Planetary atmosphere research in the context of water cycle

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Water plays crucial roles in the energy budget, dynamics and chemistry of the planetary atmospheres. Specifically, the following aspects will be important.

- Cloud formation leading to high albedo
- Greenhouse effect
- Sensible heat
- Aerosols of soluble material
- OH photochemistry stabilizing CO_2 atmospheres

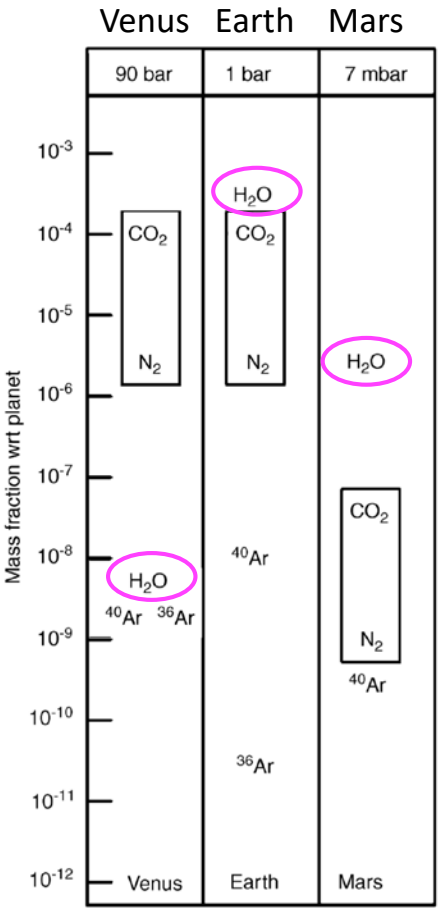
Moreover, the humidity controls the stability of surface/subsurface water, which is considered to be indispensable to habitable environment.

To understand the behavior of water in the atmosphere and the water transport among the solid planet, the atmosphere and the space, the understanding of the layered structure of the atmosphere is crucial. For Mars, seasonal cycle of the water transport among the polar cap, regolith and the atmosphere needs to be explored. Especially the redistribution of water among the reservoirs and the transport of water to the upper atmosphere associated with enhanced atmospheric circulation are important. For Venus, the control of high-albedo cloud formation, the transport of water across the clouds, and the mechanism of the enrichment of water (and SO_2) at high altitudes need to be investigated.

For these studies, global, high-resolution, continuous observations of the atmospheric variables including water vapor, combined with data assimilation, would make a breakthrough. Currently the atmosphere observation in Martian Moons eXploration (MMX) mission is under development. A continuous global mapping of clouds, dust and water vapor will be conducted in 2025-2028. As a next step, the concept of satellite-to-satellite radio occultation mission is under development. Three-dimensional monitoring of the temperature, pressure and absorbing species (H_2O, H_2SO_4) with high vertical resolution would enable the understanding of material transport across the atmospheric layers such as the surface boundary layer, the cloud layer and detached convective layers. A combined use of a terahertz sounder targeting at the radio occultation point would provide additional chemical information including D/H.

Water in planetary atmospheres

- Indispensable to habitable environment
- Playing crucial roles in energy budget, dynamics and chemistry
  - Cloud formation leading to high albedo
  - Greenhouse effect
  - Sensible heat
  - Aerosols of soluble material
  - OH photochemistry stabilizing CO_2 atmospheres
- Humidity controls the stability of surface/subsurface water



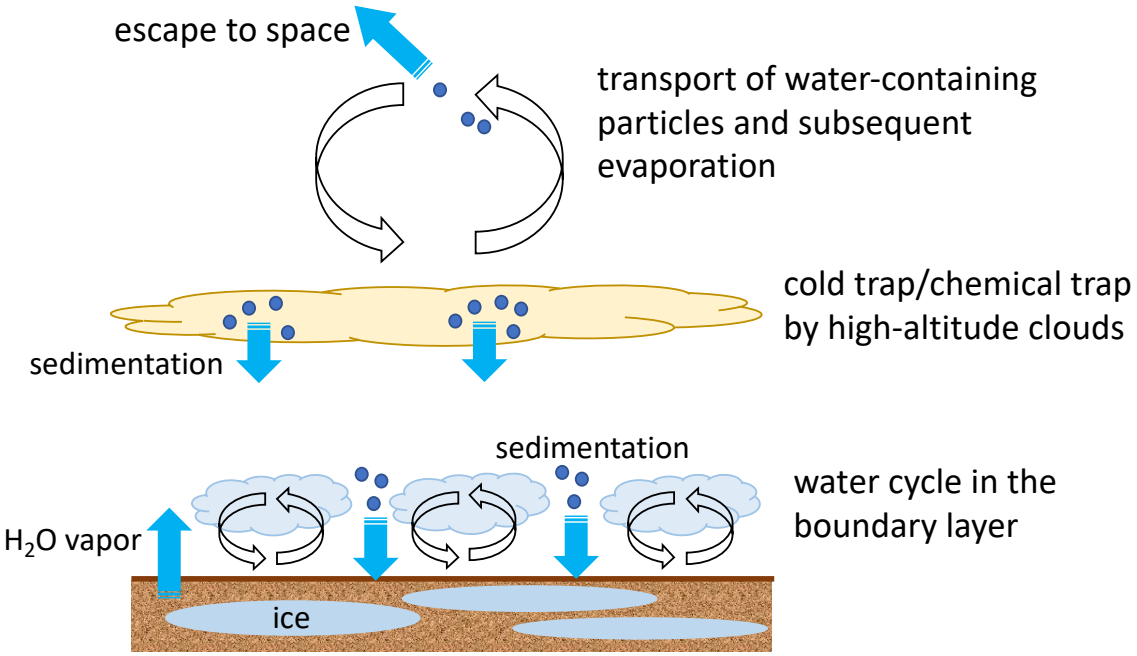
Volatile species on Venus, Earth and Mars

- The amount of H_2O on Venus is 1000-10000 times smaller than those of Mars and Earth.
- Mars has a considerable amount of subsurface H_2O.

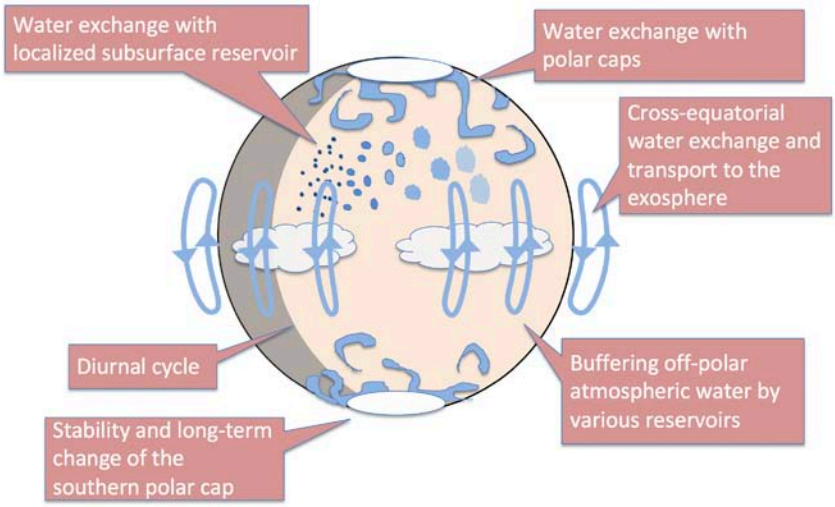
Chassefiere et al. (2007)

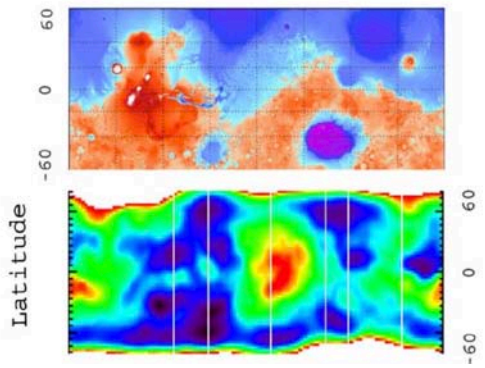
Transport boundaries

An atmosphere is NOT a single homogeneous layer



Mars' surface/subsurface water: interaction with the atmosphere determining the stability

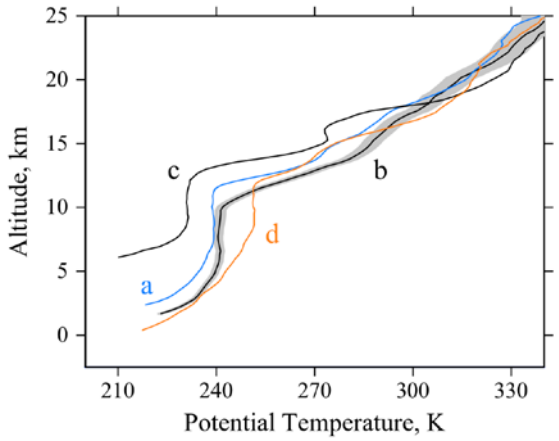




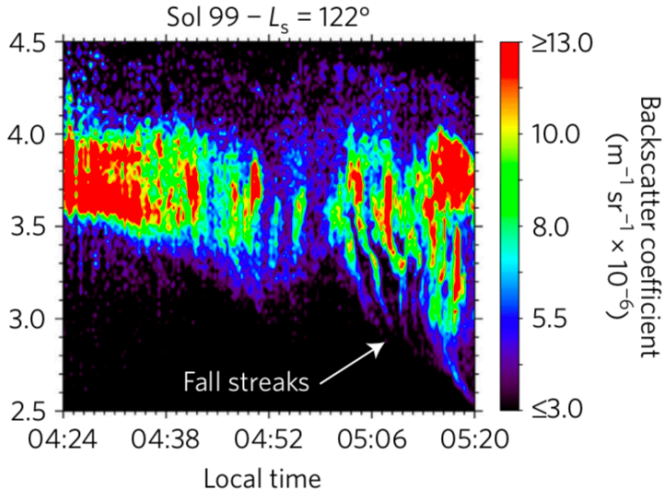
Water Equivalent Hydrogen (Feldman et al. 2005)

Previous observations failed to map globally H_2O vapor distribution with high-spatial and temporal resolution

Nocturnal high-altitude clouds on Mars



Hinson et al. (2014)

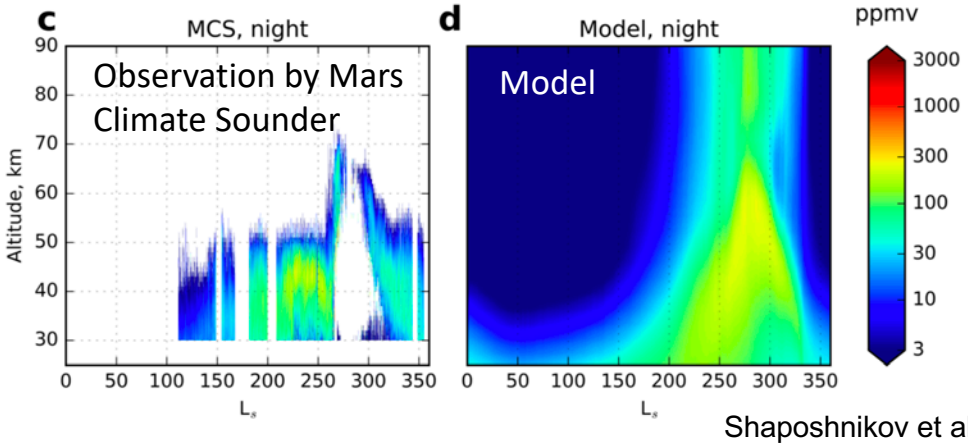


Whiteway et al. (2009)

Convection and precipitation leading to trapping of water in the lower atmosphere (?)

Rapid water transport to high altitudes on Mars

Vertical distribution of total water (vapor + ice) during one Mars year

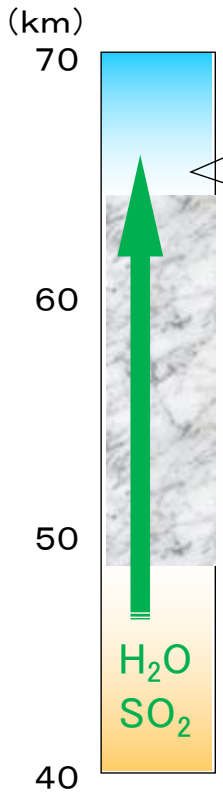


Shaposhnikov et al. (2019)

Direct interaction between the lower atmosphere and the thermosphere

Influence on atmospheric escape

Trap of H_2O by aerosol production on Venus



Scenario #1 (Net reaction driven by catalytic cycles including ClOx, HOx, NOx)

$2CO_2 + h\nu \rightarrow 2CO + O_2$

$CO + SO_2 + O_2 + h\nu \rightarrow CO_2 + SO_3$

$CO_2 + SO_2 + h\nu \rightarrow CO + SO_3$

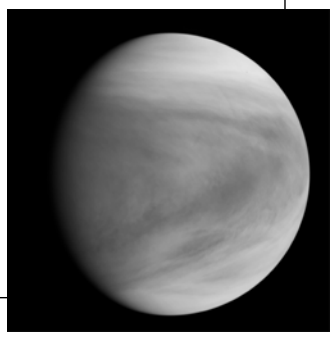
Scenario #2

$SO_2 + h\nu \rightarrow SO + O$

$SO + h\nu \rightarrow S + O$

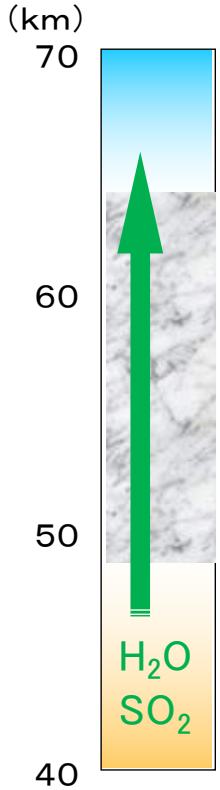
$SO_2 + O \rightarrow SO_3$ (×2)

$3\,SO_2 + h\nu \rightarrow S + 2SO_3$



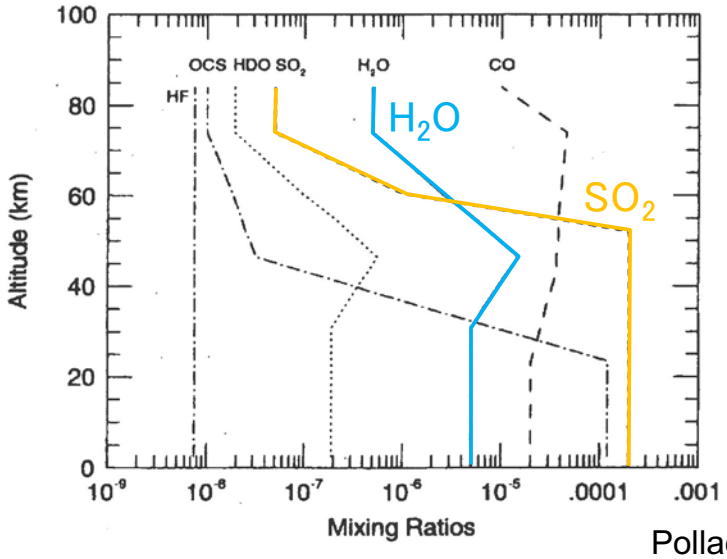
SO_3 rapidly reacts with H_2O: $SO_3 + H_2O \rightarrow H_2SO_4$

H_2O deficit problem



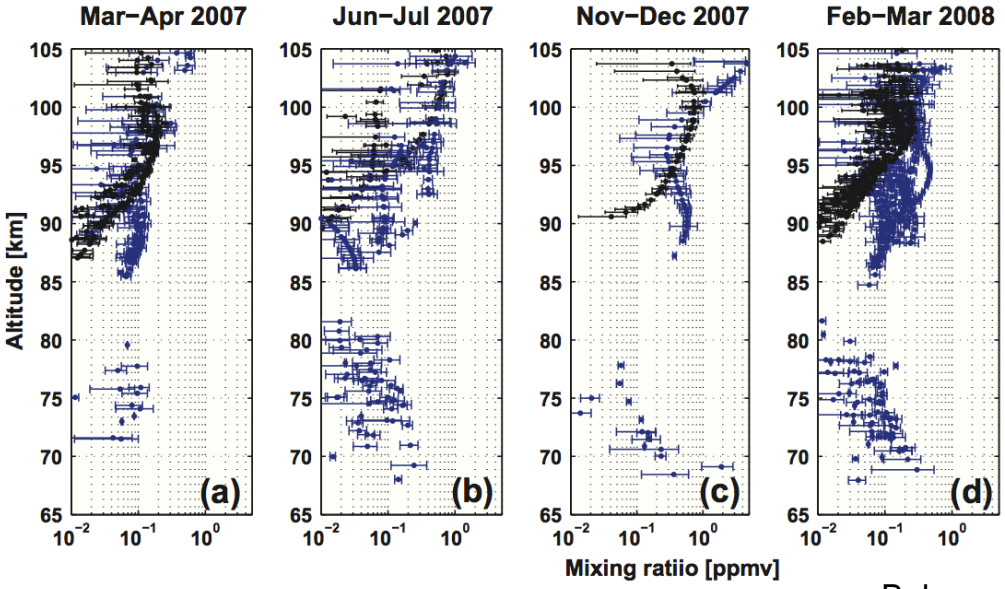
$SO_3 + 2H_2O \rightarrow H_2SO_4 \cdot H_2O$

(1–1.5) x SO_2 2 x H_2O



Pollack et al. 1993

SO and SO_2 profiles above clouds
by Venus Express SPICAV/SOIR



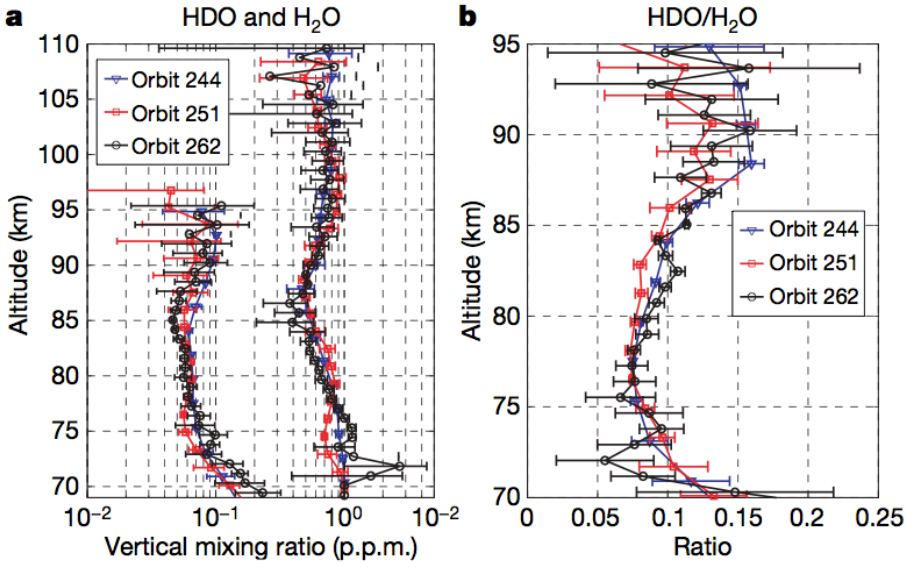
SO : black
SO_2 : blue

Belyaev et al. (2011)

Transport of aerosols to high altitudes and subsequent evaporation ?

H_2O and HDO profiles above clouds
by Venus Express SPICAV/SOIR

Fedorova et al. (2008)



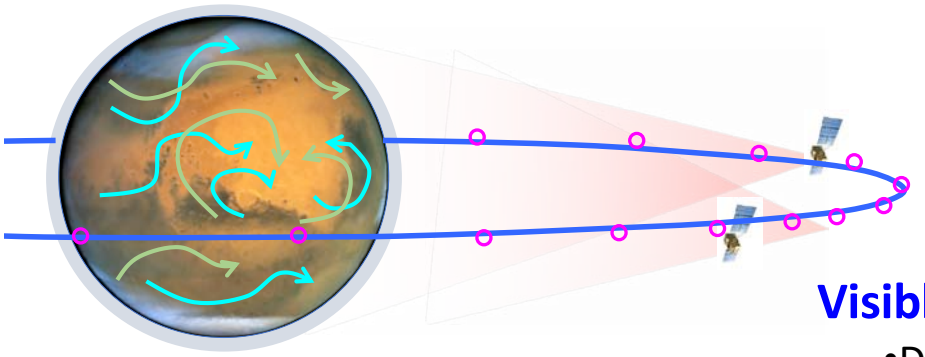
Evaporation of aerosols at high altitudes and escape of hydrogen to space ?

Need for understanding atmospheric H_2O

- Mars
  - Stability of surface/subsurface water controlled by humidity
  - Redistribution of H_2O among the reservoirs
  - Transport to the upper atmosphere where H_2O can photo dissociate and escape to space
- Venus
  - Control of high-albedo cloud formation
  - H_2O budget across the cloud layer
  - Enrichment of H_2O and SO_2 at high altitudes

→ Global, high-resolution, continuous observation including H_2O vapor (combined with data assimilation) will make a breakthrough

Atmosphere observation in Martian Moons eXploration (MMX) in 2025-2028

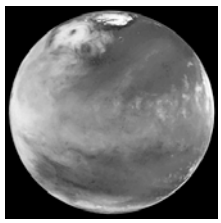


Near-IR Imaging spectroscopy

- Water vapor
- Dust, cloud
- Surface pressure

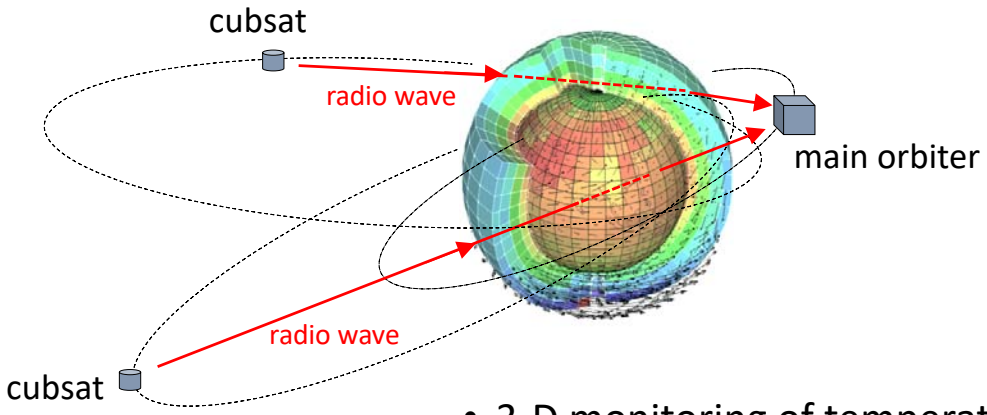
Visible imaging

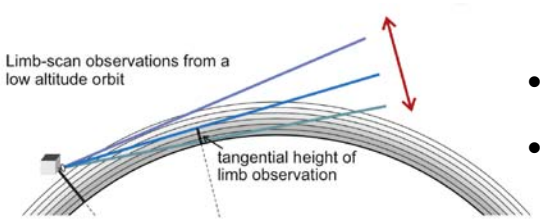
- Dust
- Cloud



First high-resolution, global, continuous mapping of H_2O vapor and other variables

Satellite-to-satellite radio occultation with limb sounding of trace gases (Mars, Venus)





Kasai et al. (2012)

- 3-D monitoring of temperature, pressure and absorbing species (H_2O, H_2SO_4) with high vertical resolution
- Mars' boundary layer is resolved
- A terahertz sounder targeting at the radio occultation point would provide more chemical information including D/H

Summary

- The behavior of atmospheric water is of major interest for Mars and Venus.
- The highly-variable nature of atmospheric water has prevented understanding of physical/chemical processes governing the distribution of H_2O vapor and reservoirs. New planetary missions dedicated to atmospheric processes are promising.
- The processes distributing H_2O to the upper atmosphere on the solar system planets serve as references for those of exoplanets, whose upper atmospheres can be observed by transit spectroscopy.