WATER VAPOR SATURATION AND ICE CLOUD OCCURRENCE IN THE ATMOSPHERE OF MARS

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Introduction:

The vertical distribution of water vapor and its relation to ice cloud occurrence in the Martian atmosphere has been a longstanding question. Saturation and cloud formation are major factors that constrain the vertical distribution of water vapor. The altitude at which water vapor saturation occurs is largely controlled by the thermal structure of the atmosphere and varies with season and in response to dust storm occurrence. The vertical distribution of water vapor has recently gained additional interest with the recognition that middle atmospheric water vapor can photolyze, leading to the formation of hydrogen, which in turn can propagate to the upper atmosphere and escape. Hence the transport of water vapor to the middle atmosphere influences the hydrogen escape rate and quantifying its variation might help explain this contribution to hydrogen escape and consequently water loss from Mars.

The saturation state of water vapor in the Martian middle atmosphere allows us to better understand the mechanisms behind the planet's water cycle and how efficient the ascent of water vapor to the upper atmosphere is. It is widely assumed that water vapor in the presence of water ice clouds usually is in saturation or near saturation, and that supersaturation is a rare behavior in the cold Martian atmosphere. However, recently this view has been challenged as findings from the Atmospheric Chemistry Suite (ACS) onboard the ExoMars Trace Gas Orbiter (TGO) suggest supersaturation even in the presence of dust and ice clouds [1]. ACS observed widespread supersaturation over a large vertical range, with saturation ratios frequently exceeding a value of 10 and even reaching values over 100. This suggests that even though condensation nuclei are present in the middle atmosphere, the process of condensation would have to be overpowered by a process that would allow for water vapor to become supersaturated in cloudy conditions, such as rapid drops in temperature and/or rises in water concentration.

In this paper, we study water vapor saturation in the presence or proximity of clouds in the Martian atmosphere by intercomparisons of water vapor profiles, derived from measurements by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard the Mars Reconnaissance Orbiter (MRO) and by the Nadir and Occultation for MArs Discovery (NOMAD) instrument onboard TGO, with saturated water profiles, derived from temperature measurements by the Mars Climate Sounder (MCS) onboard MRO. We find that the atmosphere above cloud layers is largely subsaturated, suggesting that cloud formation is fairly instantaneous upon the temperature dropping below the frost point and high levels of supersaturation are not required to form water ice clouds. We propose a schematic model of cloud evolution in which small cloud particles are formed rapidly in slightly supersaturated regions, and then fall and grow such that ice opacity is still observed even in the subsaturated regions below. Detailed findings of this study have been presented by Poncin et al. [2].

Coordinated observations between CRISM and MCS:

Part of this study was motivated by the publication of seasonal zonal averages of water vapor content from CRISM derived from $O_2(\Delta_g)$ dayglow emission rates [3] between L_s=30° and L_s=360° spanning from MY29 to MY33. Operating from the same spacecraft as CRISM, MCS was able to perform limb/on-planet measurements in coordination with most CRISM limb measurements. CRISM data are provided as zonal averages between 6 and 54 km altitude above the areoid and between 90°S and 90°N in latitude. Each individual MCS temperature profile is used to estimate water vapor volume mixing ratio at saturation [4] in the presence or proximity of clouds, as diagnosed by the MCS water ice profile. Then zonal and subseasonal averages of water vapor saturation ratio is derived from CRISM ambient water vapor and MCS saturated water vapor.

Coordinated observations between NOMAD and MCS:

In addition to comparisons with water vapor derived from CRISM we evaluate comparisons with water vapor as measured by the NOMAD instrument in solar occultation geometry from ExoMars TGO [5]. Part of these intercomparisons is based on serendipitous co-located observations between MCS and NOMAD during the global dust event in 2018. In addition, MCS performed coordinated observations with NOMAD from February 15 to March 7, 2019, in which MCS actively targeted the tangent point of a solar occultation measurement by NOMAD. NOMAD data as individual profiles between -20 and 120 km altitude above the areoid were selected as families of measurements by looking for coordinated MCS measurements that fall within a time and space window centered on each NOMAD measurement. Each individual MCS temperature profile is used to estimate water vapor volume mixing ratio at saturation [3] in the presence or proximity of clouds, as diagnosed by the MCS water ice profile. Then vertical averages of water vapor saturation ratio are derived for each family of co-located measurements from NOMAD ambient water vapor and MCS saturated water vapor.

Results:

CRISM/MCS. The CRISM part of the study allows us to evaluate the saturation state of the atmosphere and its variation with season. We separate the clear and dusty seasons averaged between MY29 and MY33 into the two L_s-ranges L_s=30°-140° and L_s=140°-360° [2]. For this abstract we focus on a subset of data during the aphelion season spanning L_s=60°-100° (Fig. 1). In this season a good correspondence of the overall morphology of the water vapor distribution in the two datasets can be observed, especially in cloud occurrence as shown in Fig. 1 (circle-shaped points). In the aphelion season

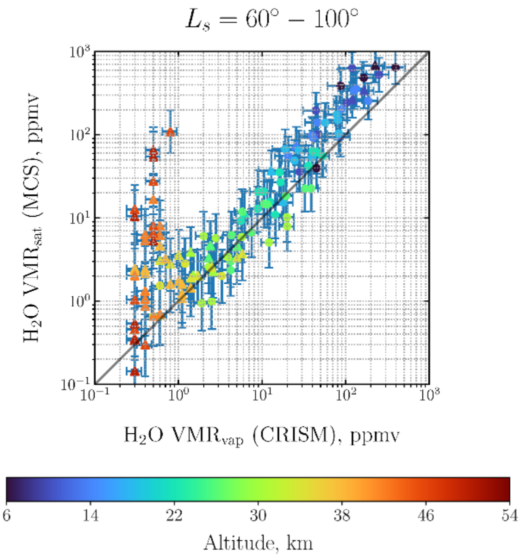

Figure 1: Correlations between saturated water vapor mixing ratio from MCS and ambient water vapor mixing ratio from CRISM for L_s=60°-100°.

CRISM ambient water vapor is usually near saturation or slightly supersaturated in the presence of clouds.

The dusty season is characterized by a rise of the hygropause, with the region of cloud occurrence almost reaching the top of the considered altitude range of 54 km. Higher atmospheric temperatures lead to an increase in MCS saturated water vapor, which tends to be somewhat higher than the CRISM zonal averages so during the dustier perihelion season the atmosphere appears largely subsaturated. In some L_s-ranges of the dusty season, temperatures and water vapor mixing ratios in the southern high latitudes are somewhat higher but still suggest some level of supersaturation.

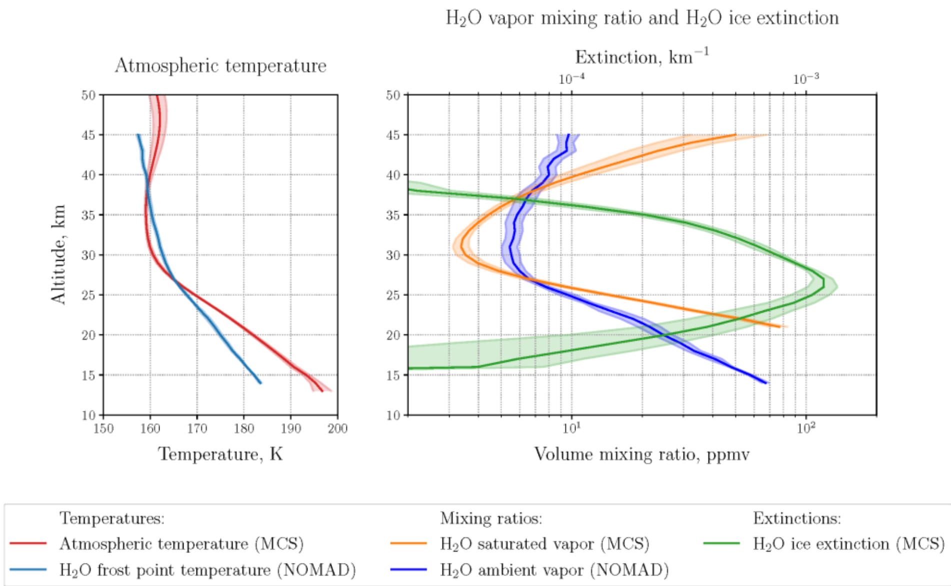

Figure 2 : Average profiles of temperature, water vapor, water ice opacity, and water saturation ratio for a southern high latitude band in southern summer (L_s=338.9°-347.3°).

NOMAD/MCS. The NOMAD part of the study allows us to evaluate the saturation state of the atmosphere during the dusty season in detail. We separate the dataset into seven families of measurements retrieved during the decay phase of the MY34 GDS (around L_s=240°) and after the MY34 C storm (around L_s=340°) [2].

For this abstract we focus on one family after the MY34 C storm (Fig. 2). We observe that NOMAD ambient water vapor is often close to saturation in the presence of water ice clouds between 10 and 40 km, with the ambient water vapor mixing ratio following the saturated mixing ratio over a large vertical extent. However, during the decay phase of the GDS the atmosphere is more dynamic and MCS observes that water ice clouds reach higher altitudes between 50 and 70 km.

Some supersaturation is observed in each profile, slightly above the peak in ice opacity, reaching no more than a factor of 2 with the exception of a single family where a supersaturation ratio of about 5 is reached at the beginning of the decay phase of the GDS. Above the top of the cloud, the atmosphere is also largely subsaturated as temperature increases slightly above the peak in ice opacity, suggesting that extended regions of supersaturation are not required to form clouds.

Conlusions:

We have evaluated water vapor saturation in the Martian atmosphere in the presence or proximity of water ice clouds by comparing profile averages of ambient water vapor derived from CRISM and NOMAD measurements with profile averages of saturated water derived from MCS temperature profiles. We come to the following conclusions:

- During the aphelion season the atmosphere is close to saturation in the presence of clouds. Supersaturation ratios reach values of no more than 2 to 3 towards the top of the cloud layer.
- During the perihelion season water vapor is close to saturation or somewhat subsaturated in the presence of clouds, with some supersaturation towards the top of the clouds. Regions towards the bottom of the clouds are often subsaturated.
- Based on the examples studied during the Global Dust Storm the region of cloud occurrence shifts to higher altitudes but the overall structure of supersaturated vs. subsaturated regions does not change markedly.
- The atmosphere above cloud layers appears largely subsaturated, suggesting that cloud formation is fairly instantaneous upon the temperature dropping below the frost point. Large amounts of supersaturation are not required to form water ice clouds.

We propose a schematic model of cloud formation and evolution in Fig. 3 that illustrates a qualitative explanation regarding the saturation state of the atmosphere in the presence and proximity of cloud occurrence as observed by MCS, NOMAD and CRISM.

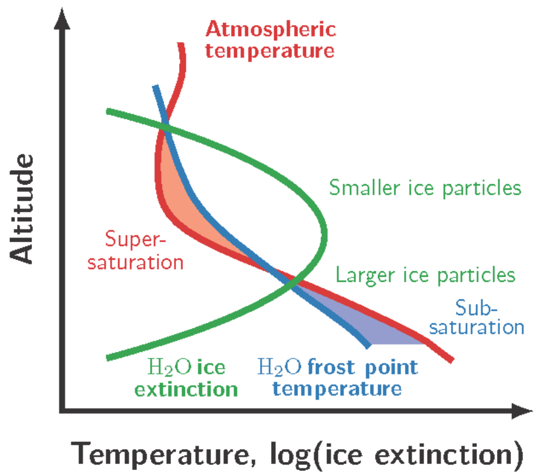

Figure 3: Schematic summarizing the saturation state of the atmosphere in the presence of cloud occurrence and the evolution of water ice particles.

When the atmospheric temperature drops below the frost point at high altitudes, small water ice particles start to form. No large supersaturations are required for this to happen, suggesting that cloud condensation nuclei, most likely in the form of small dust particles, are sufficiently abundant to enable nucleation. The water ice particles grow in size due to constant exposition to water vapor on their surfaces in conditions of saturation or supersaturation and through coagulation by colliding with other ice particles. As they grow the particles will fall due to gravity while consuming the available water vapor on their way through the atmosphere. The suggested structure in ice particle size is qualitatively consistent with recent results [6, 7] that found a general trend of decreasing ice particle size with altitude. As the particles reach warmer and more subsaturated regions of the atmosphere, they start to sublimate. Hence the condition of subsaturation at the bottom of water ice clouds is likely related to ice particles falling into these subsaturated regions and evaporating.

We suggest future coordinated measurements between MCS and the solar occultation instruments on ExoMars TGO as well as extended intercomparisons between the TGO instruments in order to further constrain the saturation state of the Martian atmosphere.

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