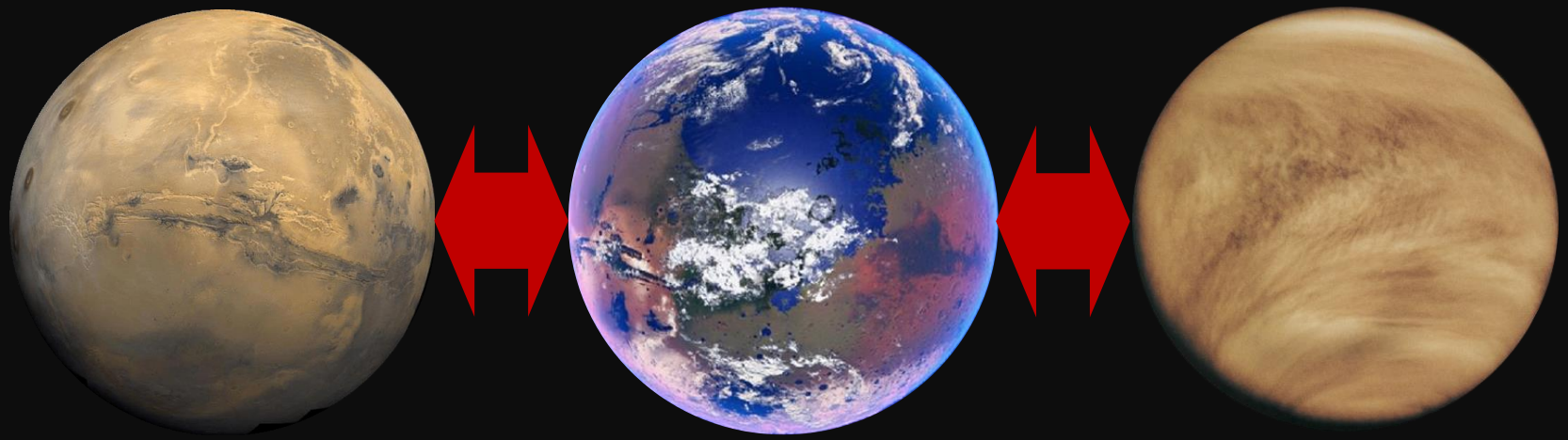
Development of a radiation code for a paleo-Mars GCM and beyond

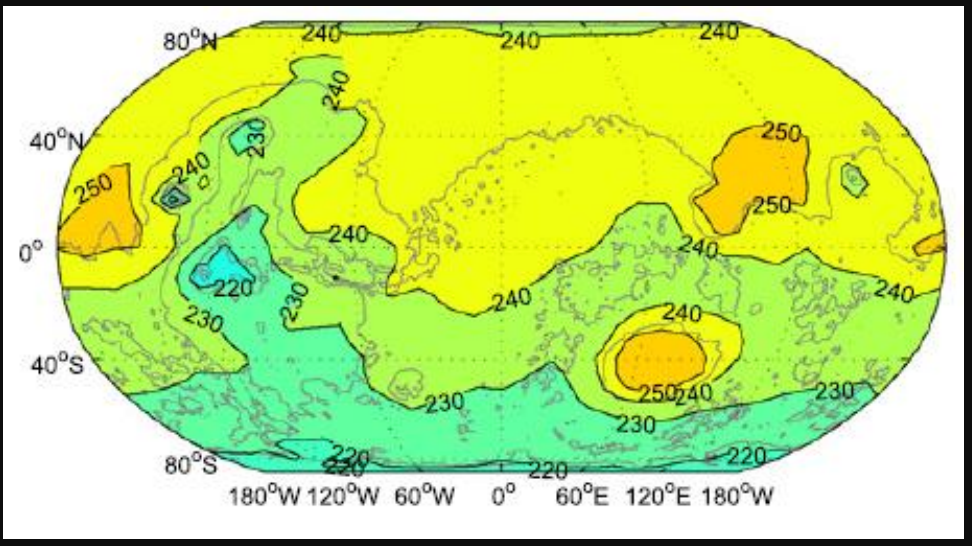


Takeshi Kuroda
Tohoku University

Simulated climate of paleo-Mars

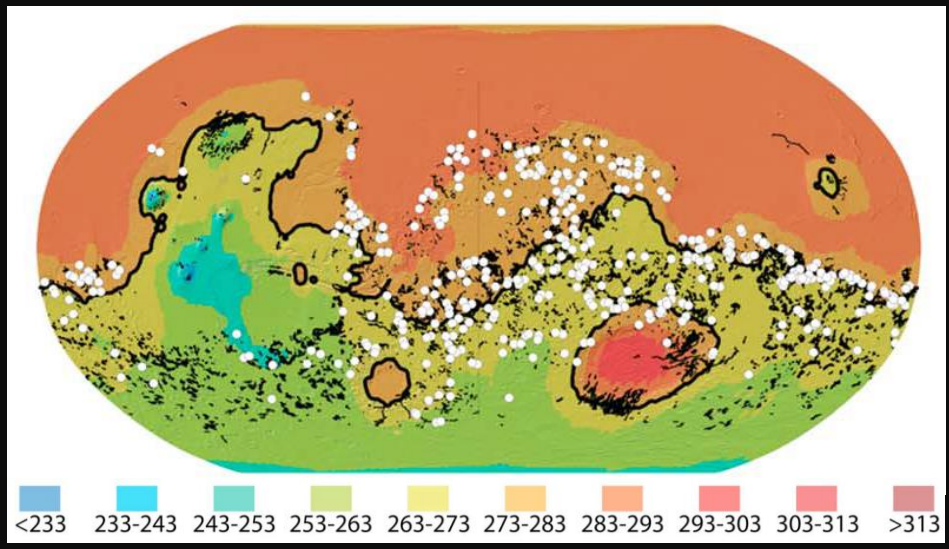
LMD model, 1 bar surface pressure and 25° obliquity

‘Cold and Icy’
[Wordsworth et al., 2013]



(only the radiative effects of CO_2/H_2O gas/clouds)

‘Warm and Wet’
[Palumbo and Head, 2018]

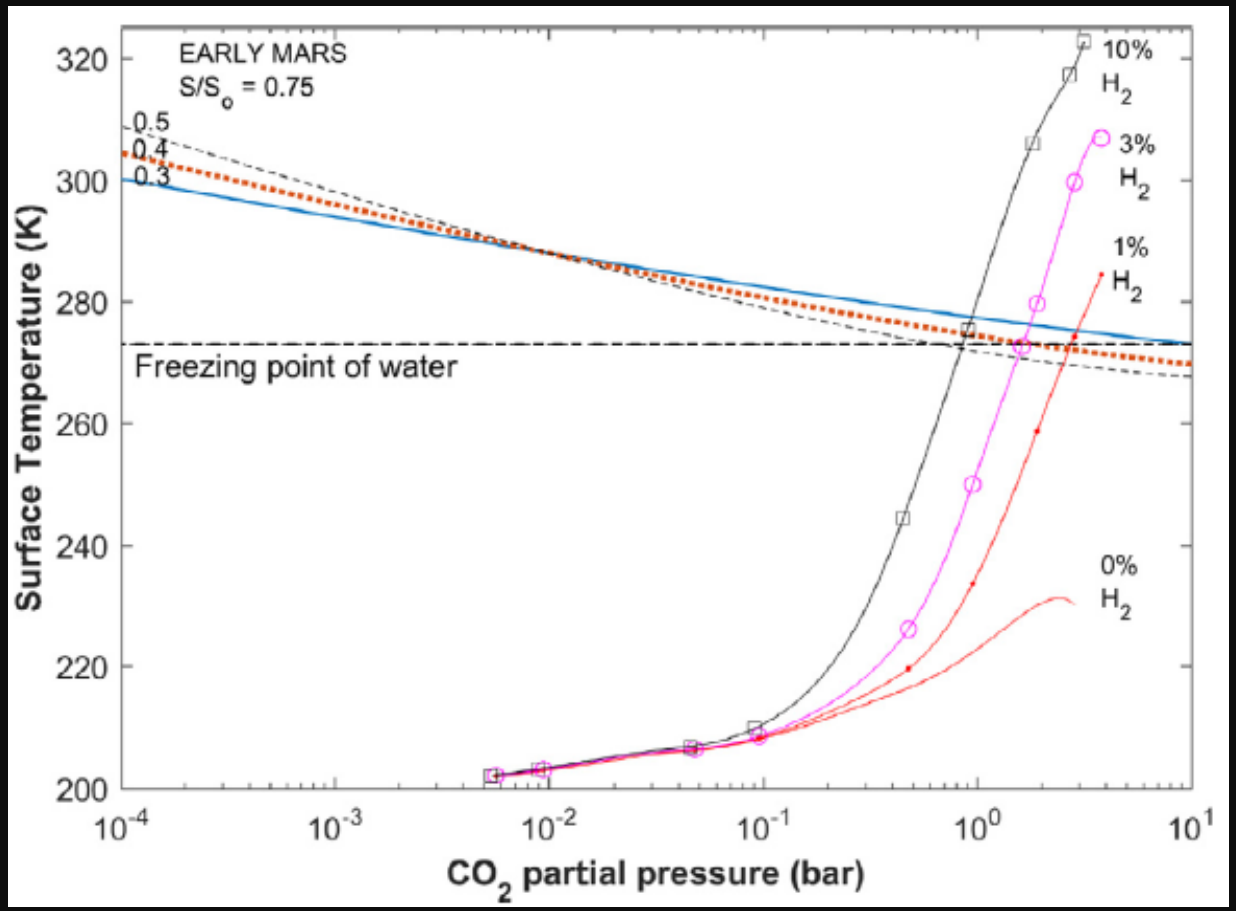


(added an artificial gray gas which absorbs the infrared)

-> Contributed to a significant warming

What is a possible infrared absorber?

Containing H_2 may contribute to the warming even with 1% composition…



[Ramirez, 2017]

Radiation code for DRAMATIC PMGCM (v1)

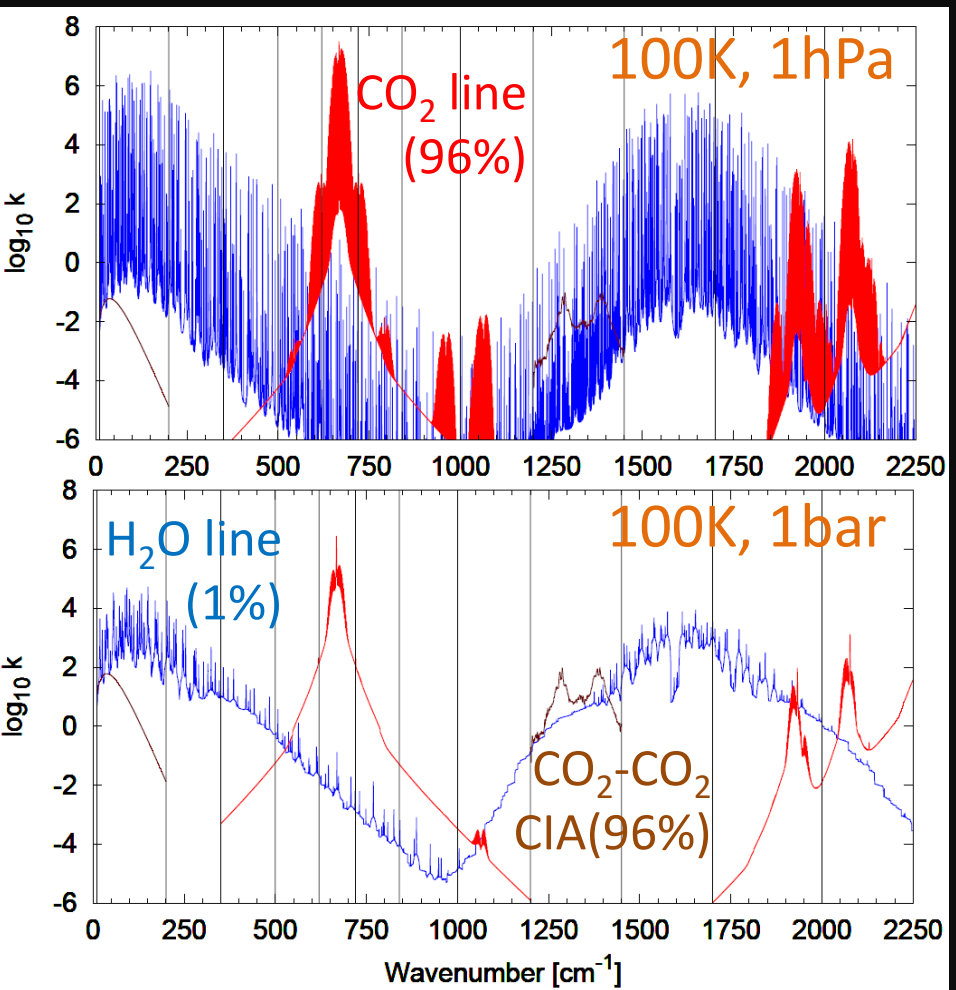
Band	IR(infrared) /SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-200	CO_2-CO_2 CIA, H_2O
2	IR	200-350	H_2O
3	IR	350-500	CO_2, H_2O
4	IR	500-620	CO_2, H_2O
5	IR	620-720	CO_2, H_2O
6	IR	720-840	CO_2, H_2O
7	IR	840-1000	CO_2, H_2O
8	IR	1000-1200	CO_2, H_2O
9	IR	1200-1450	CO_2-CO_2 CIA, H_2O
10	IR	1450-1700	H_2O
11	IR	1700-2000	CO_2, H_2O
12	IR	2000-2250	CO_2, H_2O
13	SO	2250-2500	CO_2, H_2O
14	SO	2500-3000	H_2O
15	SO	3000-4200	CO_2, H_2O
16	SO	4200-5400	CO_2, H_2O
17	SO	5400-7200	CO_2, H_2O
18	SO	7200-9700	CO_2, H_2O
19	SO	9700-13500	H_2O
20	SO	13500-19000	H_2O
21	SO	19000-26000	H_2O
22	SO	26000-35000	-
23	SO	35000-43500	-
24	SO	43500-50000	-

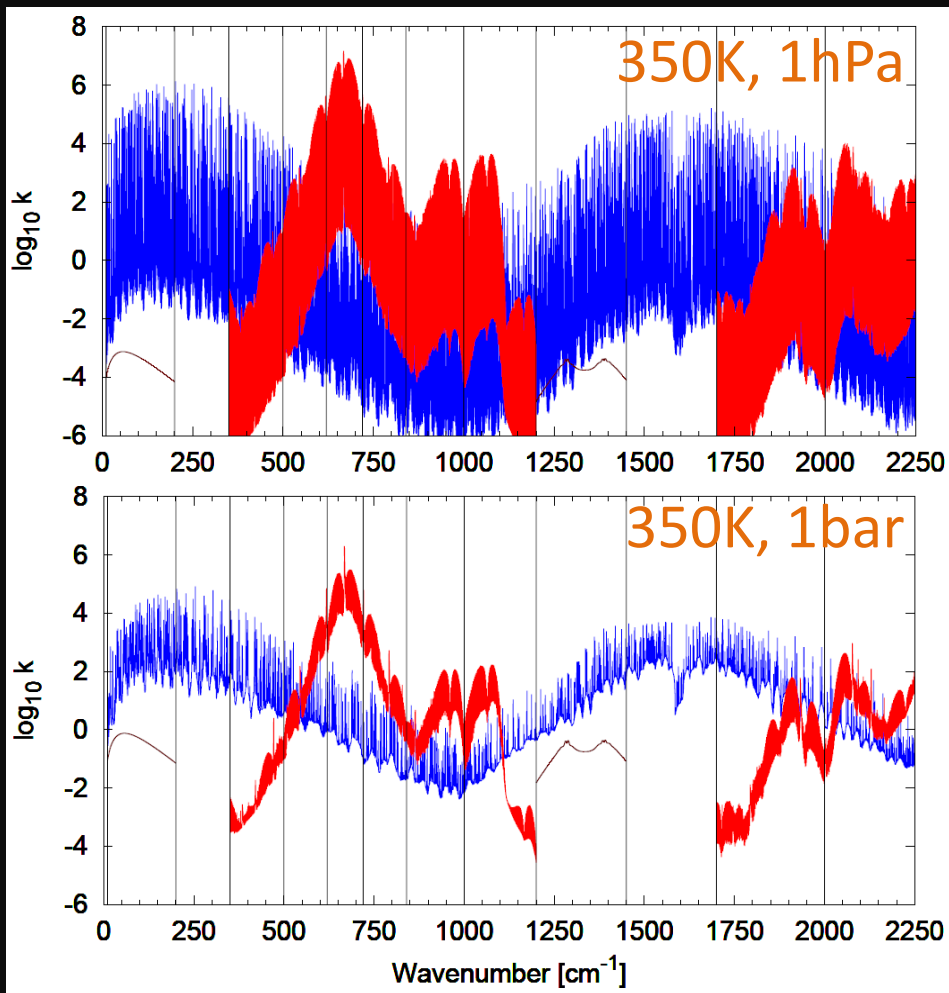
- Correlated k-distribution
- Absorption lines of CO_2 and H_2O: HITRAN2016
- 46 pressure grids: 10^6 Pa (10 bar)-10^{-3} Pa, interval of 0.2 in $\log_{10}$
- 6 temperature grids: 100, 150, 200, 250, 300, 350 K
- 8 grids of water vapor mixing ratio: 10^{-7}-10^{-1}, interval of 1 in $\log_{10}$, and no H_2O case
  D/H ratio: 2.5×VSMOW
- CO_2 CIA: Gruszka and Borysow [1998] (Band 1), Baranov et al. [2004] (Band 9)
- Radiative effects of clouds (H_2O and CO_2) are considered in all wavelengths

Only CO_2 and H_2O

Spectra (infrared)

- Voigt line shape
- H_2O: 25cm^{-1} cutoff + continuum absorption [Clough et al., 1989]
- CO_2: Sub-Lorenz [Perrin and Hartmann, 1989]





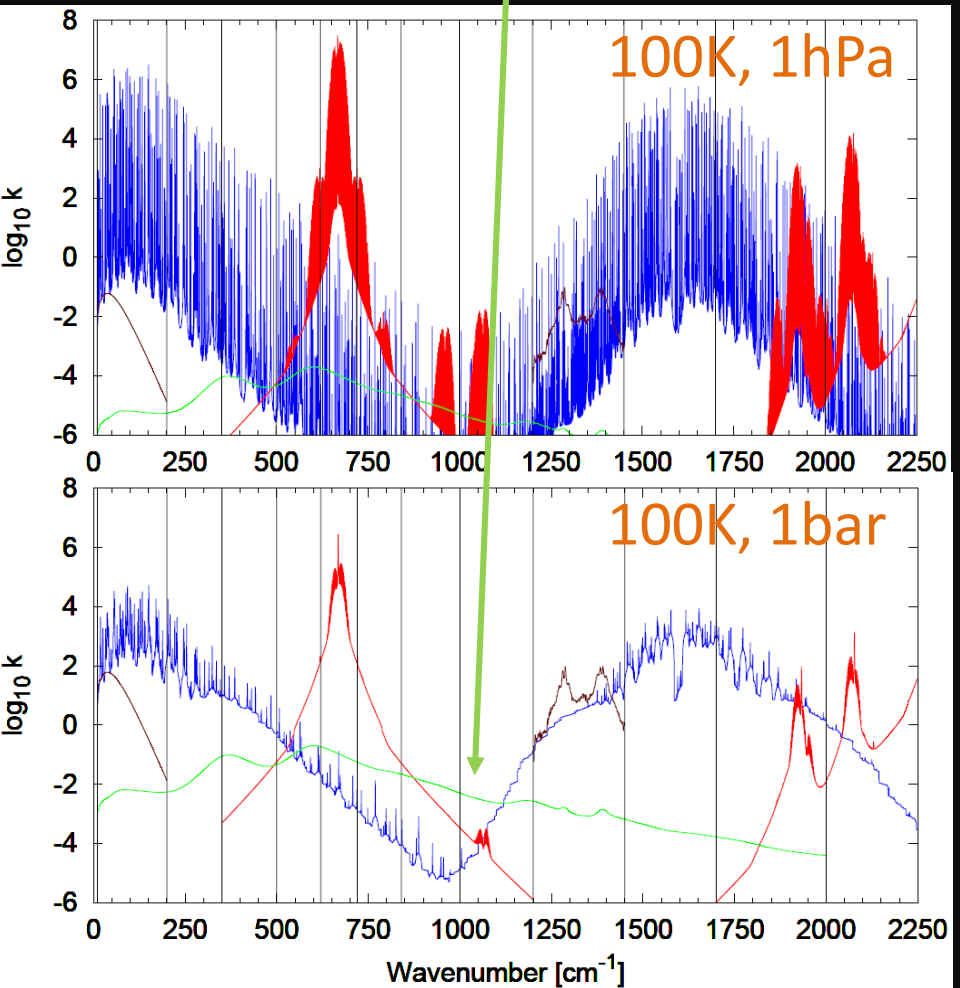
Radiation code for DRAMATIC PMGCM (v2)

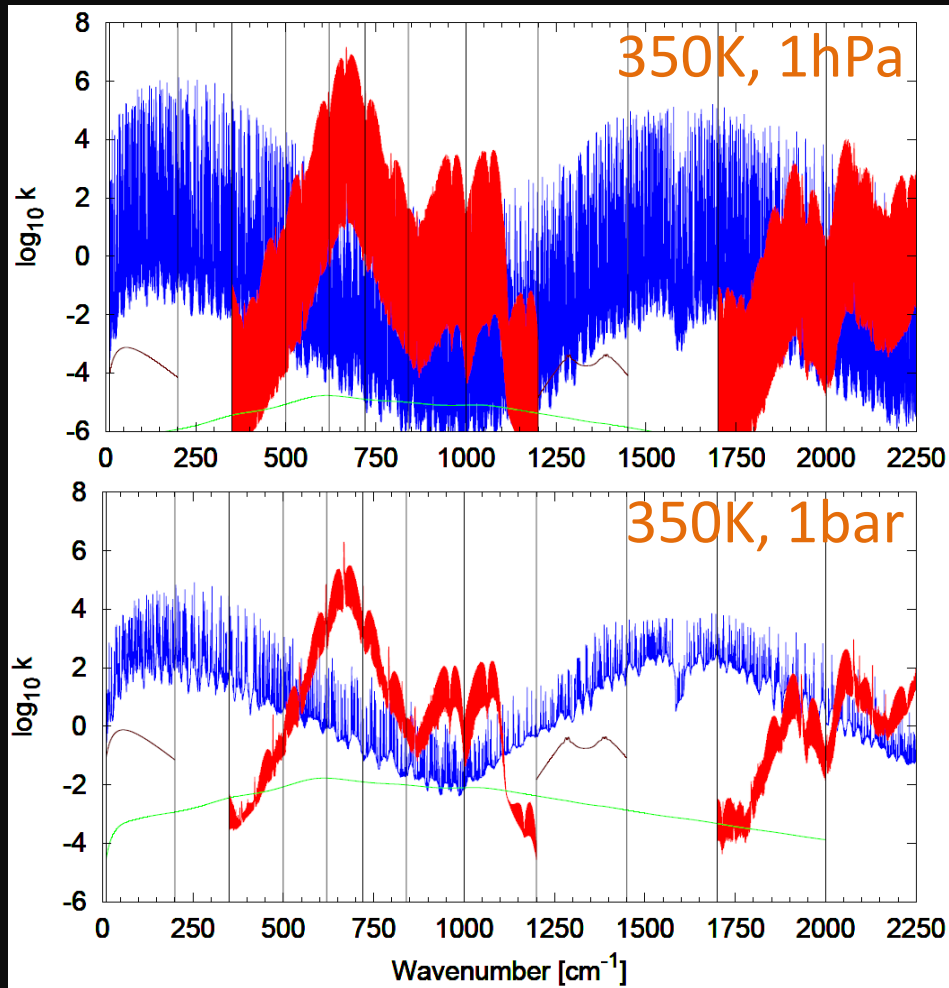
Band	IR(infrared) /SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-200	CO_2-H_2 CIA, CO_2-CO_2 CIA, H_2O
2	IR	200-350	CO_2-H_2 CIA, H_2O
3	IR	350-500	CO_2-H_2 CIA, CO_2, H_2O
4	IR	500-620	CO_2-H_2 CIA, CO_2, H_2O
5	IR	620-720	CO_2-H_2 CIA, CO_2, H_2O
6	IR	720-840	CO_2-H_2 CIA, CO_2, H_2O
7	IR	840-1000	CO_2-H_2 CIA, CO_2, H_2O
8	IR	1000-1200	CO_2-H_2 CIA, CO_2, H_2O
9	IR	1200-1450	CO_2-H_2 CIA, CO_2-CO_2 CIA, H_2O
10	IR	1450-1700	CO_2-H_2 CIA, H_2O
11	IR	1700-2000	CO_2-H_2 CIA, CO_2, H_2O
12	IR	2000-2250	CO_2, H_2O
13	SO	2250-2500	CO_2, H_2O
14	SO	2500-3000	H_2O
15	SO	3000-4200	CO_2, H_2O
16	SO	4200-5400	CO_2, H_2O
17	SO	5400-7200	CO_2, H_2O
18	SO	7200-9700	CO_2, H_2O
19	SO	9700-13500	H_2O
20	SO	13500-19000	H_2O
21	SO	19000-26000	H_2O
22	SO	26000-35000	-
23	SO	35000-43500	-
24	SO	43500-50000	-

Added CO_2-H_2 CIA [Wordsworth et al., 2017] (assuming the H_2 mixing ratio of 1-20 %)

Spectra (infrared)

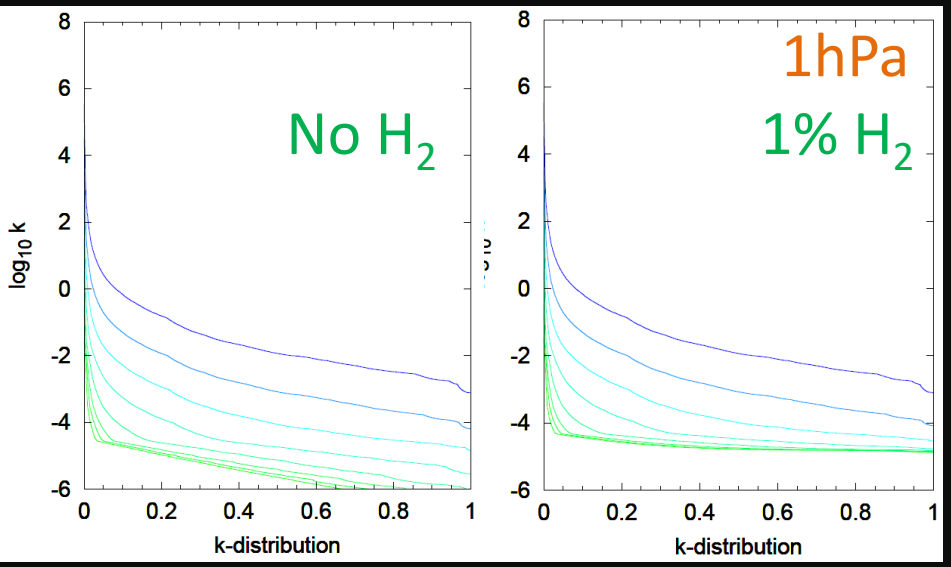
CO_2-H_2 CIA (96% & 1%)

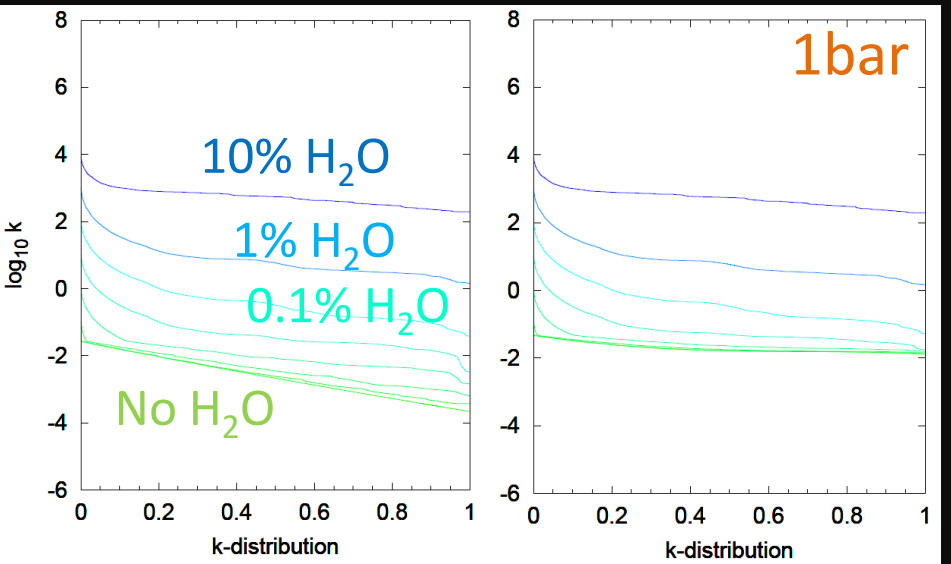




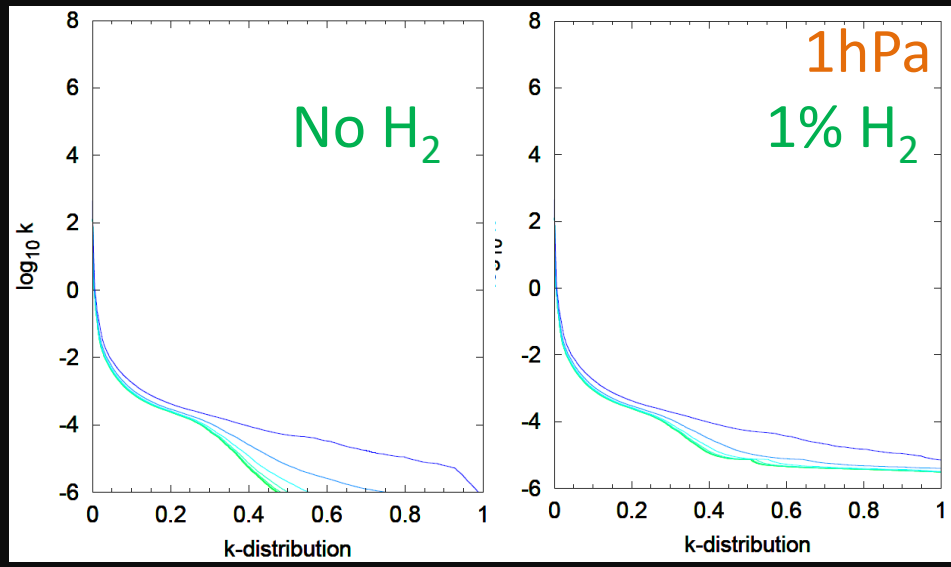
k-distribution

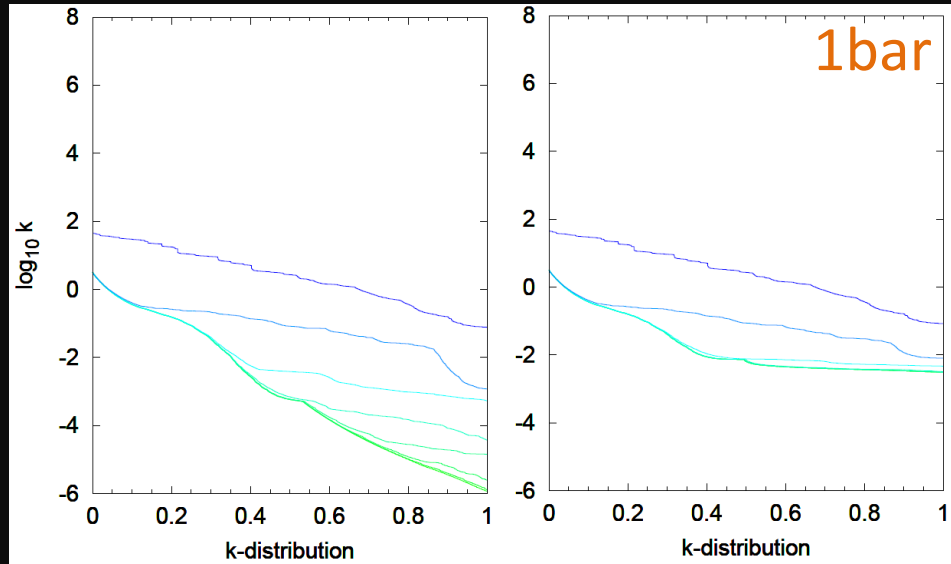
Band 3 (350-500 cm^{-1}), 200K



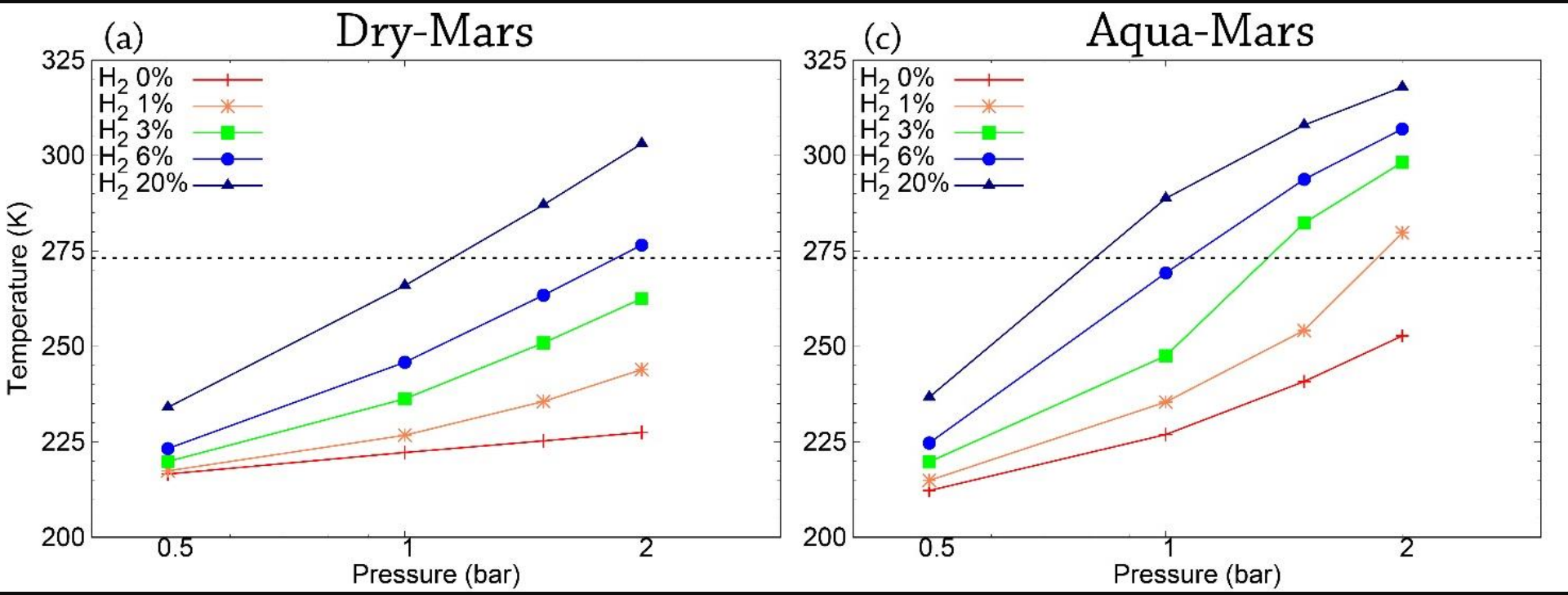


Band 8 (1000-1200 cm^{-1}), 200K





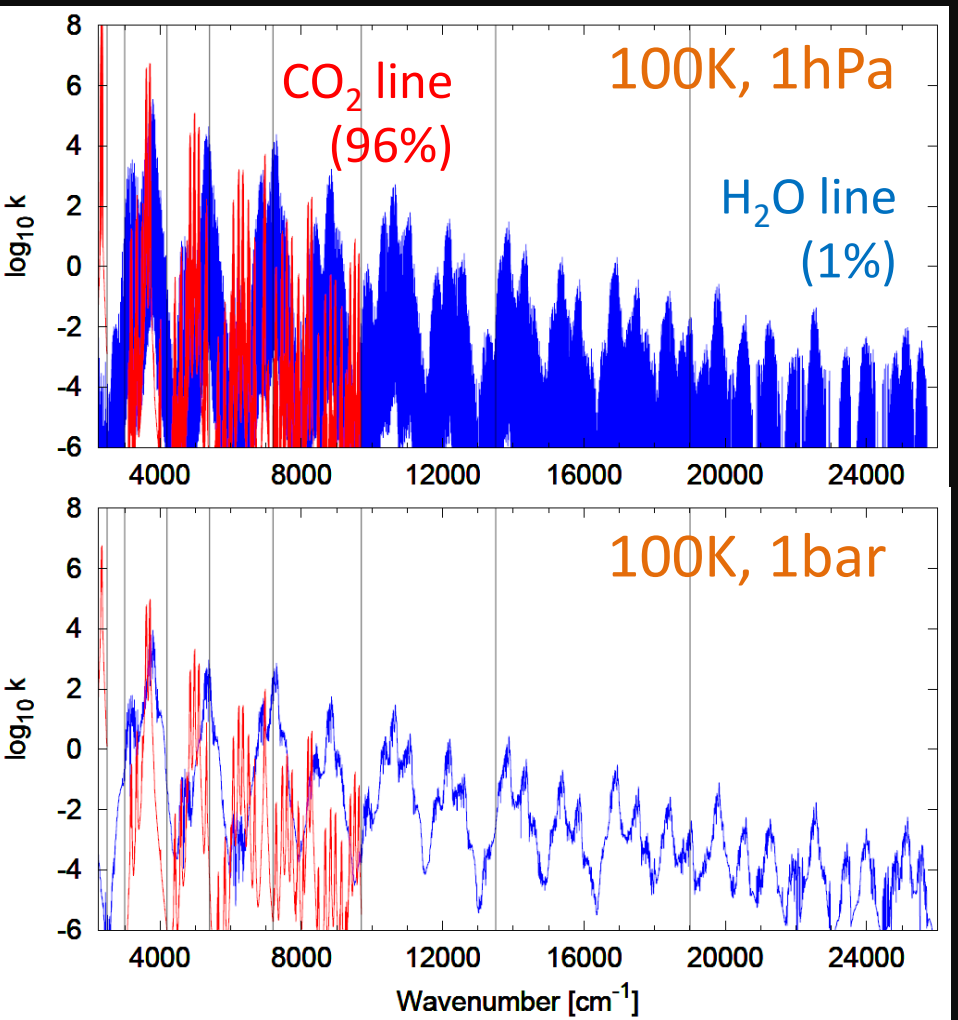
CO_2-H_2 CIA results in the warming!

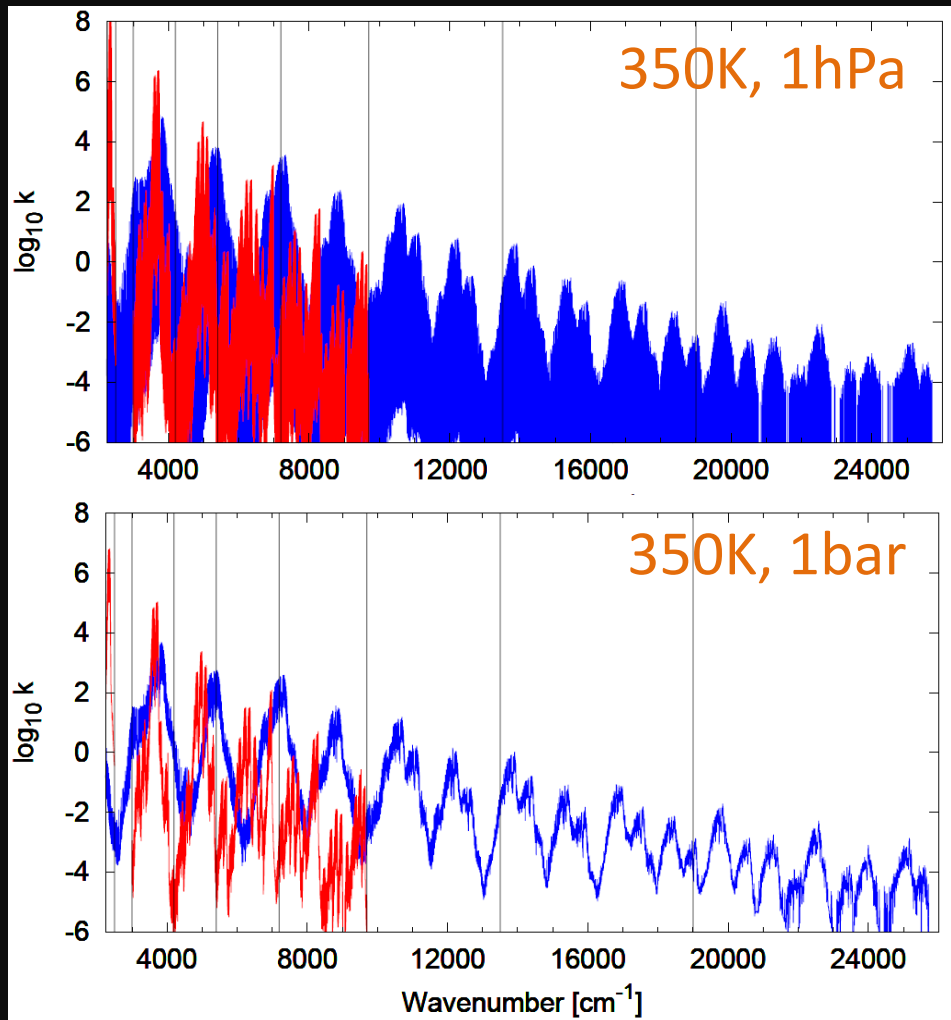


[Kamada et al., 2020]

Spectra (solar)

- Only H_2O and CO_2 lines



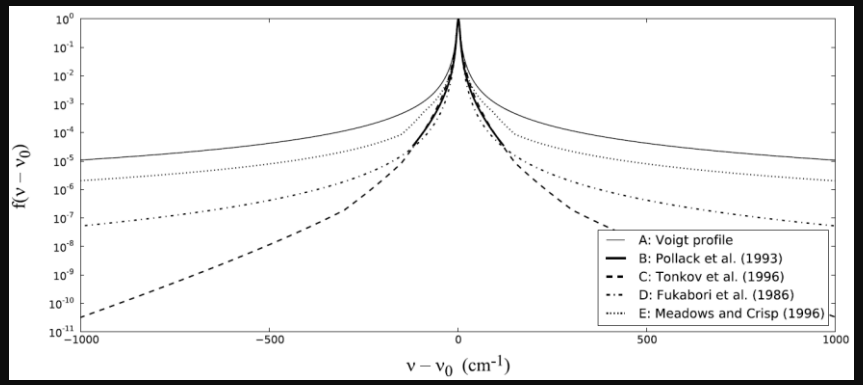


Discussion: How to deal with the line cutoff

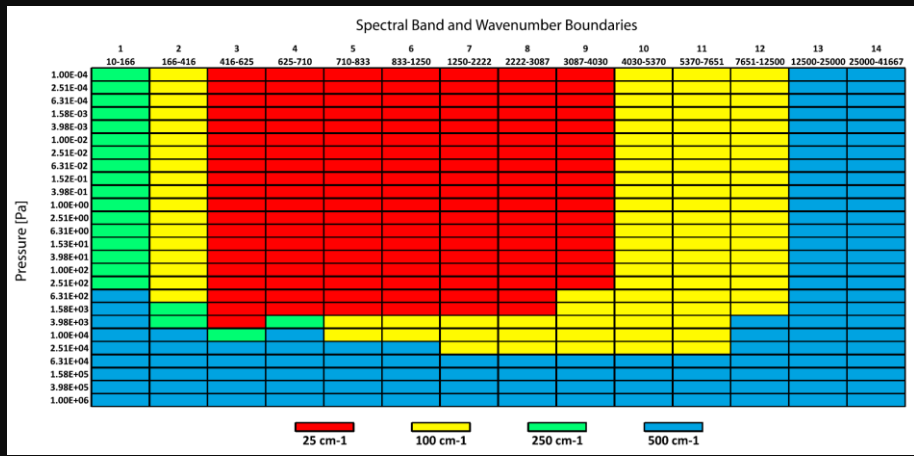
CO_2 absorption line

(for the radiation codes for Venus and paleo Mars, as far as I know)

[Takagi et al., 2010]



- Eymet et al. [2009] -> Lebonnois et al. [2010] (for Venus): Voigt line shape, 25cm^{-1} cutoff
- Ikeda [2011] (for Venus): Sub-Lorenz [Fukabori et al., 1986]
- Lebonnois et al. [2015] (for Venus): Sub-Lorenz [Pollack et al., 1993]
- Forget et al. [2013] (for paleo Mars): Sub-Lorenz [Perrin and Hartmann, 1989] (current standard?)
- Mischna et al. [2012] (for paleo Mars): cutoff of 25-500cm^{-1}, depending on the pressure and wavenumber land (see the right figure)



Discussion: How to deal with the line cutoff

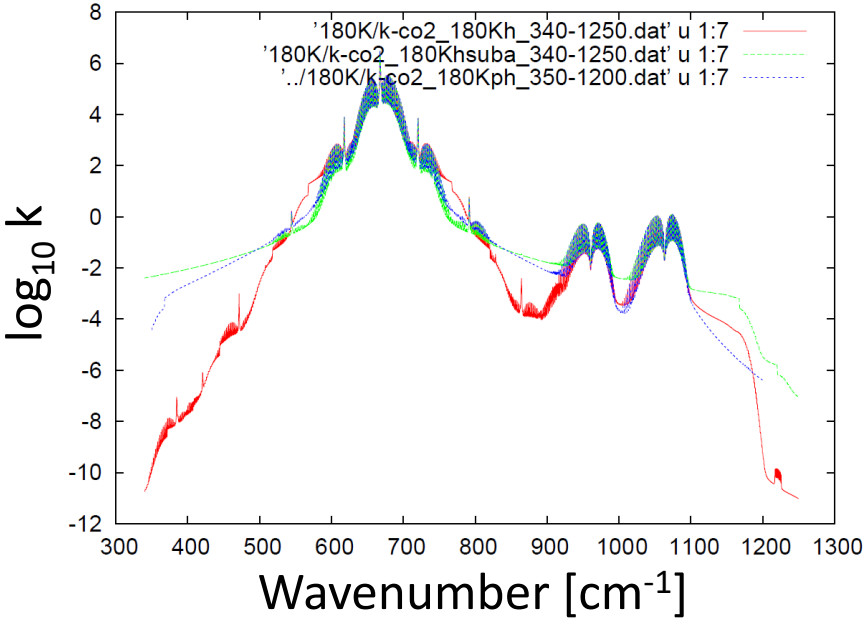
Comparison of CO_2 cutoff definitions

- Voigt 25cm^{-1} cutoff (red)
- Fukabori et al. [1986] sub-Lorenz (green)
- Perrin and Hartmann [1989] sub-Lorenz (blue)

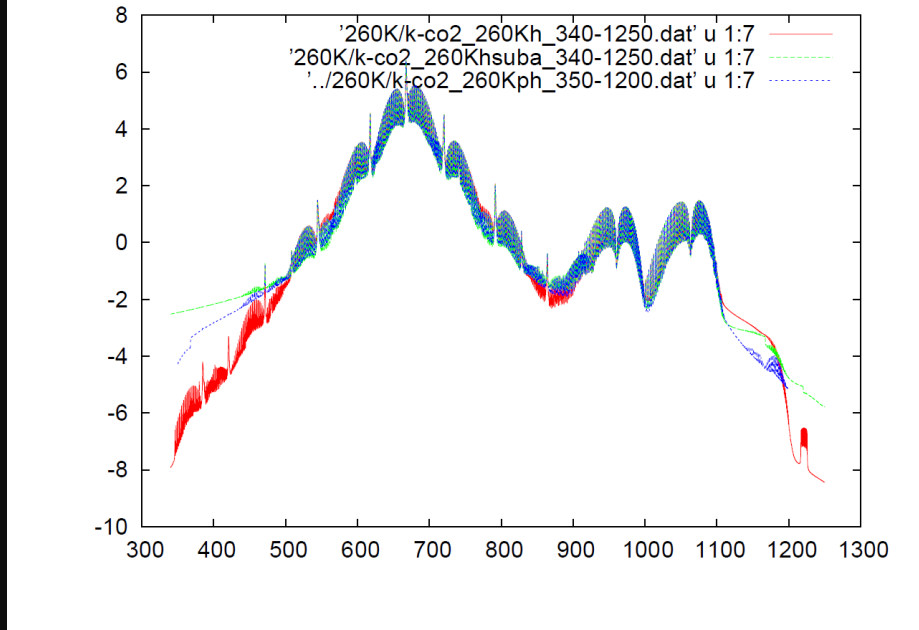
The difference is not very big between Fukabori and Perrin-Hartmann coordinates.

From my old calculations (Infrared, 1bar)

180K



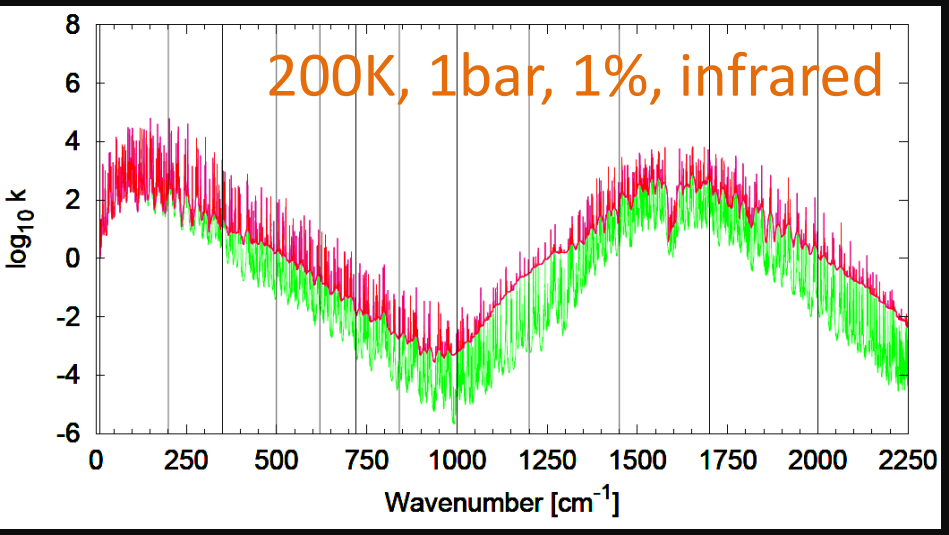
260K

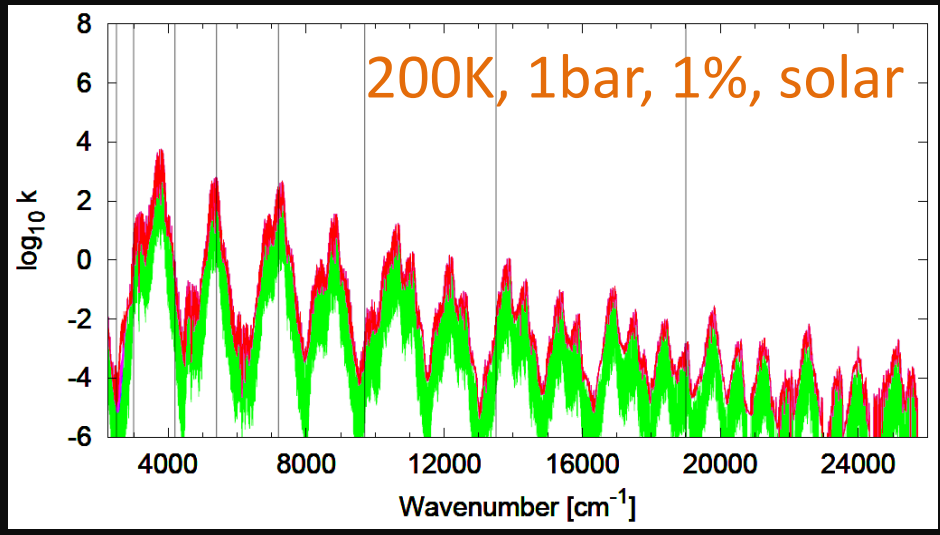


Discussion: How to deal with the H_2O lines

Importance of the continuum absorption

- Only Voigt 25cm^{-1} cutoff (green)
- Voigt 25cm^{-1} cutoff + continuum absorption [Clough et al. 1989] adopted in this study (red) (also in Wordsworth et al. [2013] (for paleo Mars) and Lebonnois et al. [2015] (for Venus))





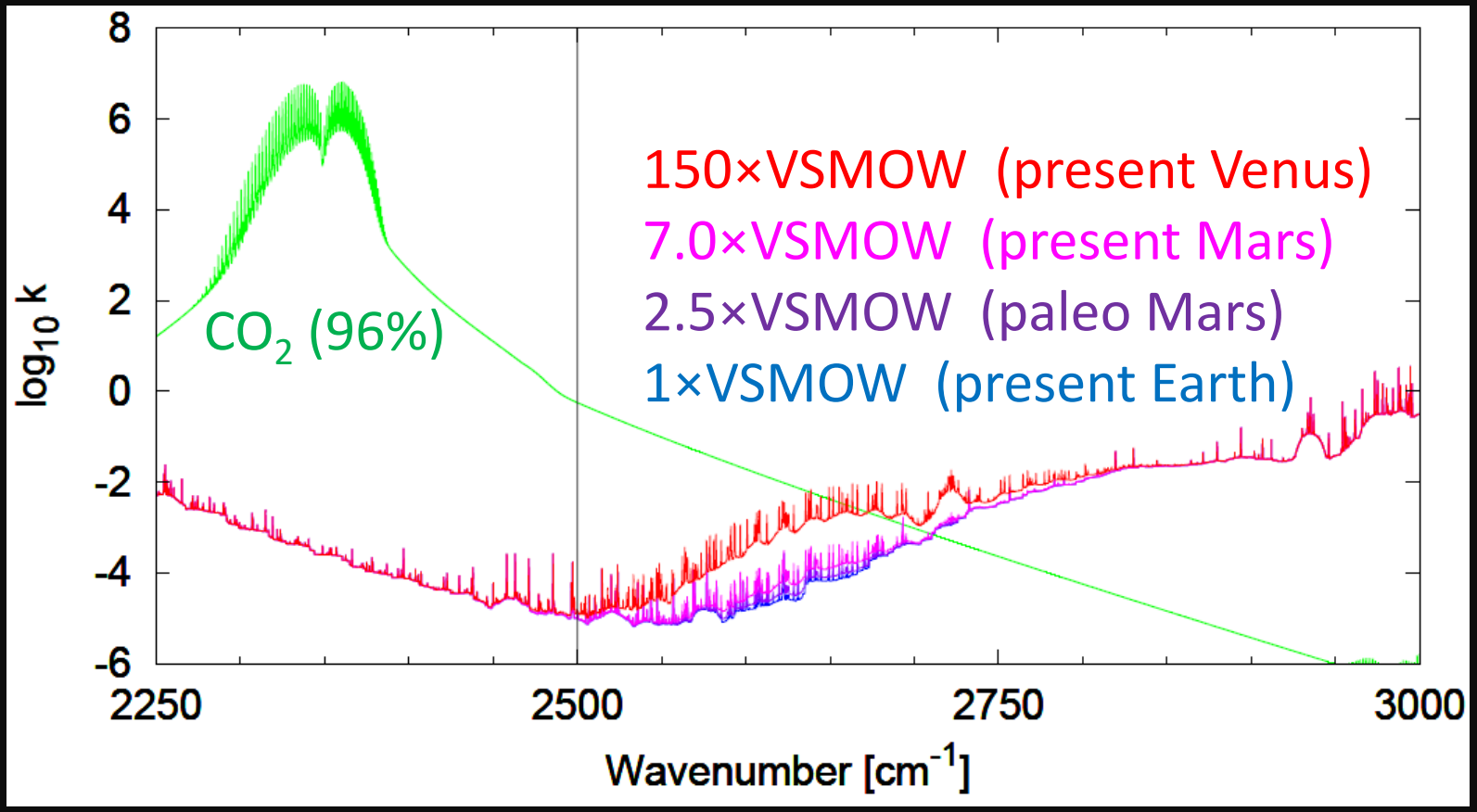
- In lower pressures or lower mixing ratios, the effects of continuum absorption become smaller.

Discussion: How to deal with the H_2O lines

Sensitivity of HDO/H_2O ratio:

obvious changes are seen only in this wavenumber region.

(window of CO_2 absorption, but depends on the pressure/temperature and mixing ratios of both CO_2 and water vapor)



Next step: extension of the radiation code

Band	IR(infrared)/ SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-200	N_2-N_2 CIA, CO_2-CO_2 CIA, H_2O
2	IR	200-350	N_2-N_2 CIA, CO_2-CO_2 CIA, CO_2, H_2O
3	IR	350-500	N_2-N_2 CIA, CO_2-CO_2 CIA, CO_2, H_2O
4	IR	500-620	CO_2-CO_2 CIA, CO_2, H_2O
5	IR	620-720	CO_2-CO_2 CIA, CO_2, H_2O
6	IR	720-840	CO_2, H_2O
7	IR	840-1000	CO_2, H_2O
8	IR	1000-1200	CO_2-CO_2 CIA, CO_2, H_2O
9	IR	1200-1450	CO_2-CO_2 CIA, CO_2, H_2O
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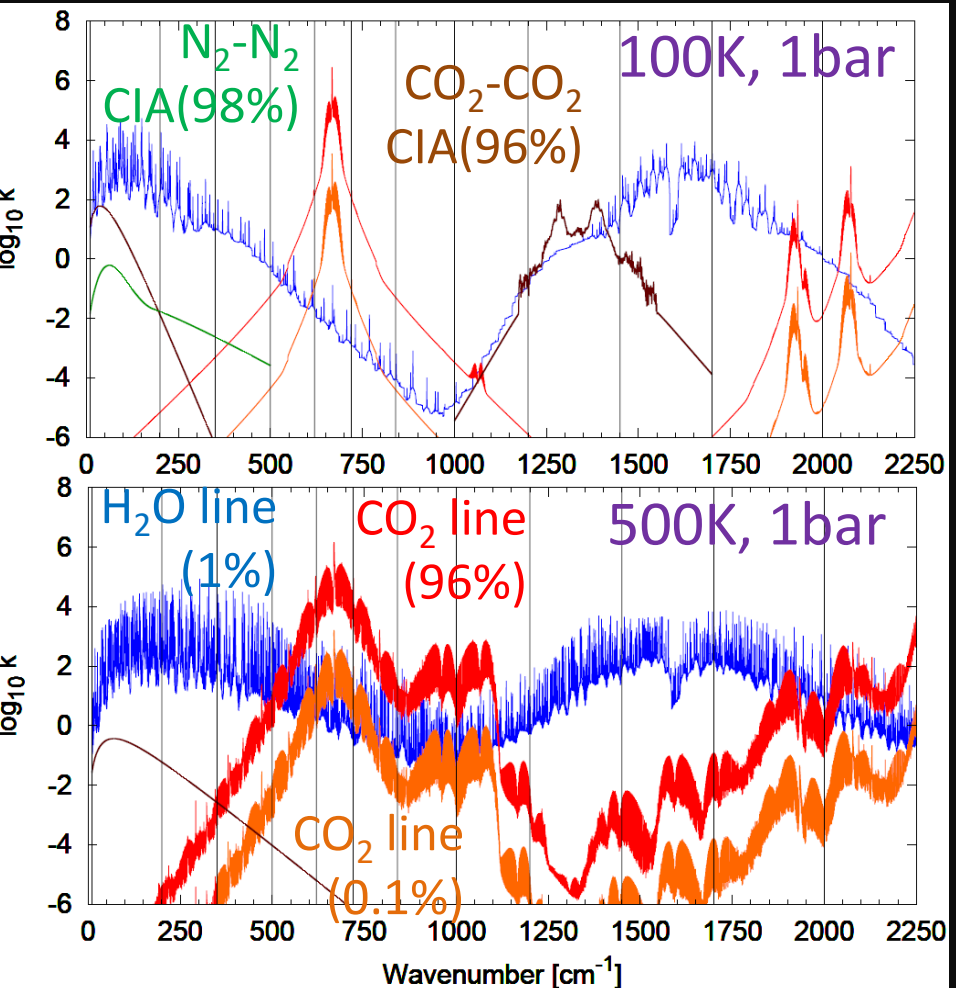
21	SO	19000-26000	H_2O
22	SO	26000-35000	-
23	SO	35000-43500	-
24	SO	43500-50000	-

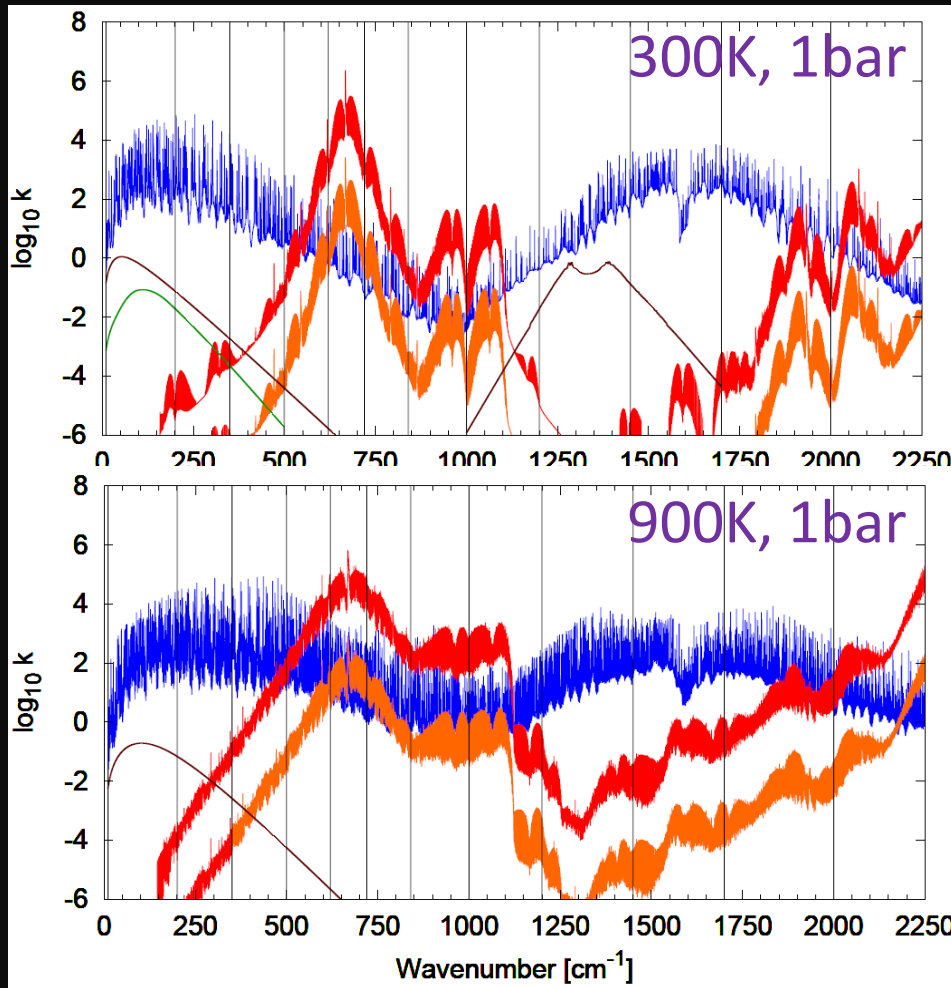
Covering also present/paleo Venus and Earth

- Pressure up to 100 bar, and temperature up to 900 K
- 51 pressure grids and 12 temperature grids (newly added 400, 500, 600, 700, 800, 900 K)
- HITEMP2010 for CO_2 absorption lines higher than 400 K
- CO_2 mixing ratios for 96, 10, 1, 0.1, 0.01%
- Assuming N_2 for the component other than CO_2 and H_2O

Next step: extension of the radiation code

- N_2-N_2 CIA: from Karman et al. [2015] (for only 100-350 K)
- CO_2-CO_2 CIA: 10-720 cm^{-1} for all T grids, 1000-1700 cm^{-1} for only 100-350 K
- H_2O lines for high temperature are still from HITRAN2016 at present (adoption of HITEMP2010 is planned for future)





Summary

- A radiation code for a $CO_2/H_2O/H_2$ atmosphere assuming the early Mars has been developed for the implementation into a GCM.
- The CO_2-H_2 collision-induced absorption covers the whole infrared band (10-2000 cm^{-1}), and critically affect the warming even with 1% mixing ratio of H_2.
- Cutoff/sub-Lorenz assumption of CO_2 lines and the continuum absorption of H_2O lines affect the estimations of their radiative effects.
- Sensitivity of the HDO/H_2O ratio on the line spectra is seen only in 2500-2750 cm^{-1}, and the effects on the actual absorption should depend on the CO_2 mixing ratio, pressure and temperature.
- Extension of the radiation code to cover up to the pressure of 100 bar and temperature of 900 K, and N_2-main atmosphere with CO_2 mixing ratio of down to 0.01% (covering the environments of present/paleo Venus and Earth) is ongoing.