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Atmospheric dynamics and material transport in the Martian lower atmosphere: towards the connection to upper atmosphere

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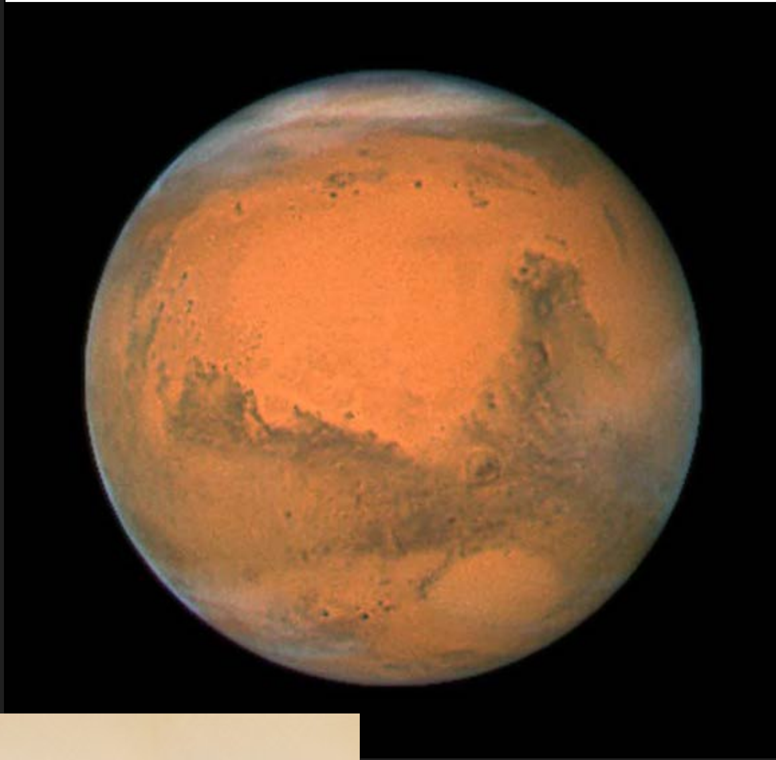
Overview of Mars

- The 4th planet of the Solar System
- CO_2 occupies 95% of the atmosphere
- Radius: about a half of Earth
- Gravity: 0.38 times of Earth
- Equivalent length of a solar day and inclination to the Earth (existence of four seasons)
- 1 Martian year corresponds to 1.87 terrestrial year.

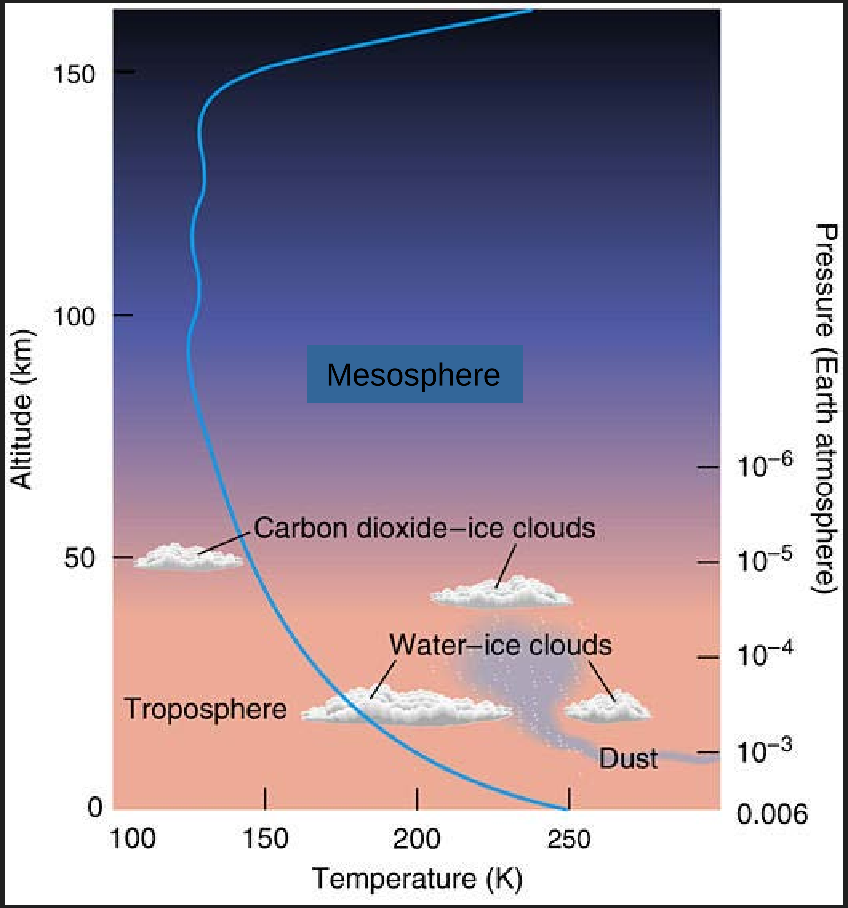
From Hubble Space Telescope



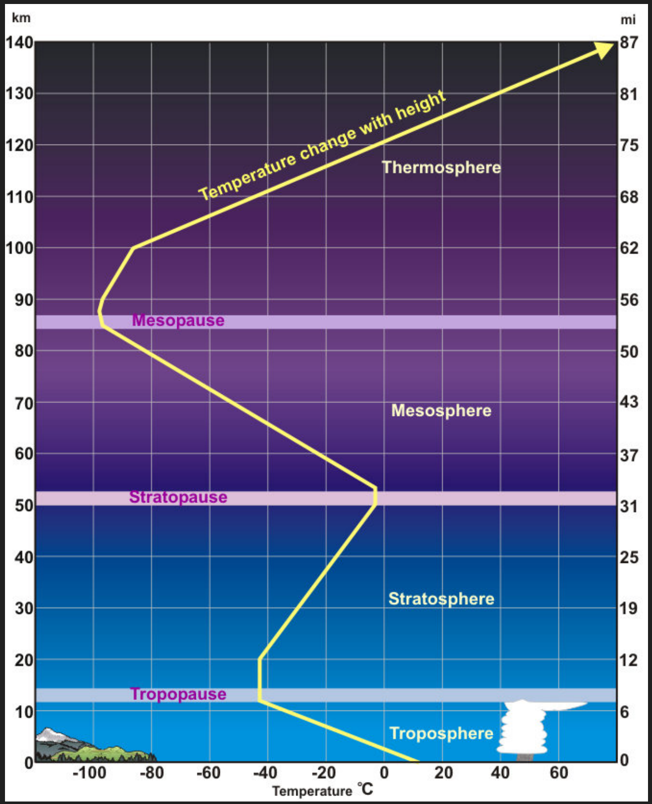
From Mars Pathfinder

Atmospheric environment on Mars

Vertical structure



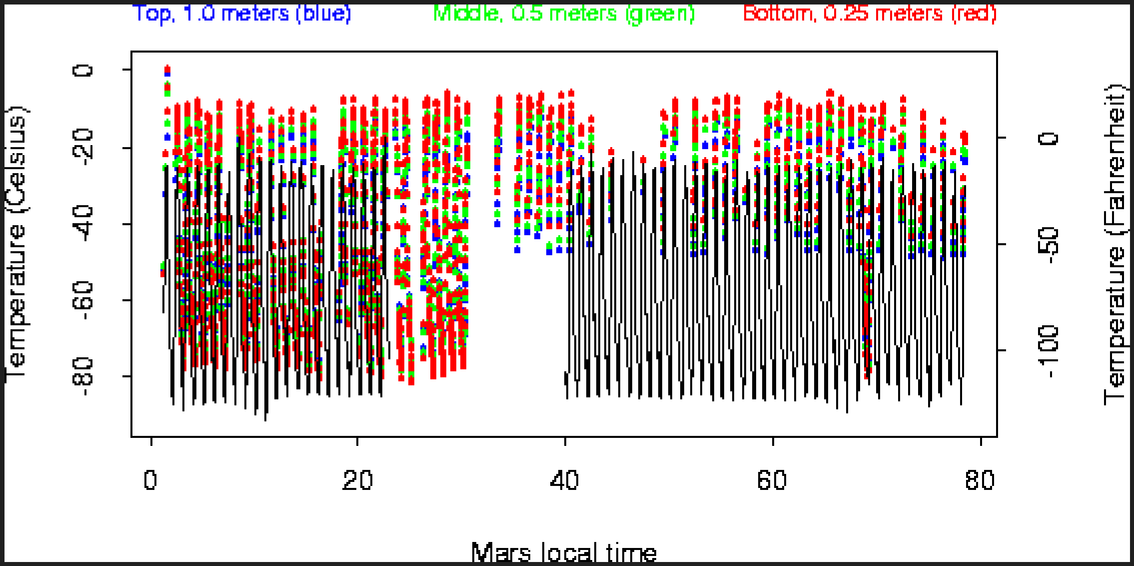
(Ref: on Earth)



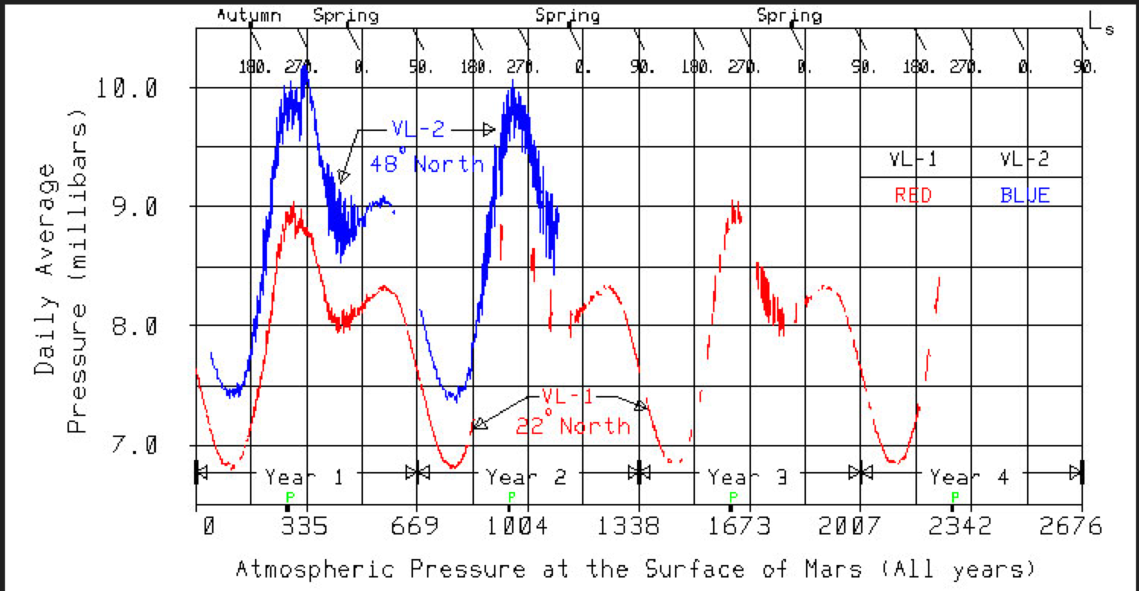
- No stratosphere
- Dust and water ice clouds: up to ~40 km height
- CO_2 ice clouds: higher than ~40 km

Atmospheric environment on Mars surface

Atmospheric temperature (Viking, Mars Pathfinder)



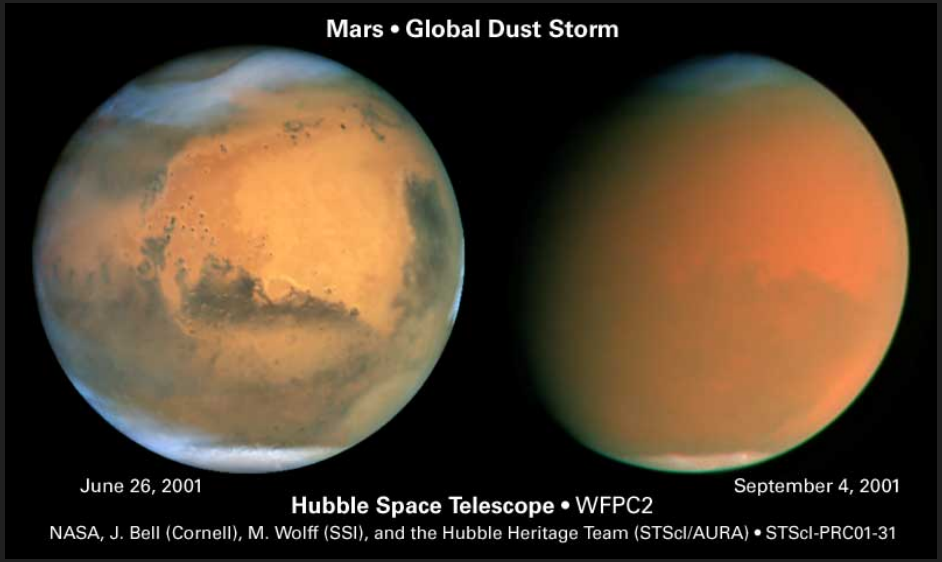
Pressure (Viking)



- Atmospheric temperature: 140~270 K (-130~0 ºC)
- Large temperature difference between day and night (~60 K)
- Surface pressure: 4~10 hPa (100~250 times smaller than on Earth)
- Large annual variance of pressure (~25 %) because CO_2 atmosphere freezes in winter pole.

Dust storm on Mars

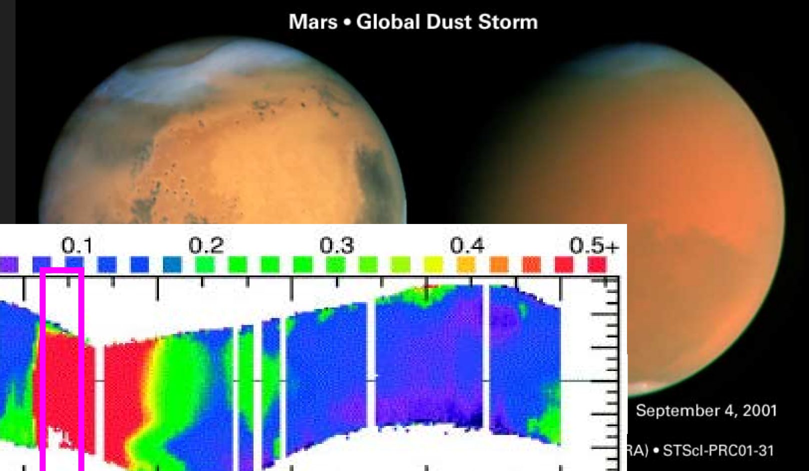
Global dust storm



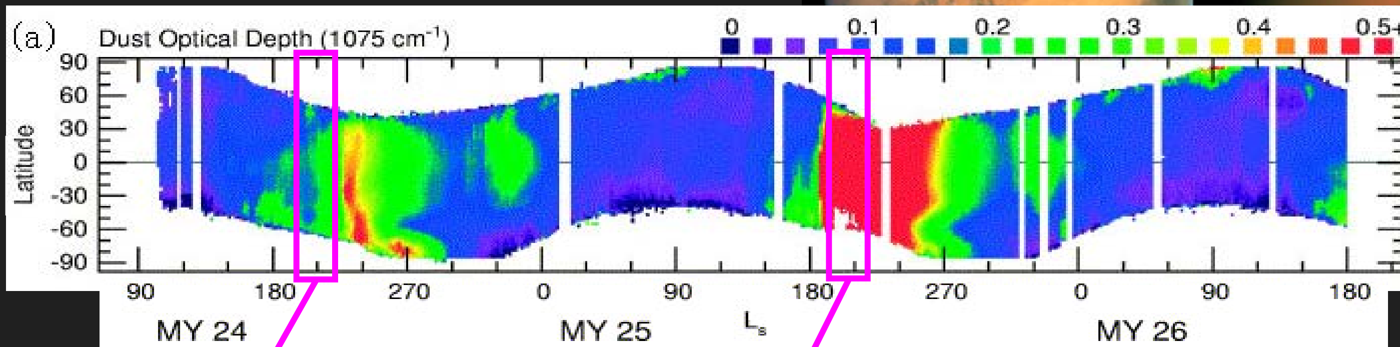
- Planet-encircling dust storms have been sometimes observed in southern spring or summer (around perihelion).
(not in every Martian year)
- Dust storms significantly affect the meteorology of Mars.

Dust devil

Impact of dust on the atmospheric field

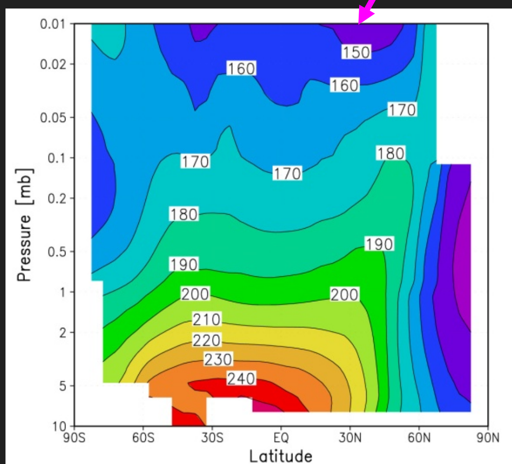


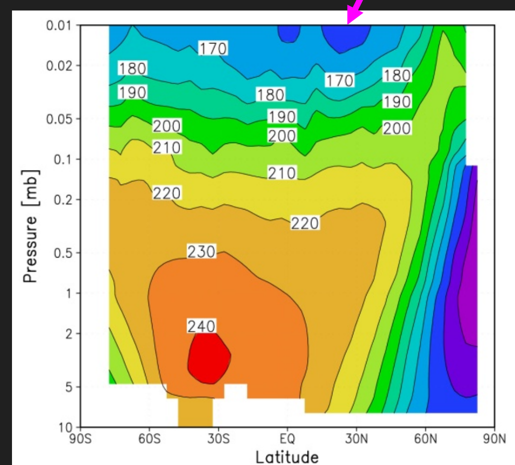
Dust opacity
[*Smith*, 2004]

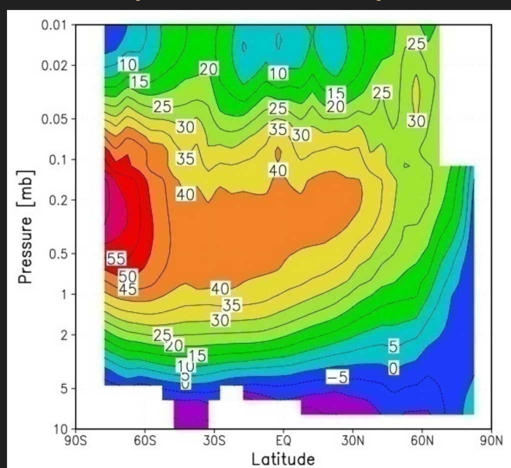


Zonal-mean temperature (daytime)
(MGS-TES observation)

Difference of temperature
(MY25-MY24)





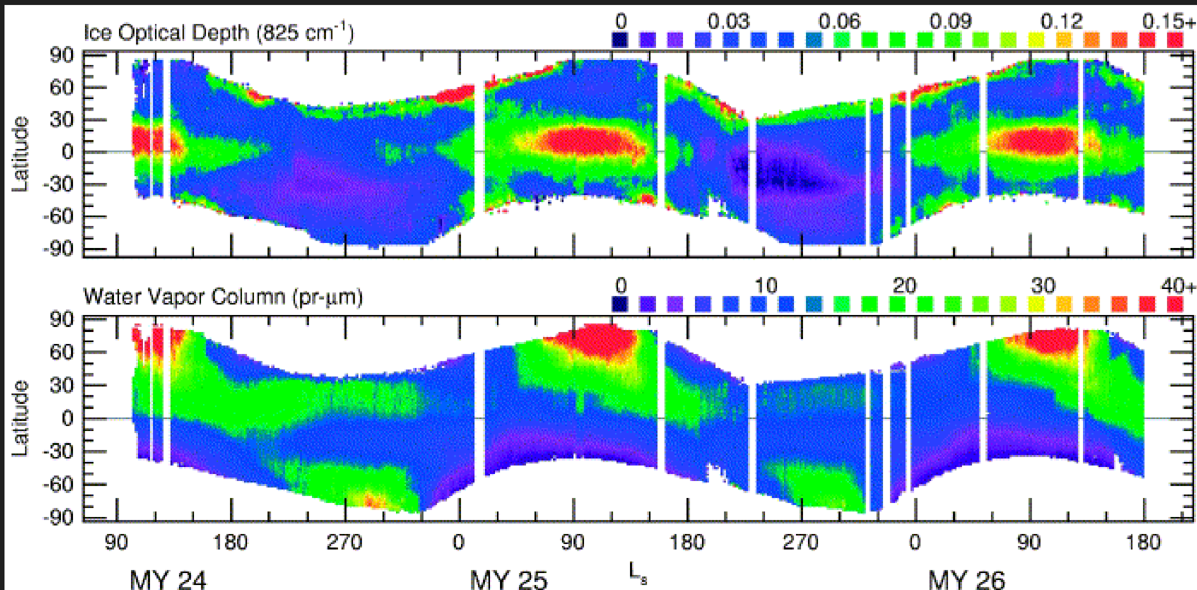


From our review paper [Medvedev et al., 2011, Aeolian Research 3, 145-156]

- During a global dust storm, temperature increases for up to ~60 K due to the radiative effects of dust.

Water cycle on Mars

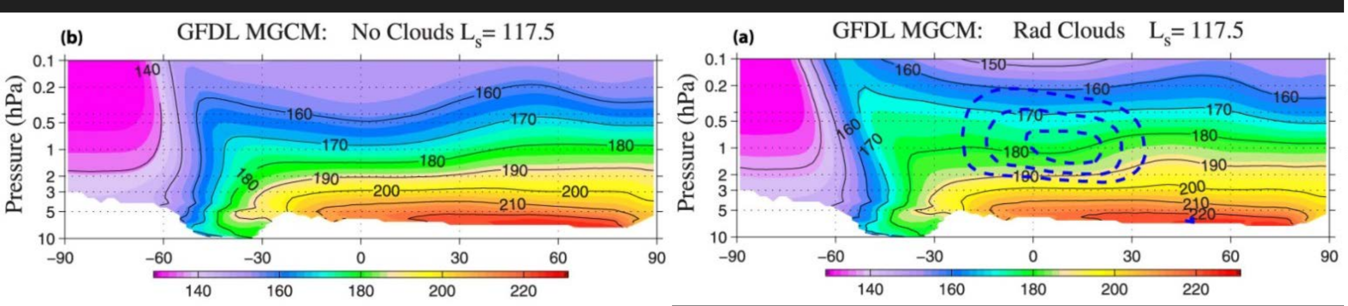
Water ice optical depth (top) and water vapor column density (bottom) [Smith, 2004]

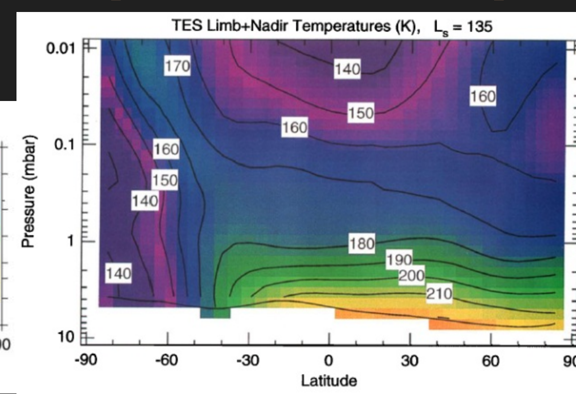


- Water is one of the minor species on the current Mars (column density of water vapor is 5-10 pr.μm in average, ~100 pr.μm in maximum).
- Even though that, the effects of water ice is not ignorable on the temperature fields (warming 5-10 K).

MGS-TES observation [Smith et al., 2001]

Radiative effects of ice clouds from GFDL MGCM [Wilson et al., 2008]





Vertical distributions of water vapor

MEx-SPICAM observations [Maltagliati et al., 2011, 2013]

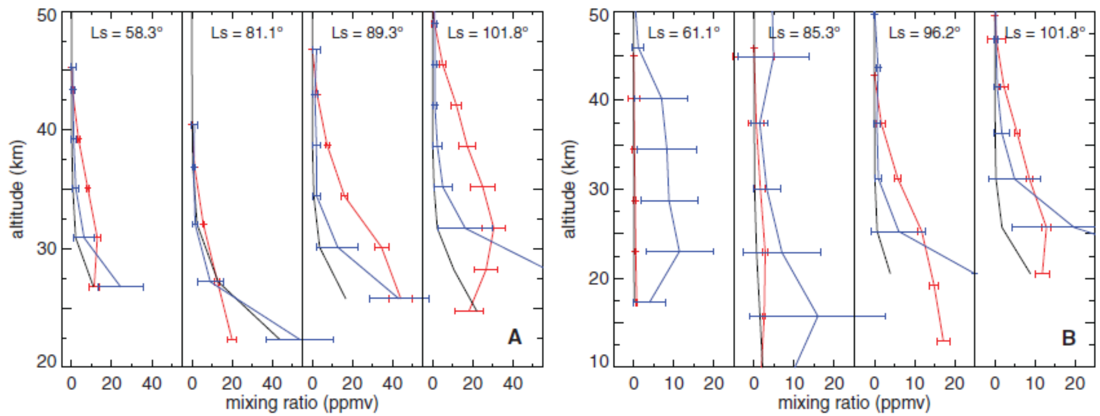


Fig. 2. Selection of typical water vapor volume–mixing ratio profiles in the (**A**) northern and (**B**) southern hemisphere. Black curve, modeled profile by the LMD-GCM; red curve, the retrieved SPICAM results; blue curve, saturation water vapor–mixing ratio. Supersaturation exists where the red values are greater than the blue ones.

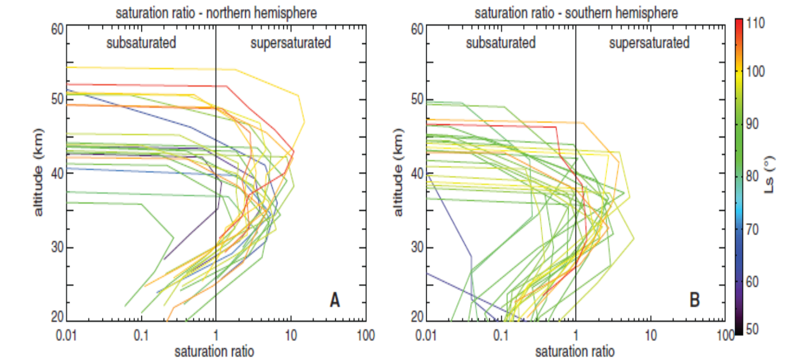
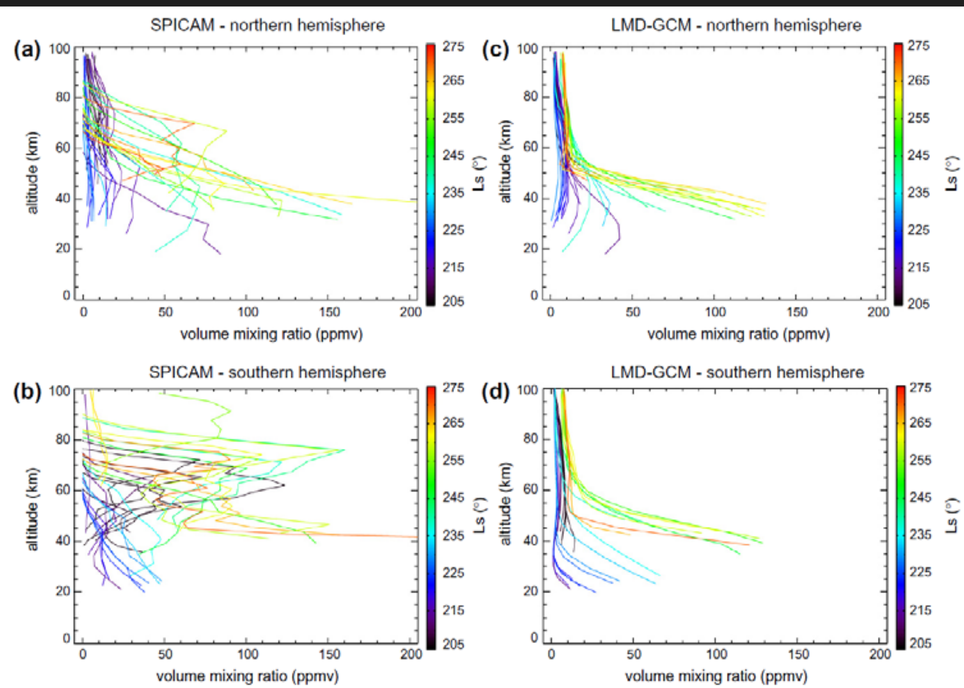


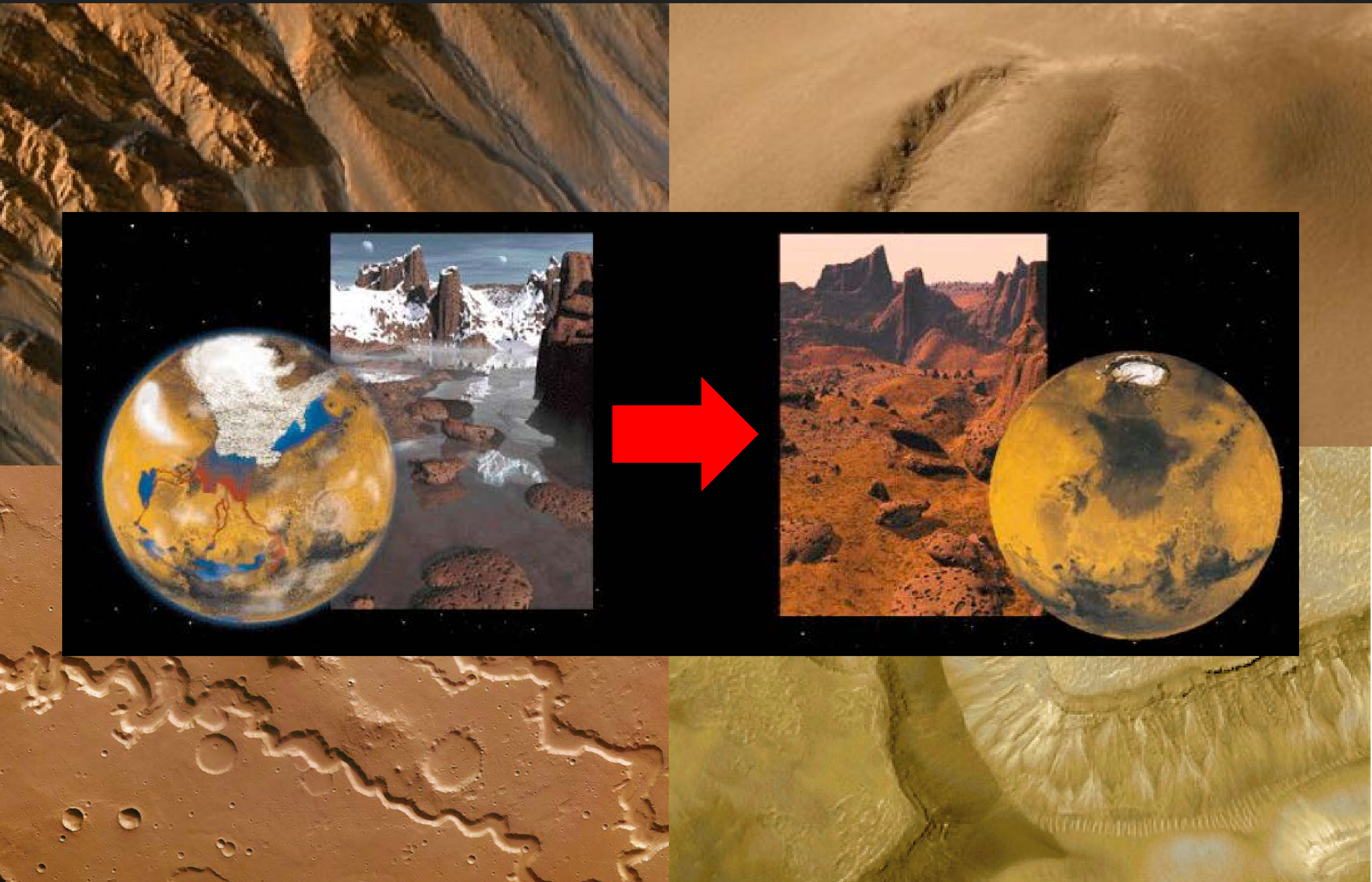
Fig. 3. Saturation ratio for all orbits of the campaign. (**A**) Northern hemisphere. (**B**) Southern hemisphere. The vertical line marks the value of 1, which corresponds to the saturated state.



- MEx-SPICAM have detected several profiles of vertical distributions of water vapor, and found that there are extreme supersaturations with the ratio of up to ~10.
- It also observed that the water vapor may exist up to ~80km height, which is much higher than theoretical ‘hygropause’.

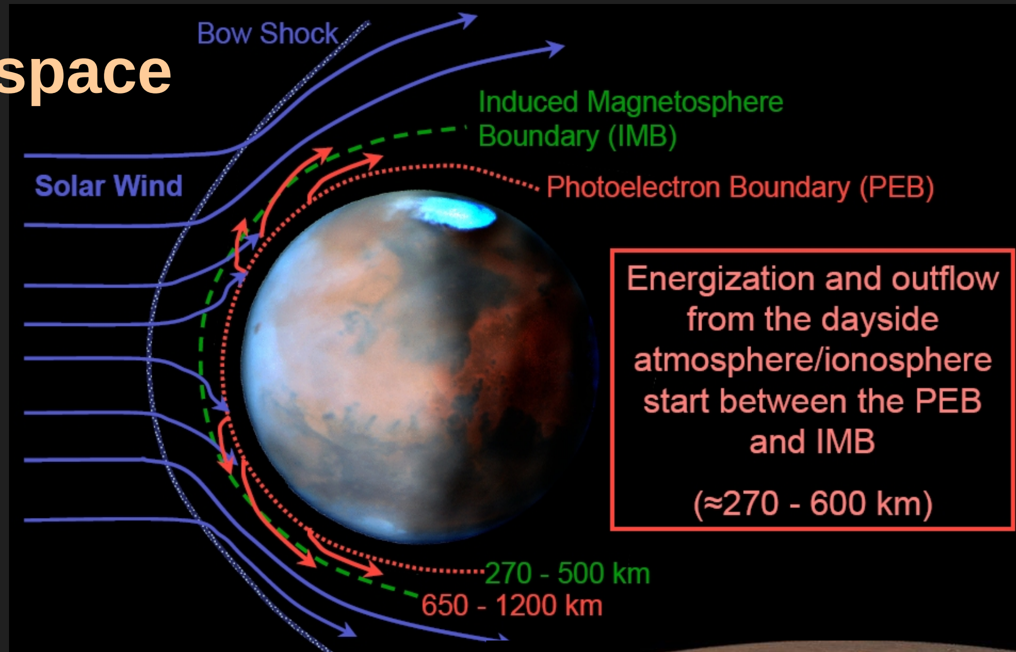
History of water on Mars

Evidences of past liquid water flow on Mars surface

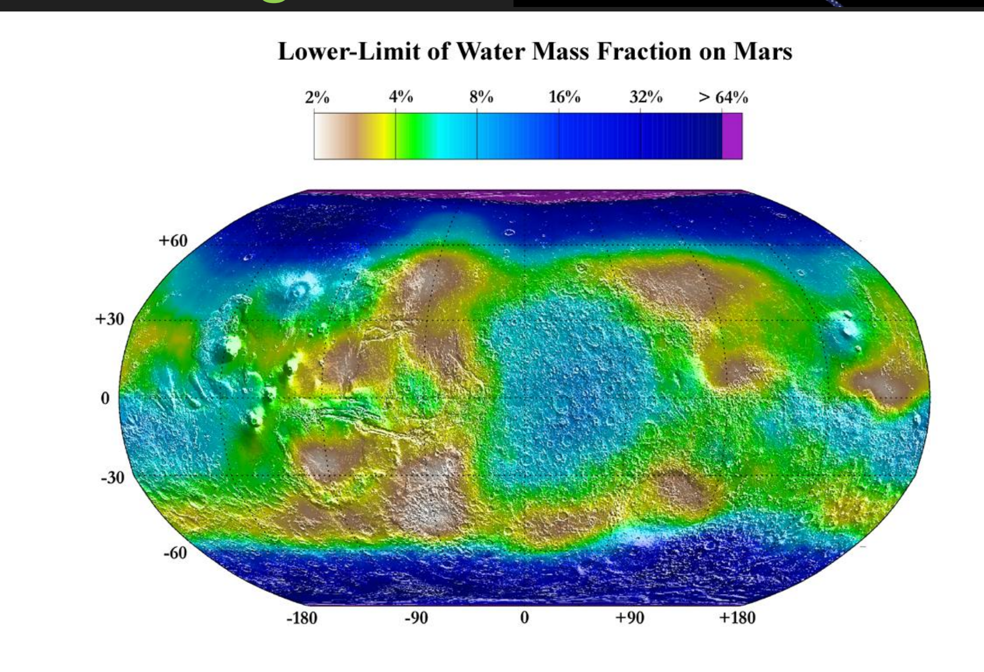


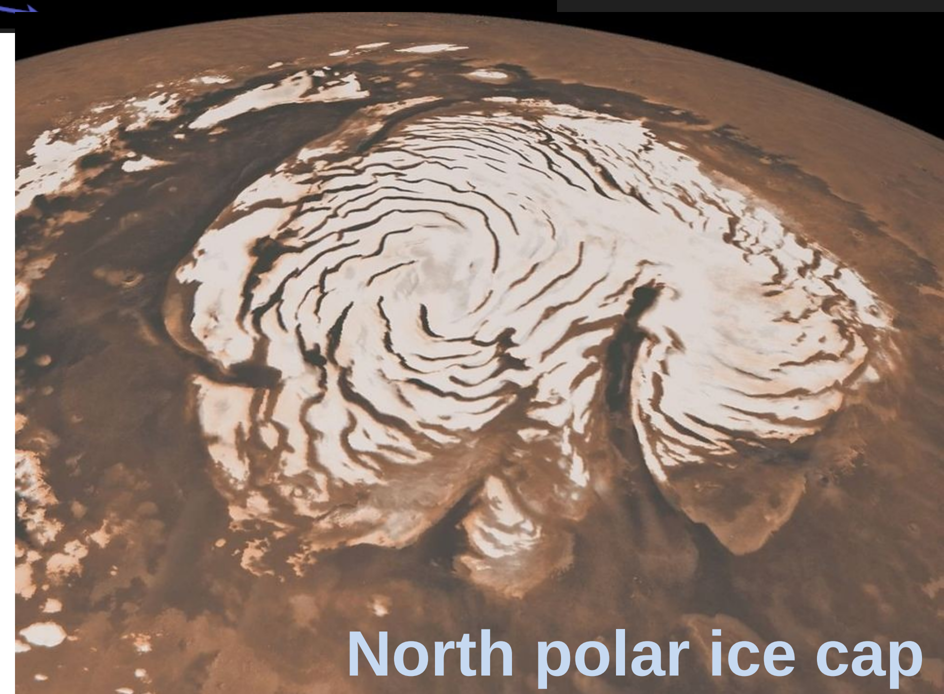
Where has the liquid water gone?

Escape to the space



Underground

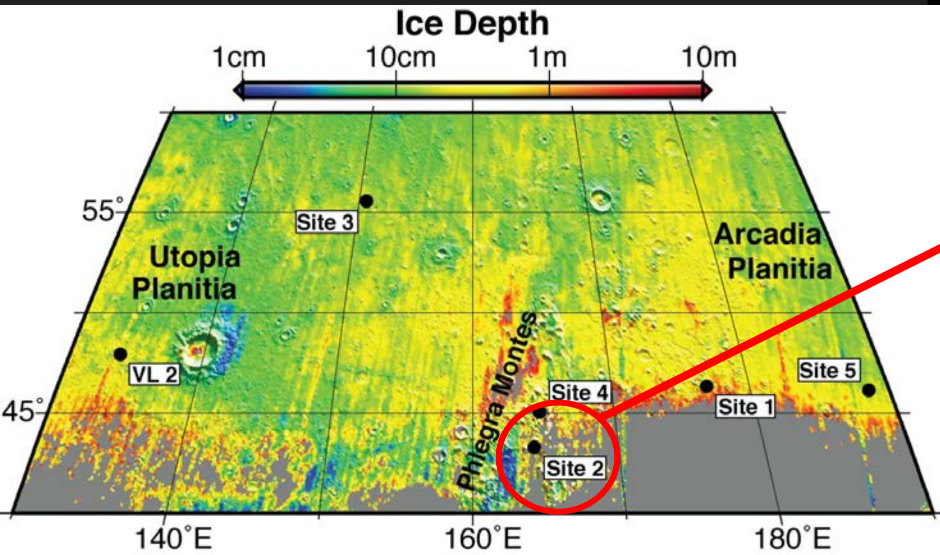


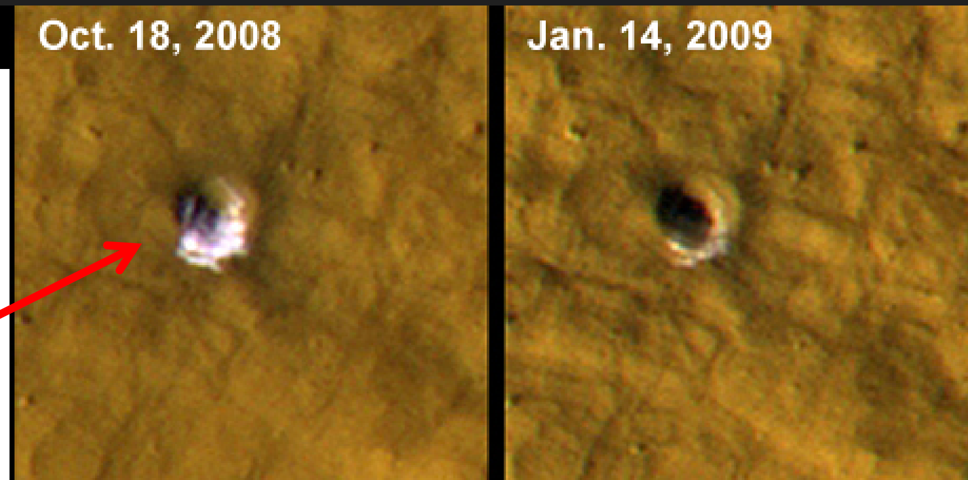


North polar ice cap

Subsurface water in the northern hemisphere

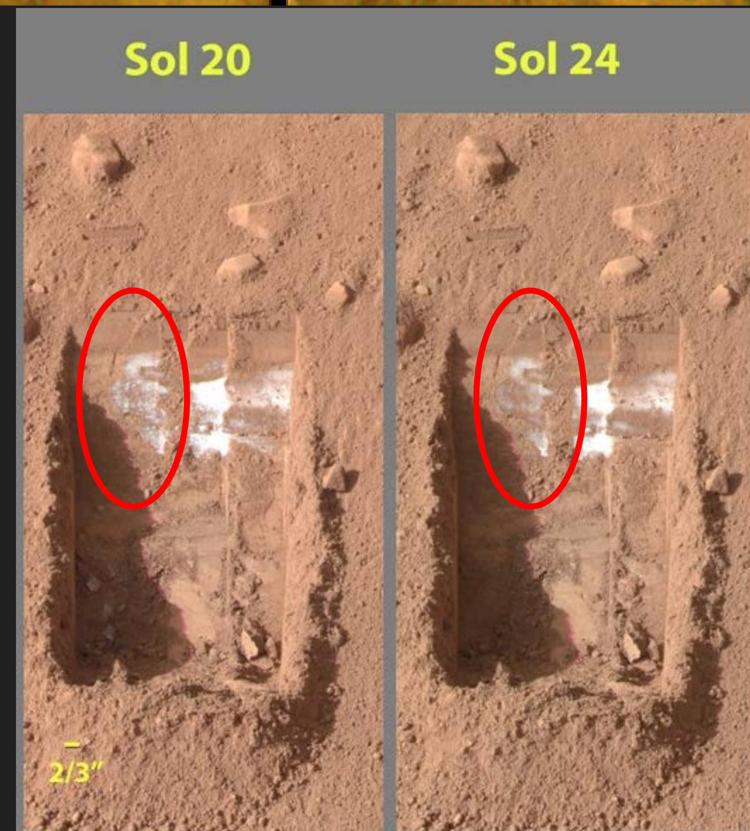
From Mars Reconnaissance Orbiter





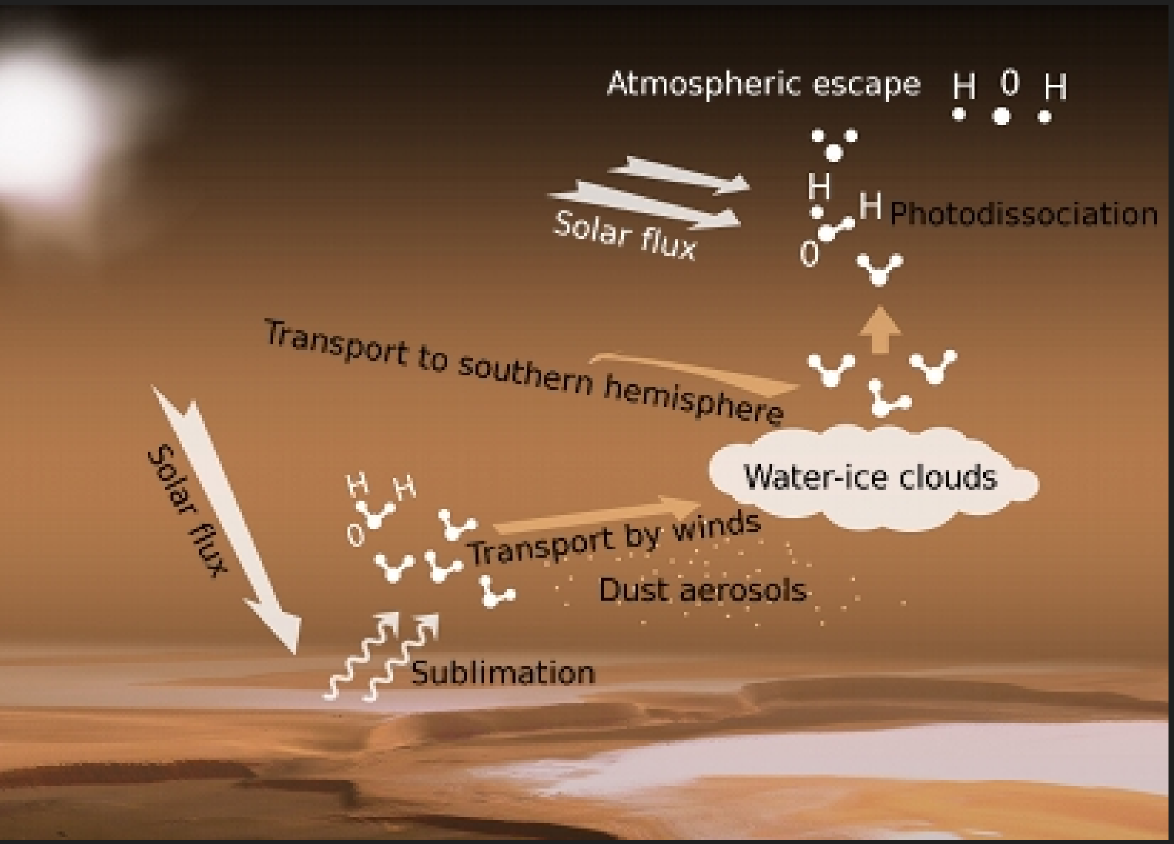
From Phoenix

[Byrne et al., 2009, Science]

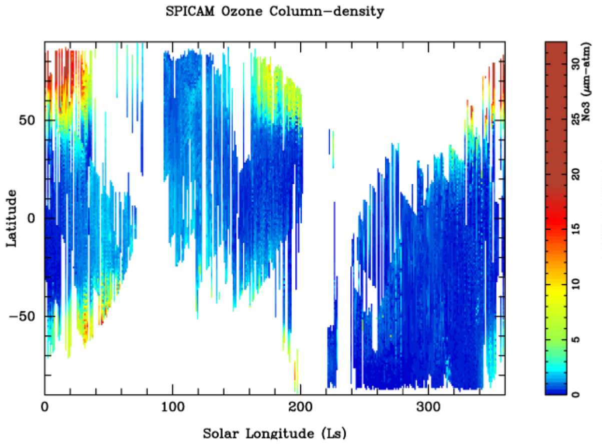


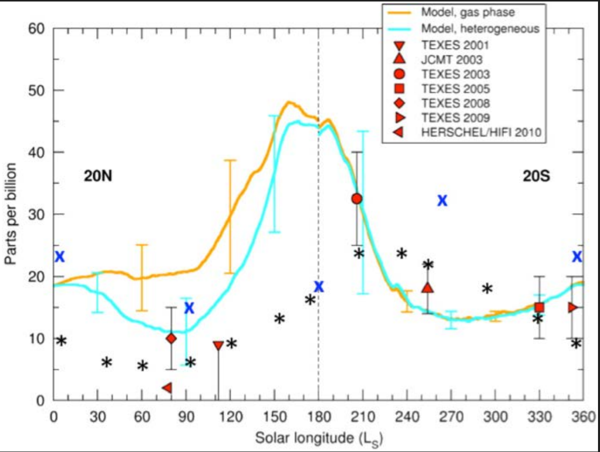
Chemistry related to water

Evolution of water on Mars from surface to space [*ESA/AOES Medialab*, 2011]



- In the upper atmosphere water is decomposed to atomic oxygen and hydrogen with the photo-dissociations, which are favorable to escape to the space.
- Ozone, hydrogen peroxide (H_2O_2, important oxidant of methane?) and radicals (OH, HO_2, key of the stability of CO_2 atmosphere?) are also generated in the atmosphere with the chemical reactions.



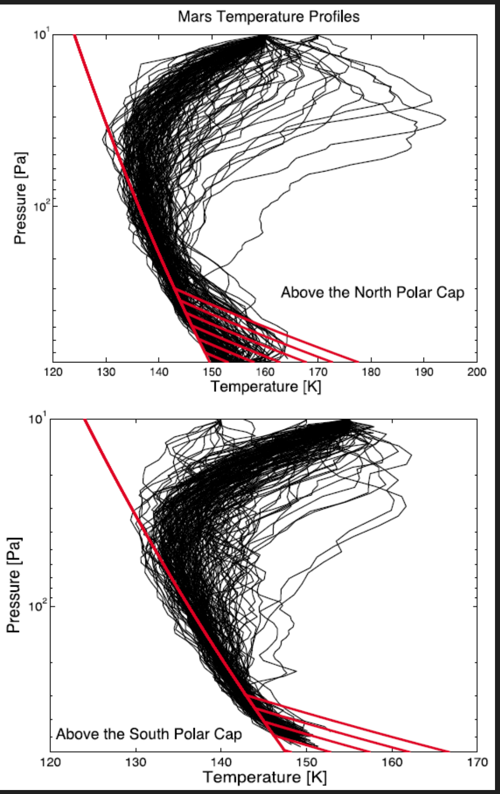


(left) Column density of ozone observed by MEx/SPICAM [Perrier et al., 2006]

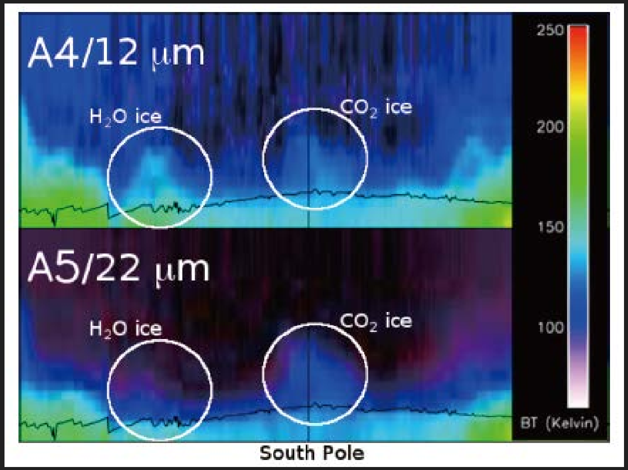
(right) Global-mean H_2O_2 abundance from observations and simulations [Encrenaz et al., 2012]

CO_2 snowfalls on Mars

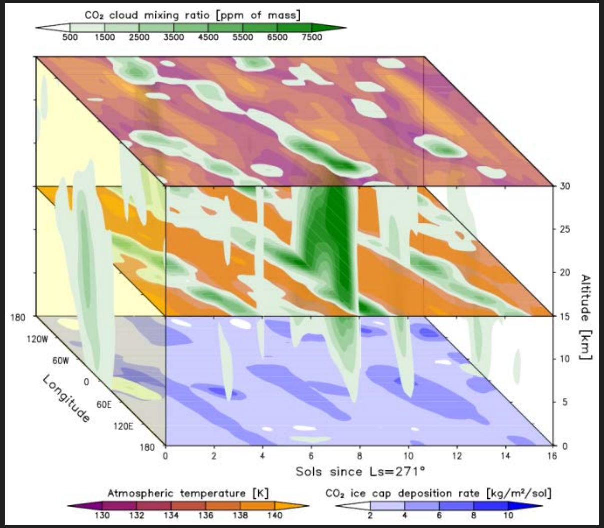
Winter polar temperature (MGS-RS) [Hu et al., 2012]



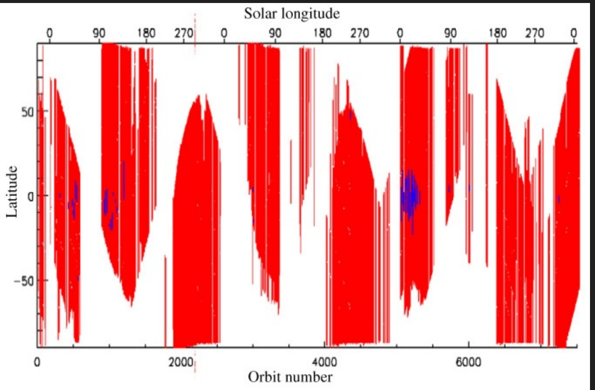
Signals in MRO/MCS brightness temperature [Hayne et al. 2014]



Simulated periodicity of CO_2 snowfall in north pole [Kuroda et al., 2013]



- In the winter polar regions, temperature from surface up to ~30 km altitude goes below the condensation level of CO_2.
- This indicates the existence of CO_2 snowfalls which contribute to form the seasonal polar ice caps.
- CO_2 ice clouds are also seen in the mesosphere, especially above the equator in northern spring and summer.



MEx-OMEGA observation of CO_2 cloud [Määttänen, et al., 2010]

Mars General Circulation Model (MGCM)

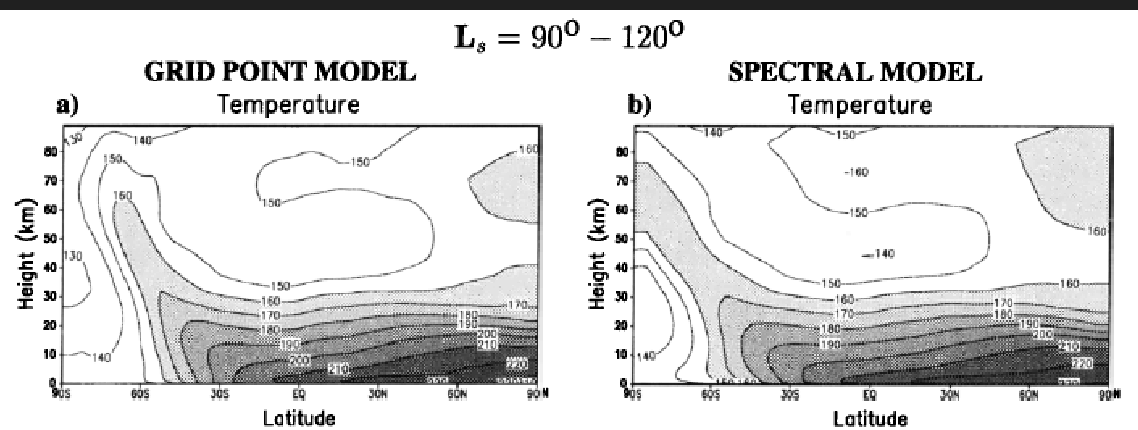
Viking
(1976~1981)

MGS-TES
(1998~)

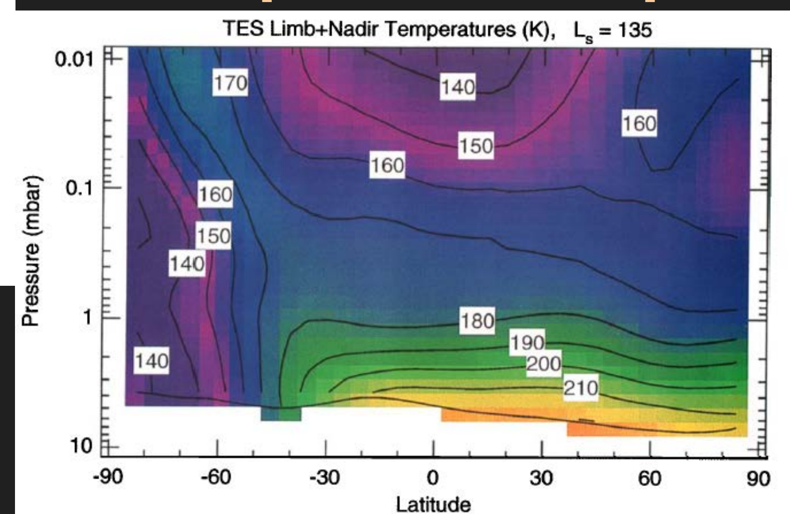
20th century: simulations of lower atmospheric temperature fields

- Started from Leovy and Mintz (1969)
- Introduction of the condensations of CO_2 atmosphere (Pollack et al., 1990) and radiative effects of CO_2 and dust

Results of LMD MGCM in France
[Forget et al., 1999]



MGS-TES observations
[Smith et al., 2001]

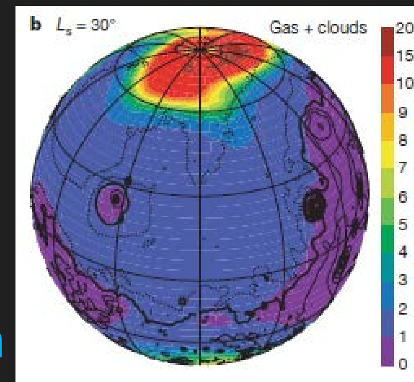


Temperature fields up to 60km height (observational limit at that time) were mostly reproduced.

21st century: implementations of material transport

- Water cycle [Richardson et al., 2002]
- Photochemistry [Lefevre et al., 2004]
- HDO [Montmessin et al., 2005]
- Argon [Nelli et al, 2007]

Ozone column density [Lefevre et al., 2008]

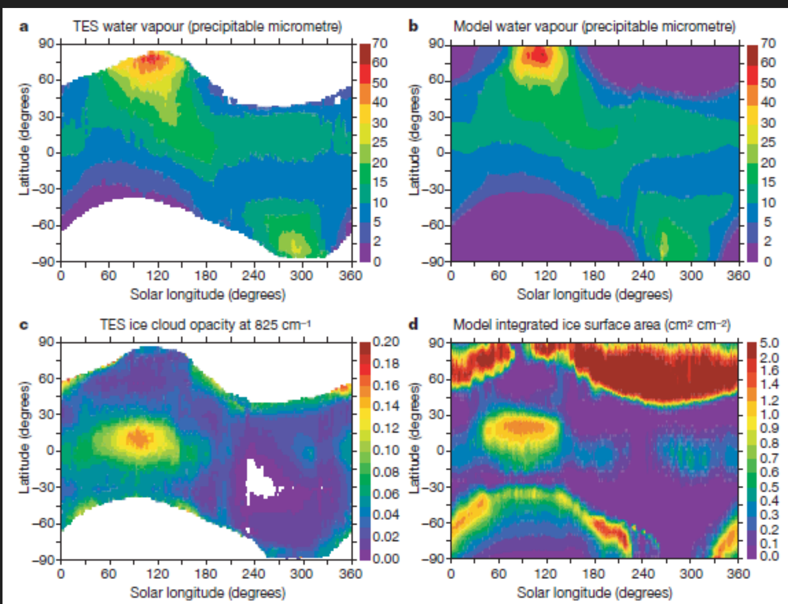


MGS-TES (1998~2004)

Mars Odyssey (2002~)

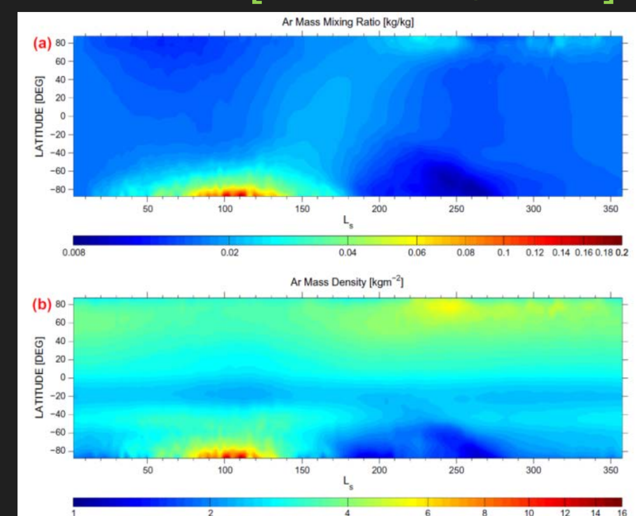
Mars Express (2004~)

MRO-MCS (2006~)



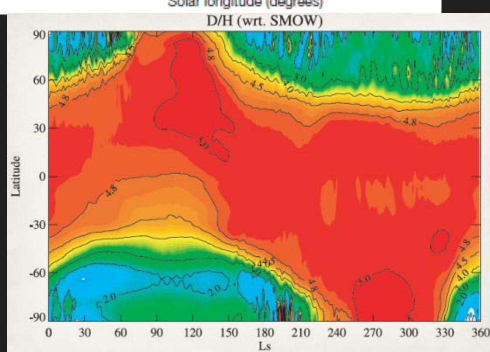
Water vapor and water ice column density in comparison with MGS-TES observation [Lefevre et al., 2008]

Argon abundance [Lian et al., 2012]



Argon abundance may affect the condensation temperature of CO_2 atmosphere [c.f. Noguchi et al., 2014, JGR]

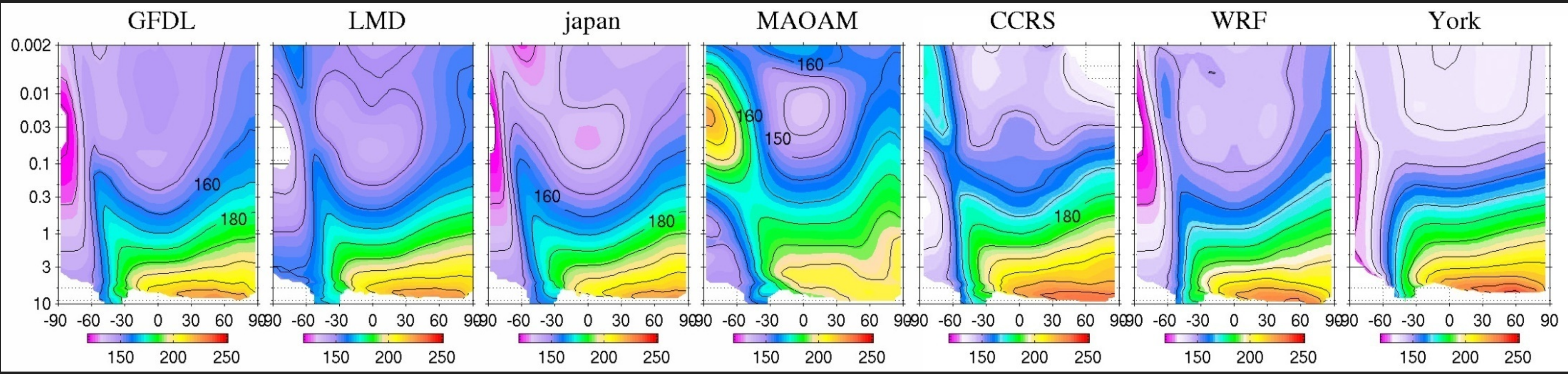
D/H ratio distribution [Montmessin et al., 2005]



Intercomparison of MGCMs in 2006 (L_s=90°)

At the Second workshop on Mars atmosphere modelling and observations @Granada, Spain [Wilson et al., 2006]

Princeton,USA | France | Y.O. Takahashi (now Kobe Univ.) | MPS, Germany | Kuroda (early DRAMATIC) | Caltech,USA | Canada



- Results of most models were close, but <u>only MAOAM had quite high temperature above the winter pole (~60km height).</u>

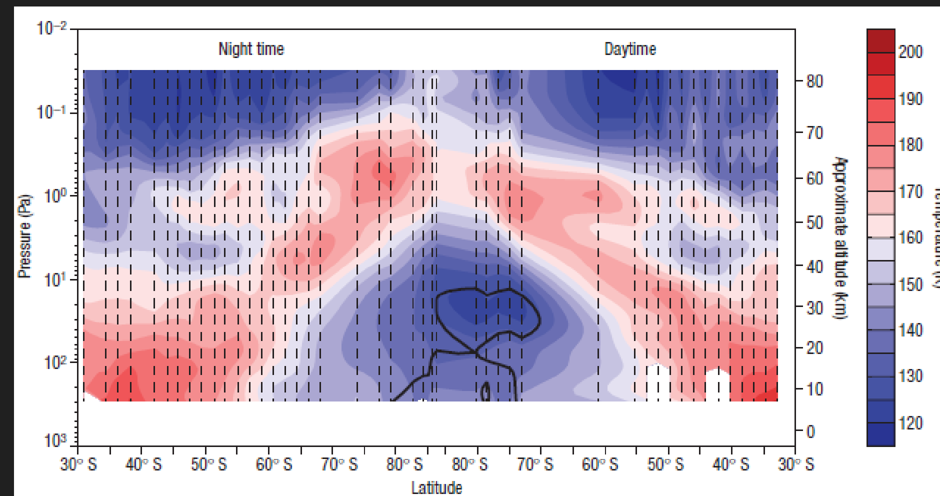
→Was MAOAM wrong? But at that time there were almost no observational data of temperature above ~60km.

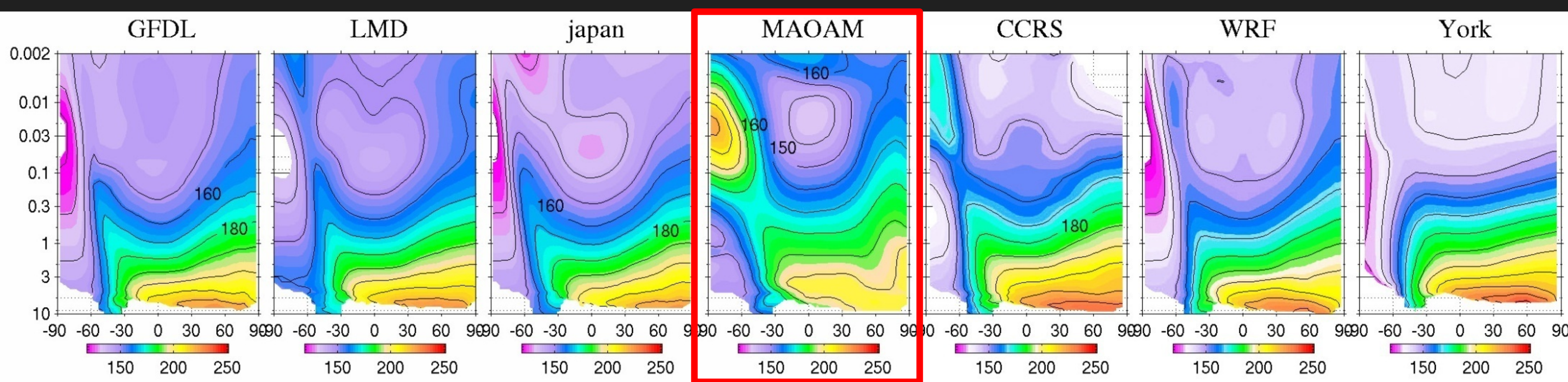
Just wait for the observations!

First observational data of temperature above ~60km (2008)

- The Mars Climate Sounder onboard Mars Reconnais-sance Orbiter (MRO-MCS) first observed the temperature in 60-80km height.
- It showed much higher temperature above the winter pole than expected, which was close to the results in MAOAM model.

MRO-MCS observations of temperature (Ls=136°) [McCleese et al., 2008]

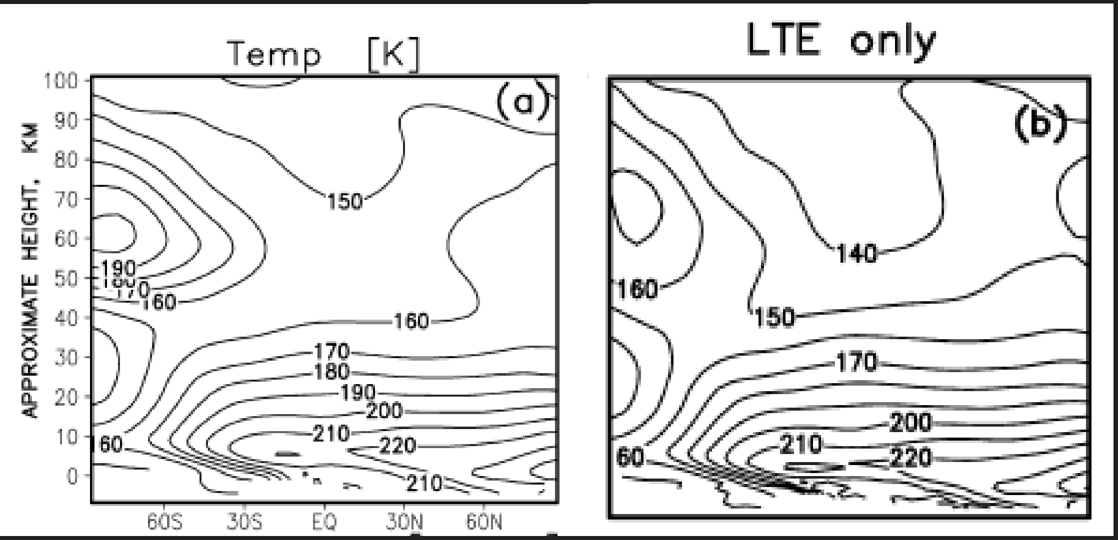




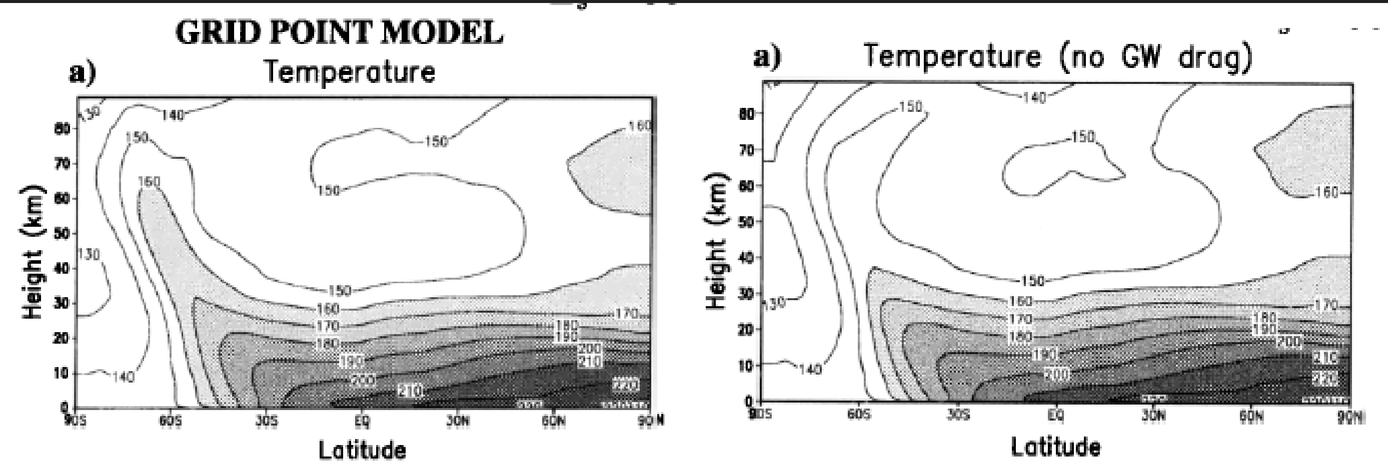
Why did MGCMs except MAOAM underestimate the temperature above the winter pole?

1. Non-LTE effects of CO_2 radiation
2. Gravity waves (small-scale eddies)

Start of active discussions about the effects of gravity waves on the atmospheric fields above ~60km



Effects of non-LTE radiation [Medvedev and Hartogh., 2007]



Effects of gravity wave drag scheme [Forget et al., 1999]

What is the gravity waves？

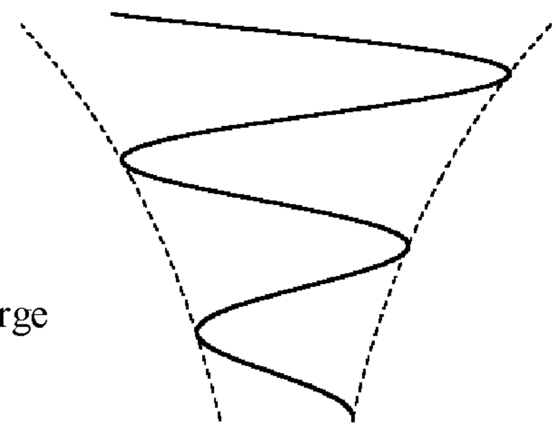
Small scale (wavelength of less than ~2000km), short period (less than ~1 day)

- Restoring force is a buoyancy.
- Atmosphere of Mars is mostly convectively stable (as on Earth) to support gravity wave existence.
- Possible sources are the topography, convection, dynamical instability of the flow, etc.
- Waves break in upper atmosphere and affect the atmospheric fields.

- Wave amplitudes grow to maintain constant energy

$$E = \frac{1}{2}\rho_o u'^2$$

- Wave amplitude becomes too large and wave breaks.
- Wave momentum deposited.
- Force exerted on atmosphere ("wave drag")
- Drives a meridional (NS) circulation.



$$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = -\frac{1}{\rho_o}\frac{\partial(\rho_o \overline{u'w'})}{\partial z}$$

$$\bar{v} = \frac{1}{\rho_o f}\frac{\partial(\rho_o \overline{u'w'})}{\partial z}$$

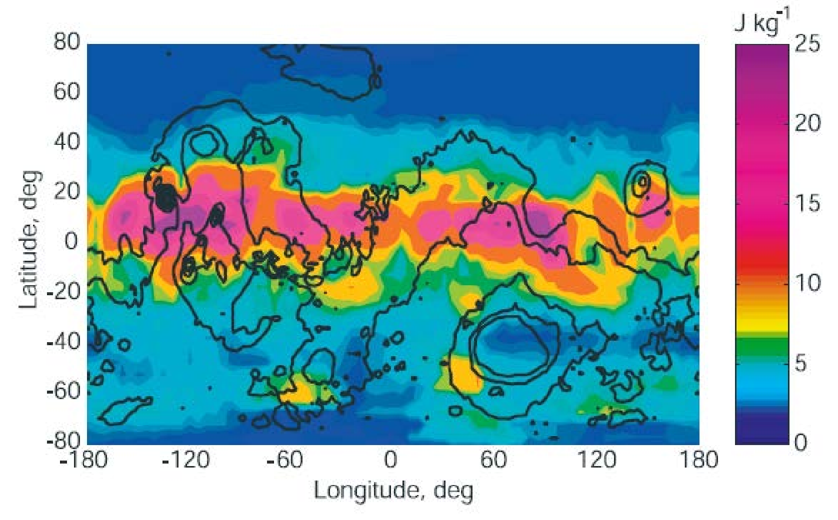
Gravity waves on Mars: from data analyses

Creasey et al. [2006a], Geophys. Res. Lett., 33, L01803

- Using the MGS radio-occultation data (from surface up to ~40km)
- The observed data did not correlate well with the orographic forcings, suggesting that wave sources other than orography should play an important role on Mars.

Gravity wave potential energy per unit mass

$$E_p = \frac{1}{2}\left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{T_0}\right)^2}$$



Creasey et al. [2006b], Geophys. Res. Lett., 33, L22814

- Using the MGS accelerometer data (thermosphere)
- The typical horizontal wavelengths of GWs were 100-300km.

Gravity waves on Mars: from data analyses

Fritts et al. [2006], J. Geophys. Res., 111, A12304

- Using the density data obtained in the aerobraking of MGS and Mars Odyssey (95-130km height)
- Amplitudes of GWs varied significantly with in space and time, and seemed to be related to the planetary-scale motions.
- Effects of the GWs on the atmospheric circulations were estimated as ~1000 m s^{-1} sol^{-1} at 70-80km height, and became one-fifth and five times of that at ~50km and ~100km heights, respectively.

Ando et al. [2012], J. Atmos. Sci., 69, 2906-2912

- Using the MGS radio-occultation data (from surface up to ~40km)
- A decline of the spectral density with wavenumber is seen in the similar way as terrestrial stratosphere/mesosphere.
- The saturation tend to occur only in lower latitudes.

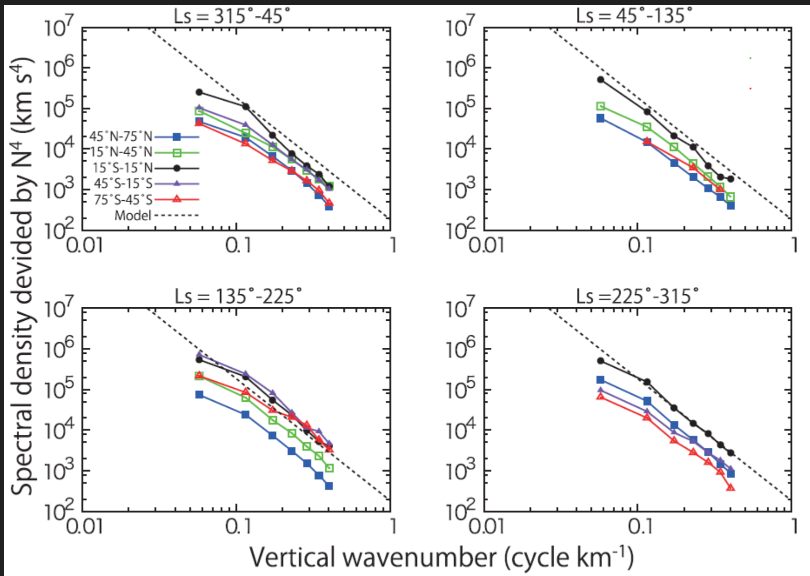


FIG. 4. As in Fig. 3, but in the altitude range 15–32 km.

Summary

- Features of lower atmosphere on Mars is strongly governed by dust storms.
- Though water is one of the minor species in the current Martian atmosphere, it still affects the temperature fields with the radiative effects ice clouds.
- Also, investigations of the movement and chemical reactions of water are important to understand the evolutions of Martian environment.
- MGCMs overall reproduce the temperature fields and material transport of lower atmosphere, but there are some mysteries of observational results which cannot be explained by simulations.
- In connection to upper atmosphere, mechanisms of generations of gravity waves and water cycles should be especially important.

About the dynamical coupling with upper atmosphere,

Please check A.S. Medvedev’s talk (from now)!