Simulation of the water cycle on Mars: Effects of the supersaturation

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Since the end of the previous century, daytime column density of water ice and vapor has been obtained by the infrared observations from the Mars orbiters [1-6] for several Mars years. Water vapor column density is the highest at summer North Pole (up to ~100 pr.μm), and the 'equatorial cloud belt' exists during northern summer (mid-infrared opacity of up to ~0.2). The interannual variability of the water cycle is very small.

As for the vertical distributions of water, MRO-MCS have detected the first data sets of 3-dimensional distributions of water ice since September 2006 [7]. Moreover, recently the existence of very large supersaturation ratio (~10 times) of water vapor in the middle (around ~40 km height) atmosphere on Mars has been indicated by the observations by SPICAM onboard Mars Express [8]. Such a large supersaturation should make a great impact on the current water cycle, consequently on the atmospheric chemistry and escape processes also, but has not reproduced by current general circulation models (GCMs) with simple water cloud schemes.

We have performed a simulation allowing the supersaturation of water vapor up to ~10 times in our Mars GCM (DRAMATIC MGCM). Here we showed the details of the water cycle scheme and numerical results of water cloud/ice distributions in comparison between with and without considering the supersaturation, and discussed the potential quantitative impacts of the large supersaturation on the water cycle of Mars.

References:

[1] Smith, 2004, Icarus 167, 148–165.
[2] Smith, 2006, Second workshop on Mars atmosphere modelling and observations, Granada, Spain.
[3] Fouchet et al., 2007, Icarus 190, 32–49.
[4] Trokhimovskiy et al., 2008, Mars Water Cycle Workshop, Paris, France.
[5] Smith, 2009, Icarus 202, 444–452.
[6] Smith et al., 2009, J. Geophys. Res. 114, E00D03, doi:10.1029/2008JE003288.
[7] McCleese et al., 2010, J. Geophys. Res. 115, E12016, doi:10.1029/2010JE003677.
[8] Maltagliati et al., 2011, Science 333, 1868-1871.

惑星圏研究会. 2012/4/4, 東北大学

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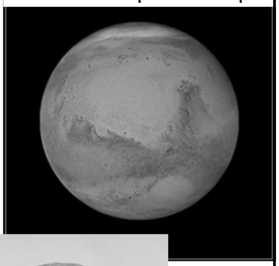
Mars: A red planet

From Hubble Space Telescope



- The 4th planet of the solar system
- CO_2 occupies 95% of the atmosphere.
- No liquid water on surface
- Thin water vapor (~100 ppm)
- Thin water and CO_2 clouds

From Mars Pathfinder

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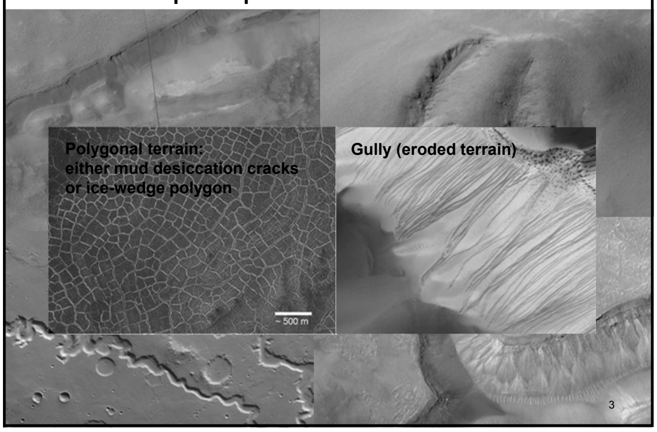
Water on Mars

Evidences of past liquid water flow on Mars surface



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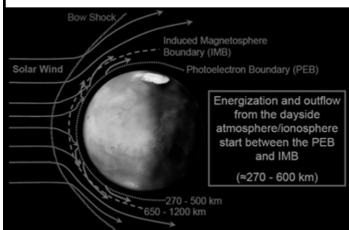
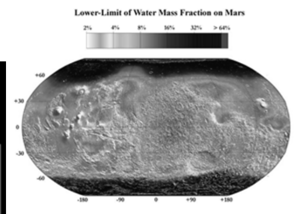
Where has the water gone?

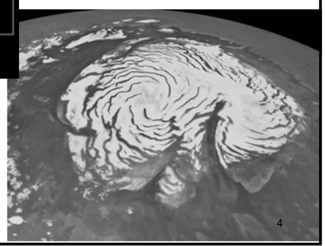
Escape to the space



Underground



How is the current condition of the atmospheric water on Mars?



North polar ice cap

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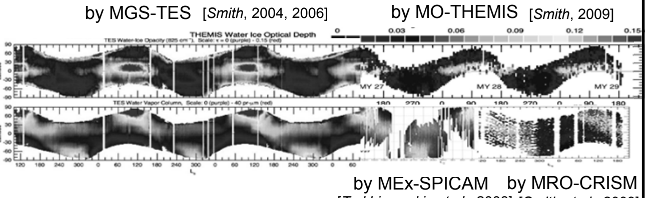
Observations of water on Mars

Horizontal distributions of water ice/vapor

by MGS-TES [*Smith*, 2004, 2006] by MO-THEMIS [*Smith*, 2009]



by MEx-SPICAM by MRO-CRISM
[*Trokhimovskiy et al.*, 2008] [*Smith et al.*, 2009]

- Daytime column density of water ice and vapor have been obtained by the infrared observations for several Mars years.
- Water vapor column density is the highest at summer North Pole (up to ~100 pr.μm), and the 'equatorial cloud belt' exists during northern summer (mid-infrared opacity of up to ~0.2).

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Vertical distributions of water ice

by MRO-MCS [*McCleese et al.*, 2010]

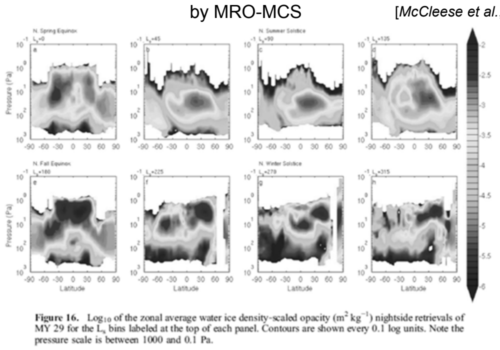

Figure 16. Log_{10} of the zonal average water ice density-scaled opacity ($m^2 kg^{-1}$) nightside retrievals of MY 29 for the L_s bins labeled at the top of each panel. Contours are shown every 0.1 log units. Note the pressure scale is between 1000 and 0.1 Pa.

- MRO-MCS have detected the first data sets of 3-dimensional distributions of water ice since September 2006.
(i.e. we already have accumulation of data for 5 years)

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Vertical distributions of water vapor

by MEx-SPICAM [*Maltagliati et al.*, 2011]

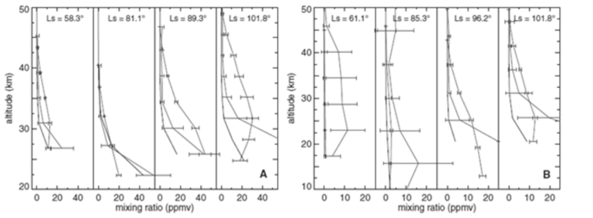
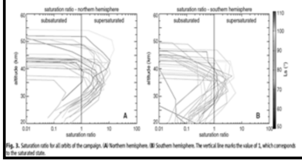


Fig. 2. Selection of typical water vapor volume–mixing ratio profiles in the (**A**) northern and (**B**) southern hemisphere. Black curve, modeled profile by the LMD-GCM; red curve, the retrieved SPICAM results; blue curve, saturation water vapor–mixing ratio. Supersaturation exists where the red values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



- MEx-SPICAM have detected several profiles of vertical distributions of water vapor, and found that there are <u>extreme supersaturations with the ratio of up to ~10</u>.

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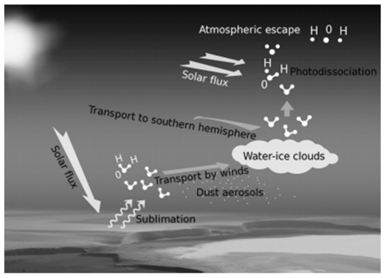
Movement of water on Mars



[*ESA/AOES Medialab*, 2011]

- The effects of supersaturation can provide strong impacts on the water cycle and escape processes, eventually the climate changes.
- In this study, we mainly show the changes of numerical results between with and without the consideration of the supersaturation of possible degree from the observation.

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DRAMATIC MGCM

DRAMATIC = Dynamics, **RA**diation, **MA**terial **T**ransport and **I**ntera**C**tions between them

Dynamical core	CCSR/NIES/FRCGC AGCM 5.7b (MIROC 4.0) 3-dimensional primitive equations, spectral solver
Resolutions	Horizontal resolution of ~5.6°× 5.6° (grid interval of ~333km at the equator) 49 layers with σ levels, the model top is at ~100km.
Radiation	CO_2: Absorption and emission in the infrared wavelength (15μm, 4.3μm) and near-infrared solar absorption (only LTE effects) Dust: Absorption, emission and scattering in 0.2-200μm
Tracers	Water vapor, water ice, CO_2 ice (Radiative effects of them are not included)
Surface	Realistic topography, albedo, thermal inertia and roughness Deposition of CO_2 and water ice

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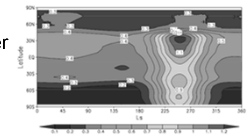
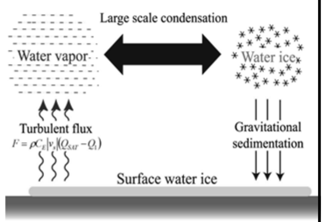
Dust distribution

- Standard observed opacity without global dust storm; 0.2-1 in visible, higher near the perihelion (northern autumn and early winter), zonally constant



Water cycle scheme

- Large scale condensation (condensation of oversaturated water vapor)
- Gravitational sedimentation of ice particles
- Deposition of the fallen water ice on surface
- Change of the surface albedo (>0.3) by the water ice
- Sublimation of the surface water ice: by the turbulent flux



(Regolith and radiative effects of water are not included currently.)

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Estimation of the particle size of clouds

- The sedimentation velocity of the water/CO_2 ice particle depends on its size and density.
- For water ice: assuming the nucleation on dust particles, based on Montmessin et al. (2004) (1-3)
- For CO_2 ice: assumption with scale height (3), density of 1000 kg m^{-3}

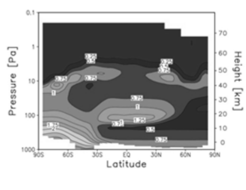
$$r_c = \left(\frac{M_c}{(4/3)\pi \rho_i N} + r_0^3 \right)^{1/3} \quad (1)$$

r_c: Radius of water cloud
M_c: Mass of water ice in the layer
ρ_i: Density of water ice(917 kg m^{-3})
N: Number of dust particles in the layer (2)
r_0: Radius of dust (3)

$$N = \frac{M_d}{(4/3)\pi \rho_d r_0^3} \quad (2)$$

M_d: Mass of dust in the layer
ρ_d: Density of dust (2500 kg m^{-3})

Particle size of water ice at Ls=90°



$$r_0(z) = r_{z0} \exp(-z/h) \quad (3)$$

r_{z0}: Radius of particle at 0 km height (0.8 μm for dust, 50 μm for CO_2 ice)
h: Scale height of particle (18 km for dust, 20 km for CO_2 ice)

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Setting of the simulations

- The calculations started from the 'dry' isothermal state without water vapor/ice in atmosphere and on surface except <u>permanent water ice cap in the north of 80° N</u>.
- The calculations has been made up to 20 Martian years from the initial (isothermal) state.
- Case A: Supply of water from the permanent ice cap/surface ice is considered with the formula of turbulent flux, with β=1
- Case B: Same as Case A, except with β=0.01
- Case C: The 'supersaturation' case which replaced Q_{sat} to Q'_{sat} (=10* Q_{sat}), β=0.01

Formula of turbulent flux

$$F = \beta \rho C_E |v_s| (Q_{sat} - Q_1)$$

β: Evaporation efficiency (which depends on the surface physicality and moistness)
ρ: Atmospheric density
C_E: Bulk coefficient (which depends on the surface roughness and atmospheric instability)
v_s: Wind velocity of the lowest layer
Q_{sat}: Water vapor mixing ratio for saturation at surface
Q_1: Water vapor mixing ration at the lowest layer

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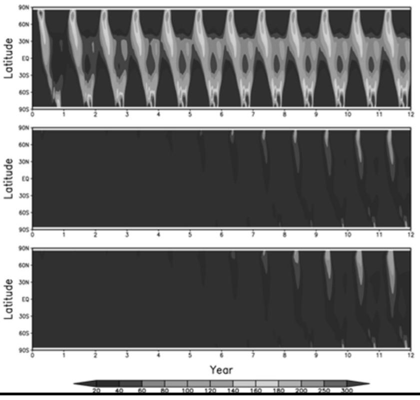
Numerical results

Water vapor column density [pr.μm] for <u>12 Mars years</u> from the initial (isothermal) state

Case A (β=1) — Unrealistically too much, steady

Case B (β=0.01) — Still not steady…

Case C (β=0.01, SS) — Still not steady…



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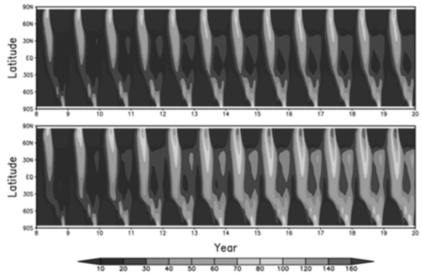
Water vapor column density [pr.μm] for <u>8-20 Mars years</u> from the initial (isothermal) state

Case B (β=0.01) — Mostly steady

Case C (β=0.01, SS) — Mostly steady…?



- There are clear differences in the amount and structure of water vapor distributions, especially in low-latitudes.
- There seems to be differences in the water transport processes (the analyses are ongoing…).

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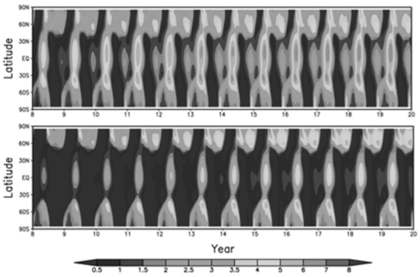
Water ice cloud opacity (mid-infrared) for <u>8-20 Mars years</u> from the initial (isothermal) state

Case B (β=0.01) — Mostly steady

Case C (β=0.01, SS) — Mostly steady…?



- Considering the supersaturation, the 'equatorial water cloud belt' becomes thinner. (but quantitatively still ~20 times thicker than the observation…)

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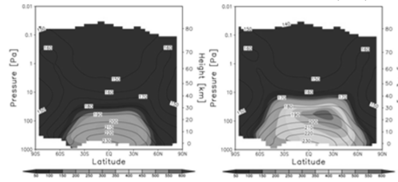
Zonal-mean distributions (20th year, L_s=180°)

Water vapor [ppm of mass] Contour: Temperature [K]

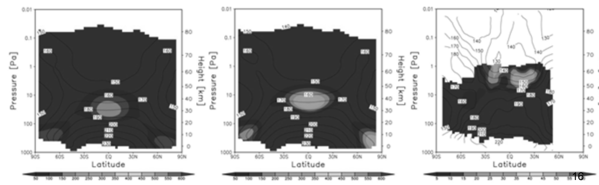
Case B Case C (SS)



- The hygropause (cut-off height of water vapor) slightly goes up due to the supersaturation.

Water ice cloud [ppm of mass]

Ref: MRO-MCS observation (MY29)
Note that the scale of abundance is 1/10.



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Summary

- Recently extreme supersaturations of water vapor on Mars have been observed, which can provide strong impacts on the the water cycle and escape processes.
- We did numerical simulations of water cycle on Mars, and the preliminary results showed clear qualitative differences of water distributions by accounting for the supersaturation.

Future works

- Include the radiative effects of water ice/vapor, which can provide strong impacts on the quantitative structures [Haberle et al., 2011]
- Include the absorption of water by surface regolith and interaction of water transport between subsurface and atmosphere
- Include the photochemical processes and effects of atmospheric escape
- Simulation of water isotopic ratio (ongoing in parallel)

For the investigations of water transport processes from surface to space

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