How important is CO_2 to planetary habitability?

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Exoclimes, Aspen, 17/01/12

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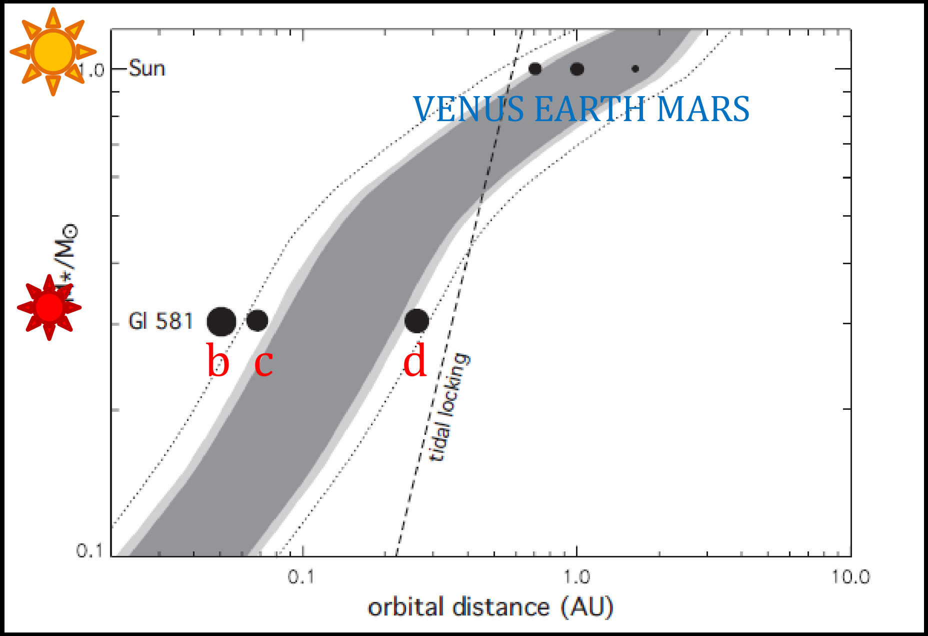
Talk Outline

- CO_2 and the outer edge of the habitable zone
  - Uncertainties: absorption spectra, CO_2 clouds
  - Simulations of the Early Martian climate
  - Simulations of Gliese 581d
- Importance of other greenhouse gases
  - Hydrogen-nitrogen warming on Early Earth
  - Transient conditions for biogenesis on young super-Earths
- Conclusions

Carbon dioxide defines the outer edge of the classical habitability zone

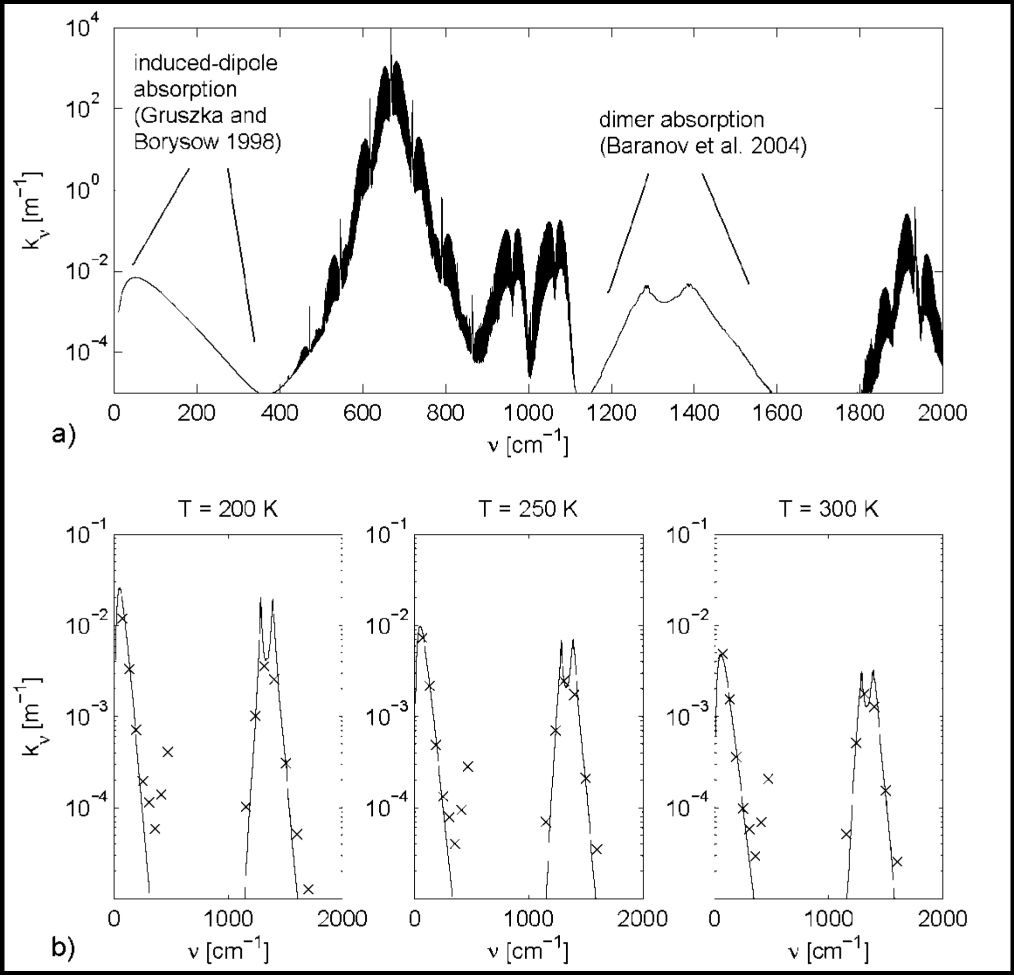
- Kasting (1993): Habitability means surface liquid water
- Inner edge = runaway H_2O greenhouse, outer edge = max. possible CO_2 greenhouse
- Even for pure CO_2 atmospheres, uncertainties persist!



Selsis et al. 2007, Astronomy & Astrophysics

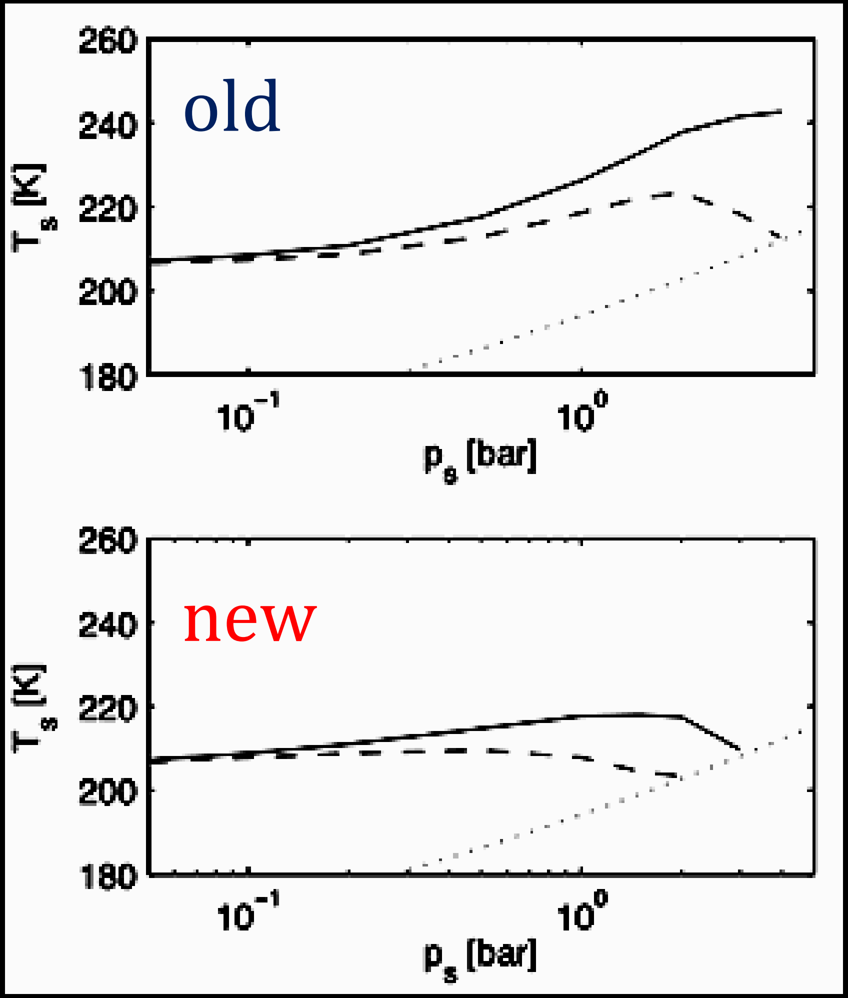
http://www.webmastergrade.com/wp-content/uploads/2010/08/Ocean-View.jpg

CO_2 collision-induced absorption



Wordsworth, Forget & Eymet, Icarus (2010)

Resultant warming in pure CO_2 atmospheres (1D simulations):



CO_2 clouds (1D studies)

- Kasting (1991): CO_2 clouds will increase albedo, probably cool
- Forget & Pierrehumbert (1997): CO_2 clouds will warm via IR scattering
- Colaprete & Toon (2003): Yes, but warming effect small due to microphysics of cloud formation

CO_2 clouds (GCM studies)

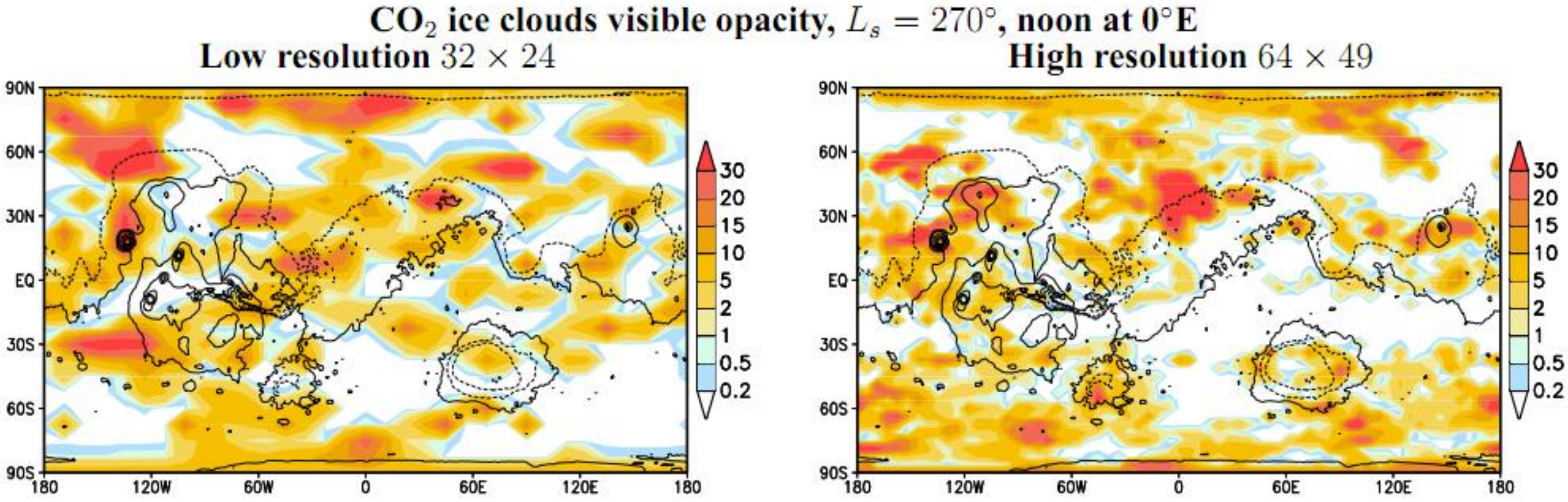


Figure 10. An example of the instantaneous CO_2 ice clouds coverage for two simulations with different horizontal resolution (mean surface pressure 2 bar, obliquity=25°, [CCN]=10^5 kg^{-1}, circular orbit)

Forget, Wordsworth, Millour et al. (2012):

Dry warming of up to ~15 K (a little more with water vapour included)

Two outer edge planets: Mars and Gliese 581d

Mars

1.34 AU away from Earth (today!)

Extensive evidence for running surface water only in Noachian era (~3.8 Gya)

Ave. stellar flux ≈ 110 W m^{-2}

Mass = 0.107 m_E

Orbits G-class star

Gliese 581d

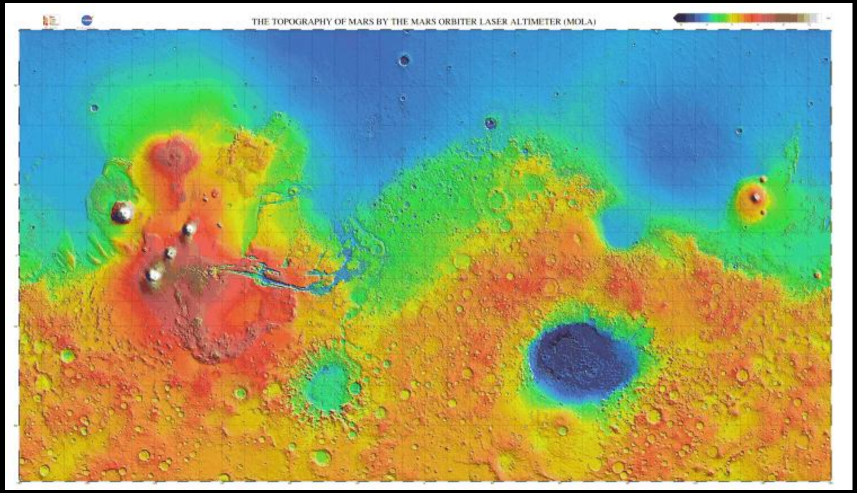
~20 light years away

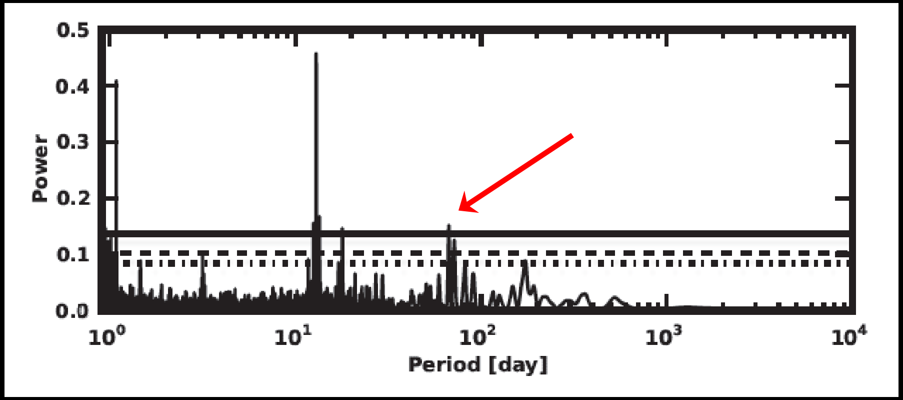
Discovered 2007 by RV measurements (Udry et al. Astron. & Astrophys.)

Ave. stellar flux ≈ 95 W m^{-2}

Min. mass = 7.1 m_E (max ~11 m_E)

Orbits M-class (red dwarf) star

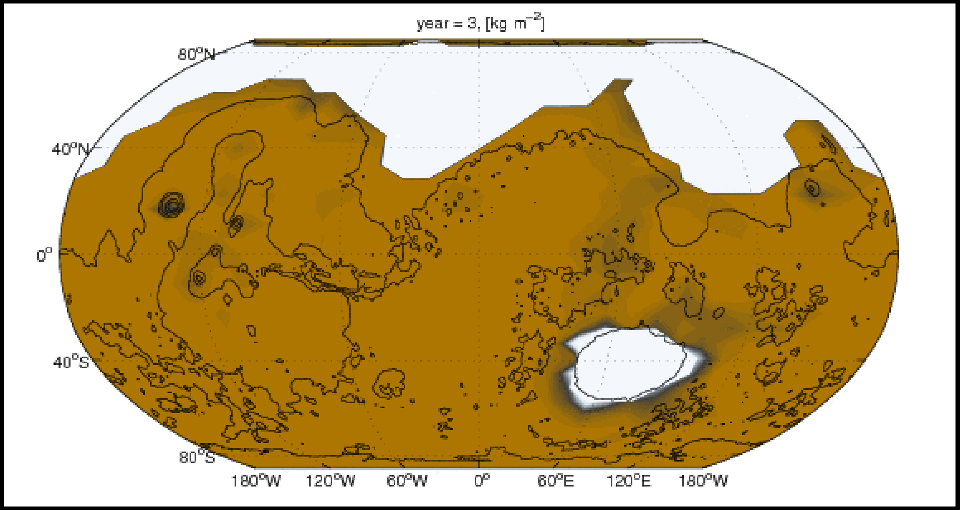


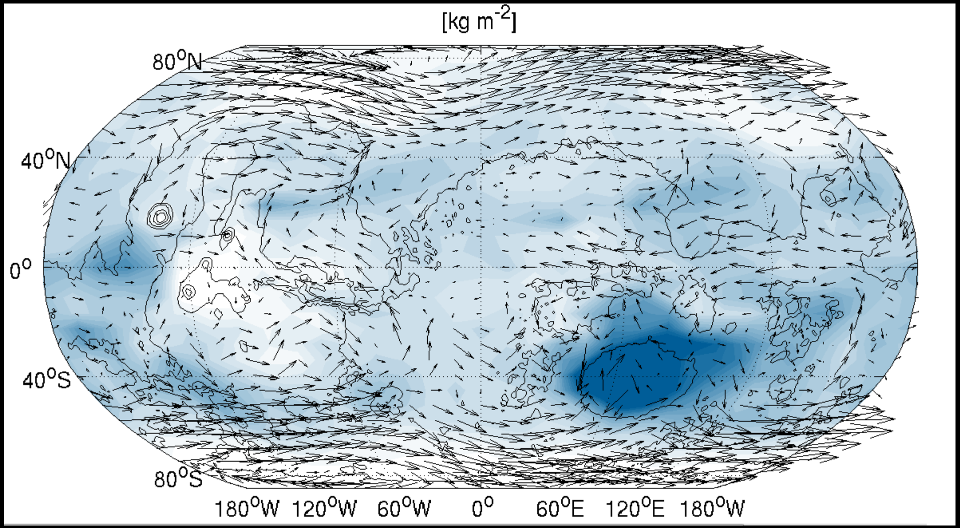


Carr (1996), Malin & Edgett (2003)
Forveille et al. (2011)

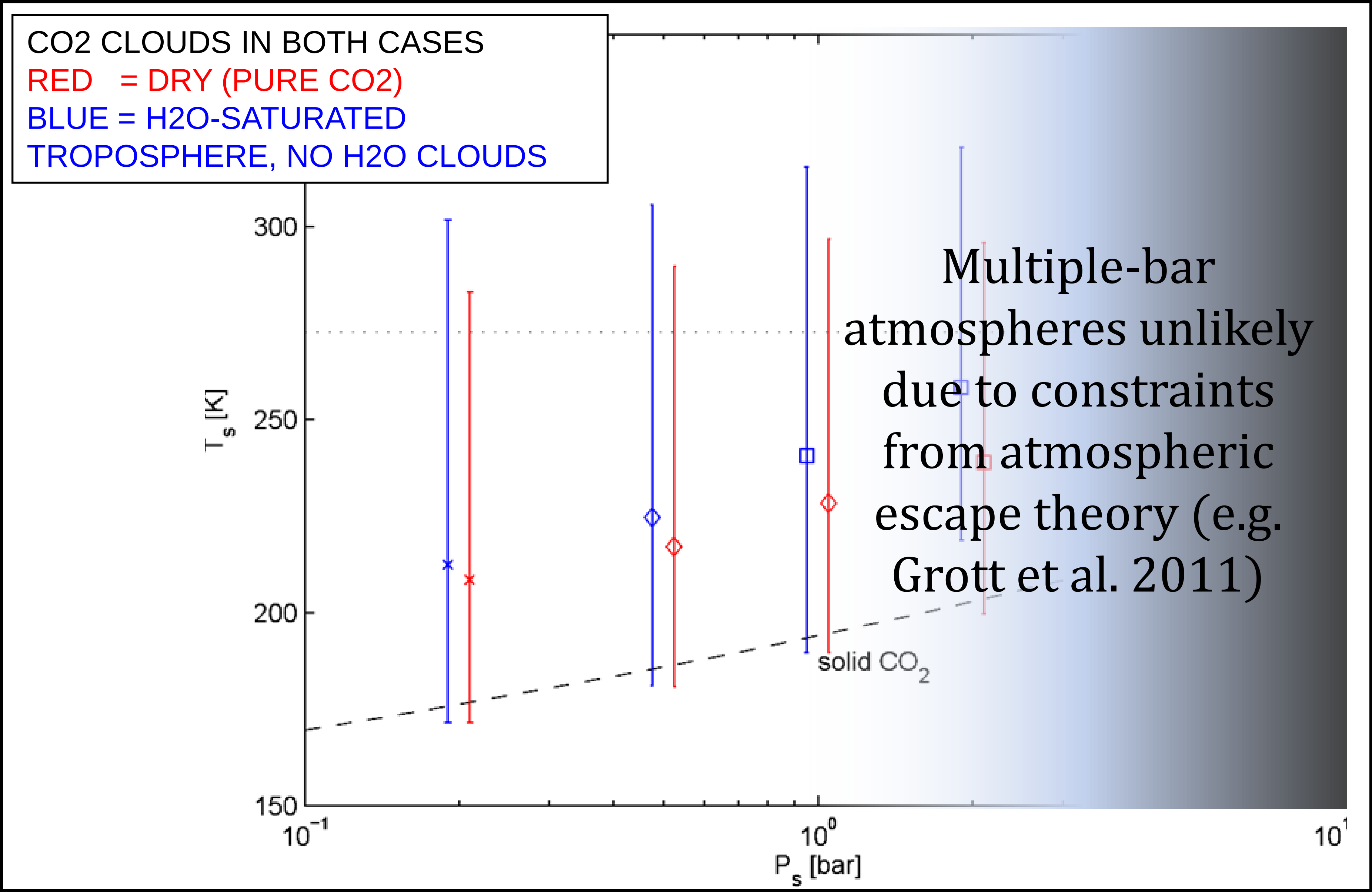
3D Early Mars simulations

- Mixed CO_2 / H_2O atmosphere
- Self-consistent water cycle, including surface exchange, precipitation, cloud and vapour radiative effects etc.
- Pressure: 600 Pa to 2 bar
- 32×32×15, 32×36 spatial & spectral resolution
- Ice evolution algorithm: $h_{ice}^{+} = h_{ice} + dh_{ice}/dt|_{1\,yr} \times \Delta t_{step}$

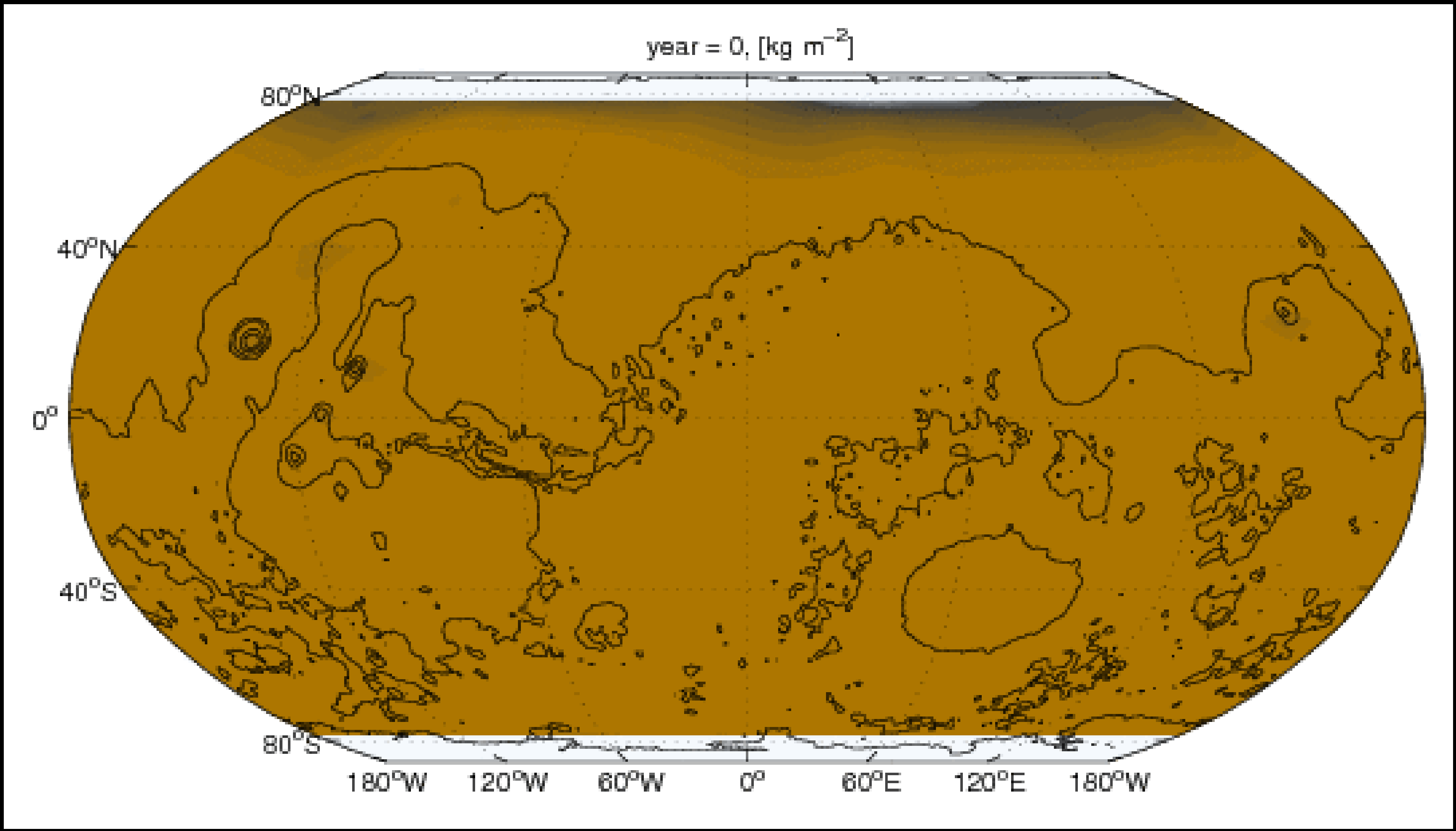




Surface temperature vs. pressure



Surface ice evolution

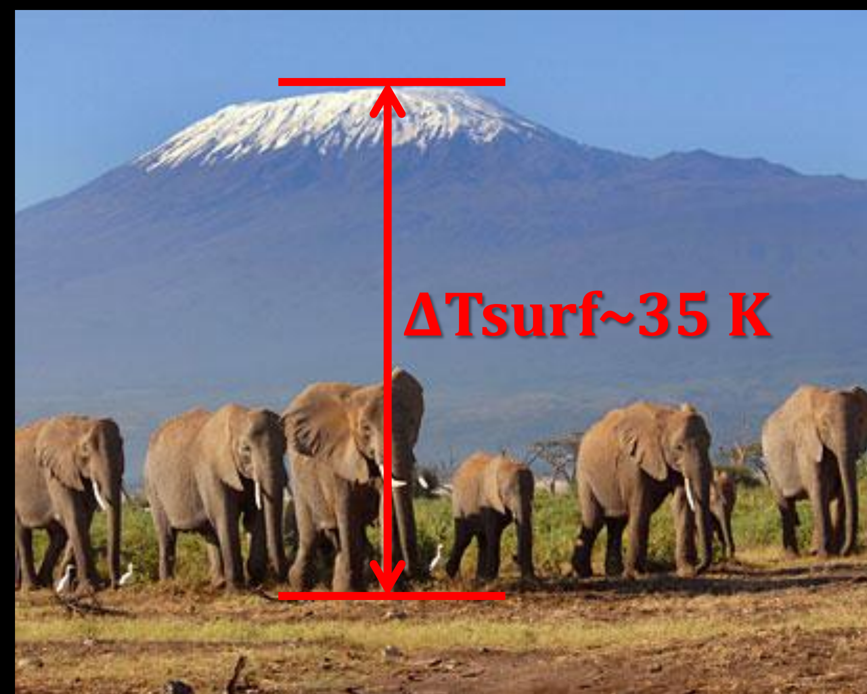


1 bar atmosphere, 25 deg. obliquity

Temperature-altitude correlation

Olympus Mons: 21 km height
600 Pa atmosphere (today)

Kilimanjaro: 5.9 km height
1 bar atmosphere



http://wallpapers.free-review.net/49_~_Mars%2C_Olympus_mons_foggy.htm
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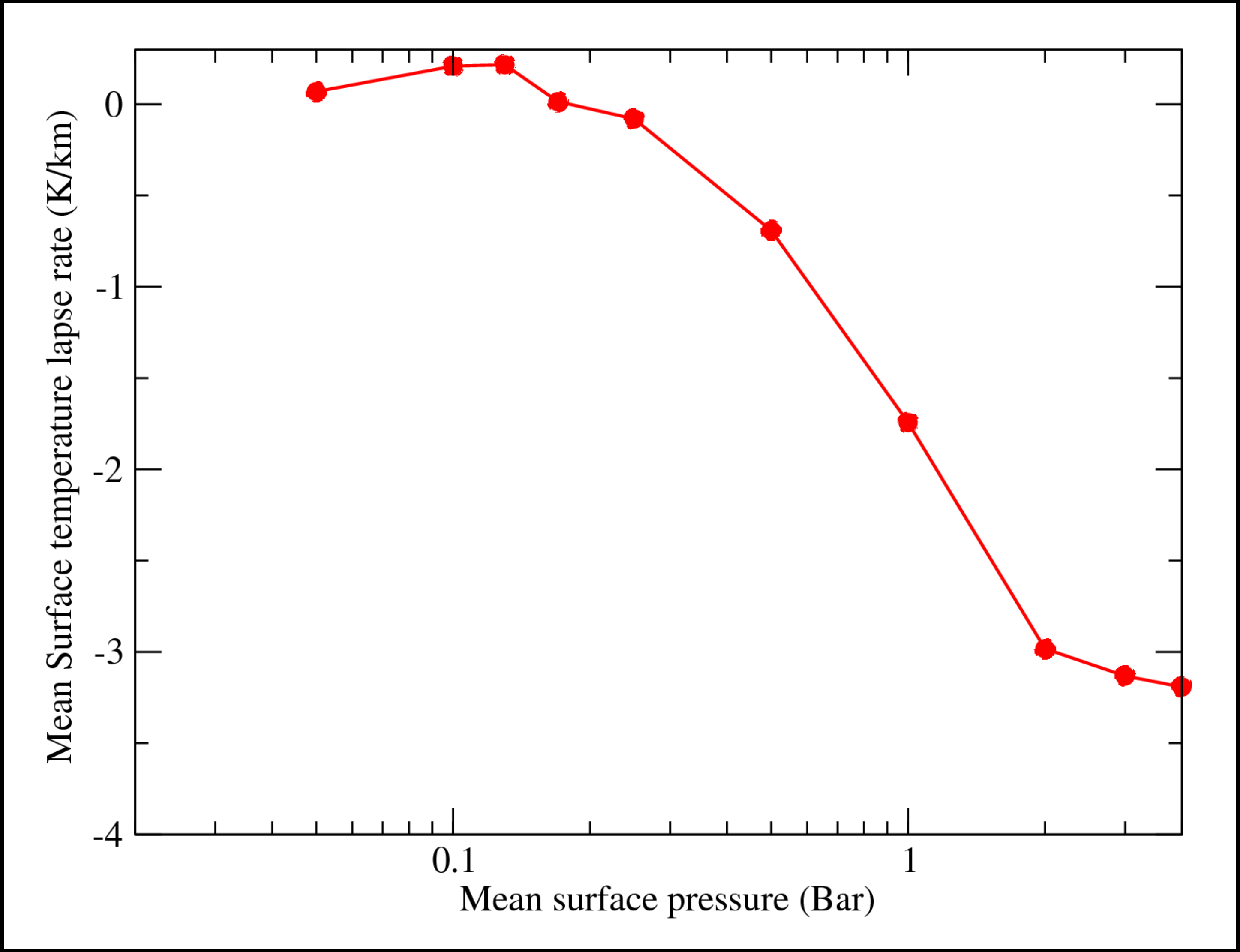
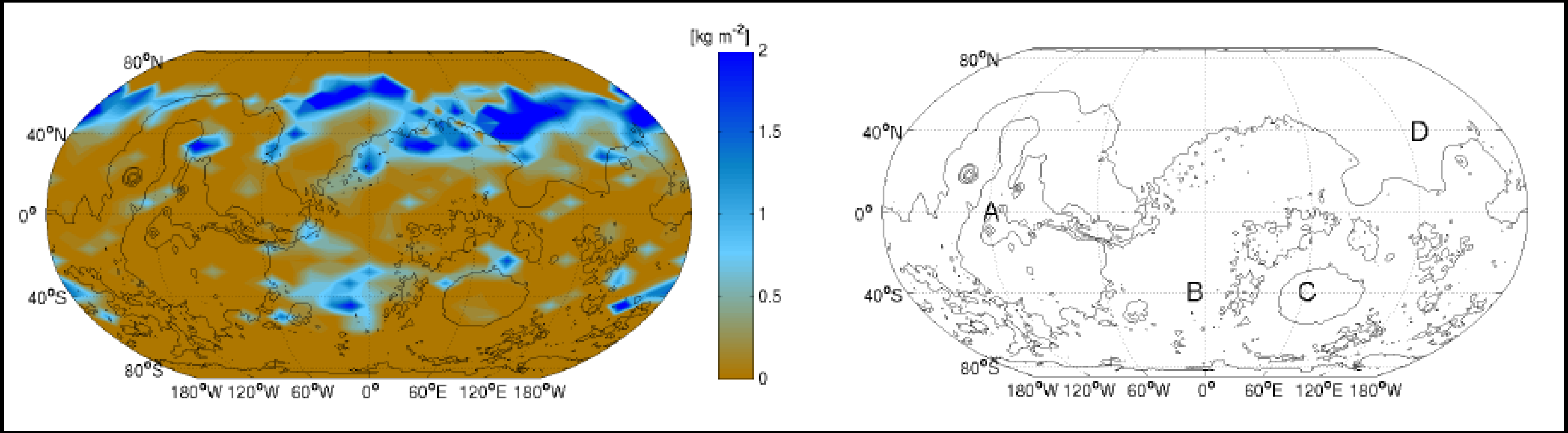
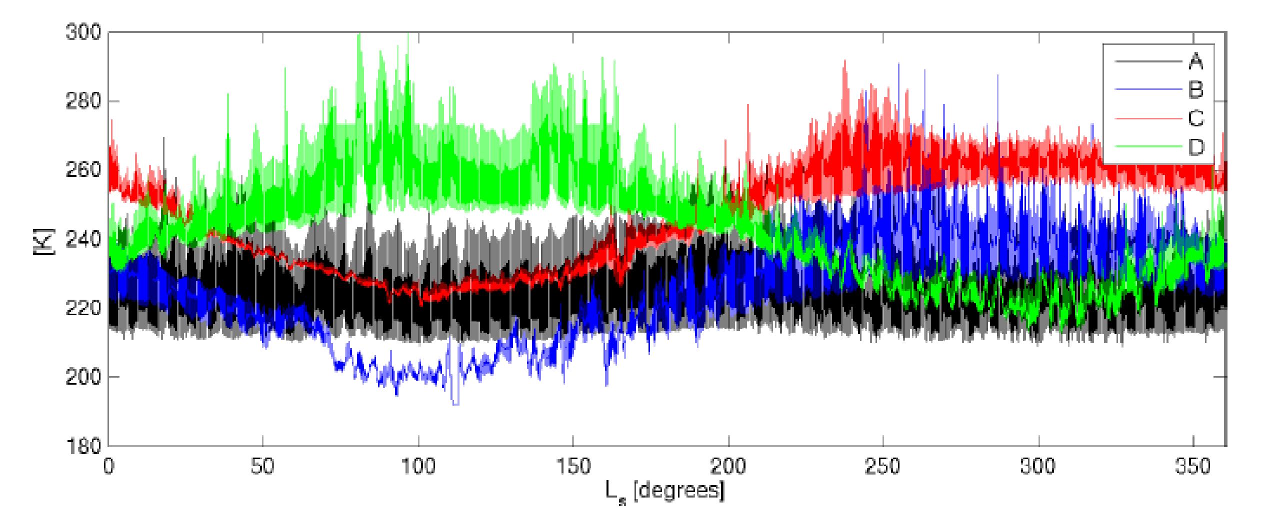
Temperature-altitude correlation

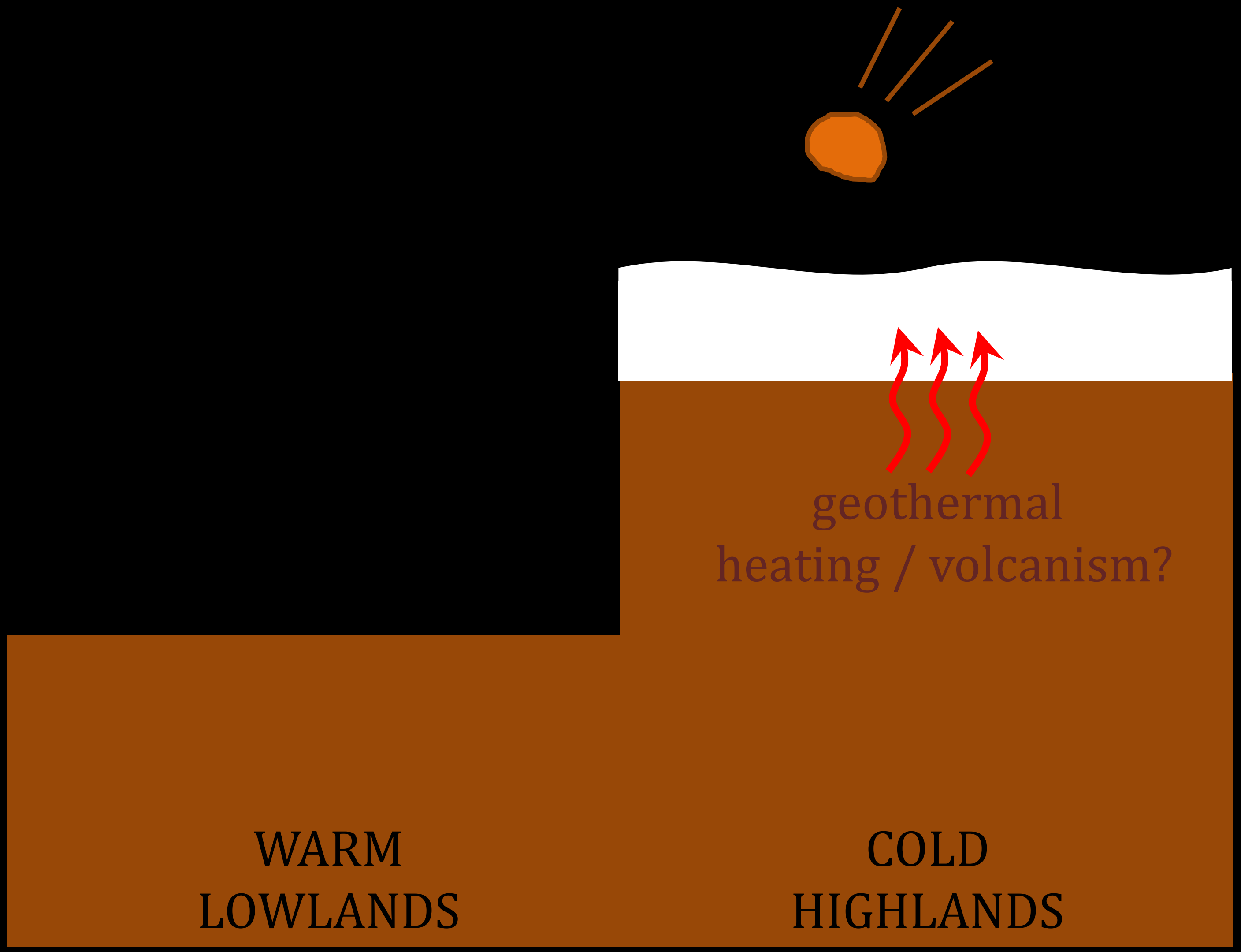


Effects of diurnal / seasonal heating



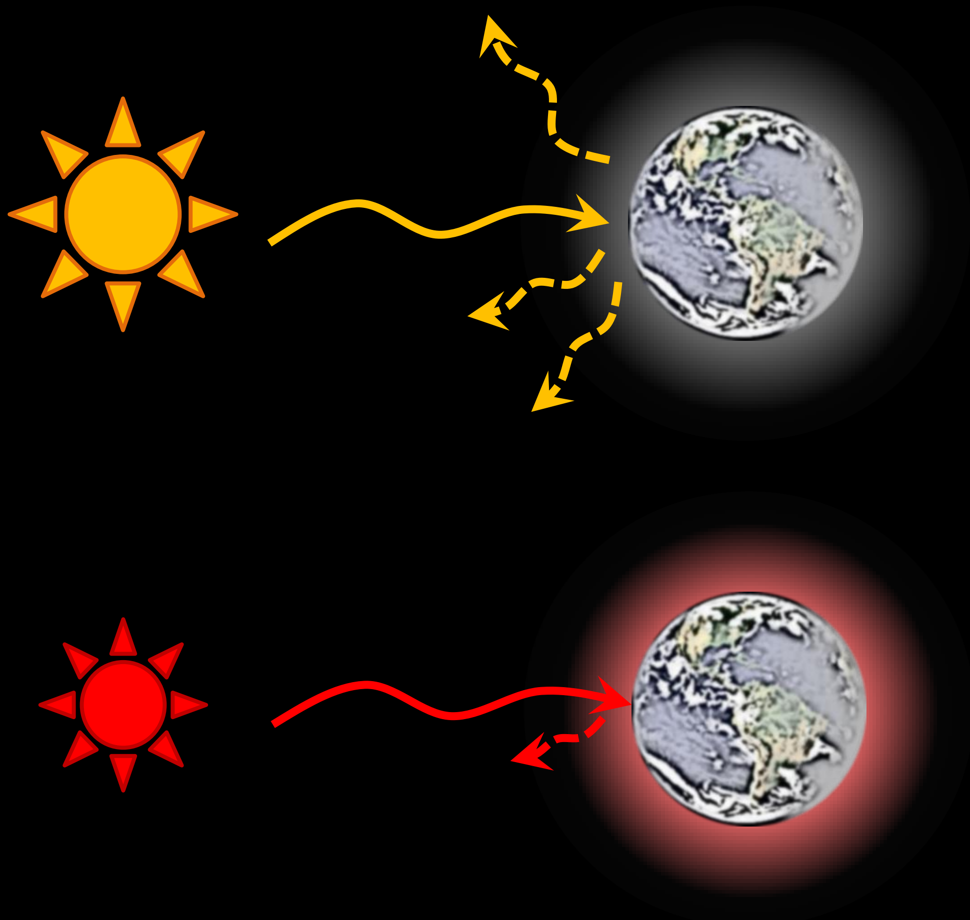


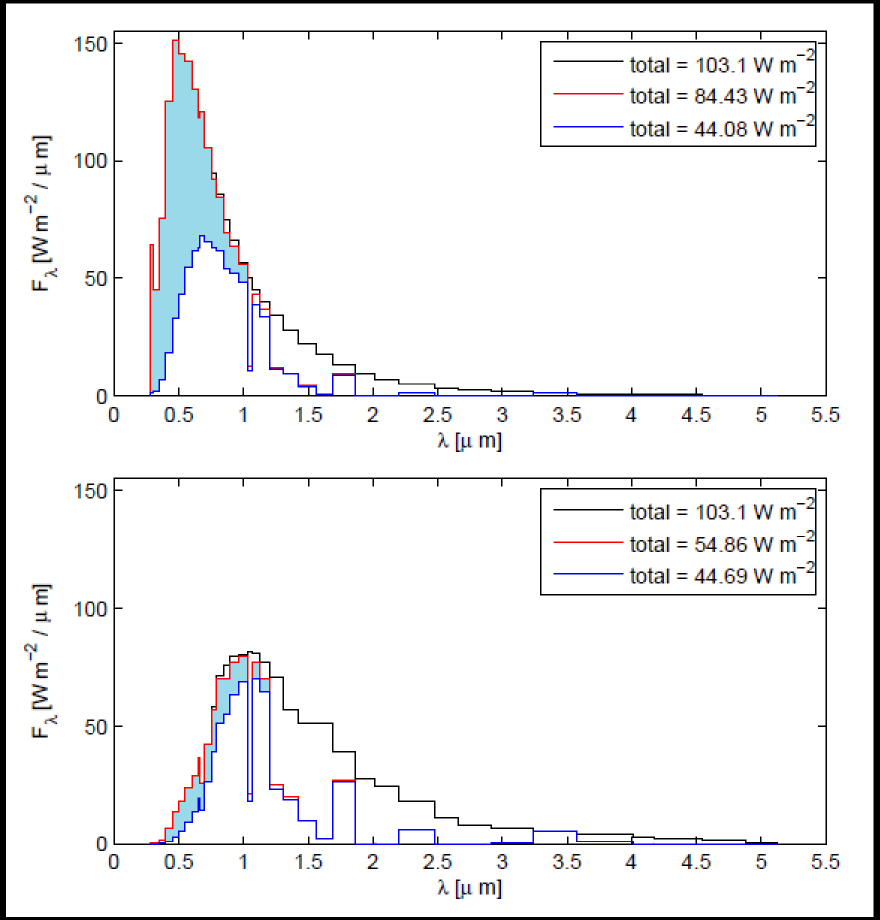
Effects of transient phenomena: jolts away from climate equilibrium



Gliese 581d simulations

Effect of the stellar spectrum

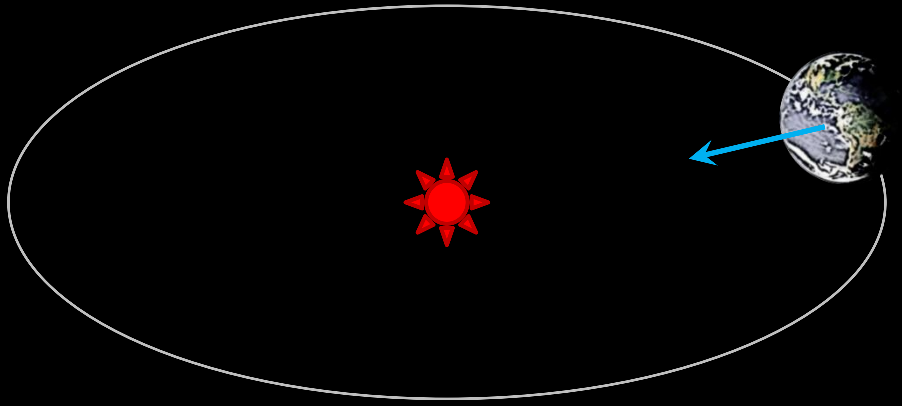


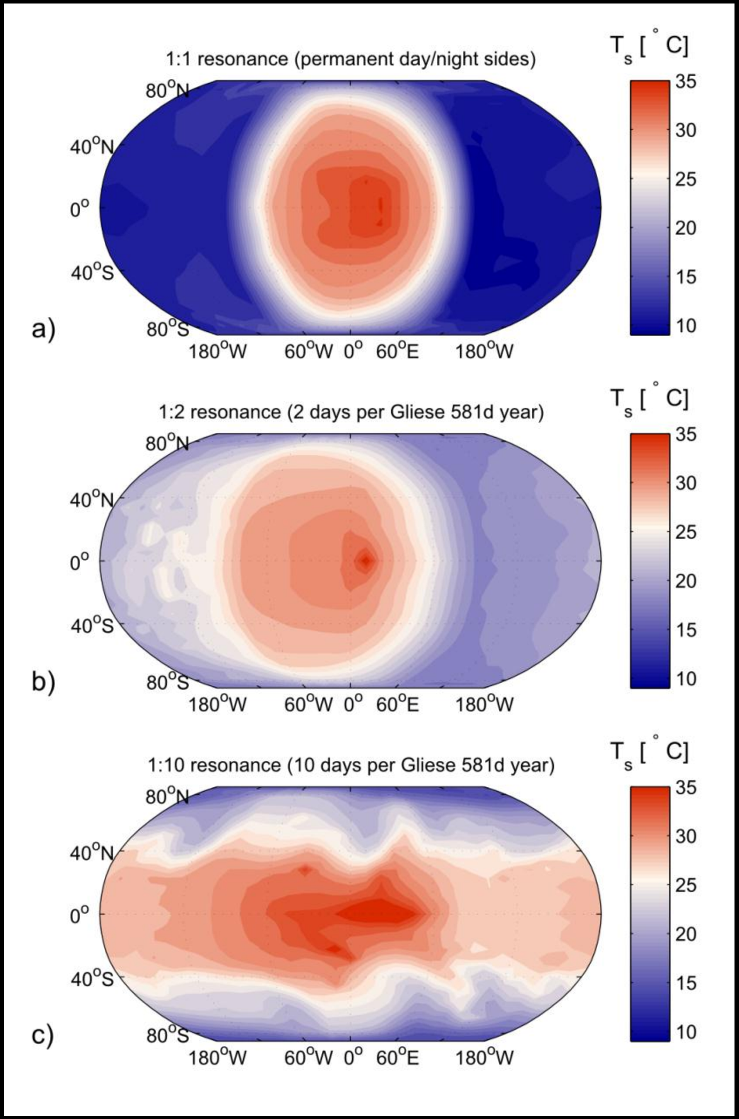


Kasting et al. 1993, Icarus
Wordsworth et al. 2010b, Astronomy & Astrophysics

Effect of the close orbit

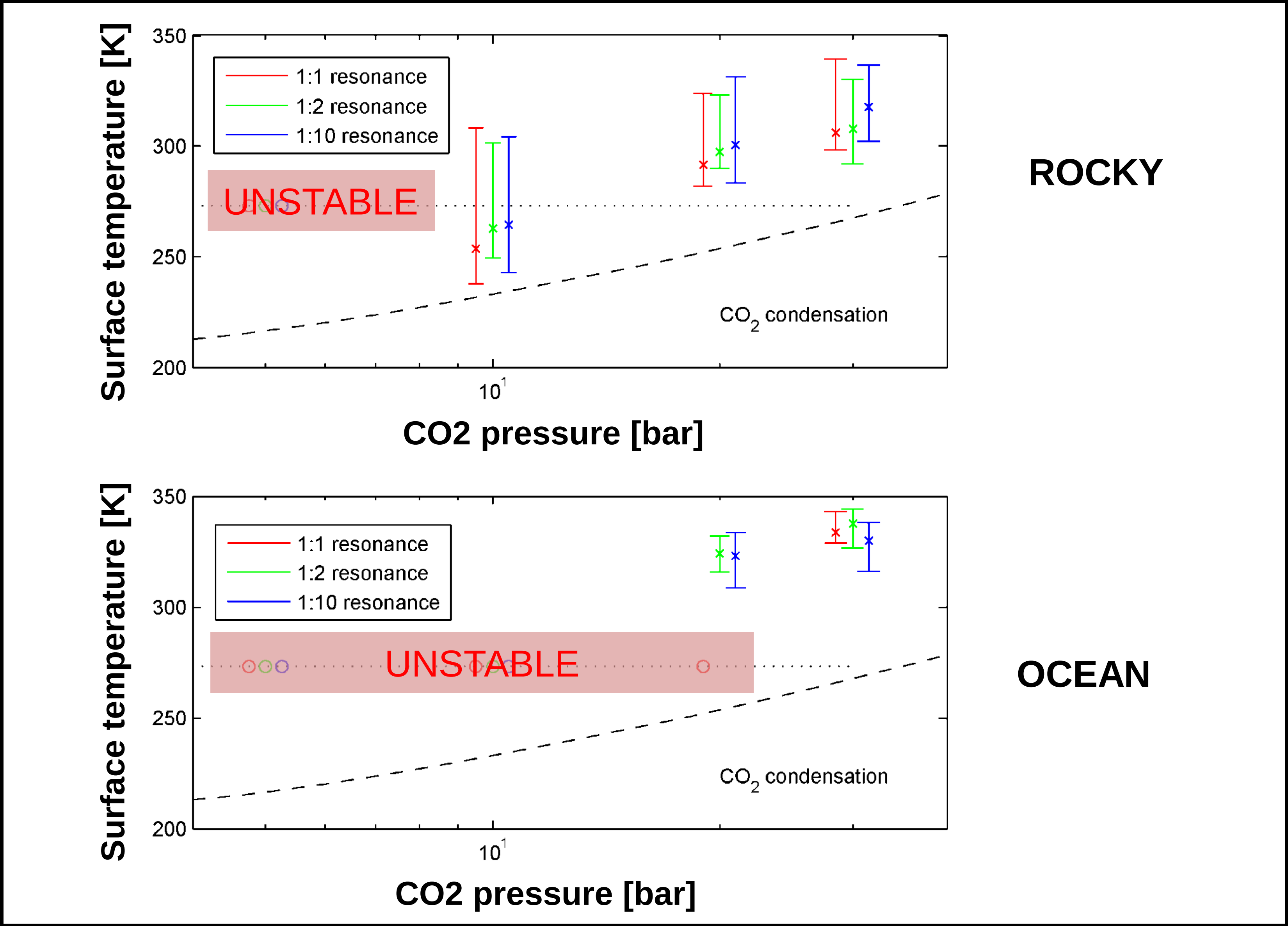
- Gliese 581d most likely in locked or synchronous orbit due to strong tidal forces (Leconte et al. 2010, Heller et al. 2011)
- Dense atmosphere could collapse on planet's dark side!





Wordsworth et al. 2011, The Astrophysical Journal Letters

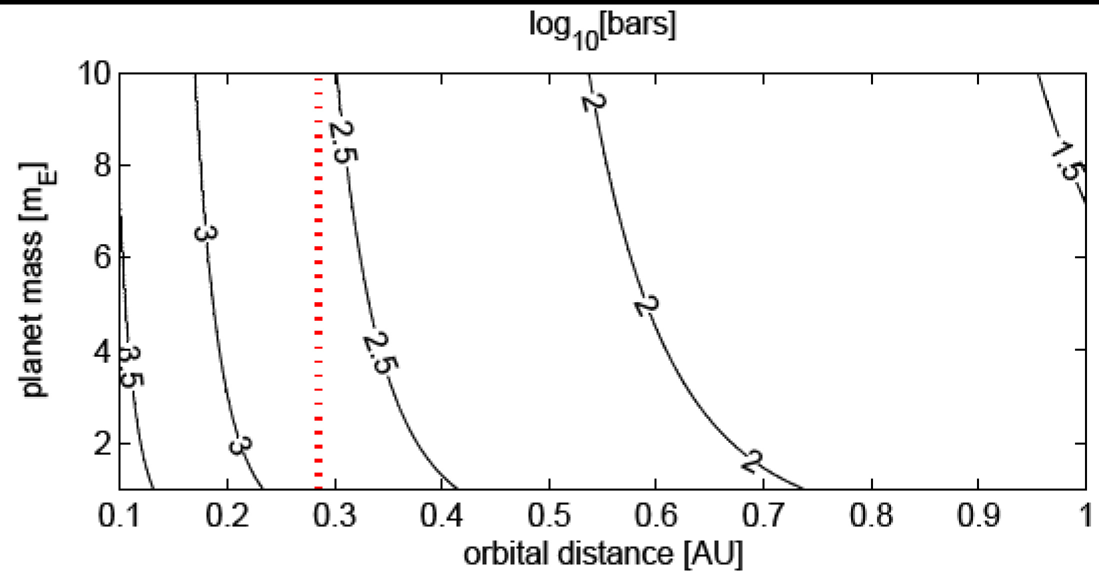
GCM simulation results



Wordsworth et al. 2011, The Astrophysical Journal Letters

So, CO_2-rich case is potentially habitable. Is it likely?

- 10 bars CO_2 on GJ581d ~4-6 bars equivalent on Earth / Venus (factor 10-100 less than their total inventories)
- H_2 / He envelope also possible (c.f. Neptune @ 17 m_E)
- But intense XUV & stellar wind for first ~1 GYr from GJ581
- More sophisticated modelling is needed! (H_3^+ etc.)



$$\phi = \frac{\epsilon F_{XUV}}{4r} = \frac{\epsilon F_{XUV}}{4\nu M^{\beta}} \quad [\mathrm{Pa\ s^{-1}}]$$

$$T^s_{exo} = C F_{XUV}/g + T^s_{min}$$

What about other gases?

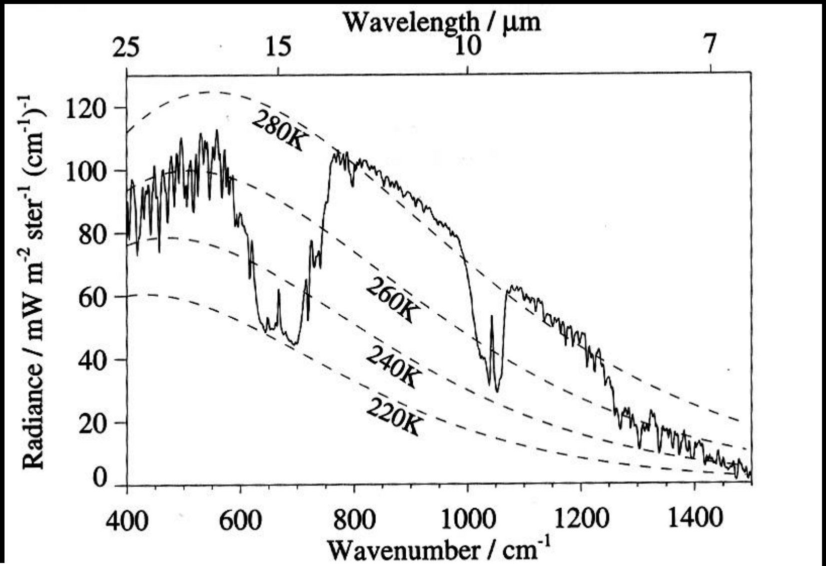
Hydrogen greenhouse warming I: Early Earth

- Classical picture of Earth's atmosphere in the Archean: N_2-CO_2-H_2O, trace amounts of H_2 and CH_4
- Constraints on CO_2 (e.g. Sheldon 2006) lead to infamous Faint Young Sun paradox
- However: recent hydrodynamic escape modelling (Tian et al. 2005) indicates H_2 levels could have been much higher (up to 0.3 v.m.r)
- Could hydrogen have played a direct role in greenhouse warming?

http://www.blc.arizona.edu/courses/schaffer/182/Archean.gif

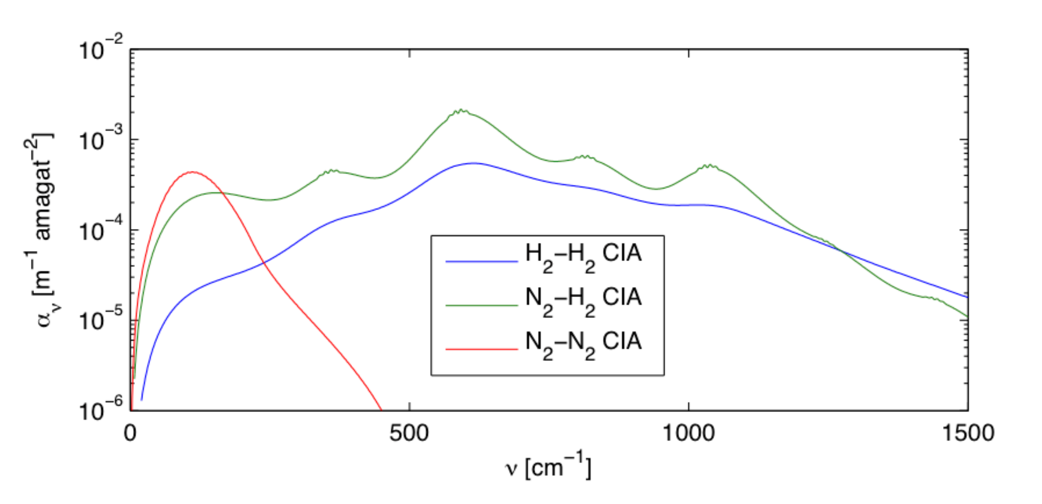
Hydrogen greenhouse warming I: Early Earth

Present-day Earth IR emission spectrum →



Hydrogen, nitrogen collision spectra @ 300 K →

(HITRAN 2012)



Wordsworth et al. 2012, in preparation

http://lasp.colorado.edu/~bagenal/3720/CLASS5/EarthBB.jpg

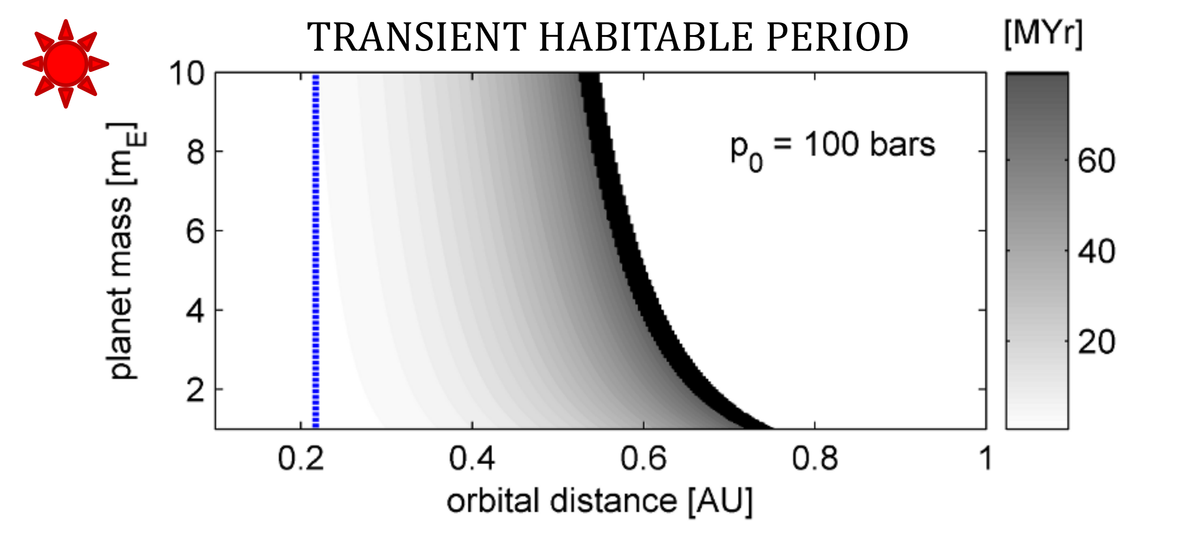
Hydrogen greenhouse warming I: Early Earth

- Assume surface albedo = 0.22, solar flux = 70% present value, clear sky & present-day CO_2 levels

Wordsworth et al. 2012, in preparation

Hydrogen greenhouse warming II: Transient habitability on young super-Earths

- Young super-Earths with slowly escaping H_2 envelopes will undergo transient habitable periods
- During this time, photochemistry under reducing conditions → atmospheric formation of pre-biotic molecules



Wordsworth, 2011
arxiv.org/abs/1106.1411
(see also Stevenson, 1999 and Pierrehumbert & Gaidos, 2011)

Conclusions

- Advances in spectroscopy and 3D cloud modelling have allowed a new, more accurate assessment of CO_2 habitable zone outer edge
- Gliese 581d is inside it (just), Early Mars is not…
- Hydrogen CIA (H_2-H_2 and H_2-N_2) can help explain the faint young Sun paradox on early Earth
- Transient hydrogen warming should also occur on a very wide range of young terrestrial exoplanets
- More research on generalised atmospheric compositions is necessary!