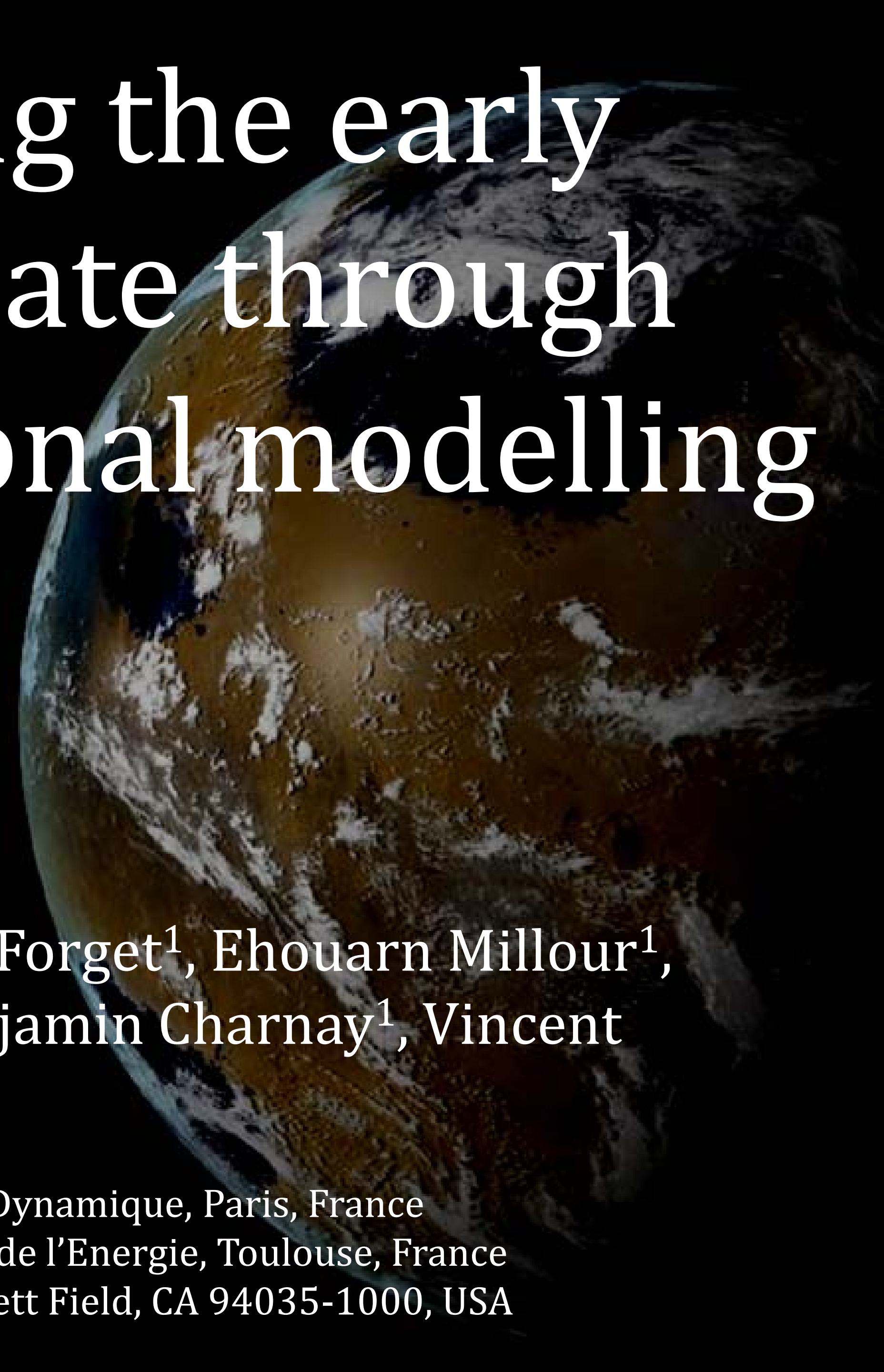
Investigating the early Martian climate through three-dimensional modelling



Robin Wordsworth[1], François Forget[1], Ehouarn Millour[1], Jean-Baptiste Madeleine[1], Benjamin Charnay[1], Vincent Eymet[2] and Bob Haberle[3]

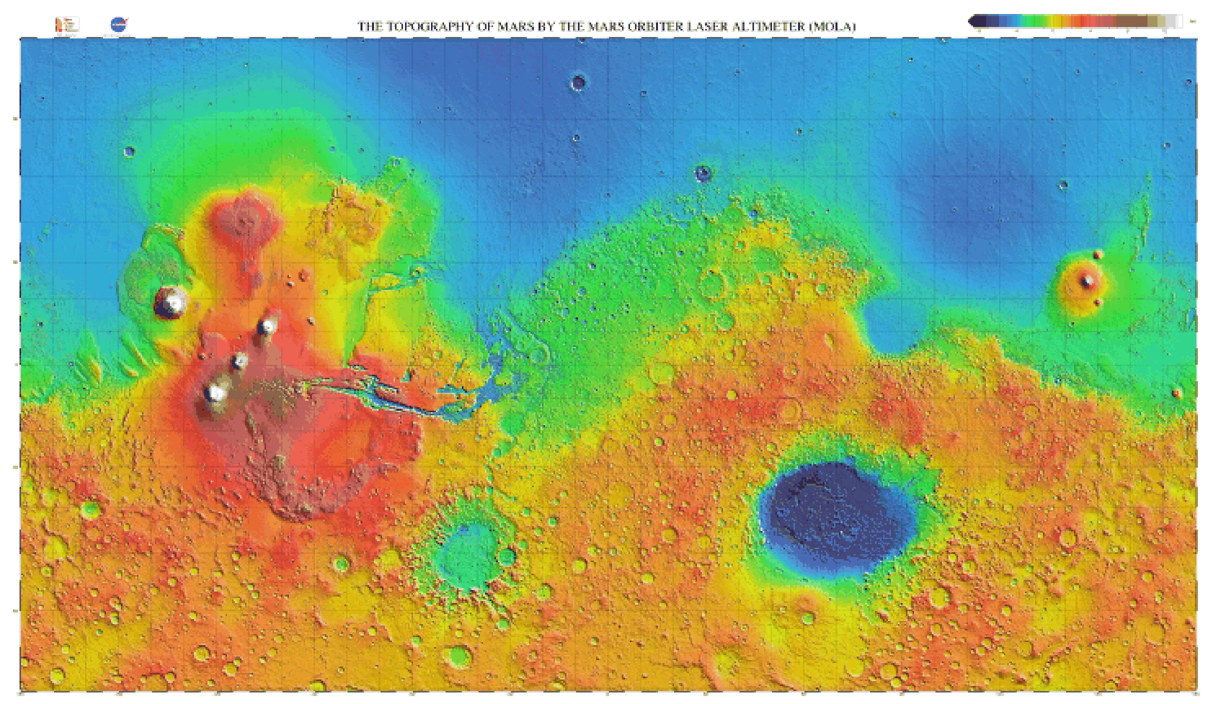
[1]Laboratoire de Meteorologie Dynamique, Paris, France
[2]Laboratoire Plasma et Conversion de l'Energie, Toulouse, France
[3]NASA/Ames Research Center, Moffett Field, CA 94035-1000, USA

Talk Overview

- Background / observational evidence
- Description of our climate model
- Spectral modelling improvements
- Dry (pure CO_2) simulations
- Simulations with a water cycle
- Conclusions
- Implications for exoplanet habitability?

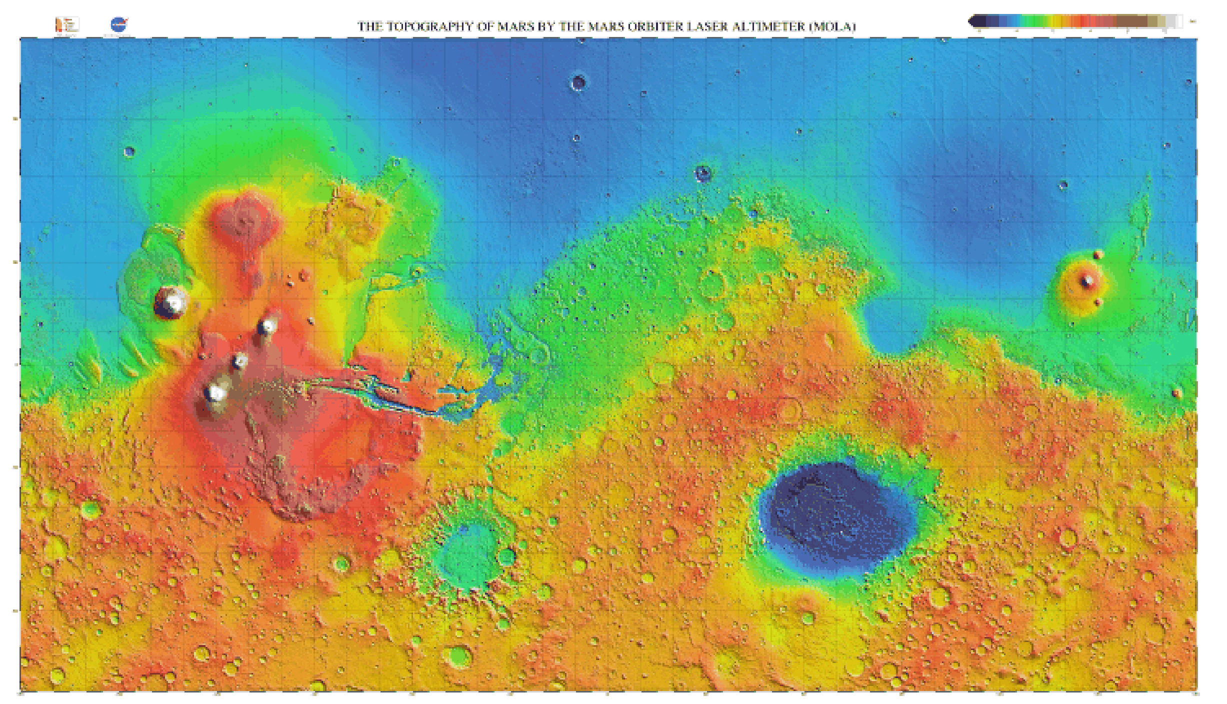
The basics

- ~1.8 GYa → Today: AMAZONIAN ERA
  - Dry, cold, global dust cycles. No surface liquid water.



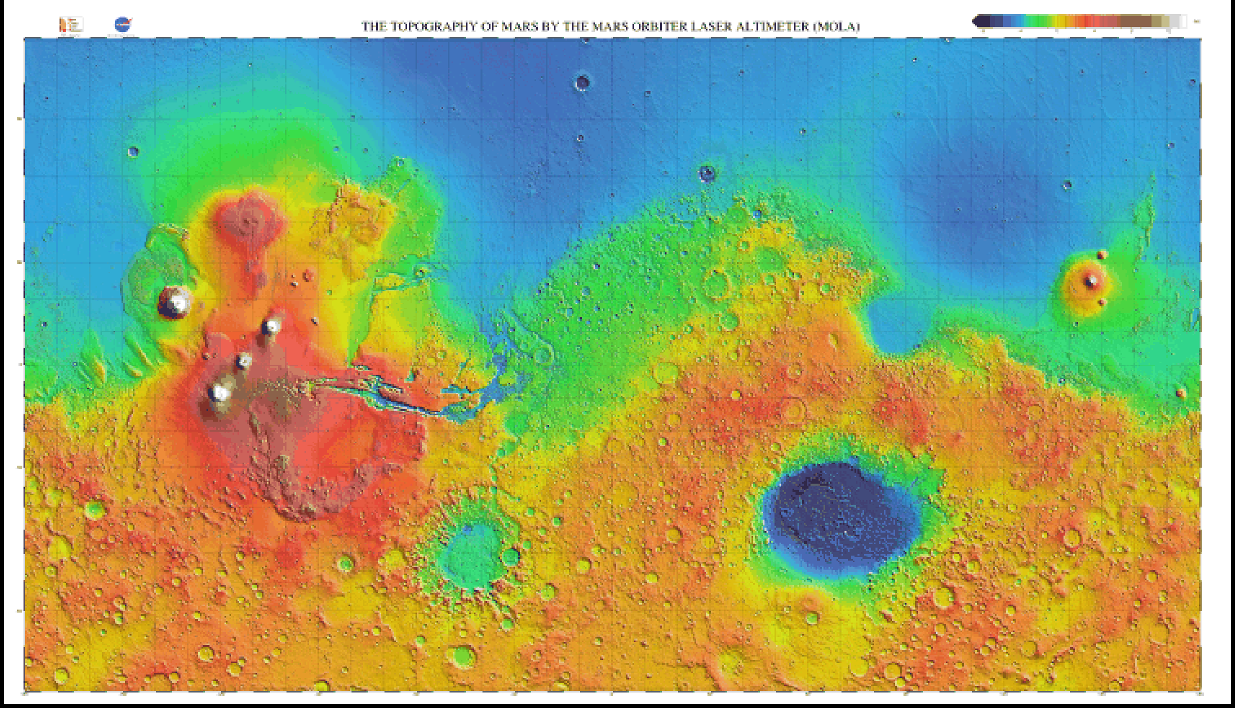
The basics

- ~1.8 GYa → Today: AMAZONIAN ERA
  - Dry, cold, global dust cycles. No surface liquid water.
- ~3.5 GYa → ~1.8 GYa: HESPERIAN ERA
  - Intermittent catastrophic flooding, vulcanism



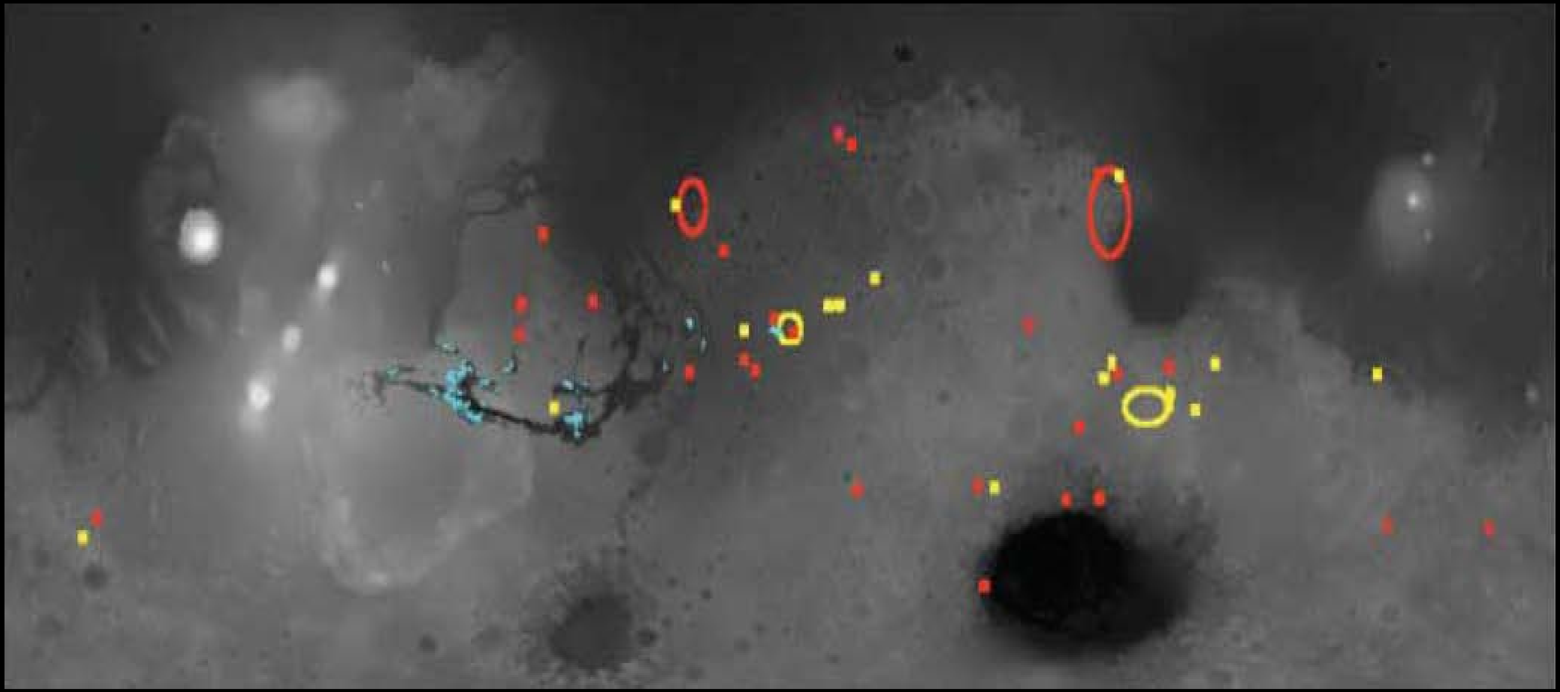
The basics

- More than 3.5 GYa: NOACHIAN ERA
  - Origin of north / south asymmetry
  - Formation of Tharsis and largest craters
  - Frequent flooding, valley networks near end of the epoch



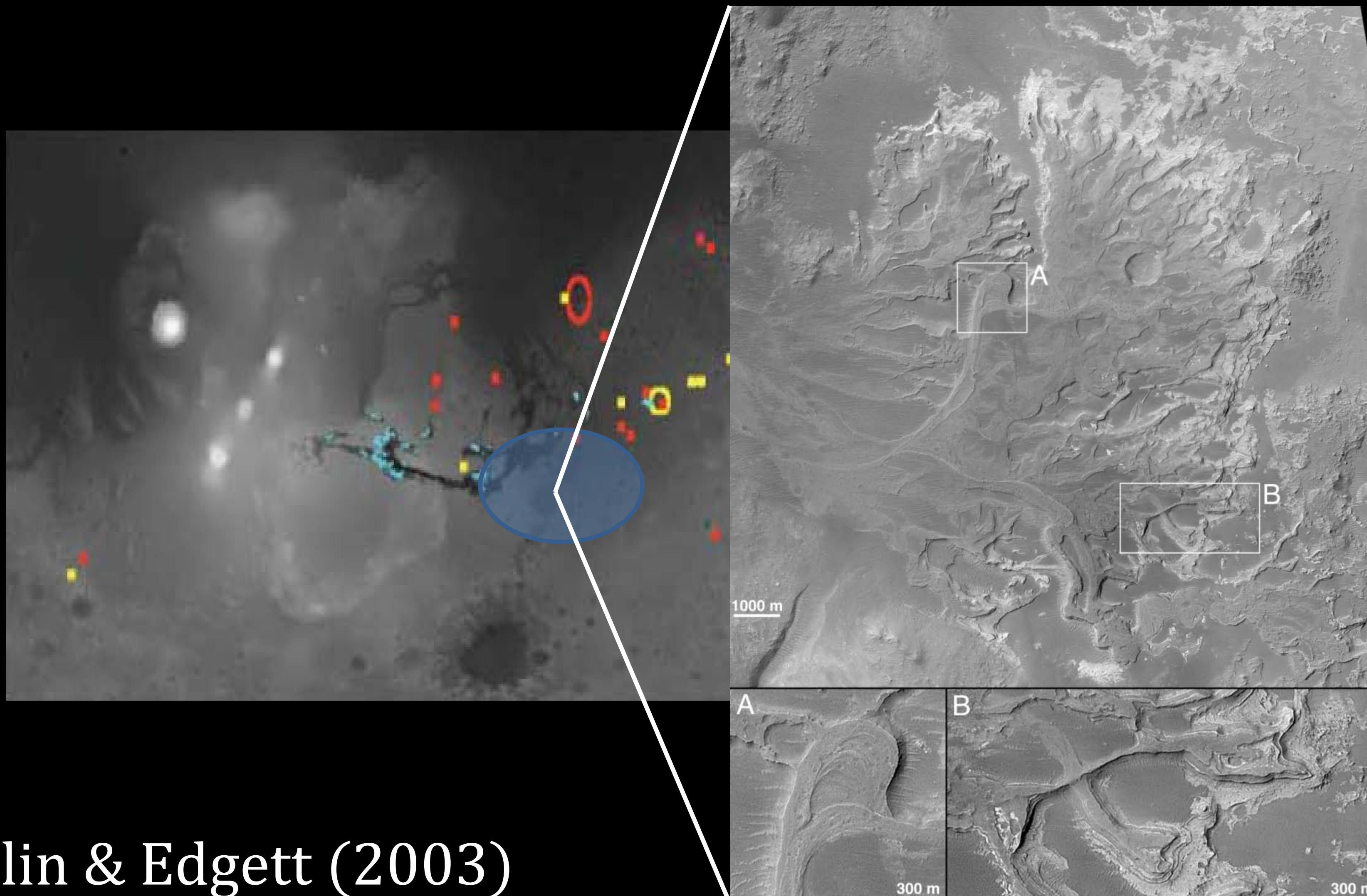
Observational background

- Bibring et al. (2006)



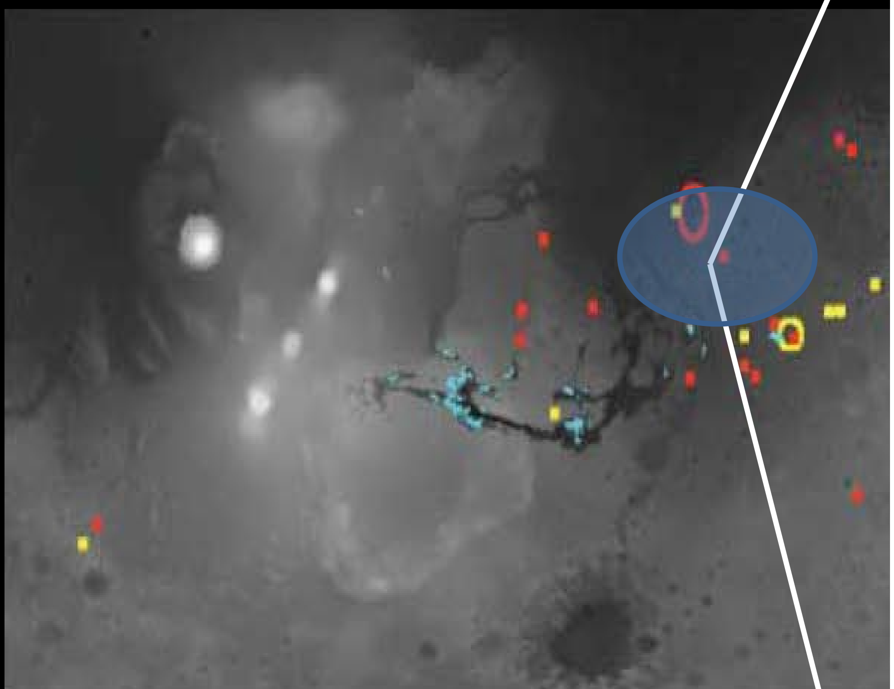
- OMEGA instrument, Mars Express
- Phyllosilicates suggest long-term aqueous alteration

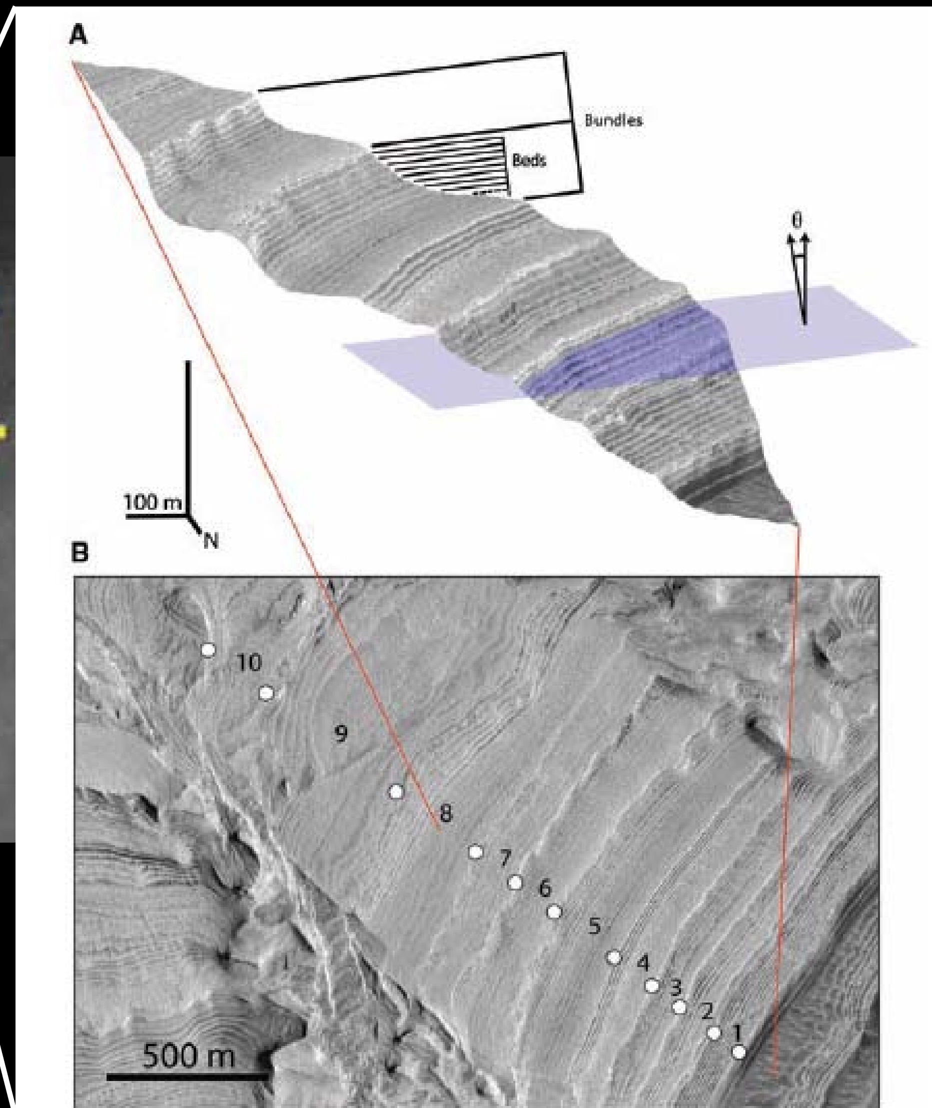
Evidence of persistent flow



- Malin & Edgett (2003)

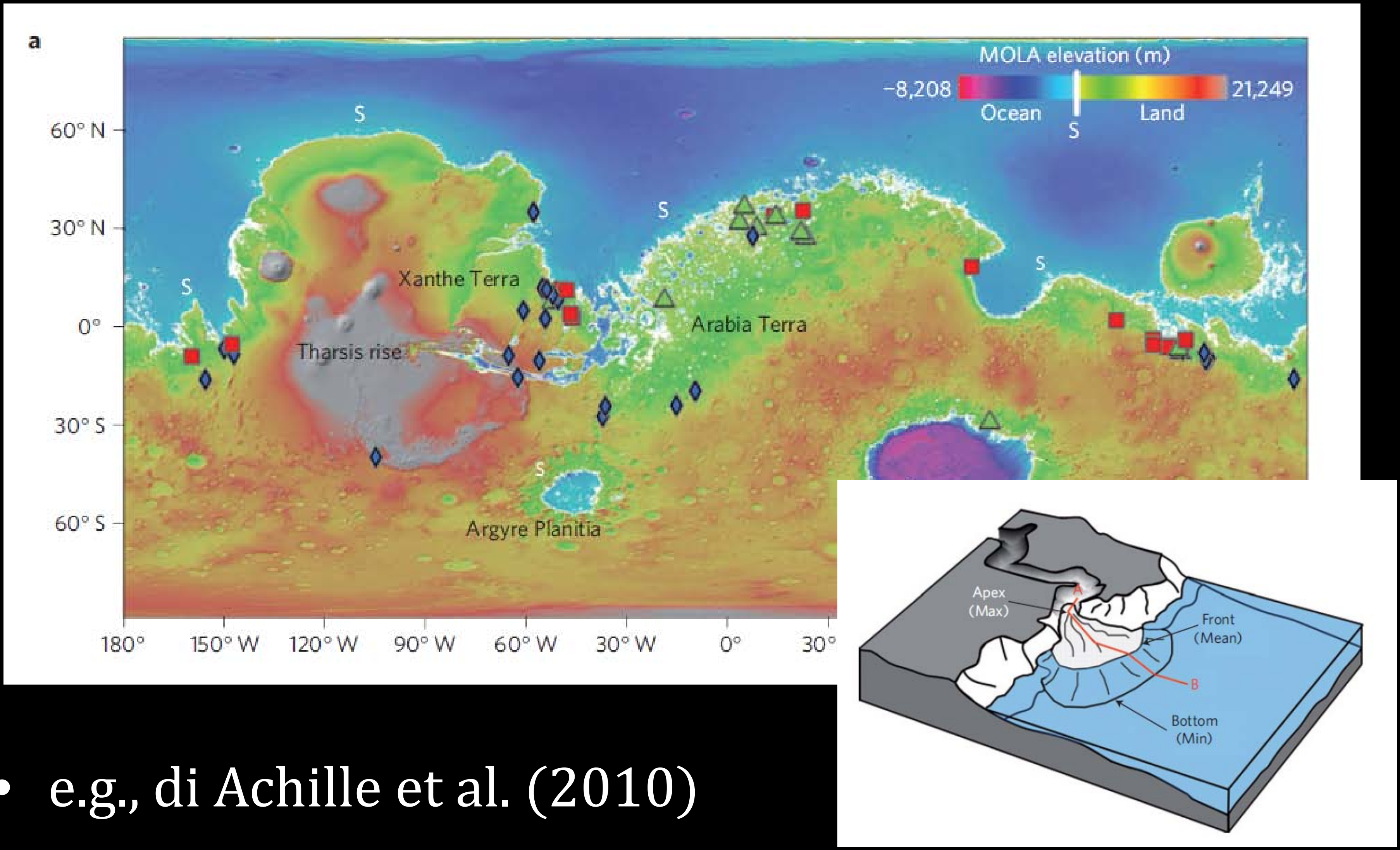
Evidence of episodic deposition





- Lewis et al. (2008)

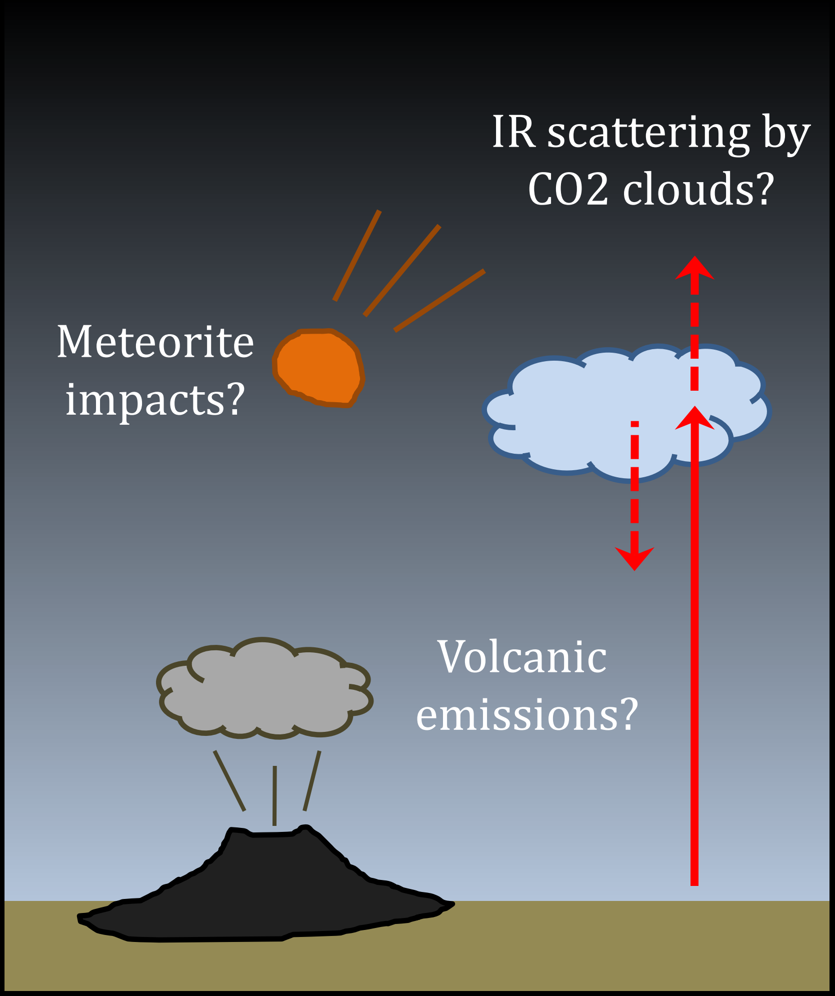
Evidence for an ancient northern ocean?



- e.g., di Achille et al. (2010)

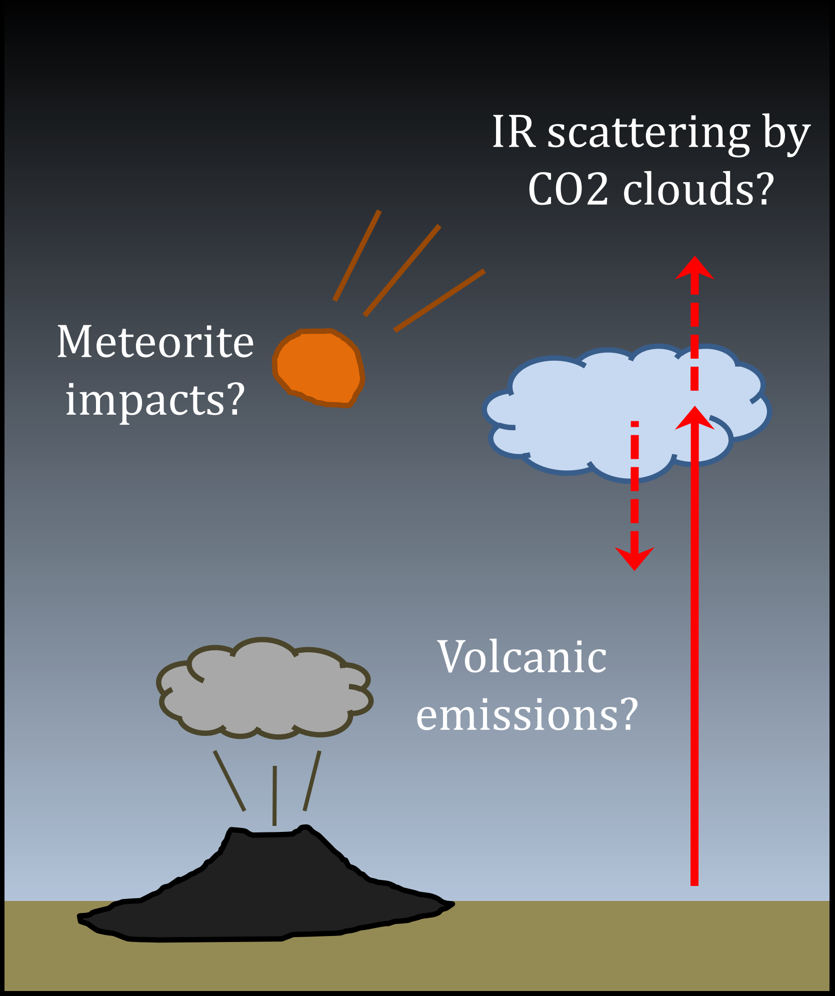
Theoretical background

- Early Sun was weaker by ~25%...
- and CO_2 condenses in cold, dense atmospheres (Kasting 1991)
- This poses a severe challenge to climate modellers



Theoretical background

- Many solutions to the problem have been proposed, but all of them have drawbacks
- Some examples:
  - Segura et al. (2002)
  - Havely et al. (2007)
  - Forget & Pierrehumbert (1997)

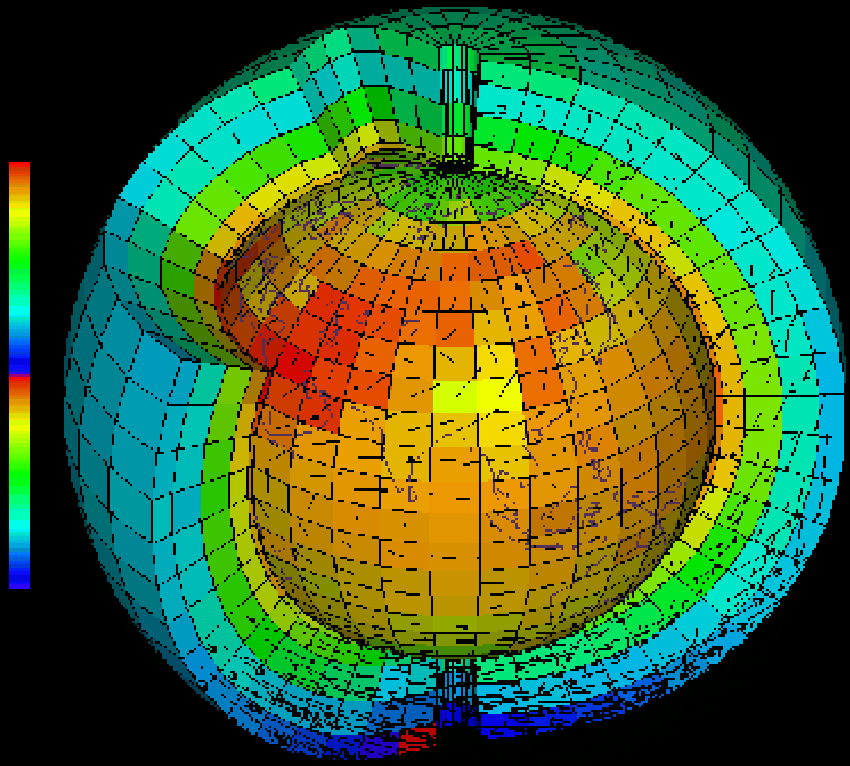


Our ‘simple’ modelling approach

- Use a bare minimum of atmospheric ingredients (CO2, H2O)
- Describe the key physical processes as accurately as possible (e.g. dense CO2 radiative transfer, clouds)
- Describe the early water cycle in 3D for the first time
- Leads inevitably to a complicated model (many feedbacks)

A 3D climate model of Early Mars

- We use the new LMDZ general planet simulator
- Fluid dynamical GCM core
- Fixed surface albedo, thermal inertia
- Present-day martian topography
- Variable orbital parameters (constrained by Laskar et al. 2004)
- Range of atmospheric pressures (0.5 to 5 bar)



Generalised tracer / radiative transfer scheme

- Correlated-*k* for the gaseous absorption
- Toon et al. (1989) two-stream method for the aerosols
- Mie theory for aerosol scattering properties
- Scheme works for any combination of gases and aerosols for which optical data exists

$$n_i,\, n_r,\, f(r_0) \rightarrow Q_{ext},\, \omega,\, g$$

$$\frac{\partial F_i^+}{\partial \tau_i} = \gamma_i^a F_i^+ - \gamma_i^b F_i^- - S_i^+$$

$$\frac{\partial F_i^-}{\partial \tau_i} = \gamma_i^b F_i^+ - \gamma_i^a F_i^- + S_i^+$$

$$\begin{aligned} \tau_i &= \frac{1}{\nu_2 - \nu_1} \int_{\nu_1}^{\nu_2} exp(-k_i[\nu]\Delta z_i) d\nu \\ &= \int_0^\infty f(k_i) exp(-k_i \Delta z_i) dk_i \end{aligned}$$

http://code.google.com/p/kspectrum/

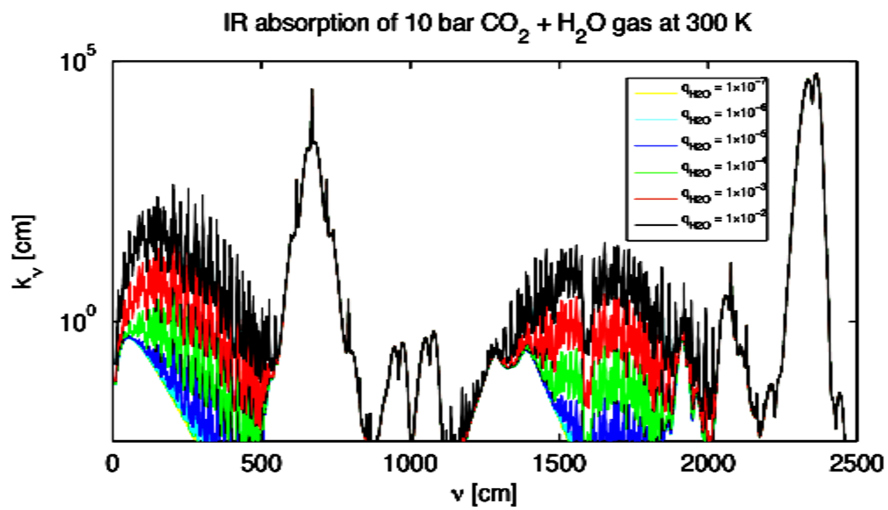
Generalised tracer / radiative transfer scheme

- Correlated-k for the gaseous absorption
- Toon et al. (1989) two-stream method for the aerosols
- Mie theory for aerosol scattering properties
- Scheme works for any combination of gases and aerosols for which optical data exists

$$n_i,\, n_r,\, f(r_0) \rightarrow Q_{ext},\, \omega,\, g$$

$$\frac{\partial F_i^+}{\partial \tau_i} = \gamma_i^a F_i^+ - \gamma_i^b F_i^- - S_i^+$$

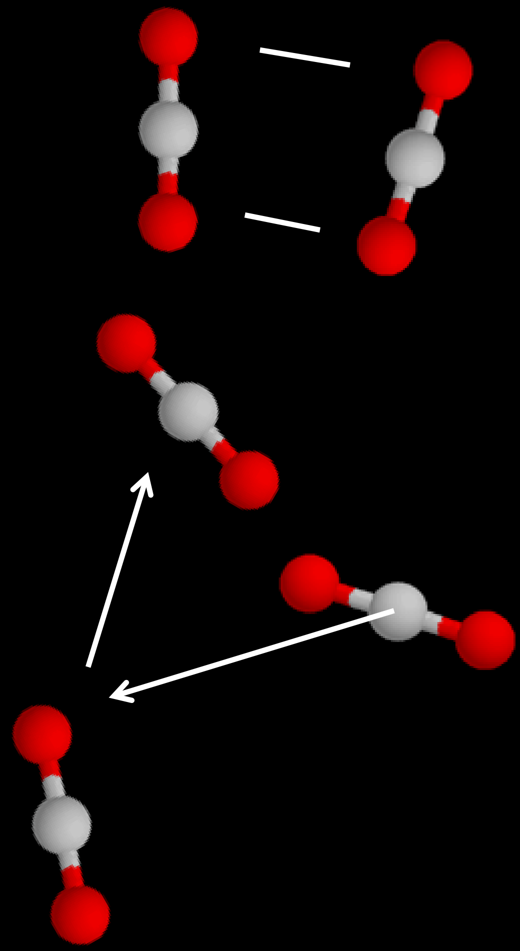
$$\frac{\partial F_i^-}{\partial \tau_i} = \gamma_i^b F_i^+ - \gamma_i^a F_i^- + S_i^+$$



http://code.google.com/p/kspectrum/

Spectral modelling improvements

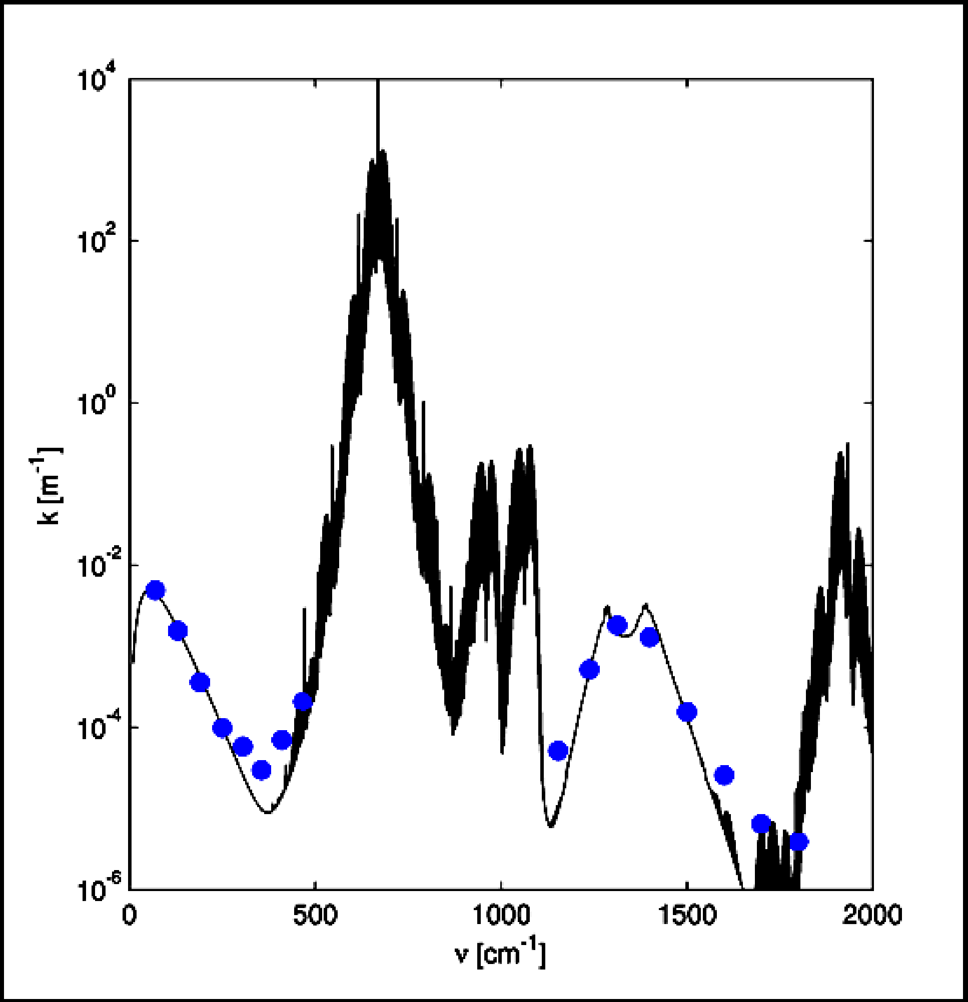
- CO_2 collision-induced absorption (CIA) is a major unknown
- We have produced a new parameterisation of the effect based on the most recent data
- Total CO_2 warming is... reduced!

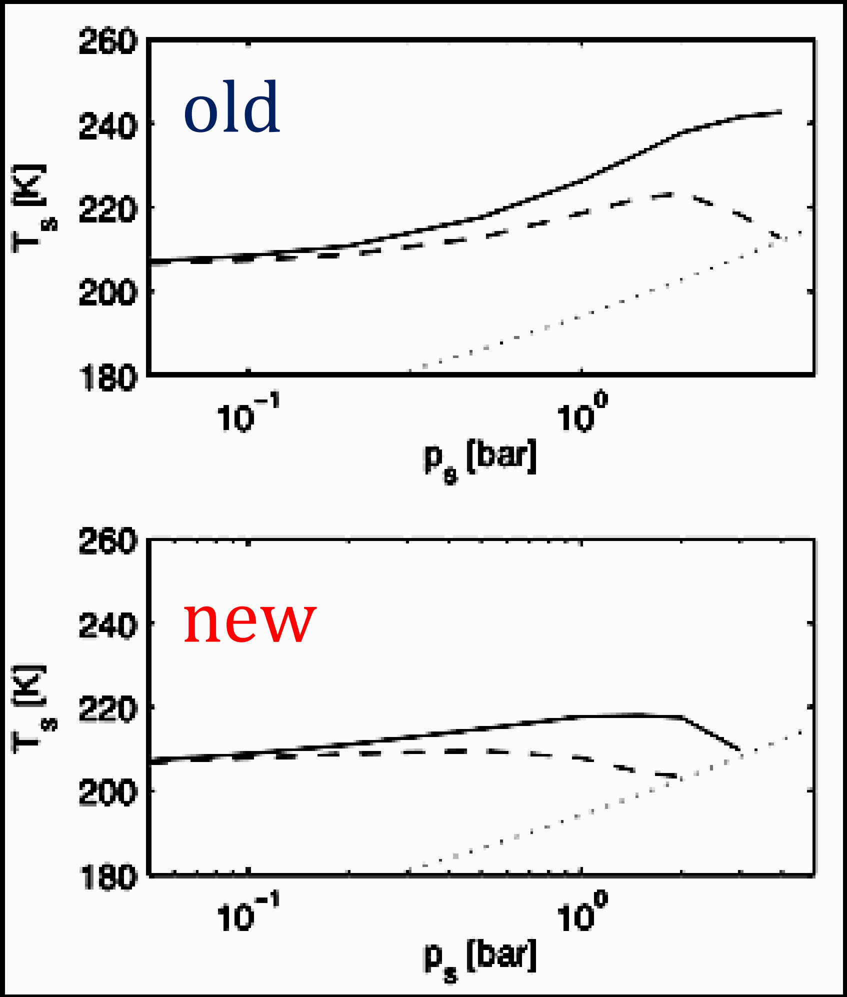


Gruskha & Borysow (1998)

Baranov et al. (2004)

Influence of the CIA on Early Mars



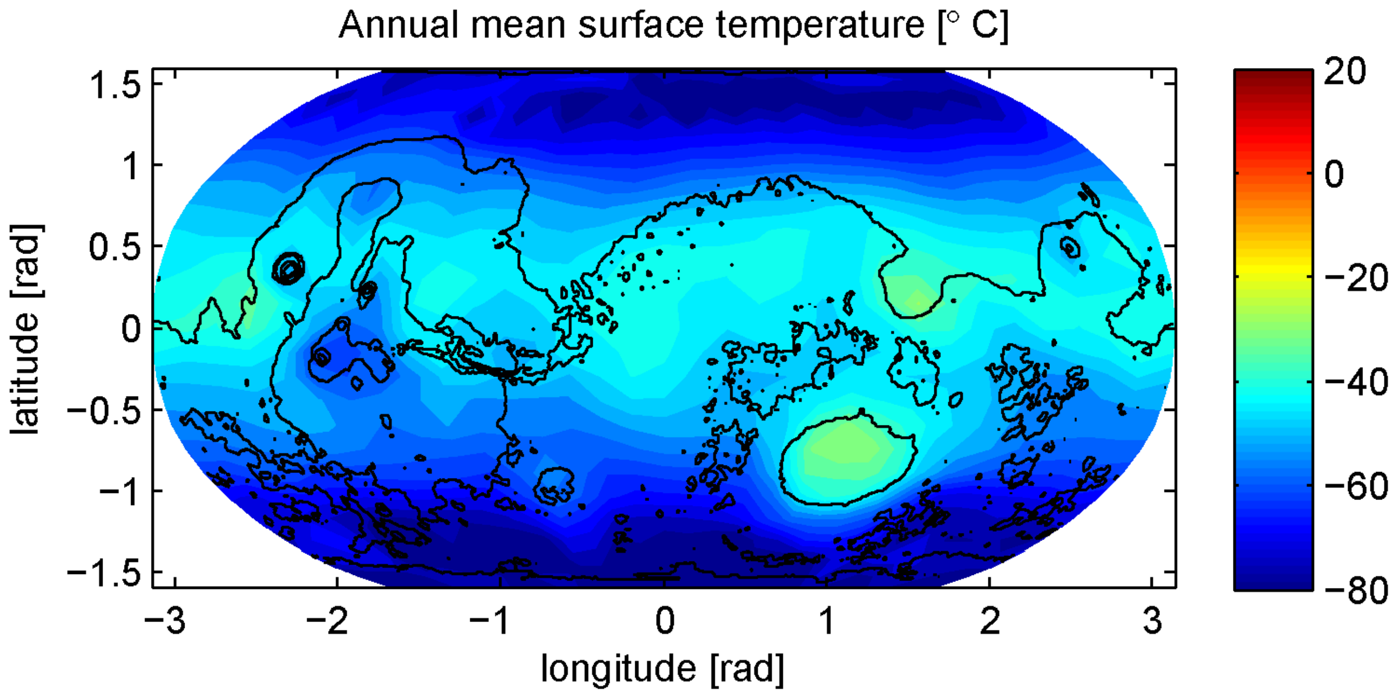


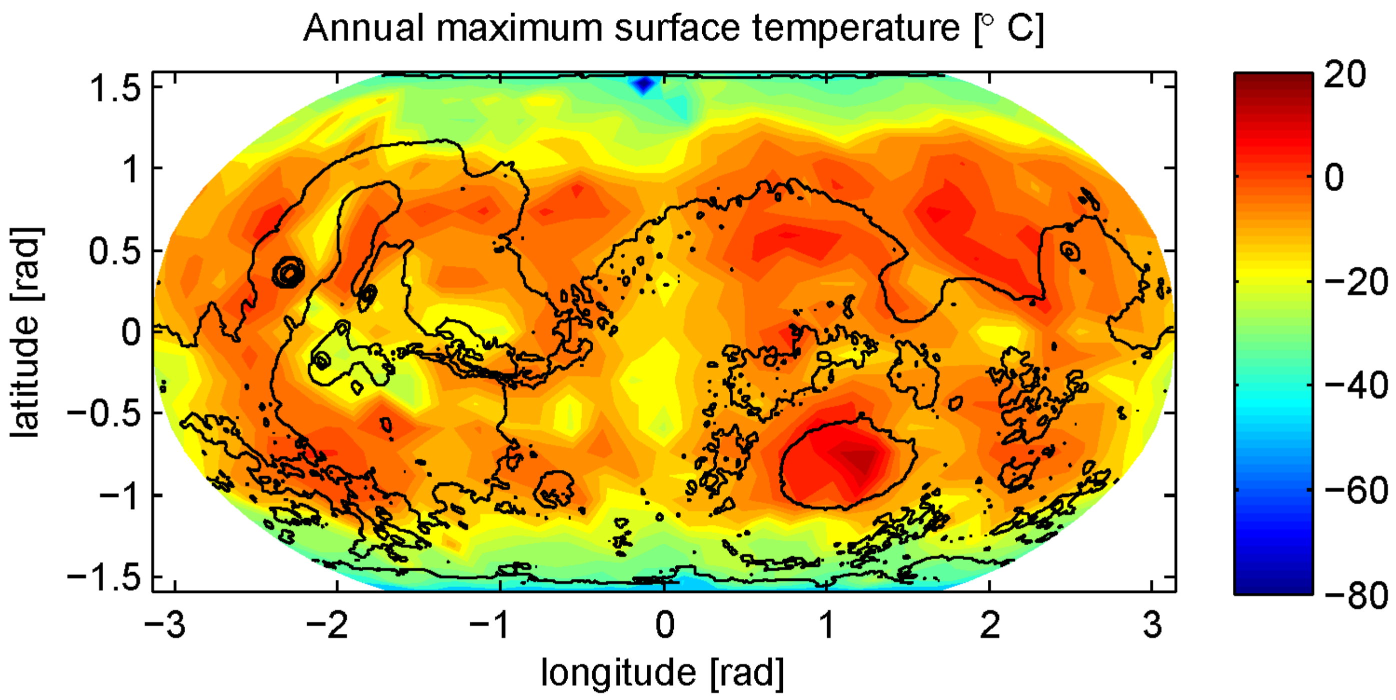
Wordsworth et al. (2010a)

Pure CO_2 results

0.5 bar

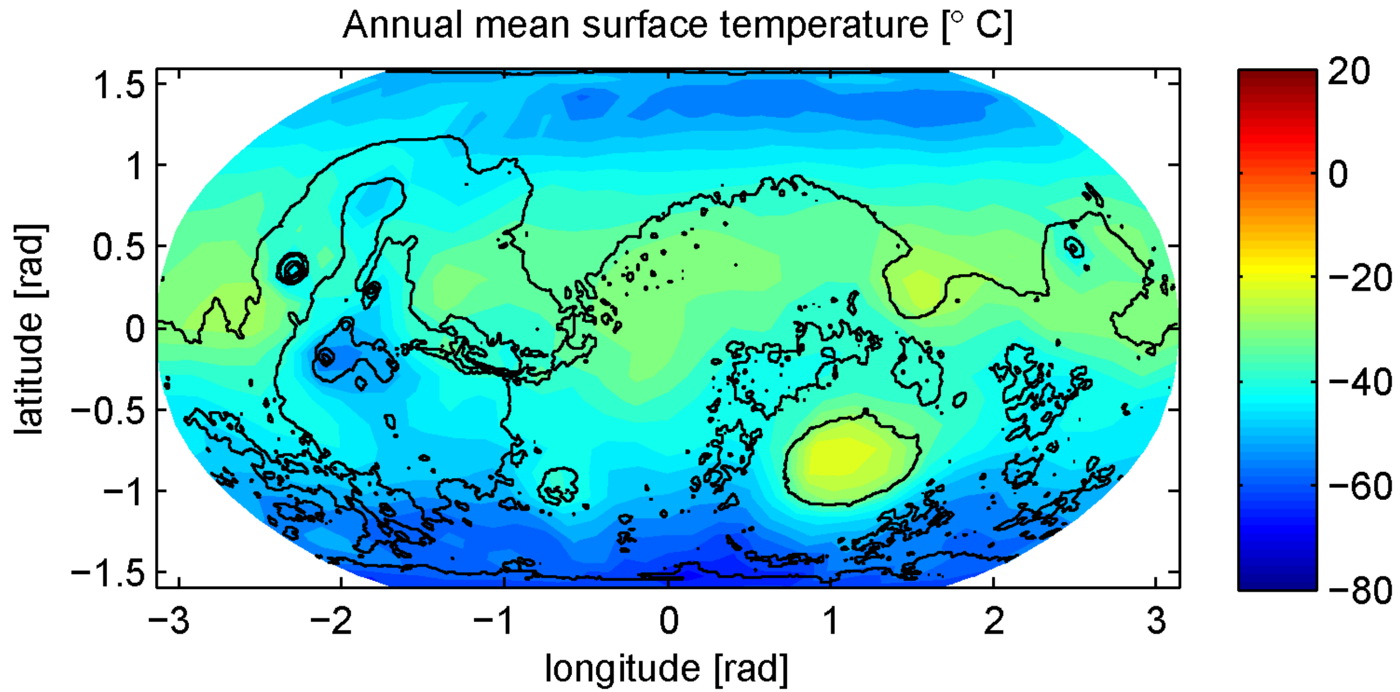
Surface
CO_2 ice

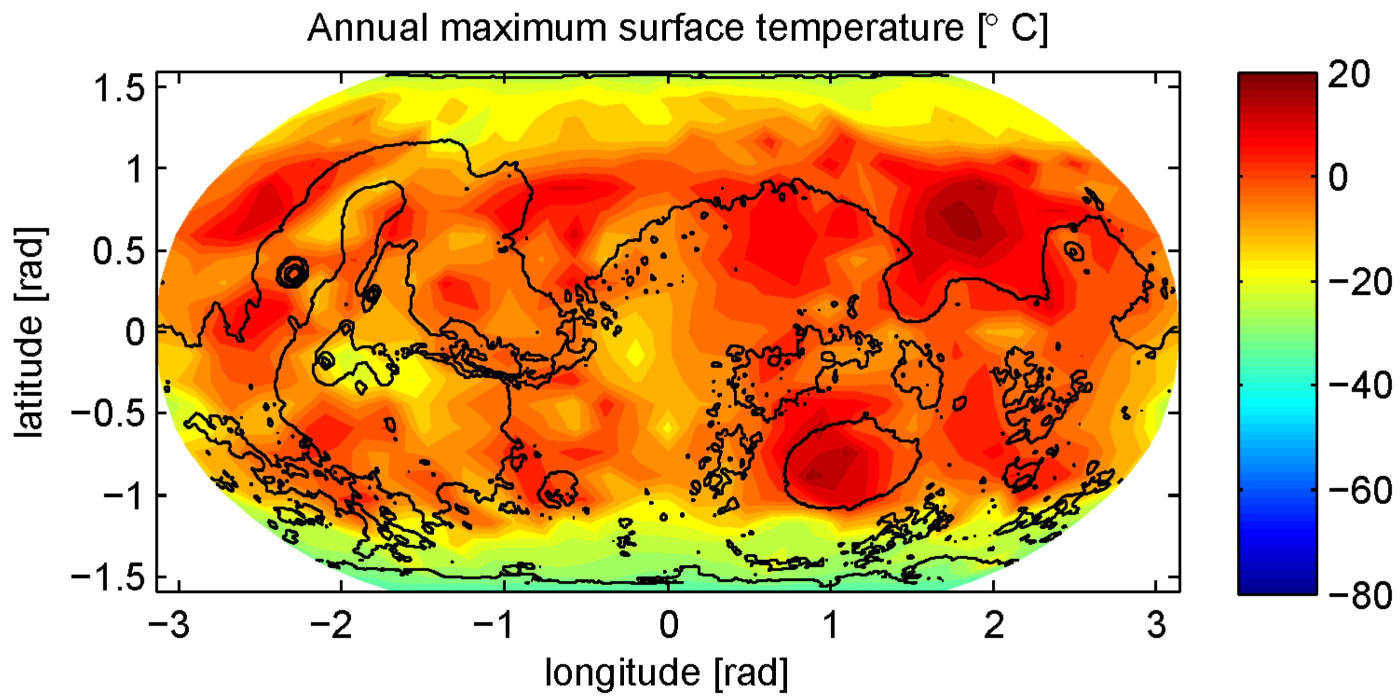




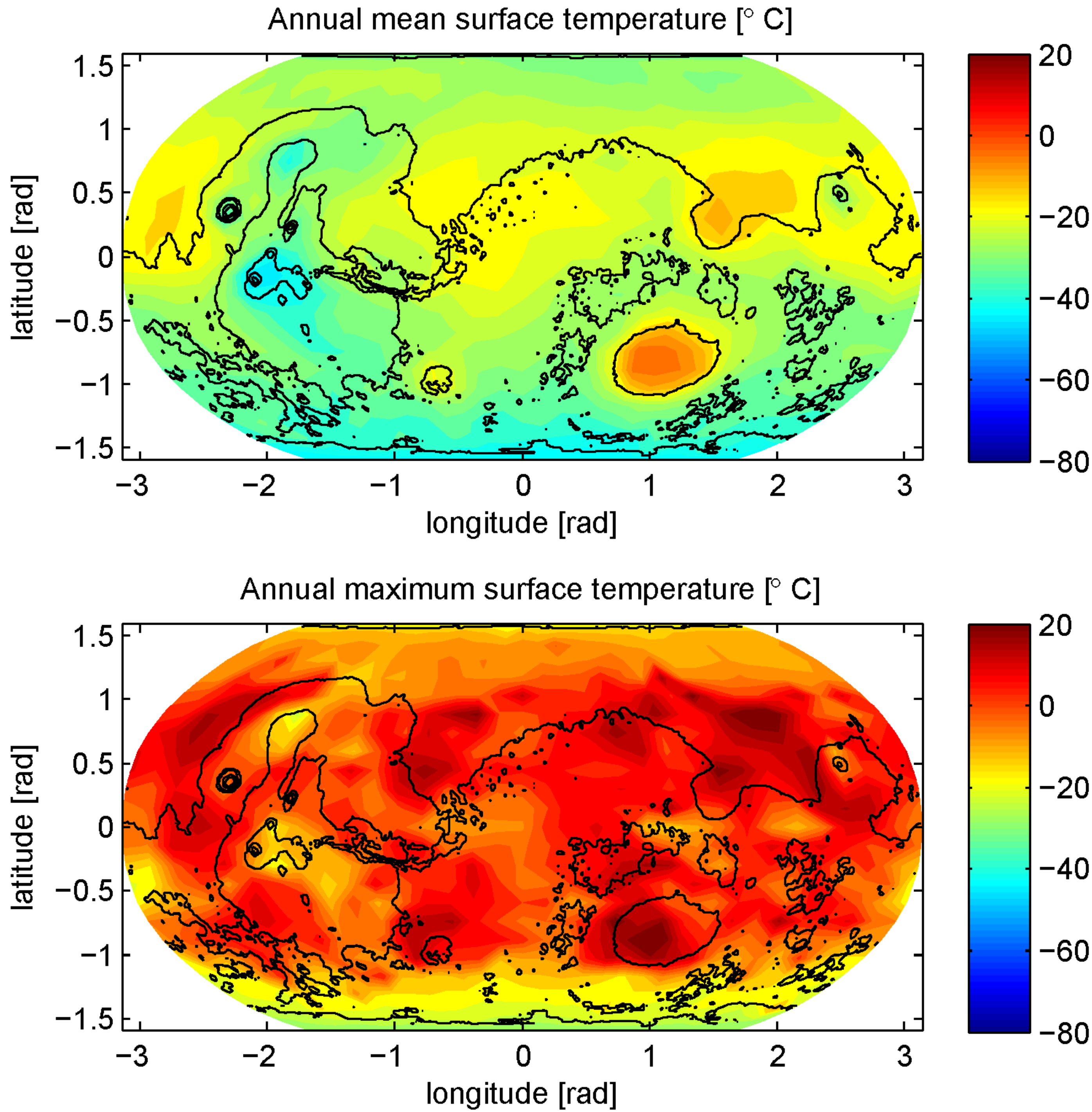
1 bar

Surface
CO2 ice

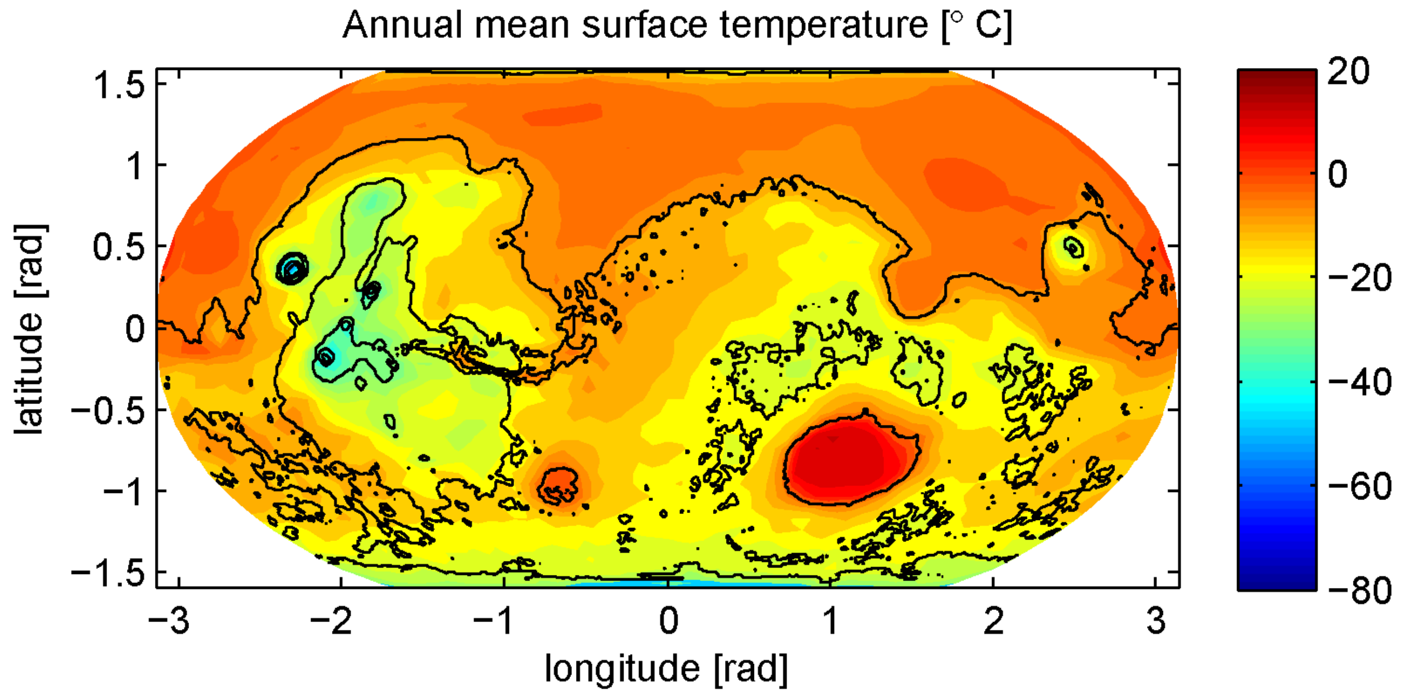


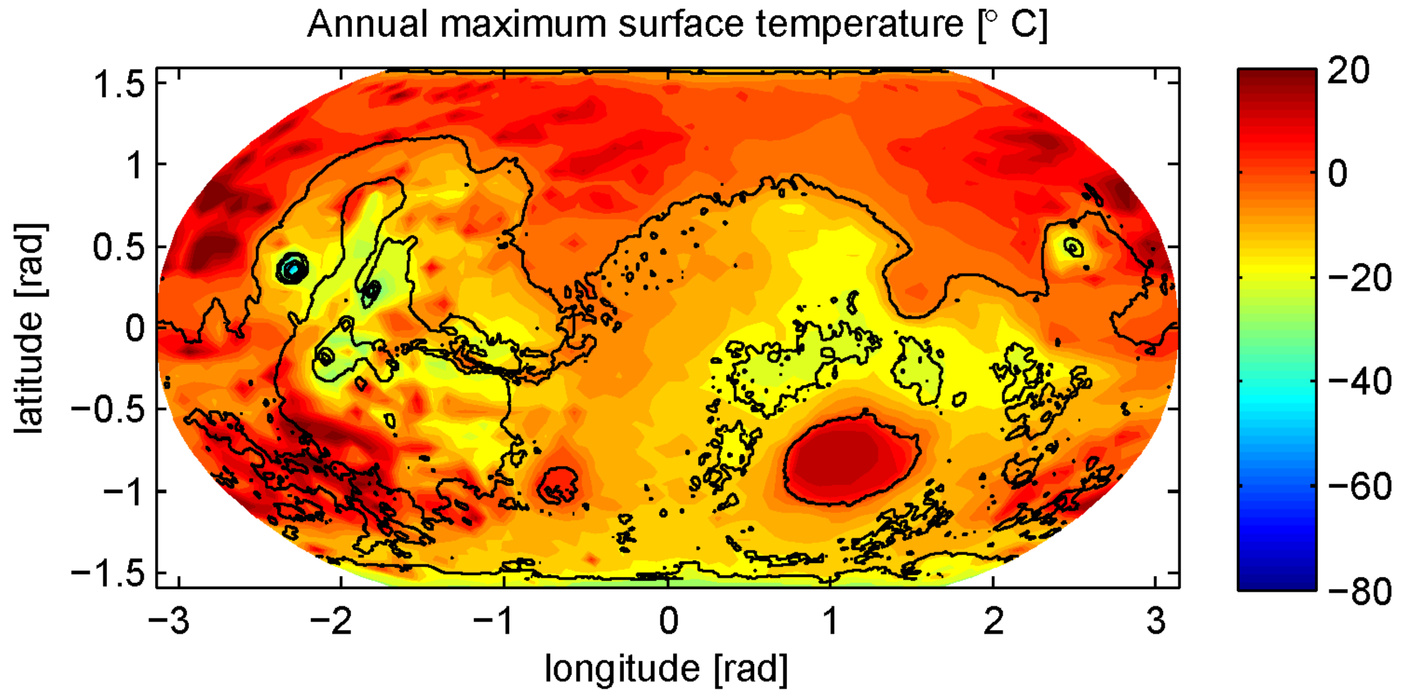


2 bar

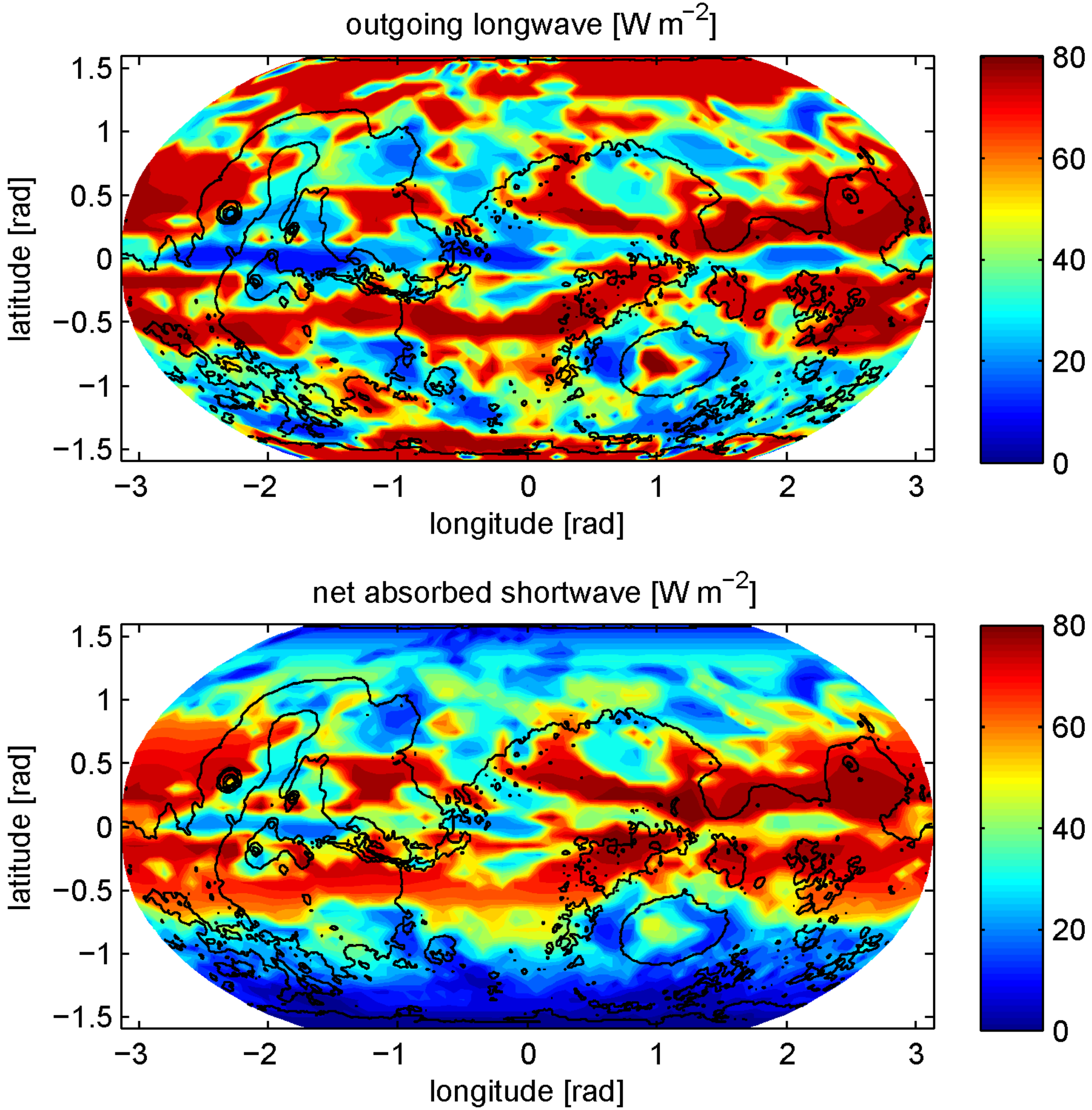

Annual mean surface temperature [° C]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
20
0
−20
−40
−60
−80
Annual maximum surface temperature [° C]
latitude [rad]
longitude [rad]

5 bar


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

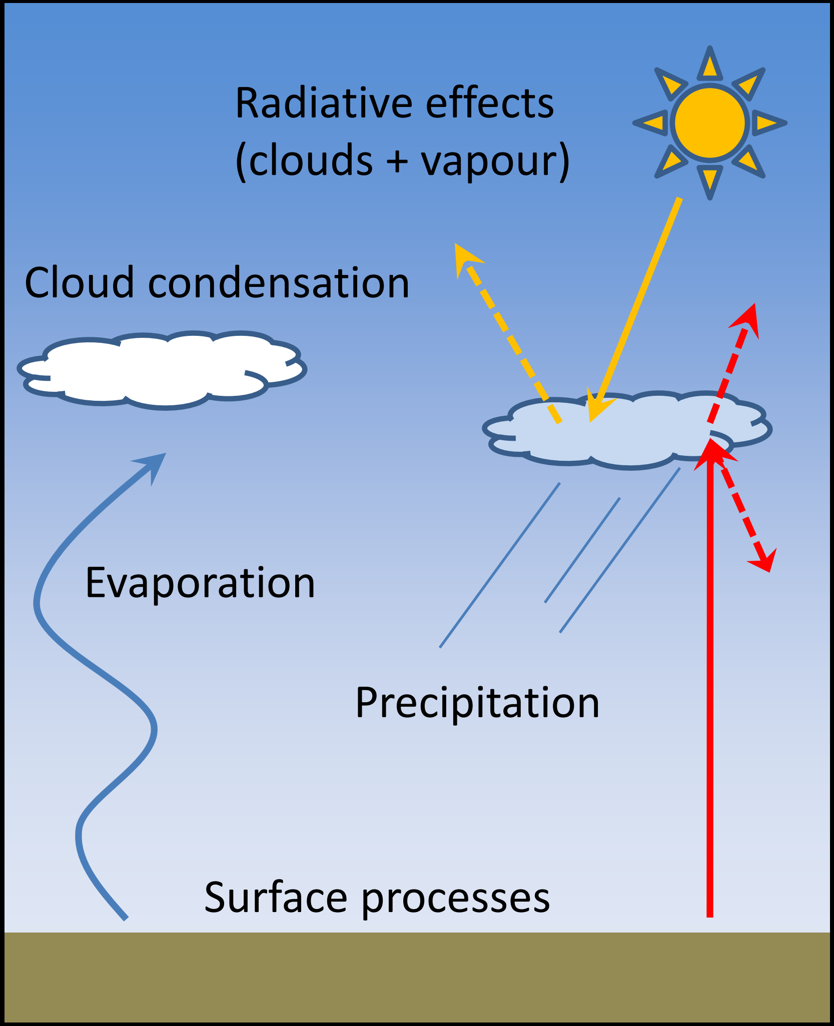

Annual maximum surface temperature [° C]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
20
0
−20
−40
−60
−80

Warming by CO2 clouds

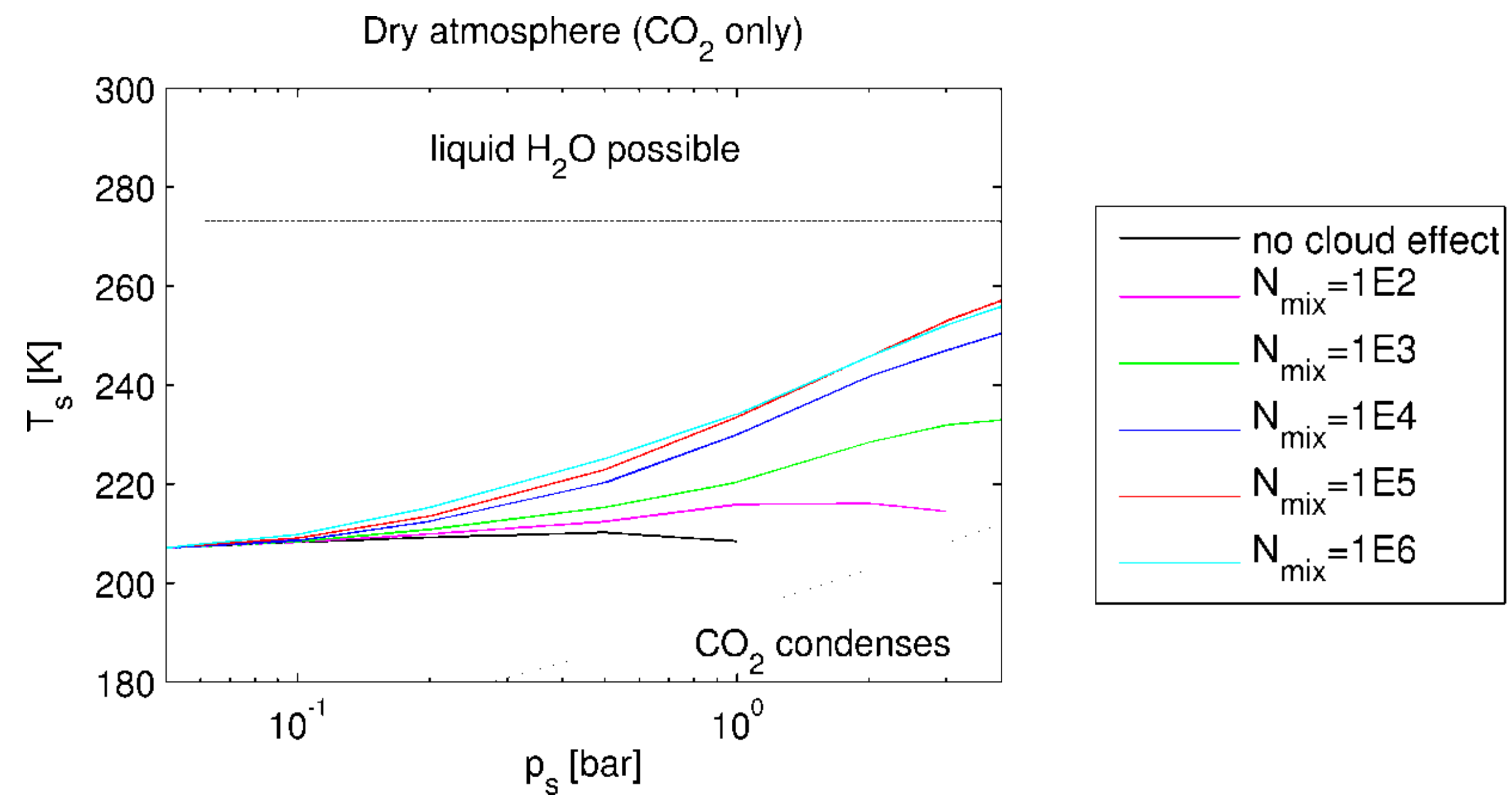


Adding a water cycle

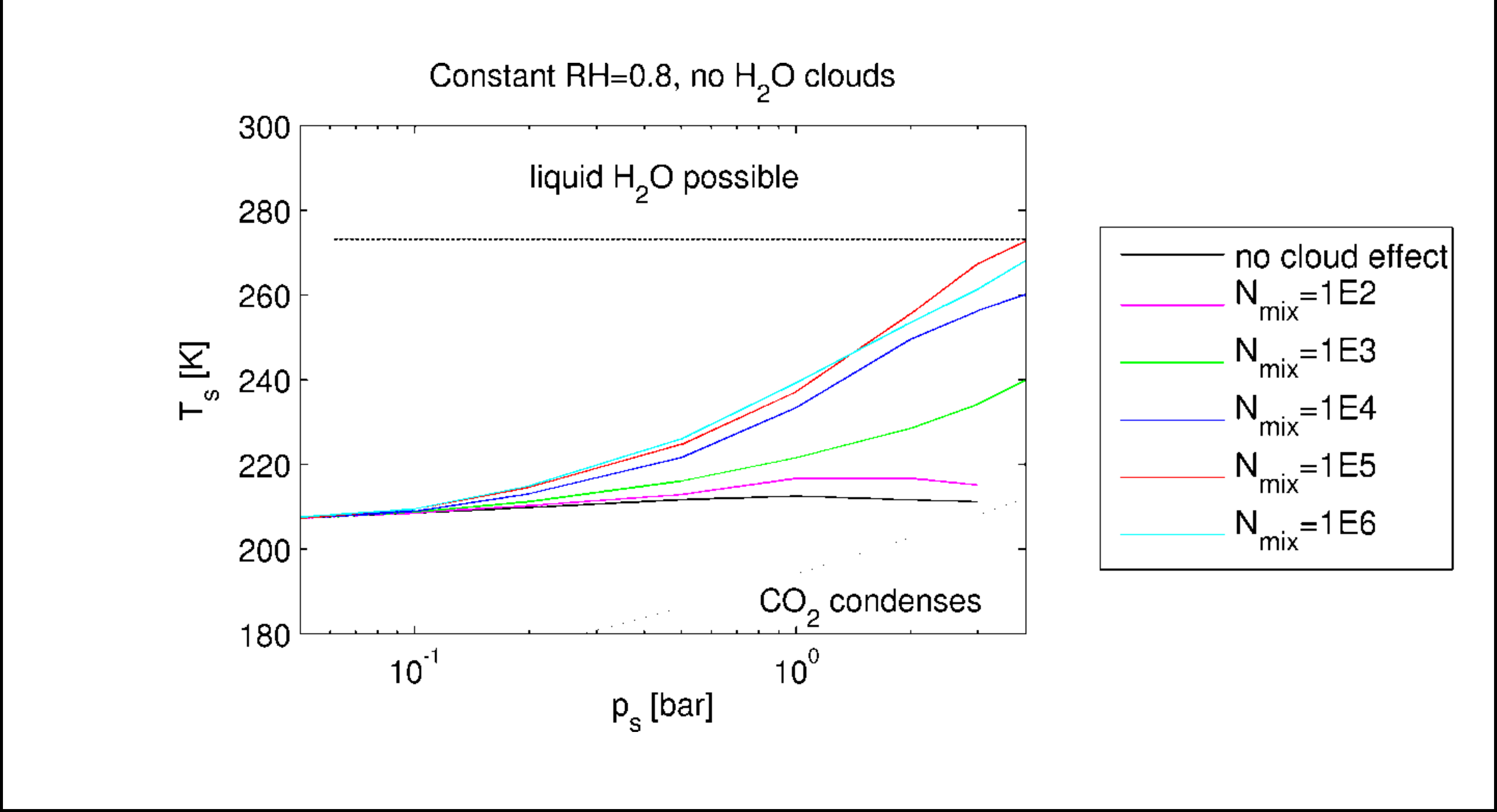
- We include radiative effects of vapour and cloud tracers
- Precipitation microphysics is important (stochastic coalescence vs. Bergeron process)
- Simple surface scheme
- Deep convection neglected



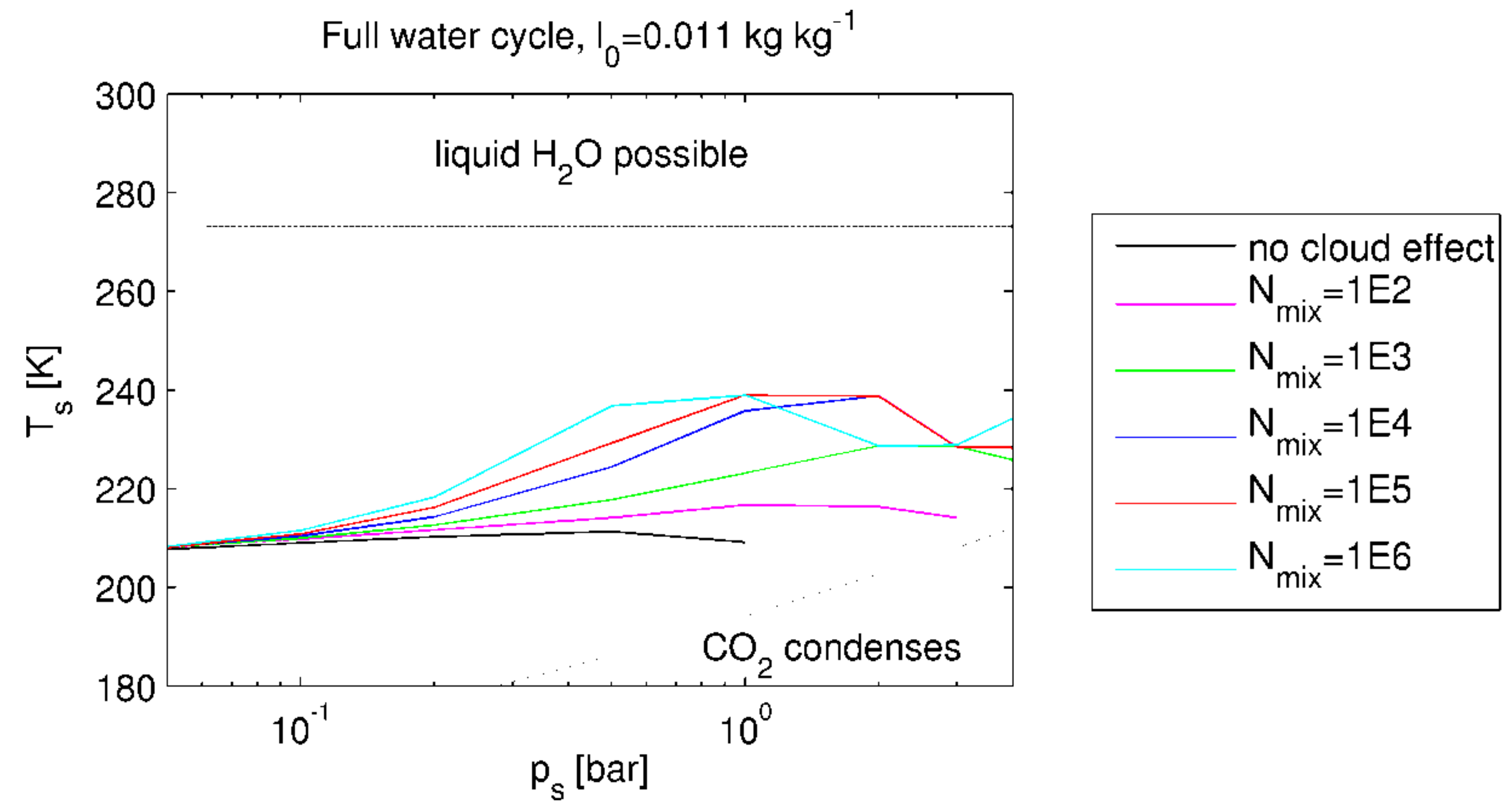
1D globally averaged simulations



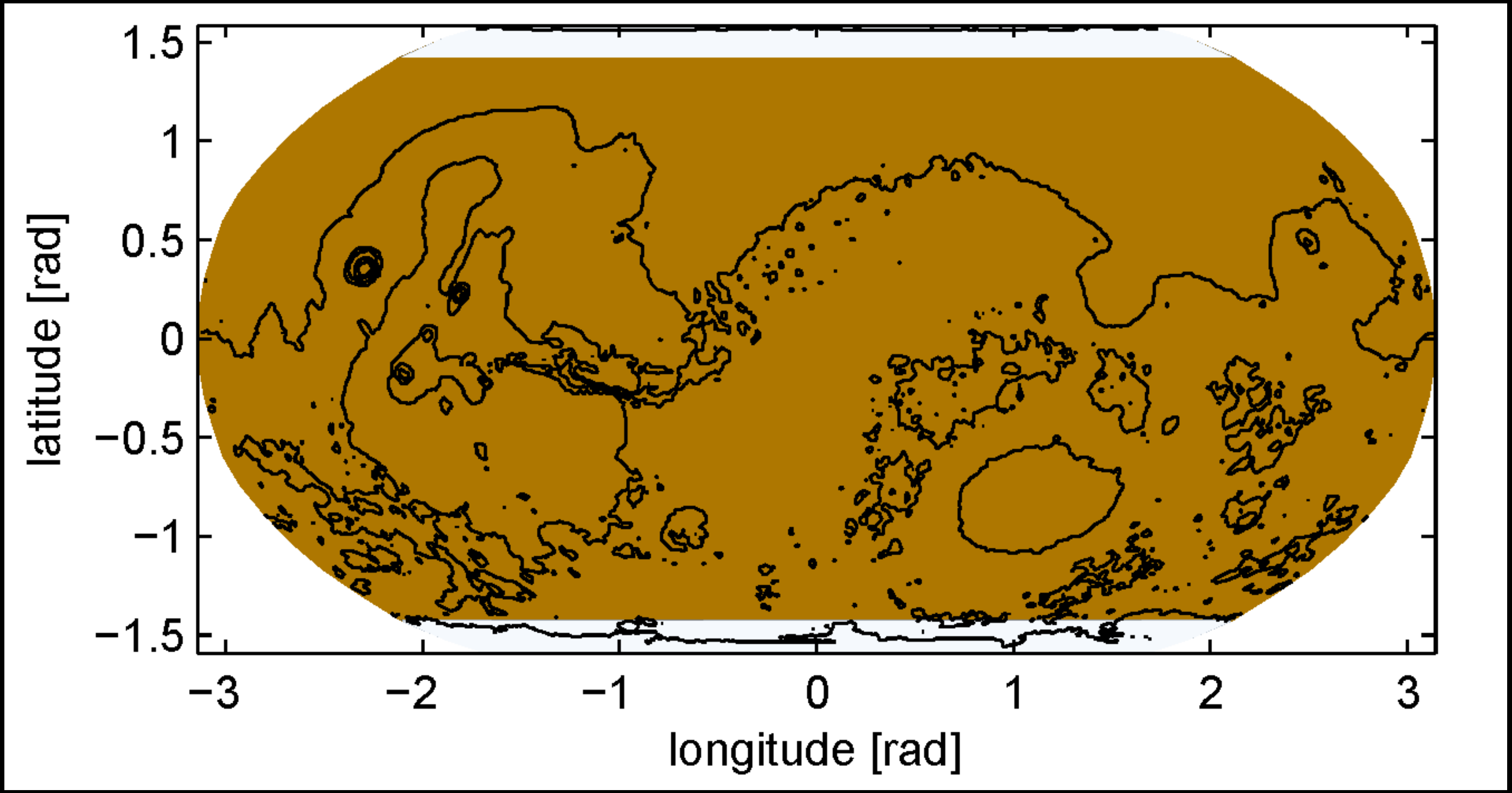
1D globally averaged simulations



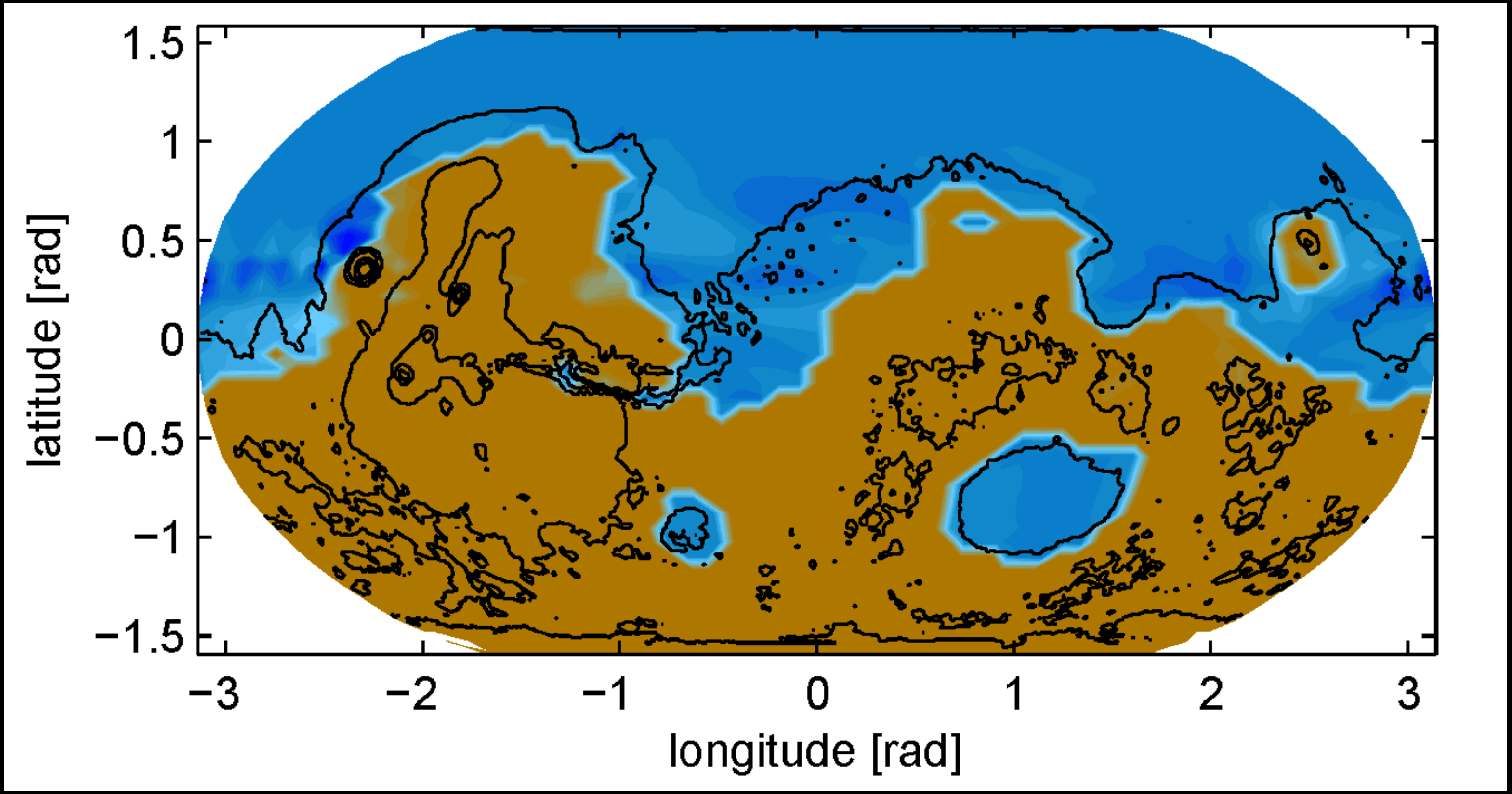
1D globally averaged simulations



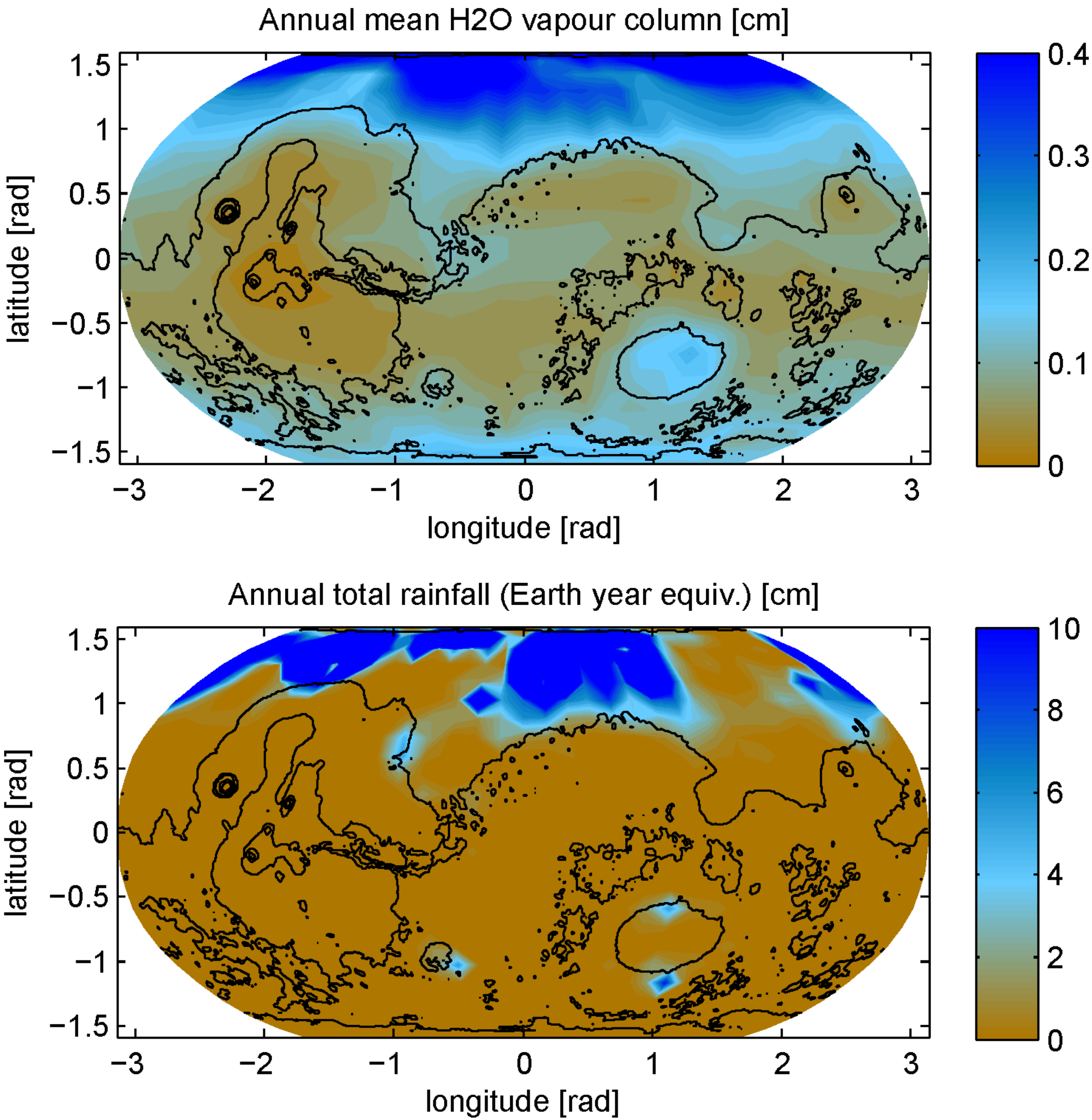
3D initial conditions for H2O



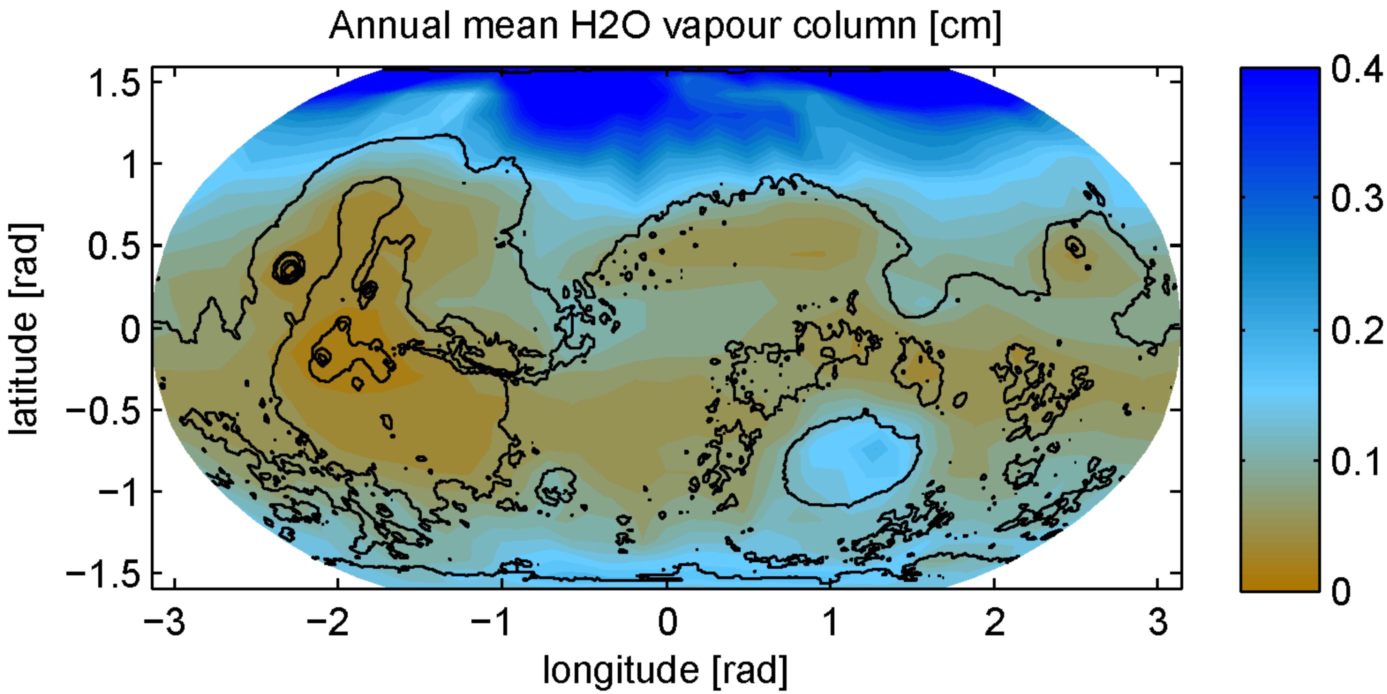
3D initial conditions for H_2O

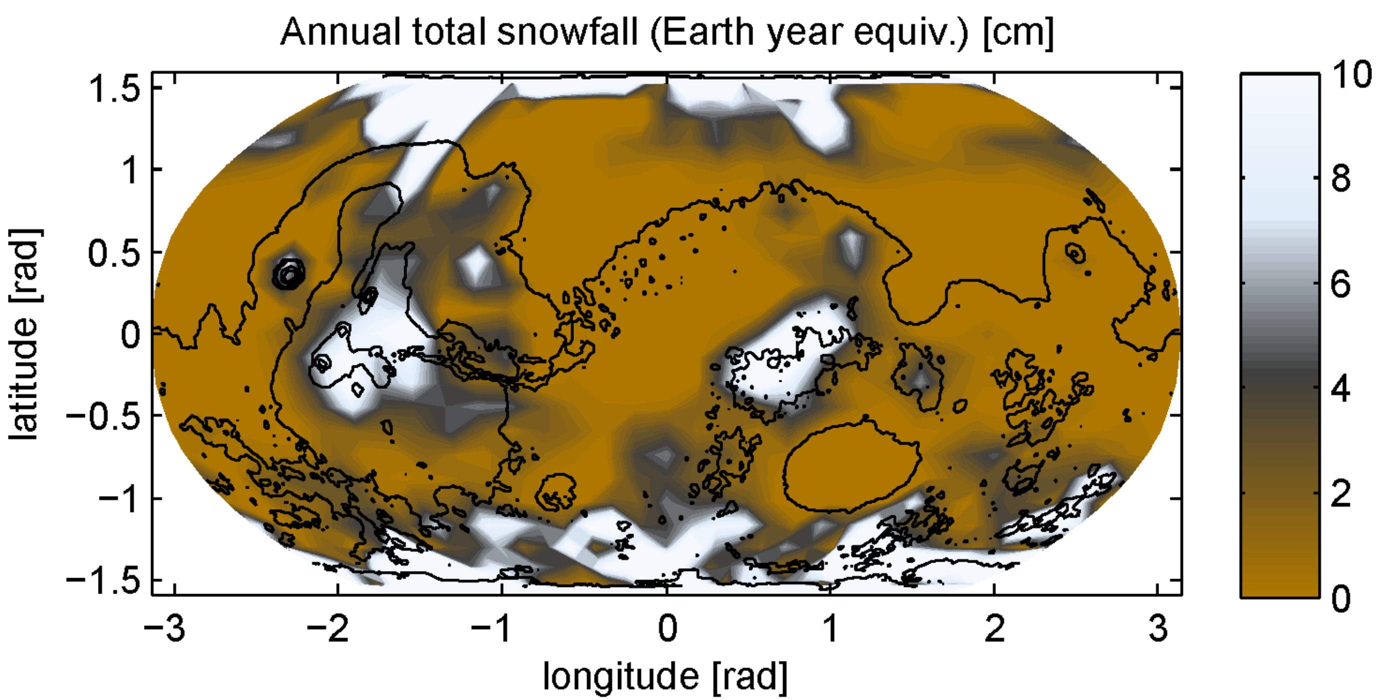


2 bar, icecaps

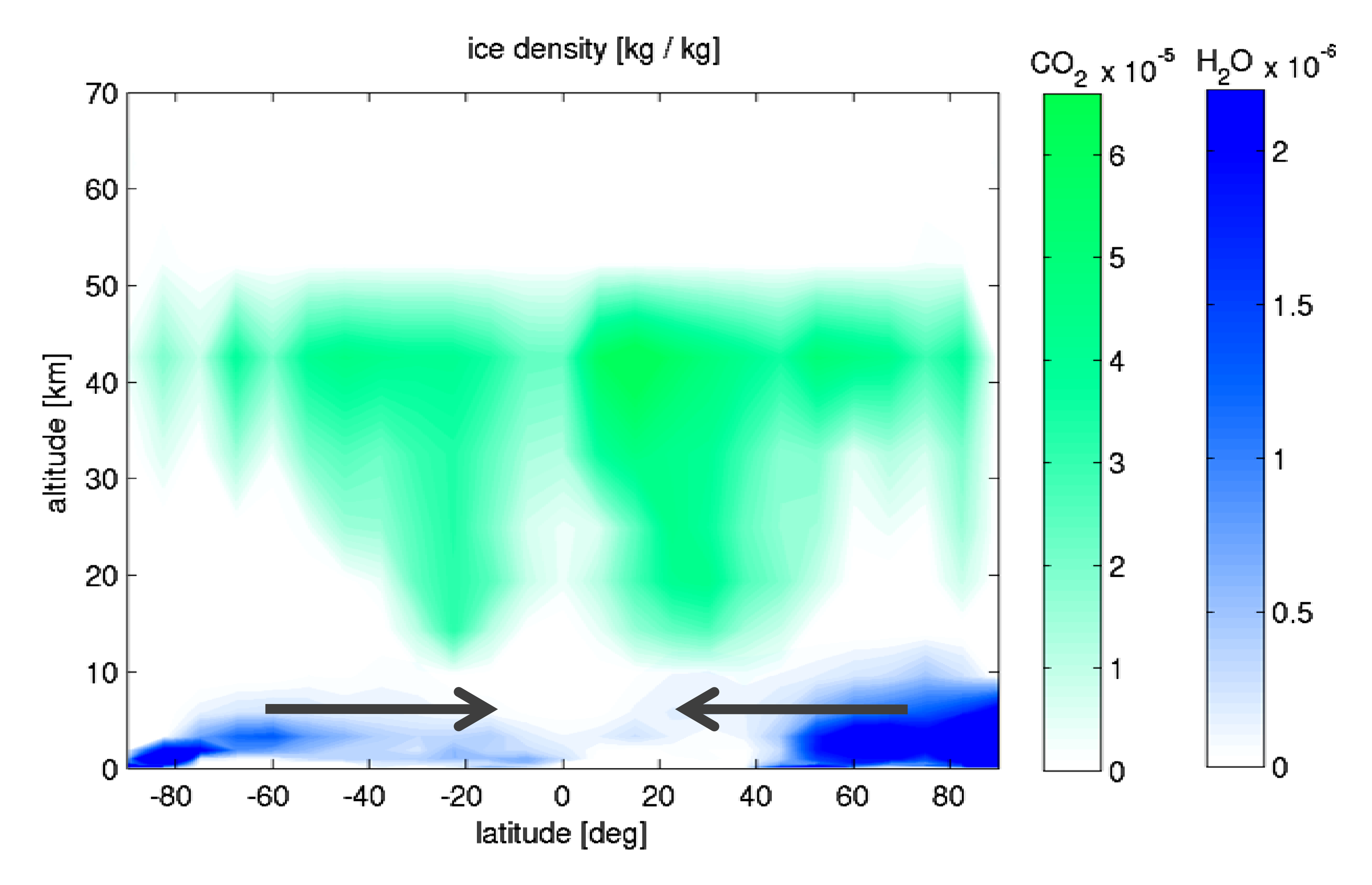


2 bar, icecaps

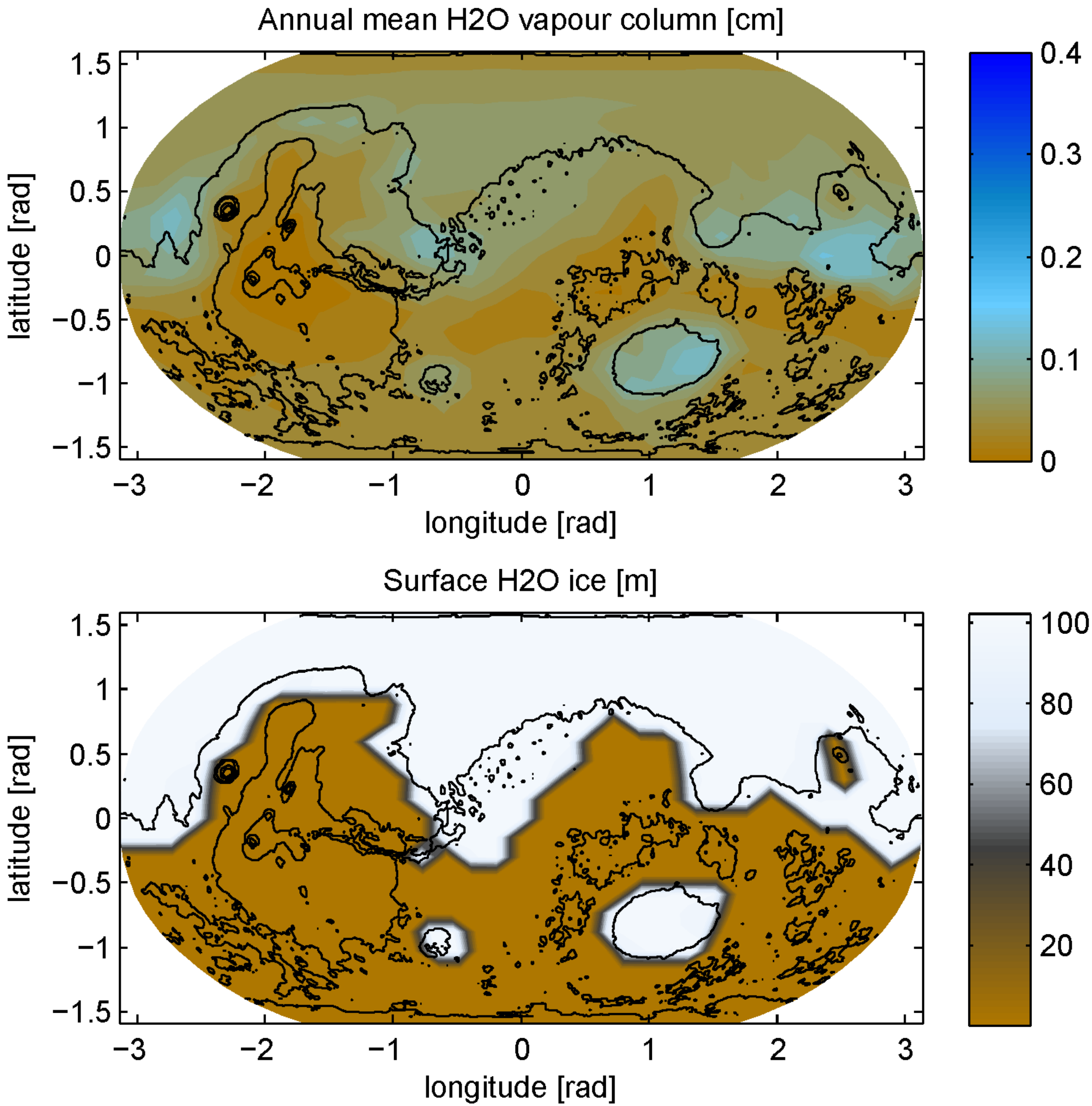




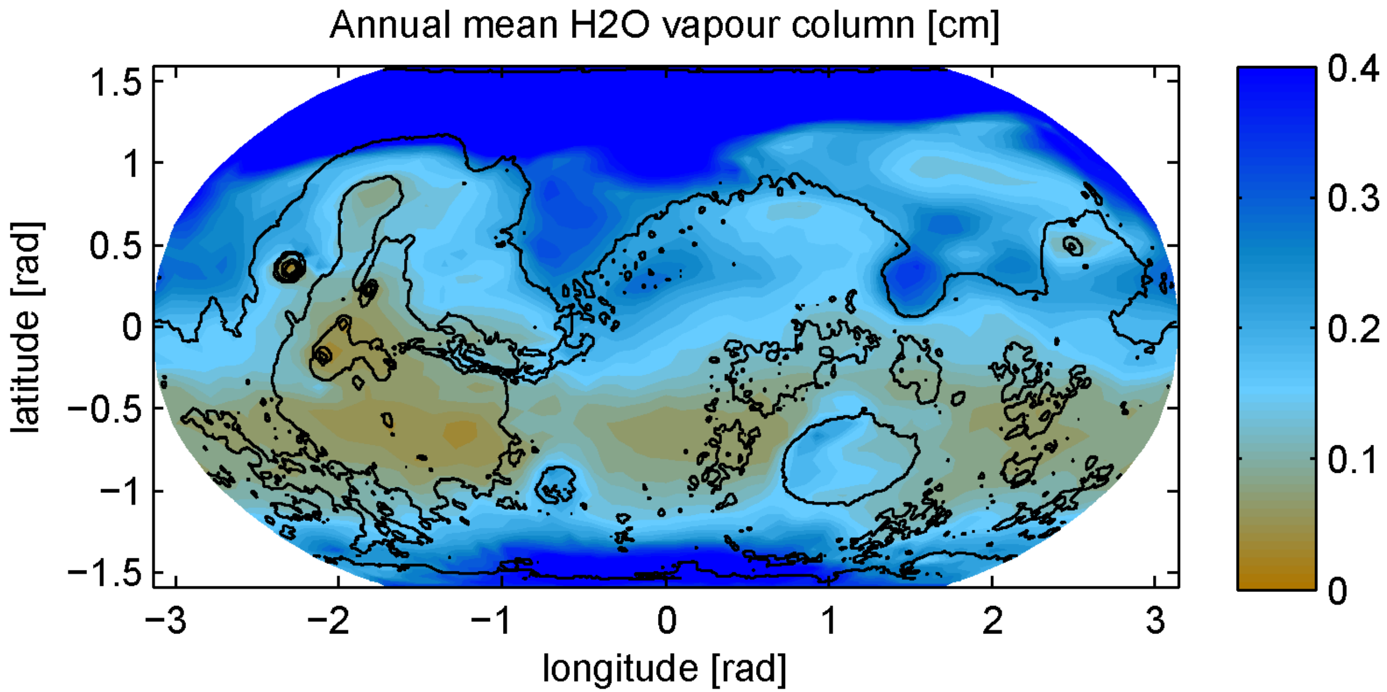
CO2 and H2O cloud cover

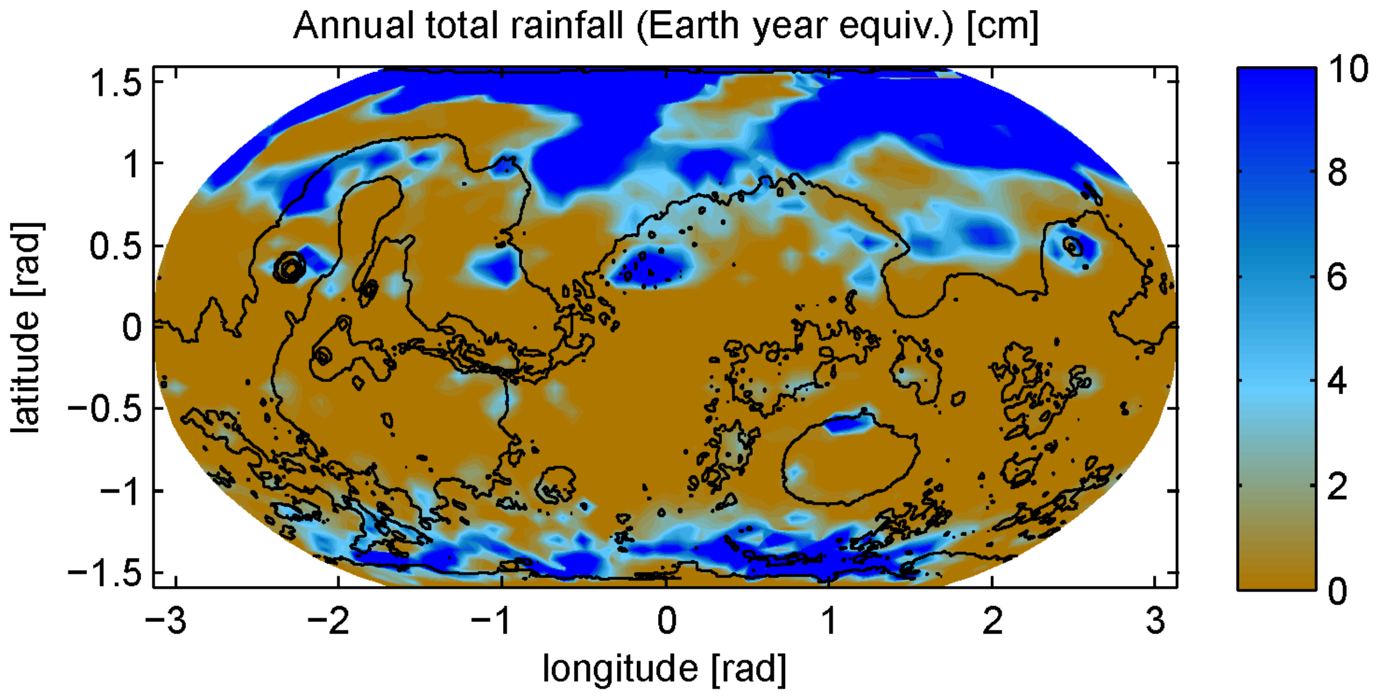


2 bar, ocean

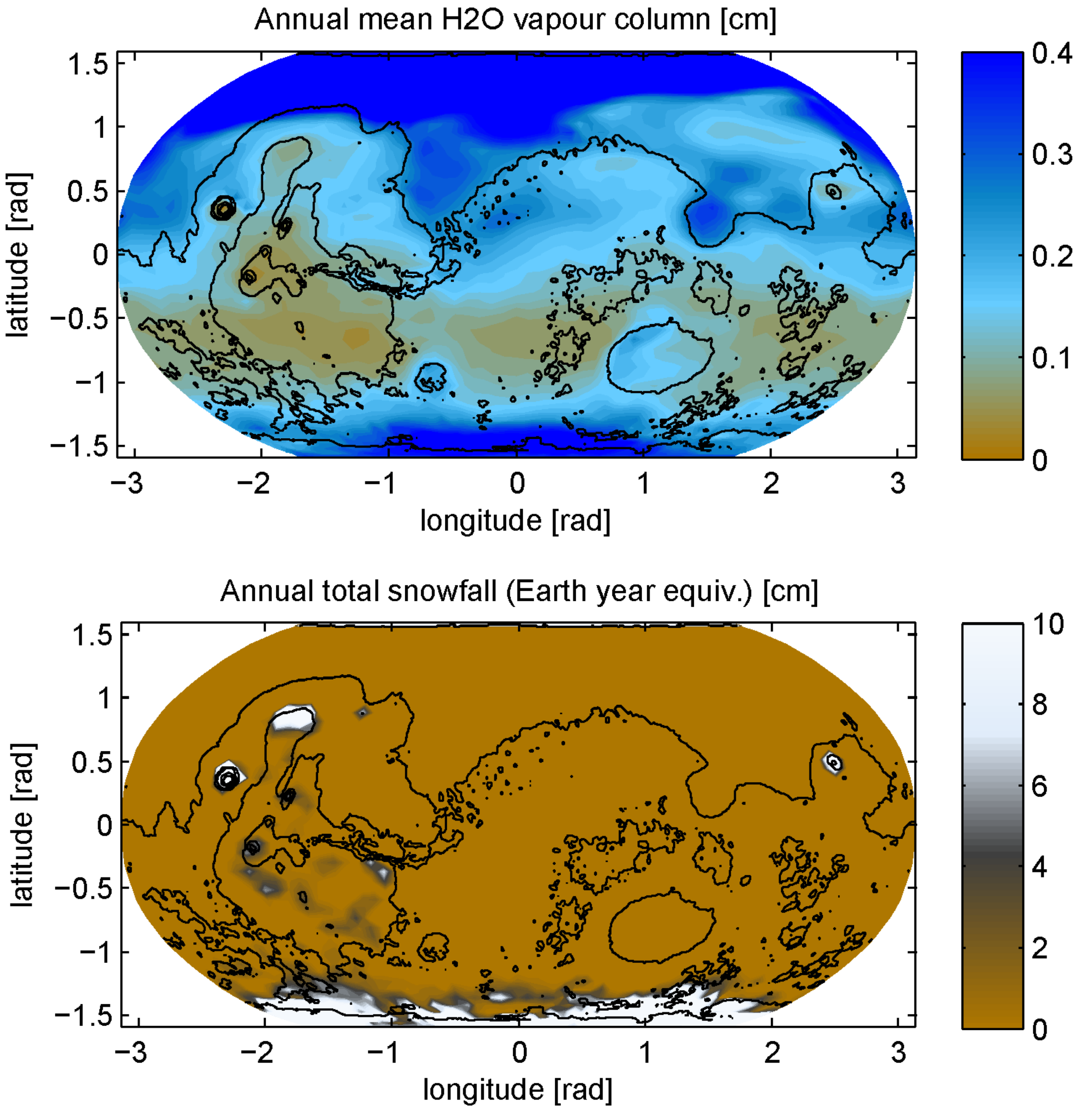

Annual mean H2O vapour column [cm]
latitude [rad]
longitude [rad]
1.5
1
0.5
0
−0.5
−1
−1.5
−3
−2
−1
0
1
2
3
0.4
0.3
0.2
0.1
0
Surface H2O ice [m]
latitude [rad]
longitude [rad]
100
80
60
40
20

5 bar, icecaps

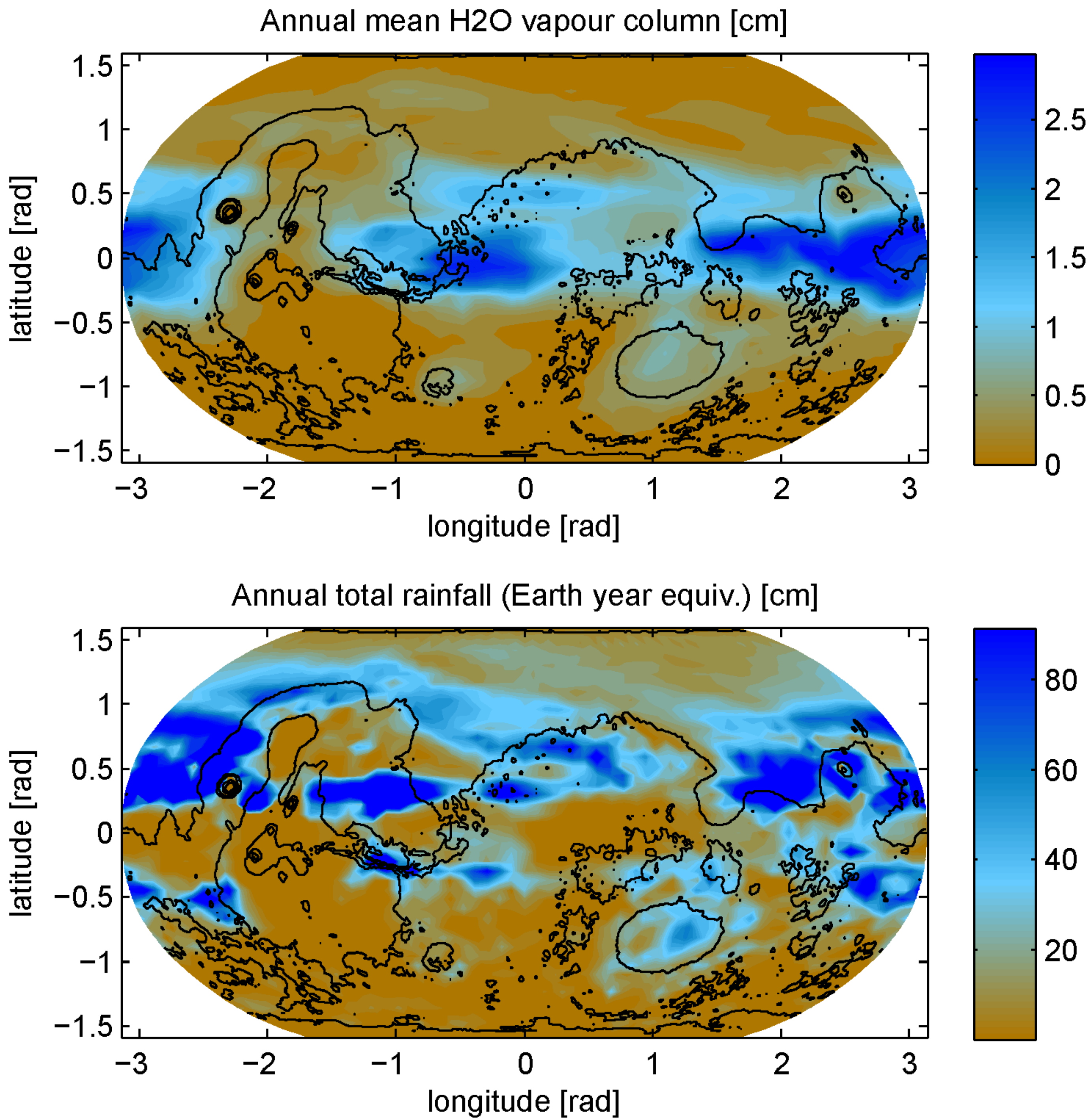




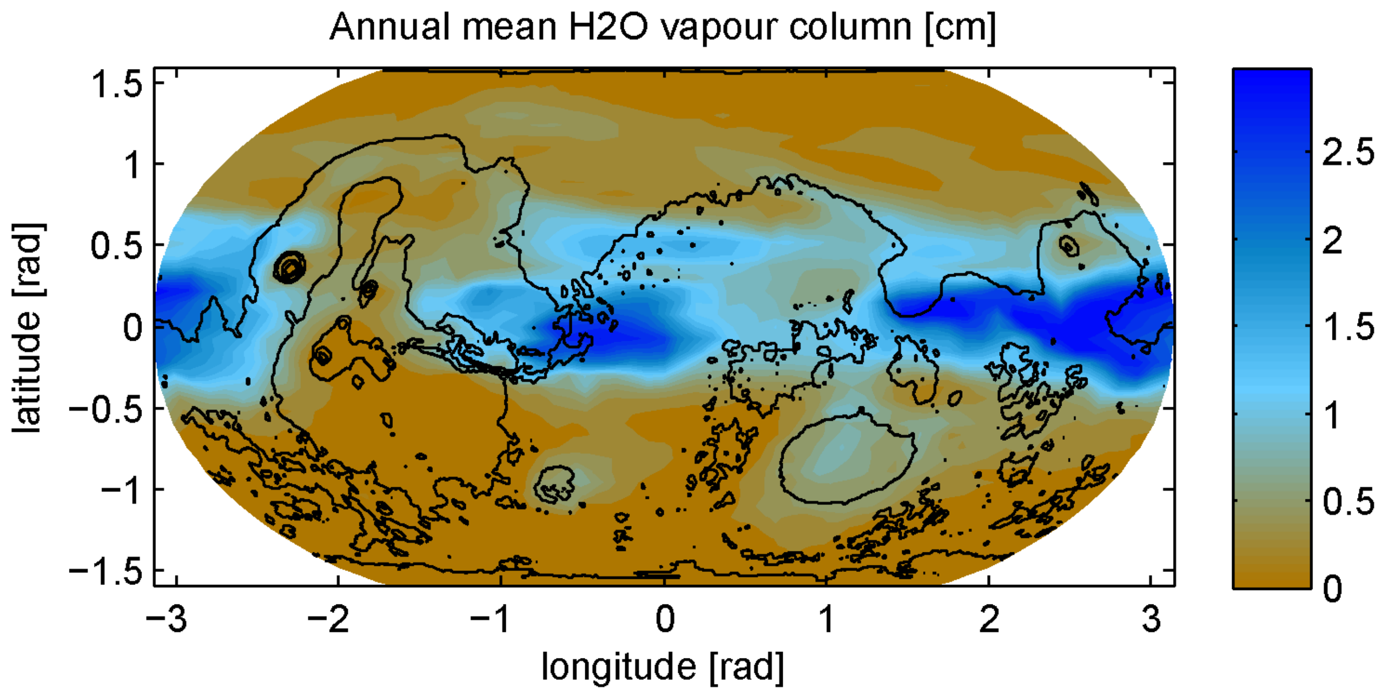
5 bar, icecaps



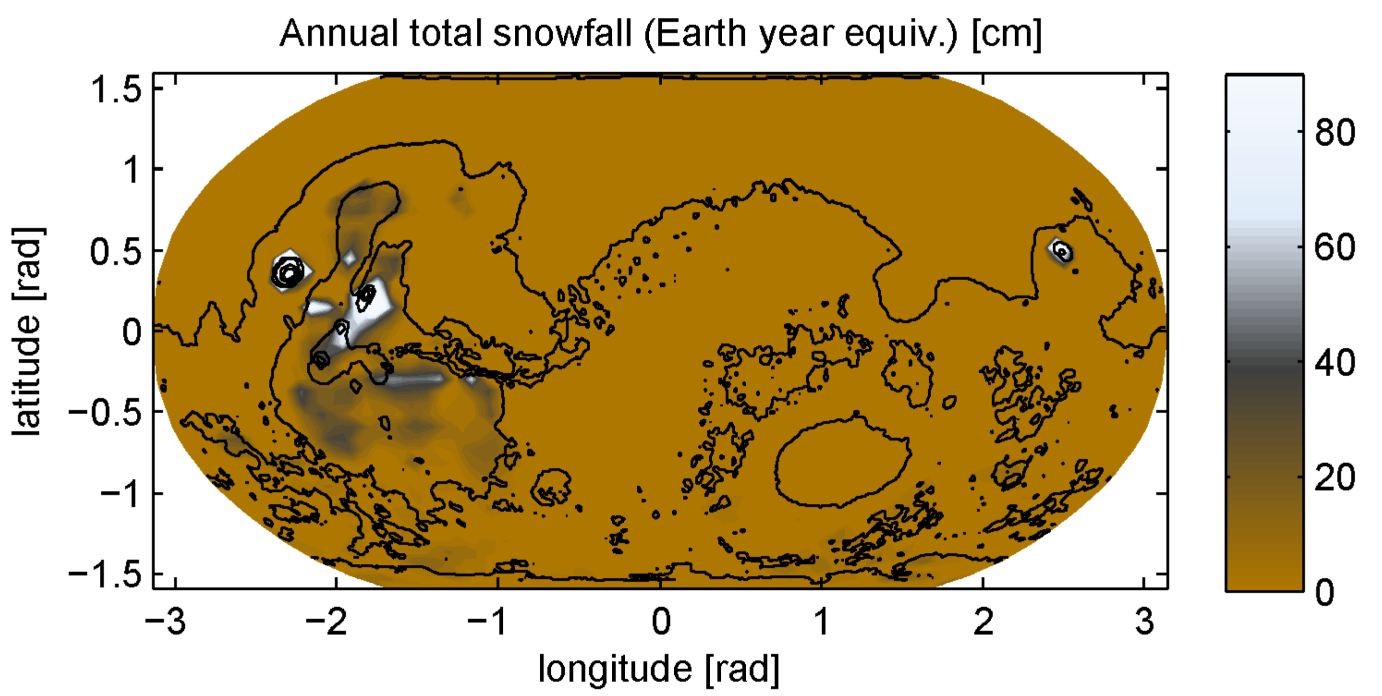
5 bar, ocean


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 rainfall (Earth year equiv.) [cm]
latitude [rad]
longitude [rad]
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

Conclusions / Questions

- An early Martian hydrological cycle is possible with pure CO_2-H_2O warming, but only for high atmospheric pressures (2 to 5 bar)
  - Could Mars have formed with this much CO_2?
  - Could Mars have lost this much CO_2 since ~3.5 GYa?
- Northern ocean only possible at highest pressures
- Below 1 bar, CO_2 begins to collapse on the surface, but orbital state (obliquity) is important
- Does an 'Early Mars Lite' solution exist?

What can Mars tell us about exoplanet habitability?

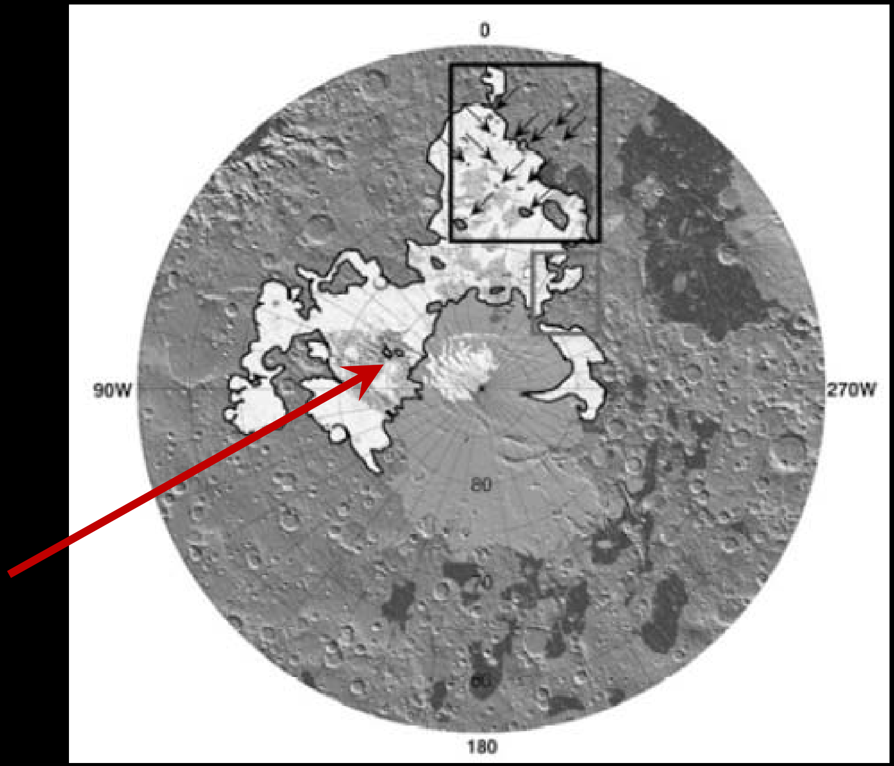
- Was Mars too far away, or simply too small?
- Smaller planet →
  - More efficient atmospheric escape
  - Reduced mantle processes / no plate tectonics?
  - No permanent magnetic field

What can Mars tell us about exoplanet habitability?

- Was Mars too far away, or simply too small?
- Smaller planet →
  - More efficient atmospheric escape
  - Reduced mantle processes / no plate tectonics?
  - No permanent magnetic field
- For planets with permanent dense atmospheres, various processes (CO_2 clouds, N_2-enhanced warming) could extend the outer edge of the habitability zone significantly

Future Work

- Investigate effects of methane, volcanic greenhouse gases
- Investigate impact heating effects?
- Closer comparison with the geological evidence, more specific studies (e.g., formation of Dorsae Argentea)



Questions?