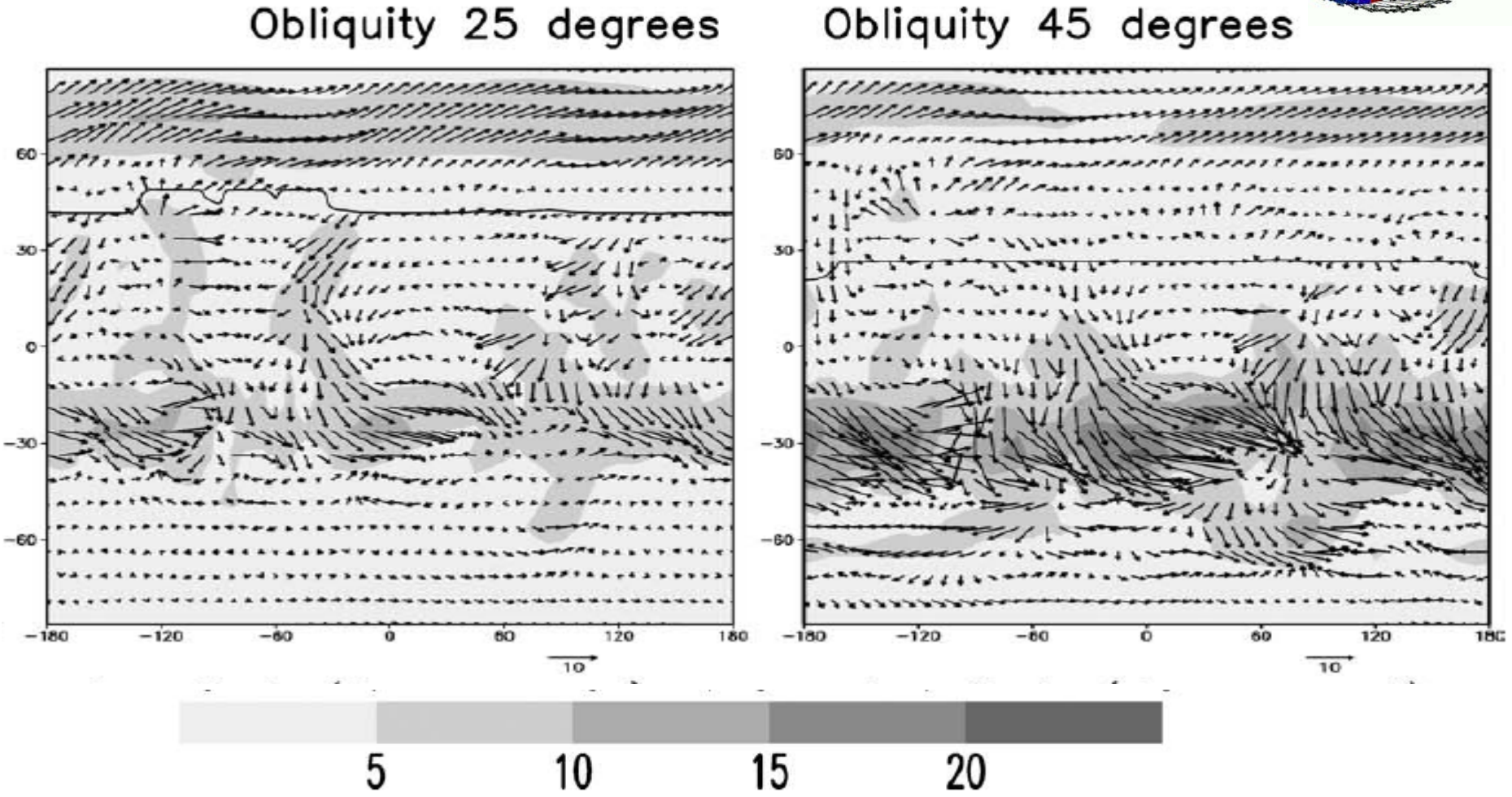
Increase of atmospheric pressure at obliquity higher than today ?

- **~6 mbar** of buried CO2 ice could be sublimed from deposits discovered in the south polar layered deposits by MRO Radar SHARAD (*Phillips et al. 2011, Bierson et al. 2016*)
- Up to **10 mbar** could be released by CO2 desorption from a warming high-latitude regolith ? (e.g. *Zent et al. 1992*) ???



Increase of Surface winds at obliquities larger than today





Modeled Near Surface winds at L=270° (m/s)

Newman et al. (2005)

Dustier ⇨ warmer ⇨ wetter mesosphere at high obliquity ?? ⇨ More H escape ?

nature astronomy

LETTERS

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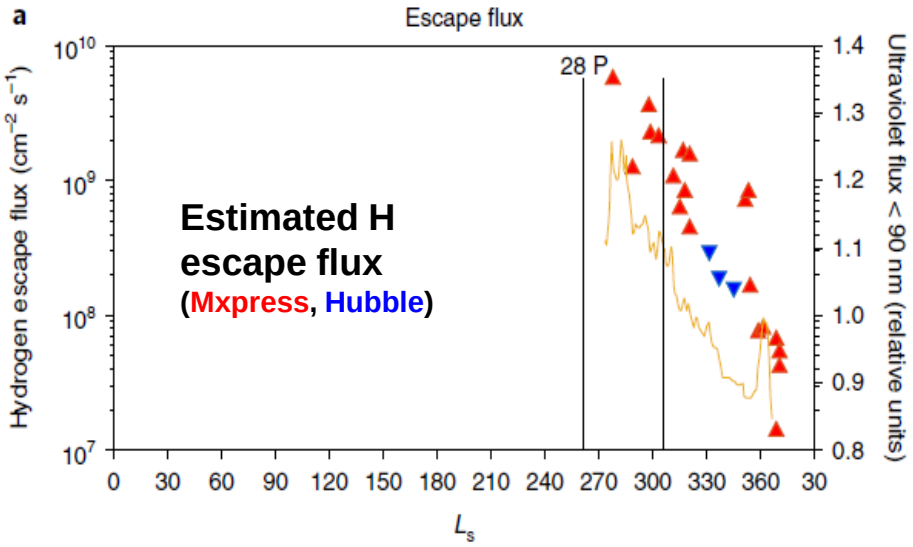
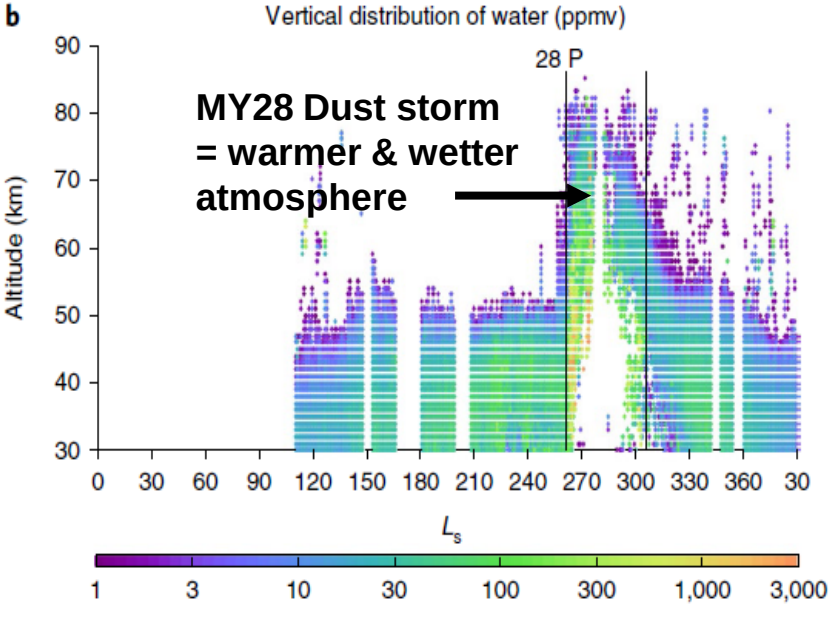




Smaller dust storms contribute to an annual mode in water content at 40–50 km that may explain seasonal variability in escape. Our results imply that Martian atmospheric chemistry and evolution can be strongly affected by the meteorology of the lower and middle atmosphere of Mars.

Observations of thermal infrared emission from Mars's limb and surface sense the thermal and aerosol structure of Mars's atmosphere. To study variability in atmospheric water content, its relationship with dust transport and implications for hydrogen escape, we used retrievals of temperature, pressure,

vapour, but the increa
began is mostly driven
The rapid increase i
rapid vertical dust tran
with the hygropause altit
dust between 30 and 80 k
or more and then rapidly
phase of the storm at L_s =
vertical distribution of wat
fast dust fluxes also trigge

photochemical feedback
are inconsistent with known H escape
requires escaping H to have a source other than H_2.
Express spacecraft in seasonally variable concentrations. Here we
model to show that the introduction of high-altitude water can produce a large
of weeks, quantitatively linking these observations. This H escape pathway produces prompt H
balanced by O escape, influencing the oxidation state of the atmosphere for millions of years. Martian atmospheric
may be dominated by escape via this pathway, which may therefore potentially control the planet's atmospheric chemis
Our findings highlight the influence that seasonal atmospheric variability can have on planetary evolution.

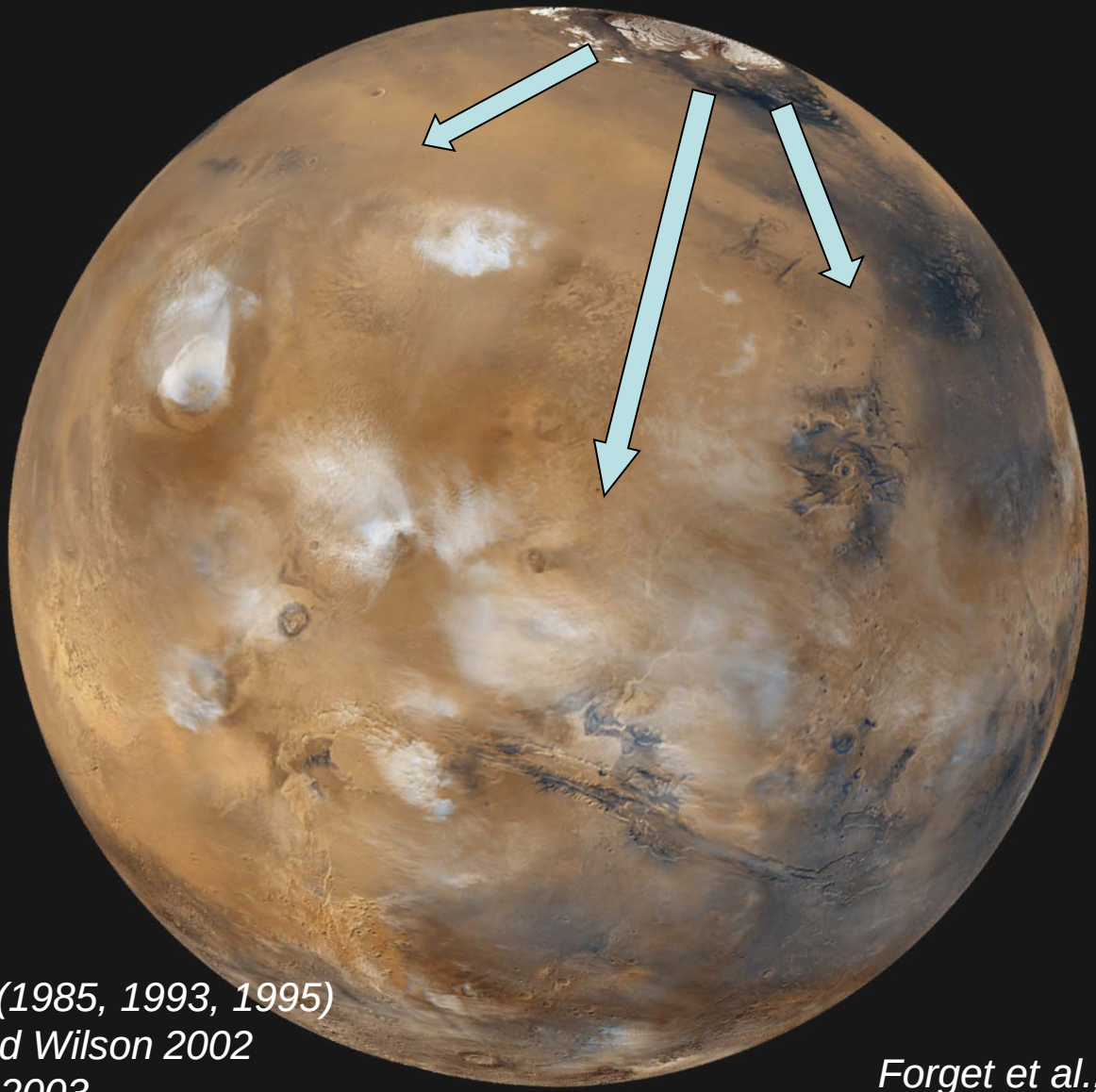
has substantially impacted the water inventory
near-surface water indicating
has

supply H to the upper atmosphere ($\sim 2 \times 10^8$ cm^{-2} s^{-1})[9], ass
the H_2 abundance of the lower atmosphere is that repor
ref. 12. Another source molecule is therefore required to
the upper atmosphere and supplement H escape. Wate
because it is the major atmospheric H
detected between 40

Were high obliquity atmospheres dustier ?

Mars water cycle at high obliquity

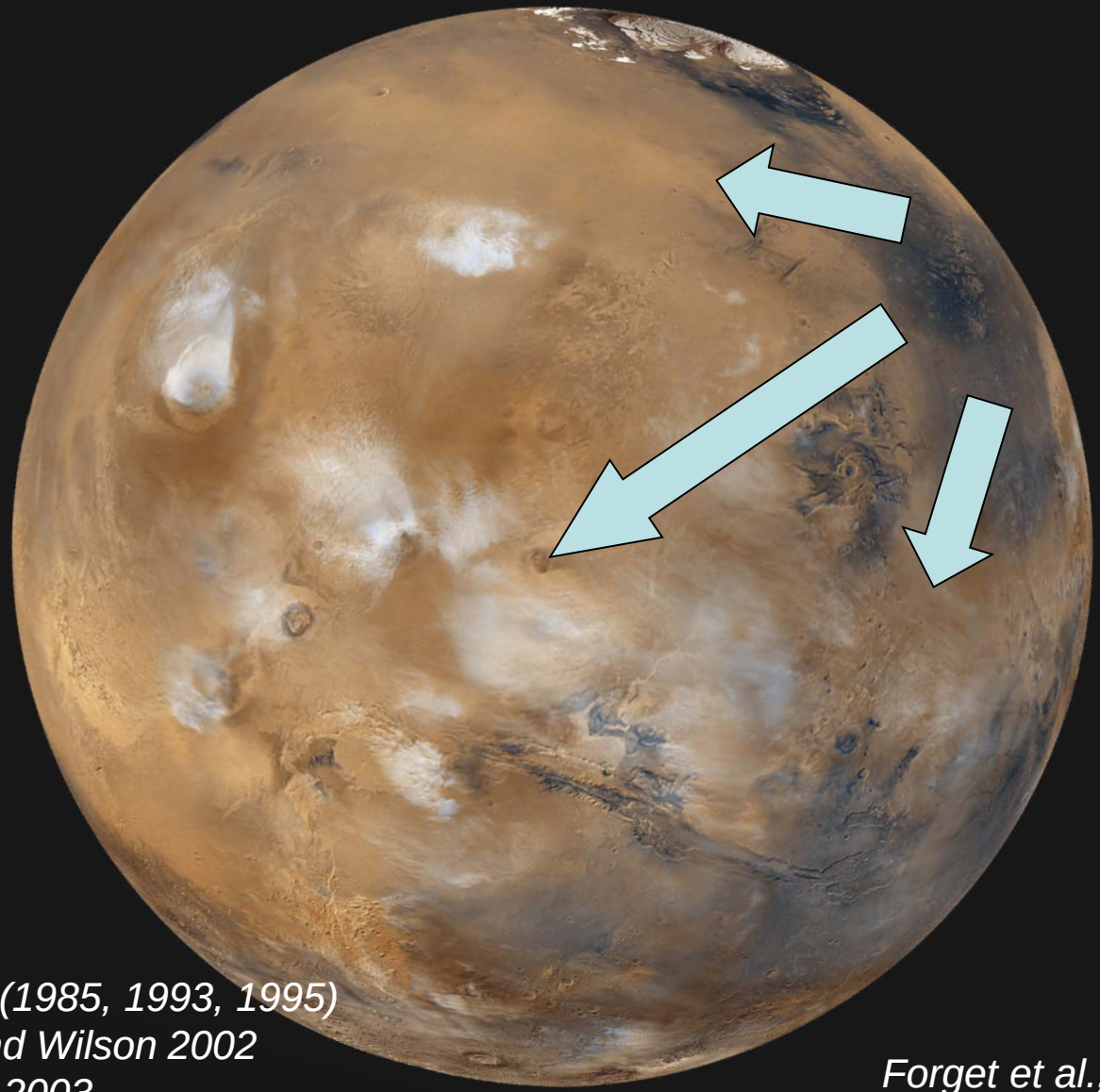
Solar flux



Jakosky et al. (1985, 1993, 1995)
Richardson and Wilson 2002
Mischna et al. 2003
Levrard et al., 2004
Mischna and Richardson 2005

Forget et al., 2006
Madeleine et al., 2009, 2014
Levrard et al. 2007

Mars water cycle at high obliquity



Solar flux

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LMD GCM Simulations:

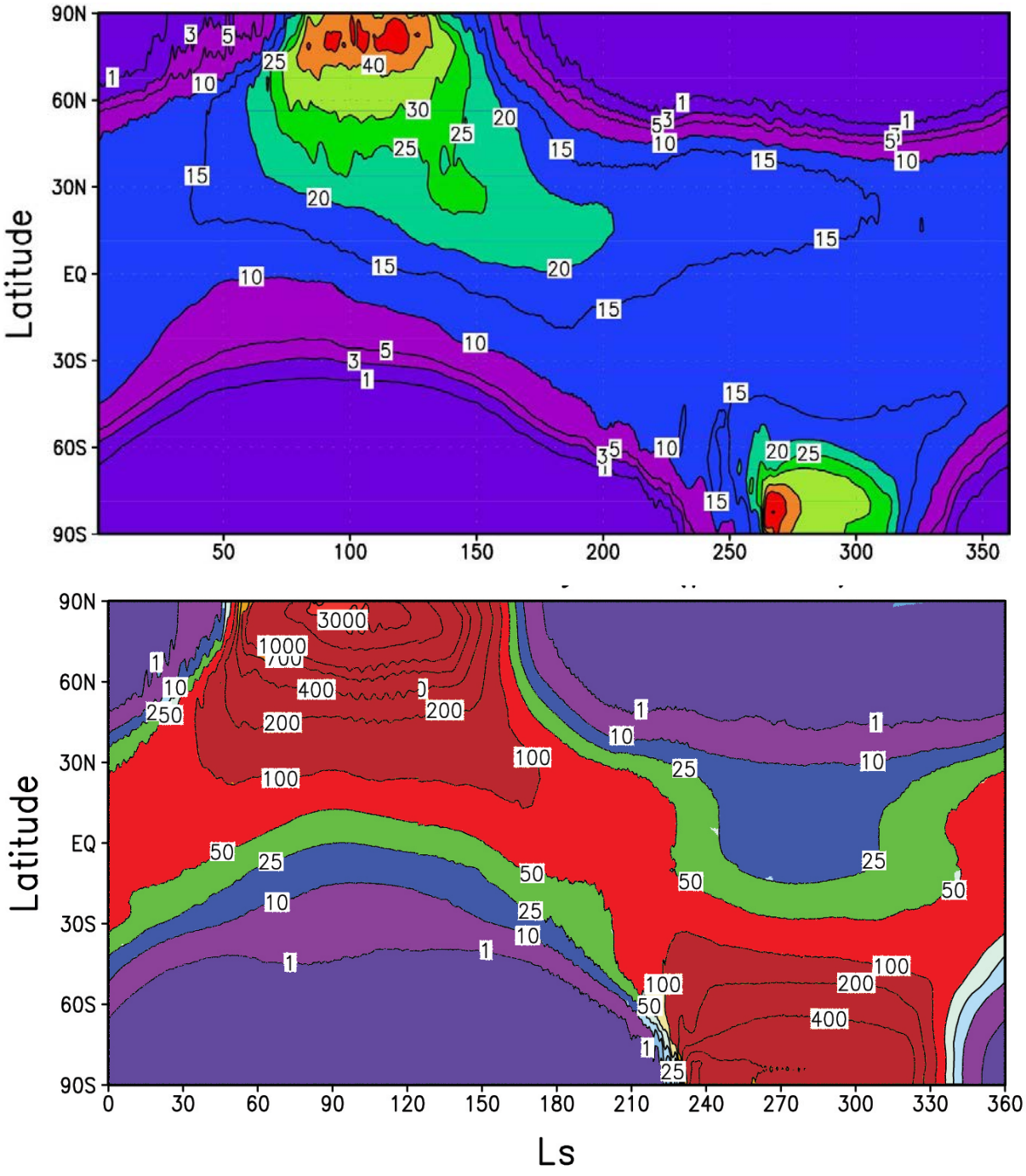
Water vapor column

(*precipitable –microns*)

On present-day Mars :

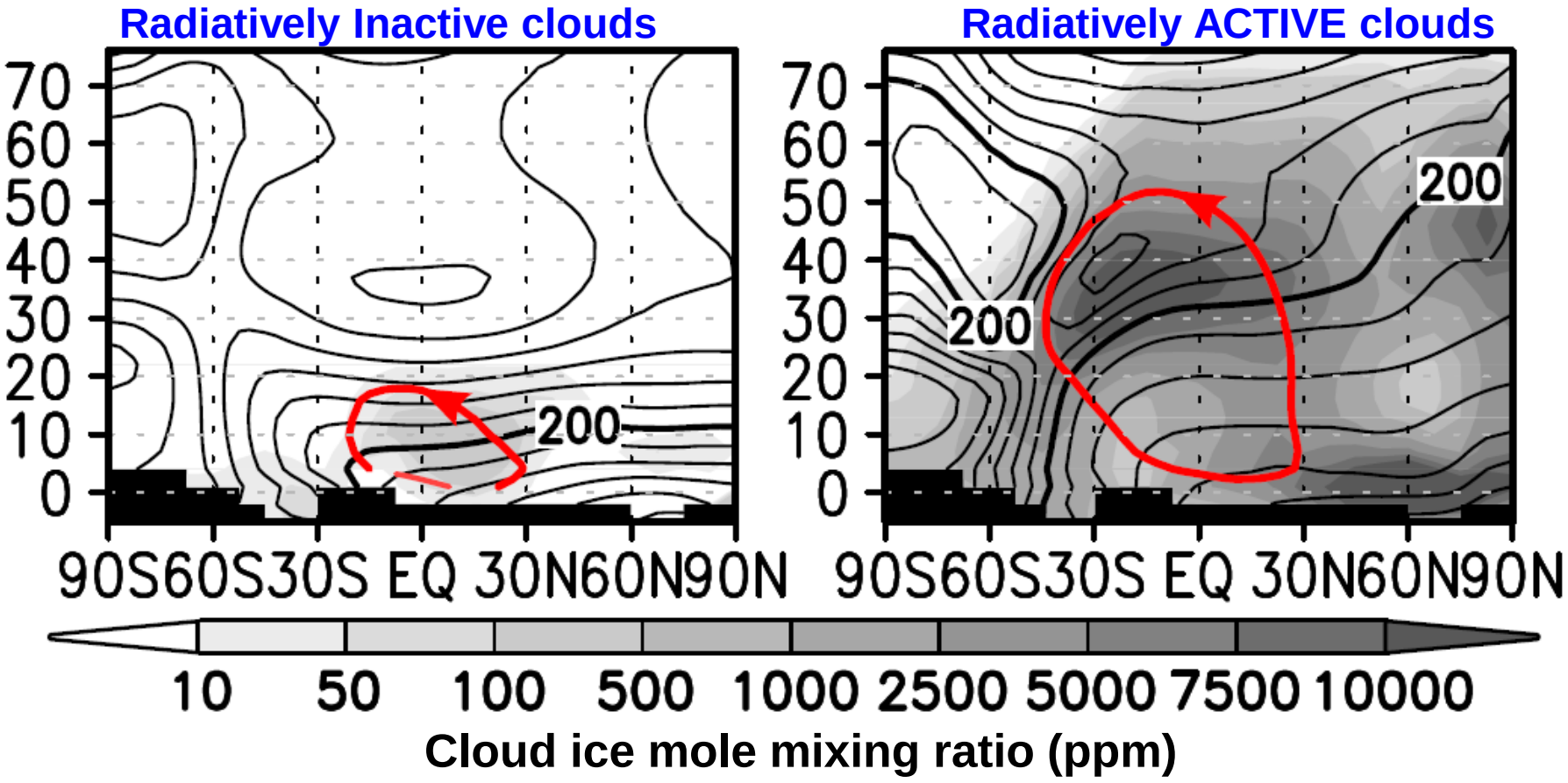
Same, but 45° Obliquity

(Circular orbit)



At high obliquity Mars mesosphere will be warmer and wetter due to the radiative effects of thick H2O ice clouds ⇨ More H escape

LMD GCM Temperature (10K contours) **and clouds at Ls=60-90°, <u>obliquity = 35°</u>**

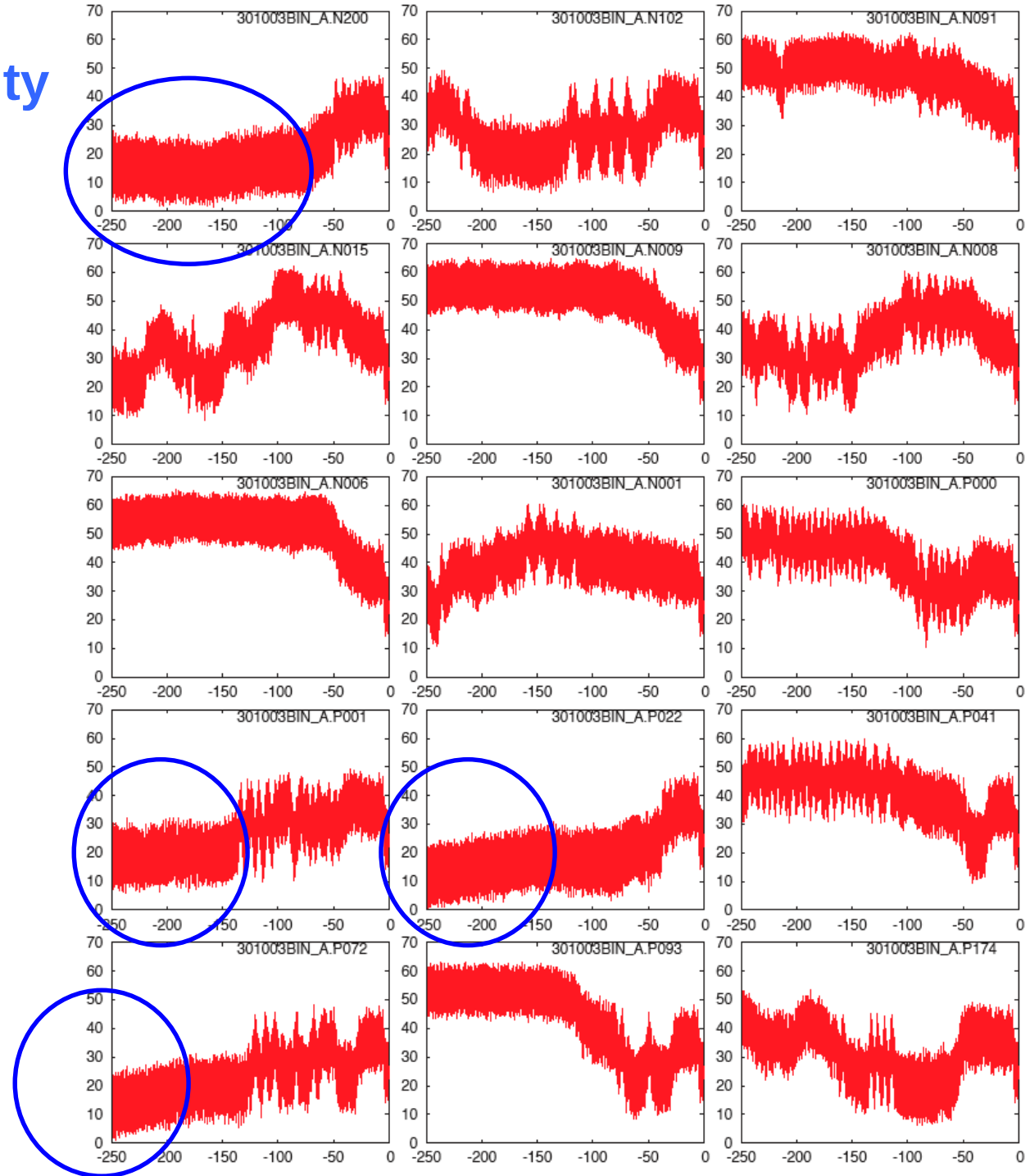


Madeleine et al. (2014)

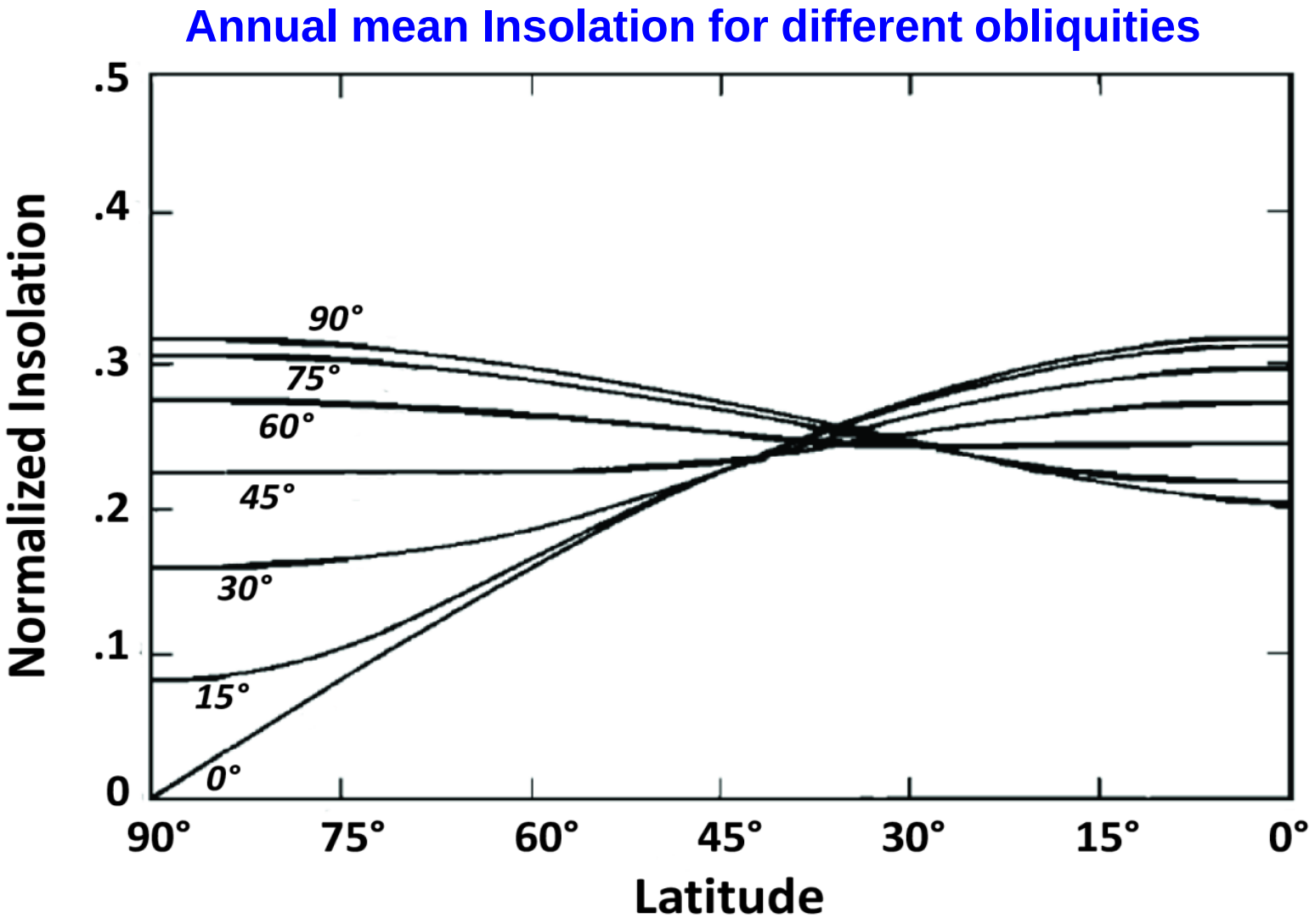
Possible Obliquity variations in the past 250 Myr

(Laskar et al. 2004) :

- ⇨ Most likely obliquity was 42º in the past billions years
- ⇨ Some periods with very low obliquities

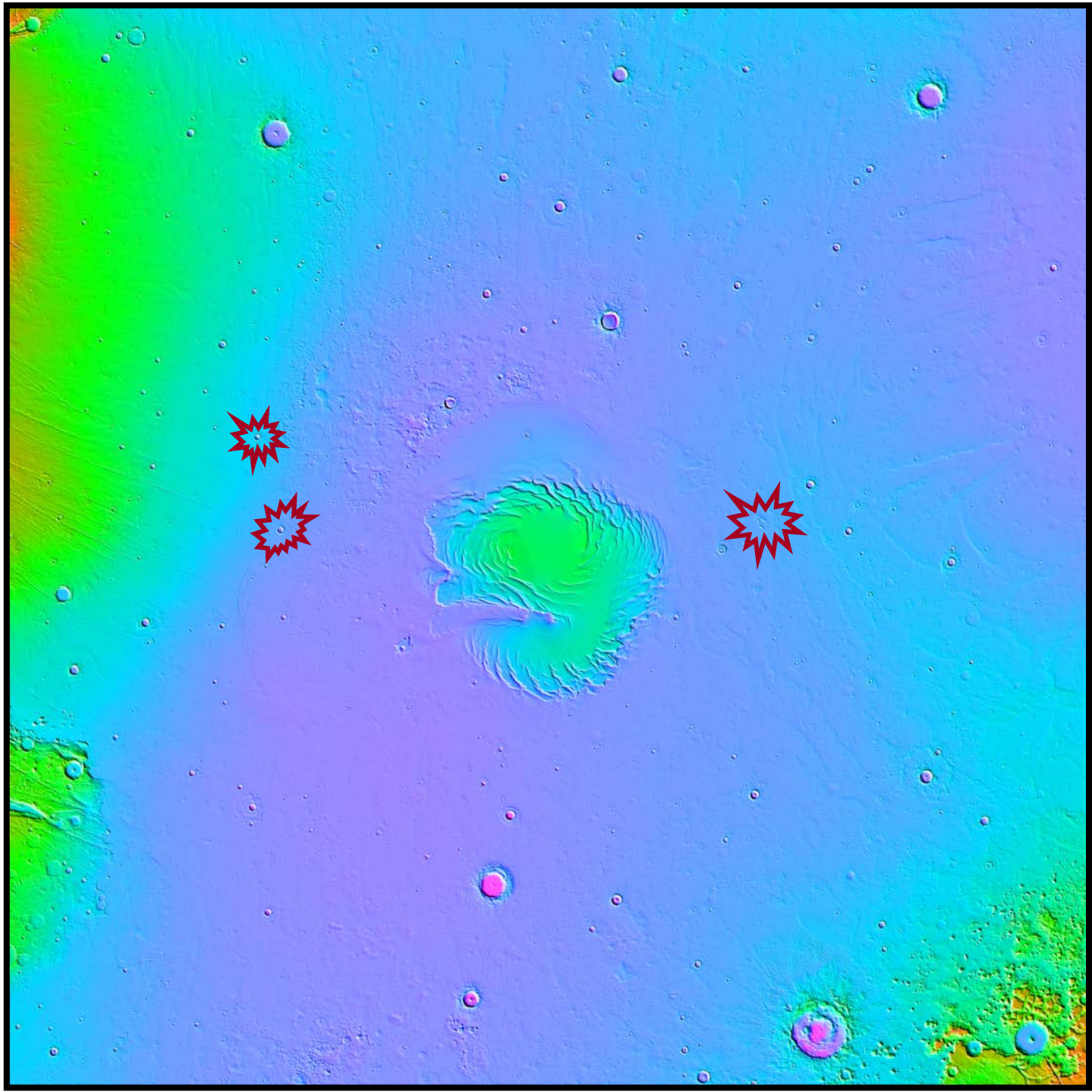


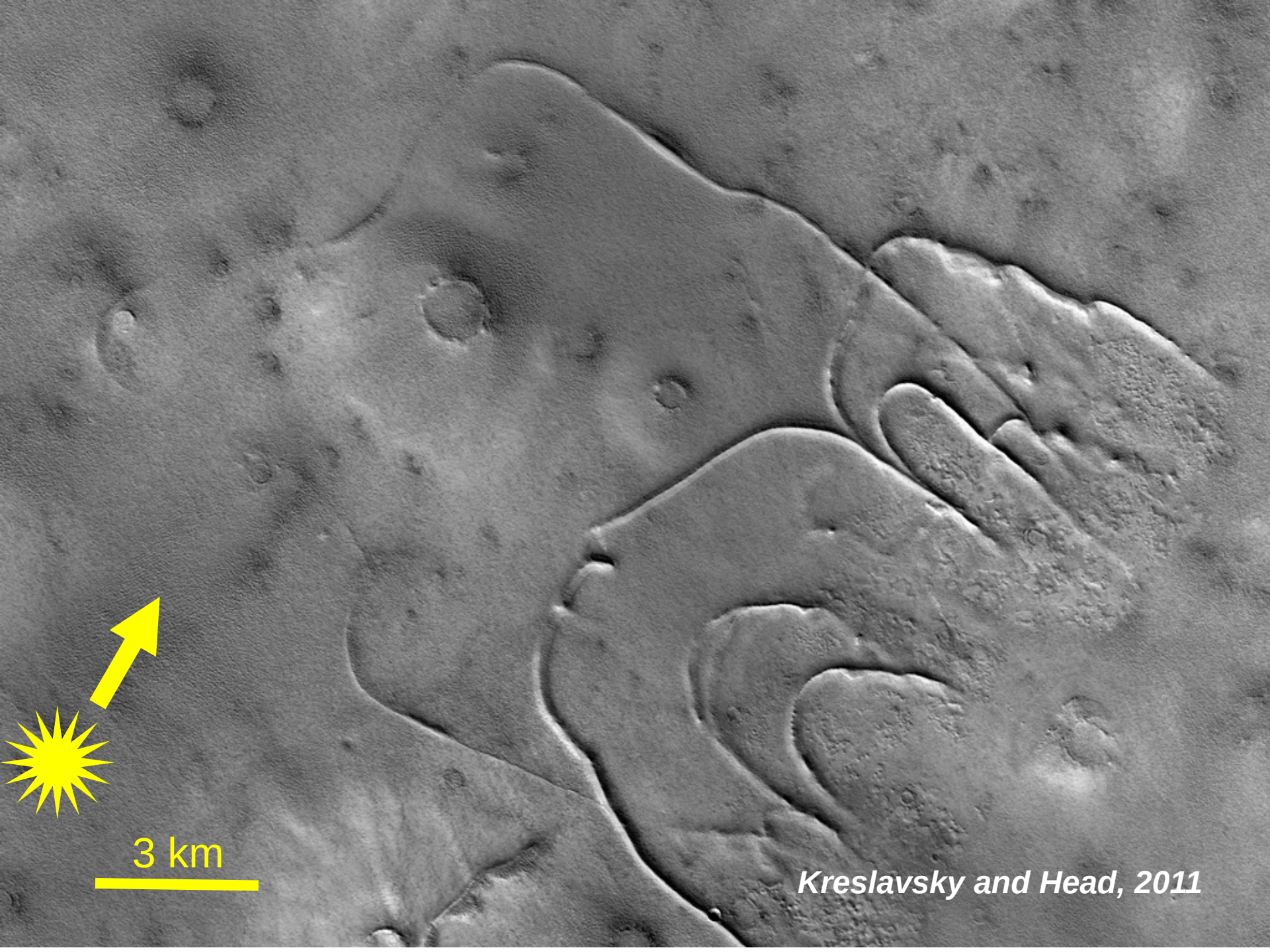
Atmospheric collapse at low obliquity ?



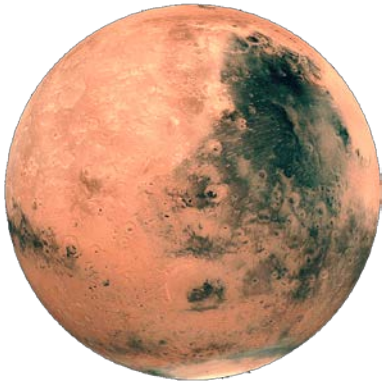
CO_2 glaciers ?

Kreslavsky and Head, 2011




3 km
Kreslavsky and Head, 2011

At very low obliquity, Mars atmosphere becomes a **25 Pa Argon-Nitrogen atmosphere** with sometime only traces of CO_2…
Very cold, very dry, transparent atmosphere….



Kieffer and Zent 1992
Kreslavsky and Head, 2005,
More next month from our team at the Amazonian Climate workshop near Denver…

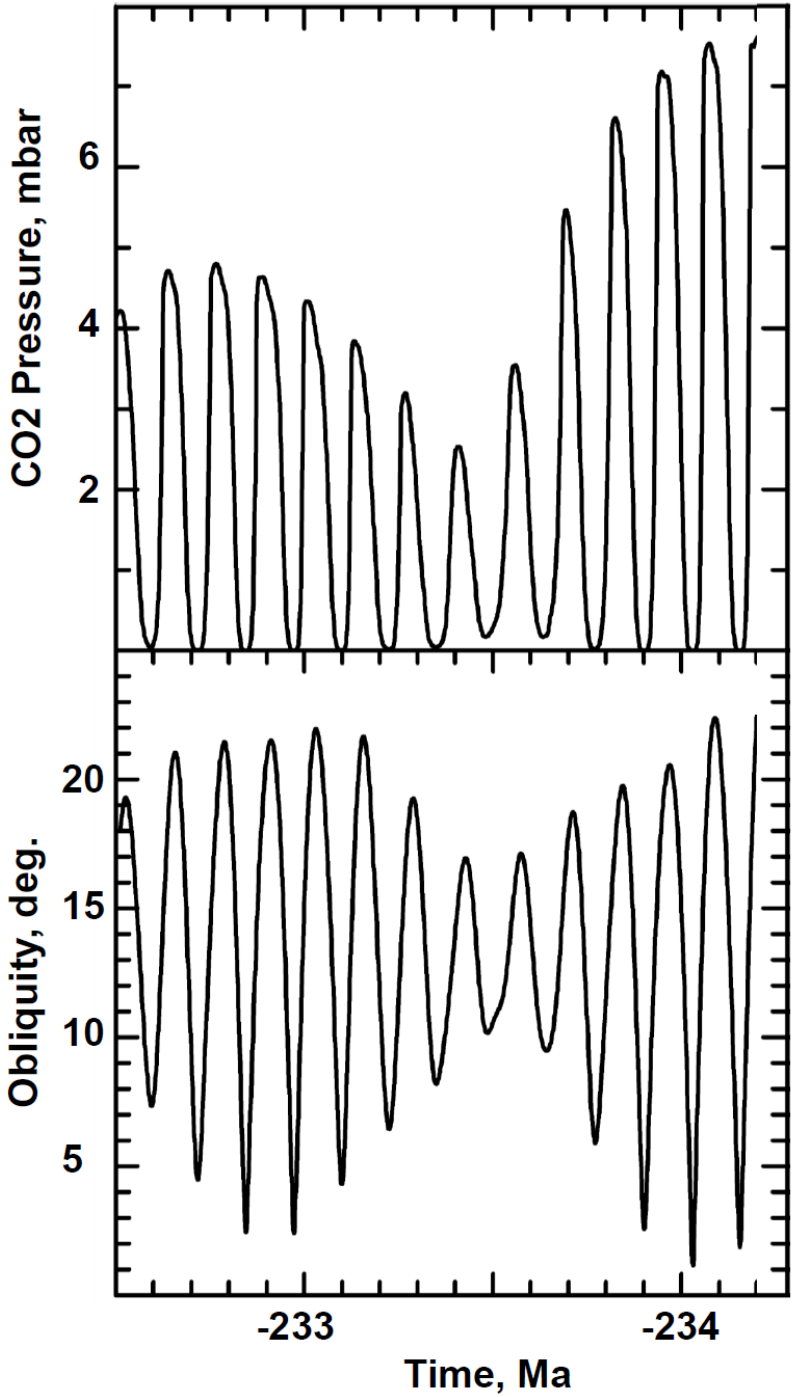
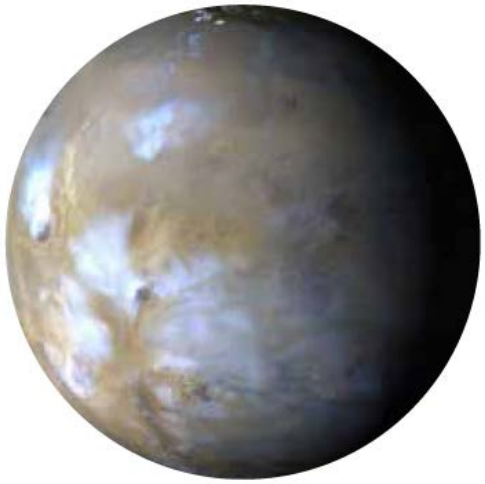
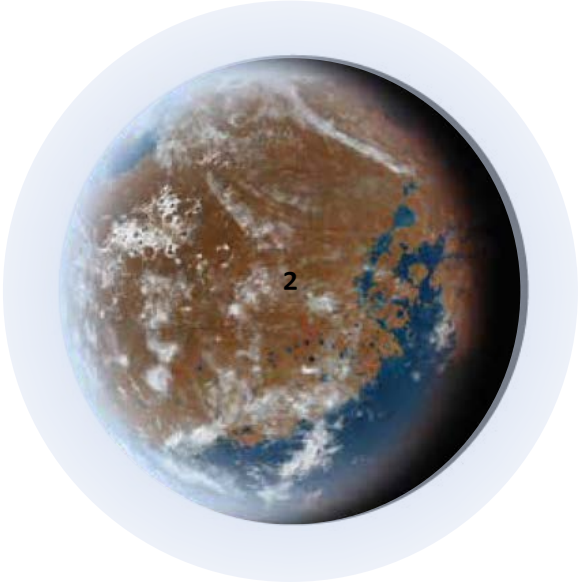


Figure adapted from Kreslavsky and Head, 2005, in Forget et al., chapter 16 in "Mars atmosphere and Climate Book"

Why the Mars Climate evolves ?

- Throughout Mars History : Variations of the obliquity and orbital parameters
- On Early Mars (Noachian, Hesperian): major changes in the Martian atmosphere



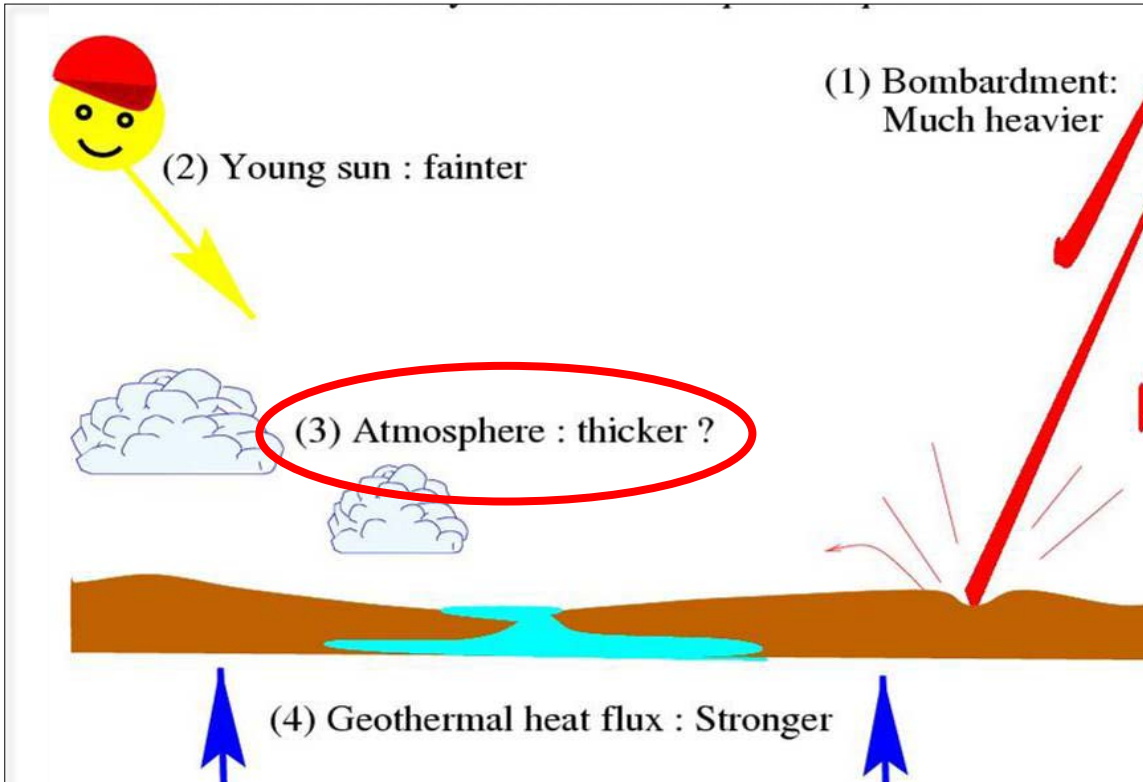


The Early Mars Enigma

Mars 4 to 3 Ga was different than what it was after this date, with apparently liquid water at the surface. **But key questions remains:**

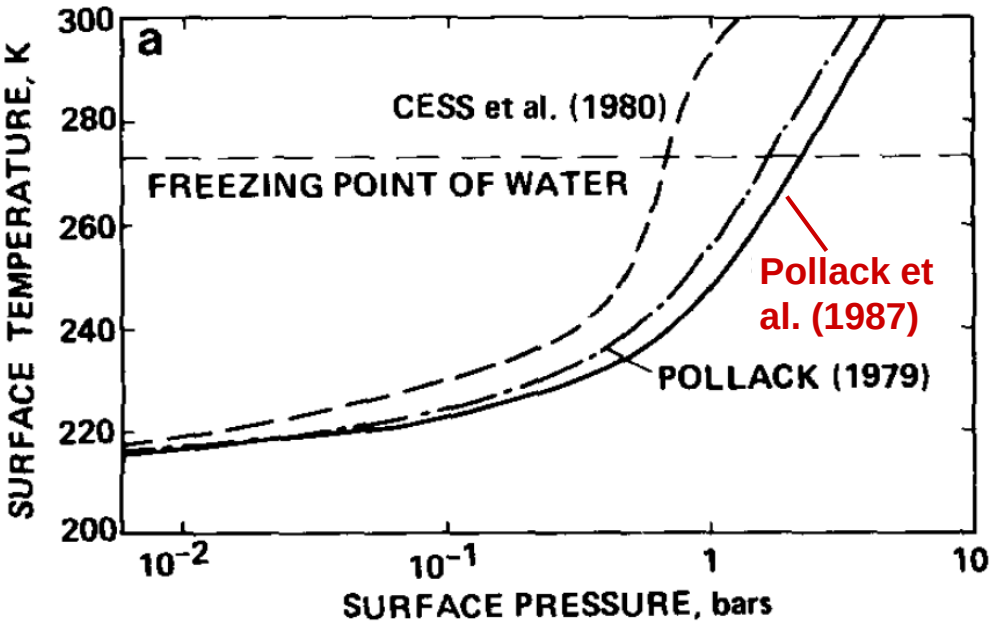
1. Were the conditions suitable for liquid water **episodic,** or **stable** on longer time scales ?
2. Role of **hydrothermalism** (volcanic, impact) versus flowing water and precipitations ?
3. **Why was early Mars different ?**

⇨ **Boundary conditions different than today**



A thick CO_2-N_2-H_2O atmosphere does not work anymore

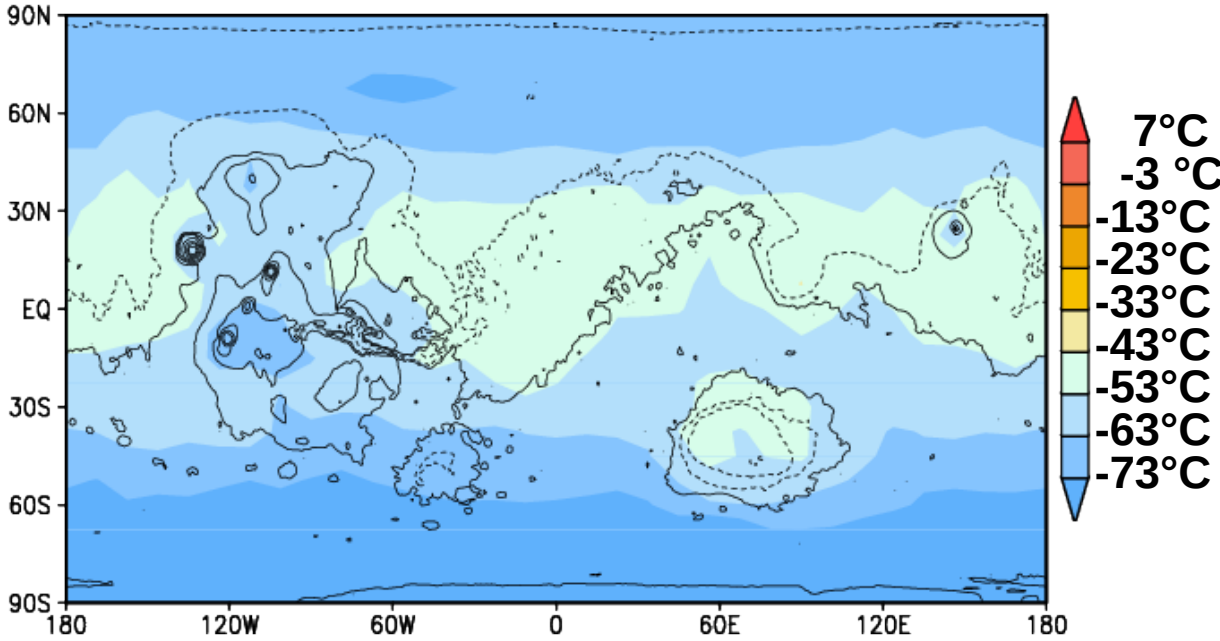
- We used to think that a CO2-rich atmosphere would explain a warm climate (e.g. *Pollack et al. 1987*) →



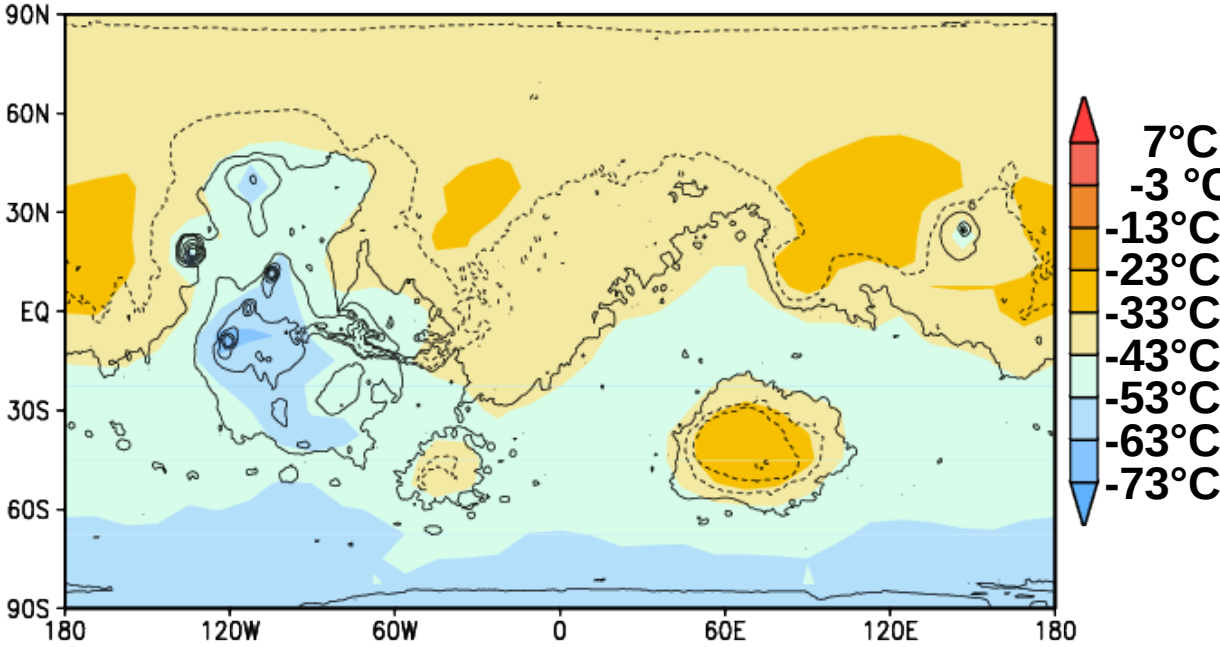
- **Since then, problems identified with:**
  - o **CO2 gas spectroscopy**
  - o **Clouds:**
    - • CO2 ice condensation (reduces greenhouse effect) & radiative effects of clouds (sligthly warms)
    - • Water ice clouds ?

CO2 atmosphere: Annual mean surface temperature

Ps=0.5 bar



Ps = 2 bar



Obliquity = 25°
[CCN] = 10^5 kg^{-1}

Forget et al. 2013

How to have liquid water flowing on Early Mars ?

- **A warmer young sun ??**
- **Impact of Impacts** ? Played a role, but cannot explain all the erosion…
- **Additional Greenhouse Gases:**
  - **NH_3** : photochmically unstable
  - **Volcanism** : SO_2 and H_2S
    - Many studies : (*Postawko and Kuhn, 1986; Yung et al., 1997; Johnson et al., 2008, 2009; Tian et al., 2010; Mischna et al., 2013; Halevy and Head, 2014,* ***Kerber et al. 2015***).
  - **Young sun "Superflares"** (XUV, energetic protons) (*Airapetian et al. 2016*): convert CO2 and N_2 in **N_2O** and HCN)
  - **If the Mantle was strongly reduced** : outgassing of **H_2 (& CH_4)**?

    ⇨ Good Greenhouse Gas dur to CO_2 –H_2 and CO_2 –CH_4 collision induced absorption of IR radiation

Warming Noachian Mars with CO_2–H_2 collision induced absorption (CIA) of IR radiation

Context:

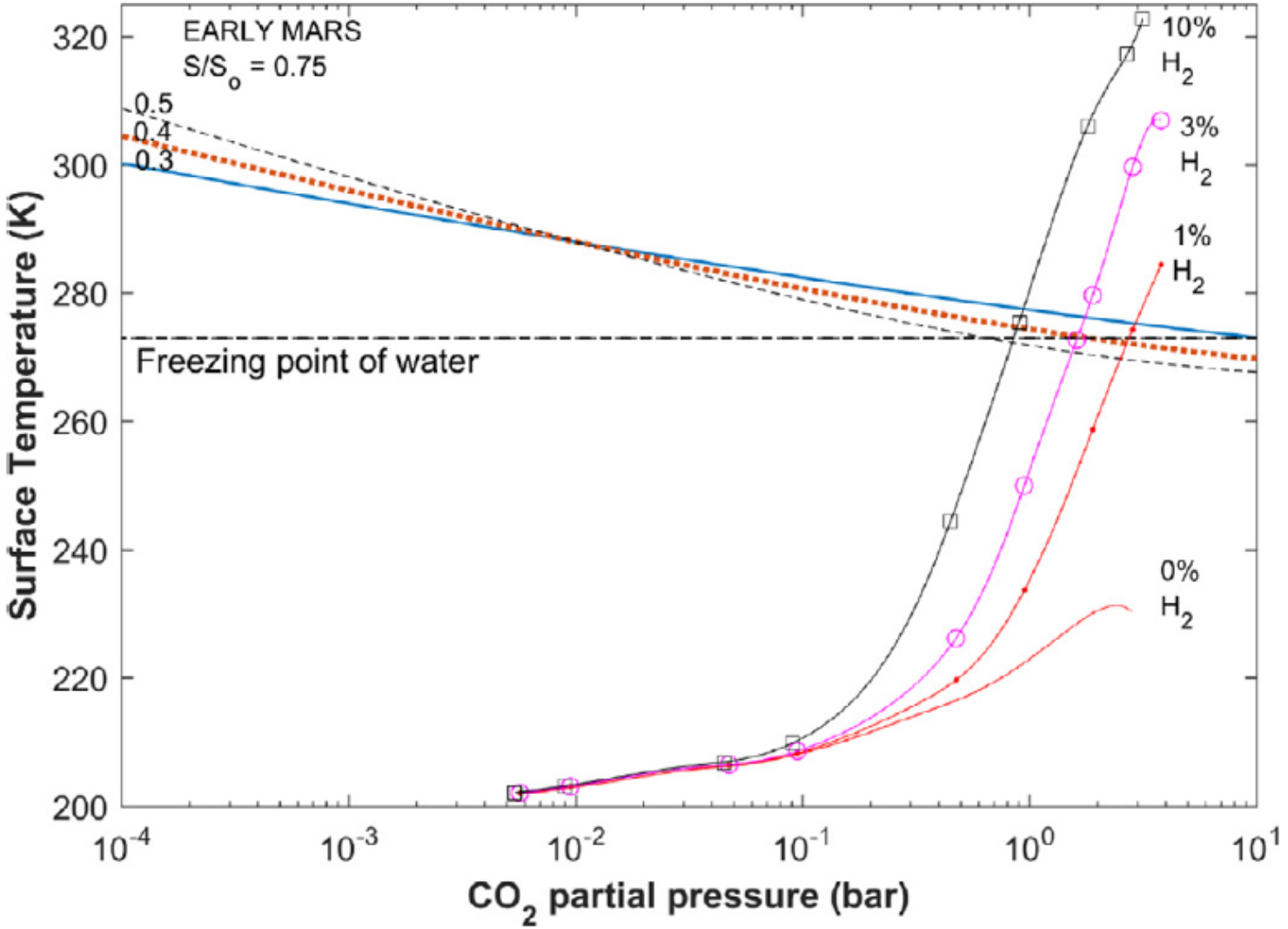
- *Wordsworth and Pierrehumbert (2013)* : show that H_2 could act as an important greenhouse gas in terrestrial-type atmosphere.
- *Ramirez et al. [2014]* : a lot of H_2 (e.g. 20% in 1.3 bar of CO2) could warm early Mars
- *Wordsworth et al. (2016)* : In theory CO_2–H_2 CIA could be much stronger than assumed before (using N_2 –H_2 coefficient…)

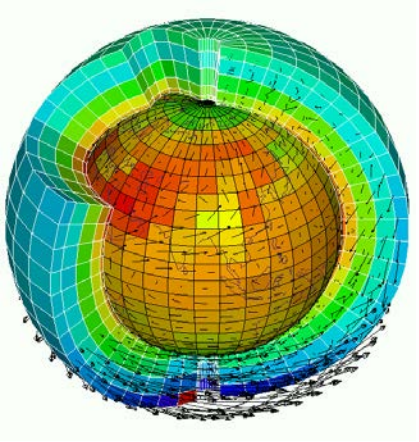
⇨1D modelling performed by *Wordsworth et al. (2016)* and *Ramirez (2017)*

⇨ New ! Spectrocopic measurements performed

Warming Noachian Mars with CO_2–H_2 collision induced absorption (CIA) of IR radiation

1D model results by Ramirez (2017)





3D simulations of early Mars with a $CO_2 - H_2$ atmosphere ⇨Temperate climate

Several simulations with different initial state

A) Ps=0.8 bar with 20% H_2 // **B)** Ps=3 bar with 1% H_2

(⇨Atmospheres that yield Tsurf = 0°C in 1D simulations)

1) "Low water" Mars: Initially a global 200 kg m^{-2} of water

2) "High water" Mars with a Huge ocean below 0m

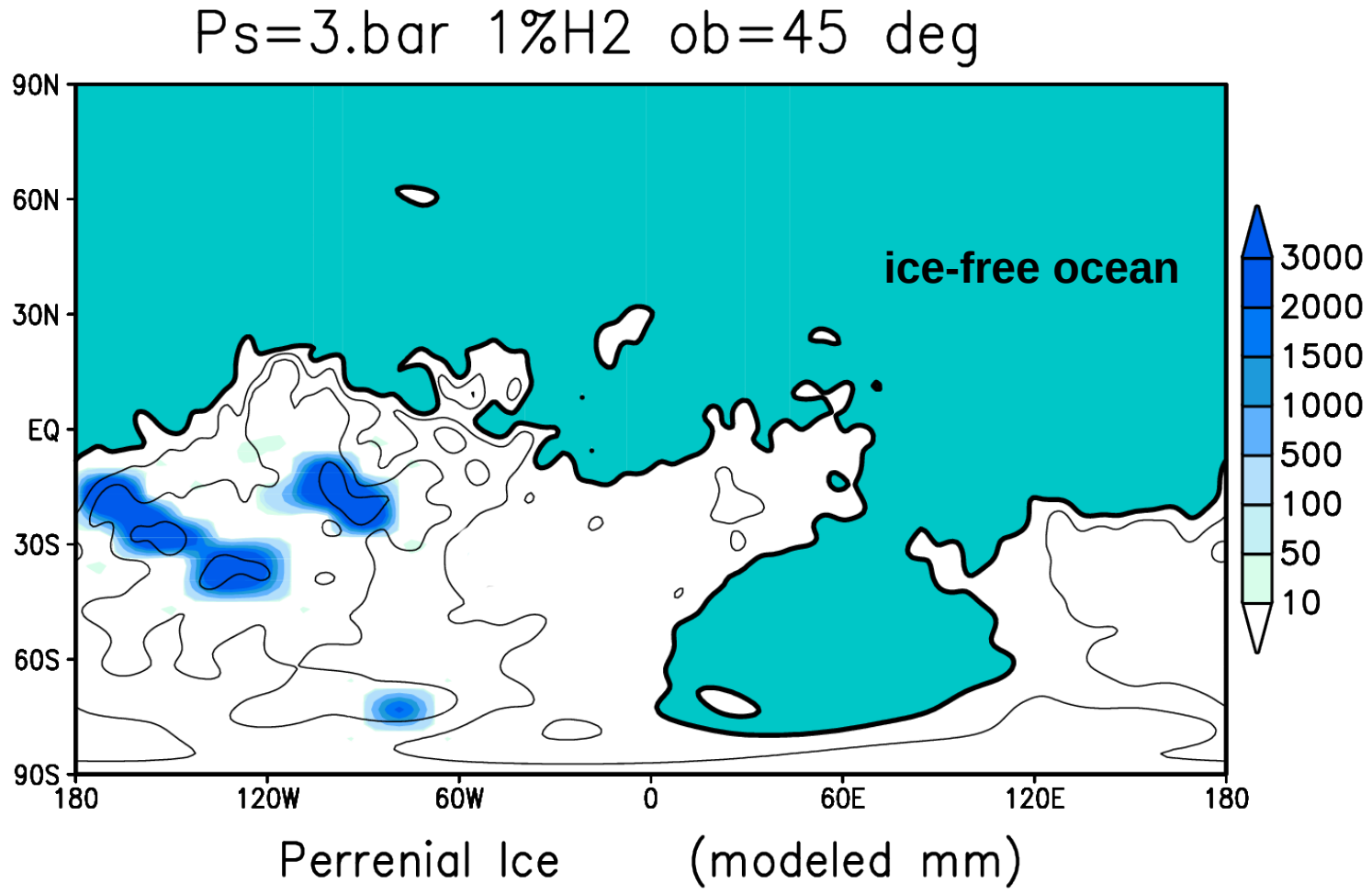
⇨600 years simulations (equivalent) to stabilize water cycle

+ Various obliquities + pre-tharsis topography.

(See also *Wordsworth et al. 2015 for further temperate Mars sims*)

“Ocean” Mars :

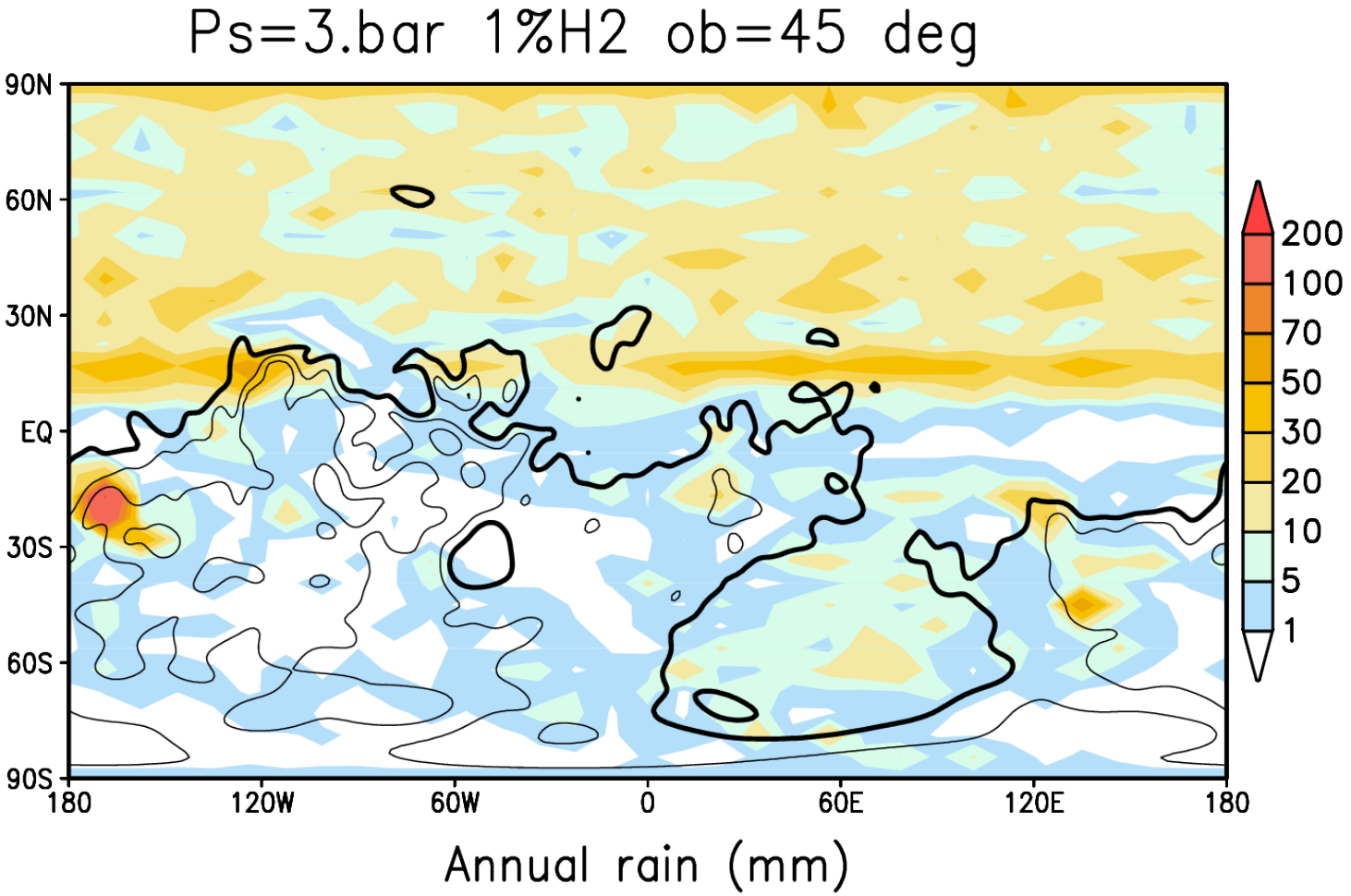
Perennial ice reservoir after ~600 years



Global mean <Tsurf> = +13°C

“Ocean” Mars :

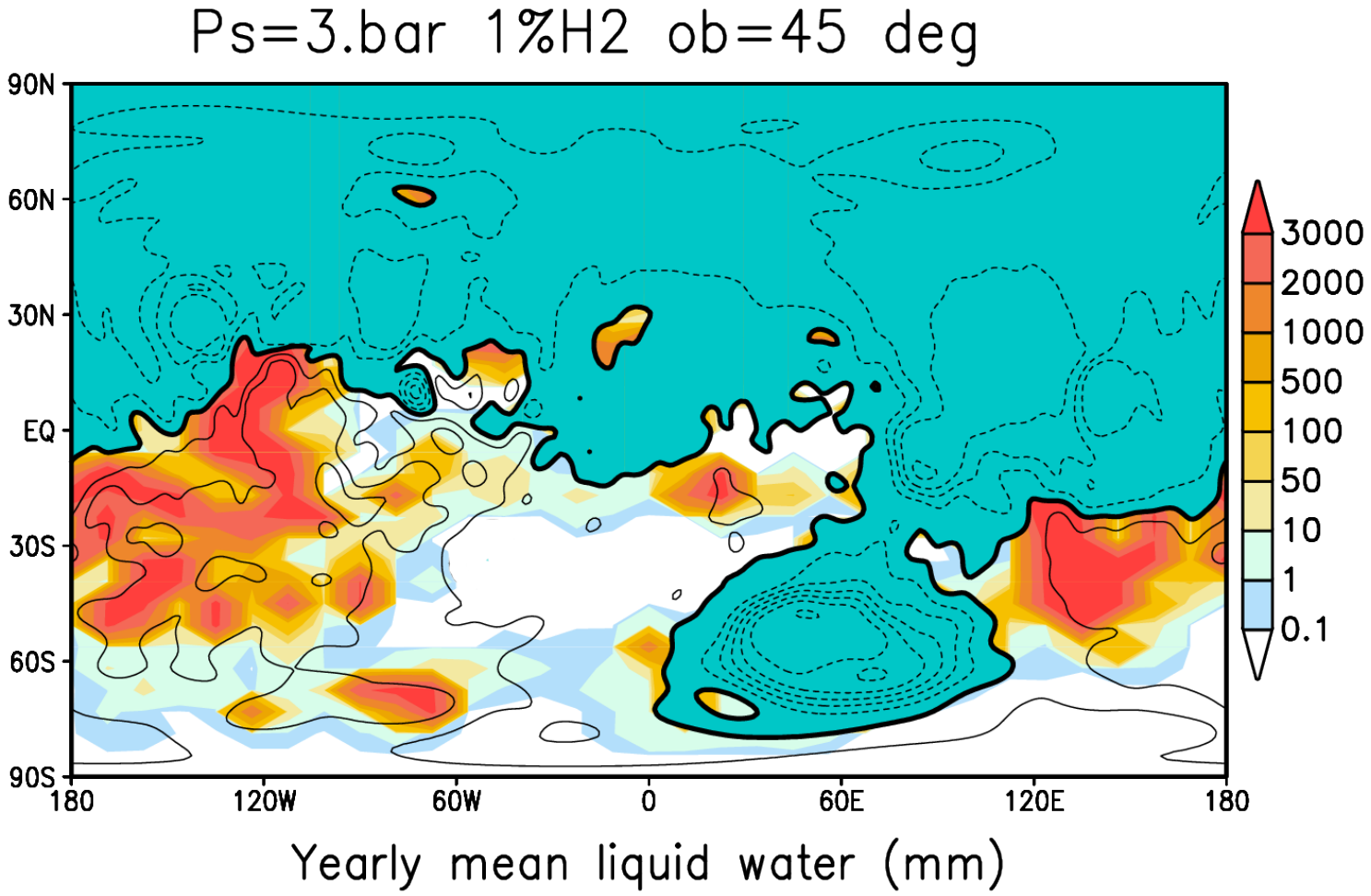
Annual rain (mm)



Global mean <Tsurf> = +13°C

“Ocean” Mars :

Yearly mean liquid water (mm)



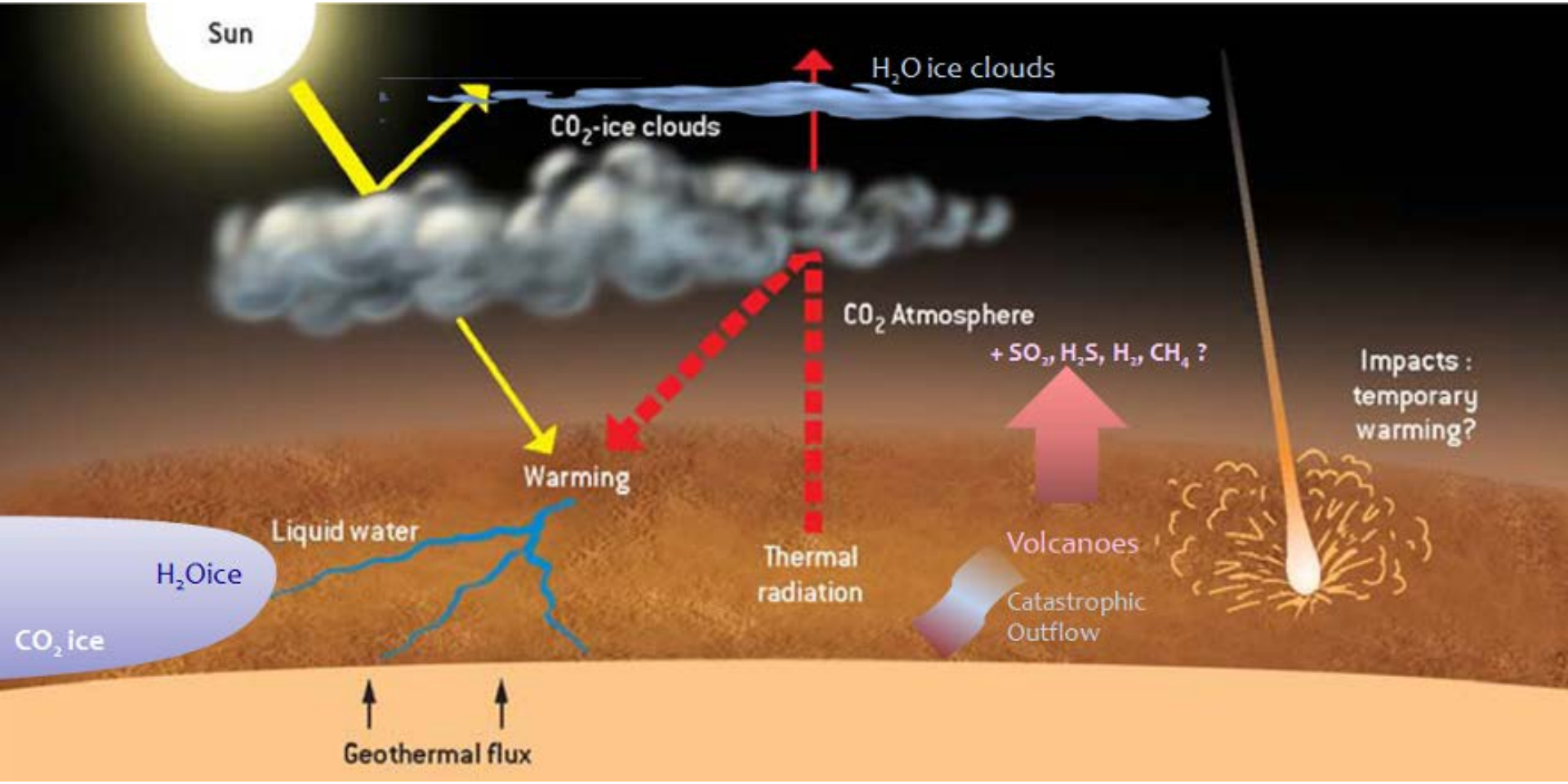
Global mean <Tsurf> = +13°C

The early Mars Climate enigma and atmospheric escape:

- The $671 million dollars enigma: How much CO2 escaped from Mars in the past 3.9 billion years ?

- Could Mars have accumulated up to 30 mbar of hydrogen sometime during its history ?

Thank you !


Sun
H_2O ice clouds
CO_2-ice clouds
CO_2 Atmosphere
+ SO_2, H_2S, H_2, CH_4 ?
Impacts : temporary warming?
Warming
Liquid water
H_2Oice
CO_2 ice
Thermal radiation
Volcanoes
Catastrophic Outflow
Geothermal flux