

# On the impact of the vertical structure of Martian water ice clouds on nadir atmospheric retrievals from simultaneous EMM/EXI and TGO/ACS-MIR observations.

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## ABSTRACT

Retrieving the optical depth of the Martian clouds ( $\tau_{\text{cld}}$ ) is a powerful way to monitor their spatial and temporal evolution. However, such retrievals from nadir imagery rely on several assumptions, including the vertical structure of the clouds in the atmosphere. Here we compare the results of cloud optical depth retrievals from the Emirates eXploration Imager (EXI) onboard the Emirates Mars Mission (EMM) "Hope" orbiter performed using an empirical cloud profile (typically used in similar studies) and using derived cloud profiles obtained from near-simultaneous Solar Occultation observations from the Middle-Infrared channel of the Atmospheric Chemistry Suite (ACS) instrument onboard the ESA Trace Gas Orbiter (TGO). We show that the latitudinal dependence of the cloud vertical profiles can have a strong impact on the nadir retrievals; neglecting it can lead to a significant underestimation of  $\tau_{\text{cld}}$  in the polar regions (up to 25 %). We also discuss the impact of a vertically-dependent particle size profile, as previous studies have shown the presence of very small water ice particles at the top of the clouds. From this analysis, we provide recommendations for the improvement of water ice cloud parameterization in radiative transfer algorithms in nadir atmospheric retrievals.

## 1. Introduction

Water ice clouds play an important role in the current Martian climate: they affect the thermal structure of the atmosphere by absorbing and scattering the incoming Solar radiation (Haberle et al., 2011; Madeleine et al., 2012; Navarro et al., 2014; Wilson et al., 2007, 2008), and are a major actor in the inter-hemispheric water exchange with a different dynamic compared to that of water vapor (Clancy et al., 1996; Montmessin et al., 2004, 2017b). Constraining the properties and behavior of the water ice clouds on Mars is thus of importance to a better understanding of the current climate of the planet and its evolution.

Over the past 25 years, several orbital missions and their instruments have been looking at the Martian clouds through different geometries: nadir in UV-Visible (MARCI, EXI; e.g., Wolff et al., 2019, 2022), thermal (TES, THEMIS, MCS, EMIRS; e.g., Smith et al., 2001, 2003, 2022; Heavens et al., 2011; Atwood et al., 2022) or infrared wavelength (OMEGA, CRISM; e.g., Vincendon et al., 2011b; Szantai et al., 2021), limb (OMEGA, CRISM; e.g., Vincendon et al., 2011a; Clancy et al., 2019), or Solar occultation (SPICAM, ACS, NOMAD; e.g., Montmessin et al., 2017a; Määttänen et al., 2013; Stcherbinine et al., 2020, 2022; Luginin et al.,


2020; Liuzzi et al., 2020; Stolzenbach et al., 2023). Because several missions remain active at present, one can now make direct comparisons of their respective datasets. Because the information retrieved from the different geometries complements each other, it provides a more comprehensive and unique global view of Martian clouds.

Nadir observations with UV-visible multi-band cameras such as the Mars Color Imager (MARCI) onboard the Mars Reconnaissance Orbiter (MRO) (Malin et al., 2001; Bell III et al., 2009) or the Emirates eXploration Imager (EXI) of the Hope probe (Jones et al., 2021; Amiri et al., 2022) provide a large spatial coverage per image but only limited access to the vertical structure of the aerosol profile in the atmosphere. This is in contrast to Solar Occultation (hereafter "SO") geometry for instance, that provides detailed vertical profiles but only with a very limited spatial extent. Thus, nadir imagery is the easier way to constrain the spatial distribution and variations of the Martian clouds. However, retrieving the column-integrated optical depth of the clouds ( $\tau_{\text{cld}}$ ) from nadir reflectance measurements requires assumptions on the vertical structure and properties of the atmosphere, including the vertical distribution of dust and ice aerosols. Such assumptions on the aerosol properties can be a significant source of retrieval uncertainties (e.g., Wolff et al., 2019).

Typically, the retrieval algorithms for MARCI and EXI assume clouds characterized by water ice particles of the same size uniformly distributed from a given bottom altitude to 100 km, the bottom altitude being the same regardless of the time of the year or the geographic coordinates of the clouds (e.g., Wolff et al., 2019, 2022). An alternative

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approach that has been implemented for THEMIS and TES cloud retrievals implemented a variable lower altitude of the clouds, using the water condensation altitude as the bottom boundary for the presence of water ice (e.g., Clancy et al., 1996; Smith et al., 2003; Wolff and Clancy, 2003). However, recent studies have shown that the cloud altitude varies significantly with the season and latitude (e.g., Stcherbinine et al., 2022; Smith et al., 2013; Montmessin et al., 2006; Heavens et al., 2011), and that the distribution of the ice particle sizes with the altitude is characterized typically by a decrease in size when the altitude increases (e.g., Clancy et al., 2019; Stcherbinine et al., 2020, 2022; Luginin et al., 2020; Liuzzi et al., 2020; Stolzenbach et al., 2023). Thus, the question that arises is: how do more realistic vertical profiles of water ice cloud properties (i.e., obtained obtained with SO geometry) affect the optical depth retrievals from nadir data compared to those using more simple vertical prescriptions?

In this article, we combine simultaneous ACS-MIR vertical profiles of Martian water ice clouds and nadir images acquired by EXI to study the impact of refining the vertical structure of the clouds on the EXI optical depth retrievals. First, we present in Section 2 the datasets and methods used in this study. Then, Section 3 discusses the results on the impact of altitude variations and particle size gradient in the EXI retrievals. Finally, Section 4 summarizes the main points of the study.

## 2. Data and Methods

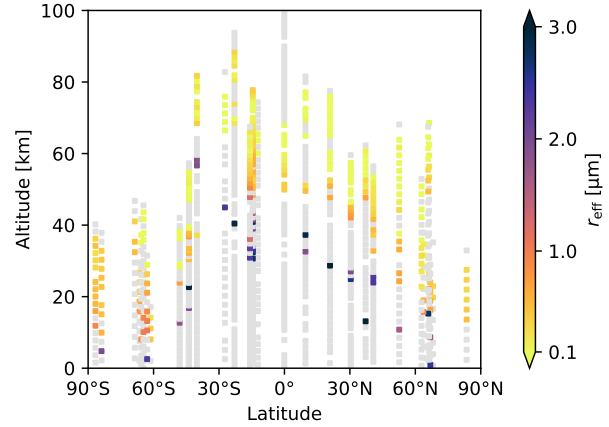
### 2.1. Vertical clouds profiles from ACS-MIR

The Atmospheric Chemistry Suite (ACS) instrument is a set of three spectrometers onboard the ExoMars Trace Gas Orbiter (TGO) ESA-Roscosmos spacecraft, which has been conducting science operations for 3 Martian Years (MY), since March 2018 (Korablev et al., 2018, 2019; Vandaele et al., 2019). The Mid-InfraRed (MIR) channel is a high-resolution cross-dispersion echelle spectrometer dedicated to SO geometry (Trokhimovskiy et al., 2015; Korablev et al., 2018).

We use the methodology and results presented in Stcherbinine et al. (2020, 2022) to retrieve the water ice opacity, as well as the ice particle effective size, as a function of altitude in the Martian atmosphere. The observations use the 3- $\mu\text{m}$  region observed with the ACS-MIR position 12 of the primary grating mirror and have a vertical resolution of  $\sim 2.5$  km. The atmospheric transmittance values measured by the instrument at each observed altitude (tangent point) are converted into extinction coefficients ( $k_{\text{ext}}$ ) through an onion-peeling (vertical) inversion algorithm (Goldman and Saunders, 1979). The resulting extinction spectra are fit with models using spherical water ice and dust particles of various sizes in order to constrain the presence and the size of water ice particles in the atmosphere.

An unfortunate limitation of the method, due to the small wavelength range covered by the position 12 acquisitions (3.1 – 3.4  $\mu\text{m}$ ), is that it is not sensitive to the larger water ice particles ( $r_{\text{eff}} \gtrsim 3$   $\mu\text{m}$ ) that may be present at the bottom

of the profiles; that is to say that one will not be able to distinguish them from dust particles (see discussion in Stcherbinine et al. (2020, 2022)).



**Figure 1:** The vertical profiles of water ice clouds derived from ACS-MIR measurements used in this study, as a function of the latitude of the observation. Observations without water ice detections are in gray.

### 2.2. Optical depths retrievals with EXI

The Emirates eXploration Imager (EXI) instrument onboard the Emirates Mars Mission (EMM) "Hope" probe is a UV-Visible framing camera that has been observing the full Martian disk in 6 bandpasses since the beginning of its science phase in May 2021 (Amiri et al., 2022; Jones et al., 2021). Here, we follow the method of Wolff et al. (2022) that uses the normalized reflectance ( $I/F$ ) at  $\lambda = 320$  nm (the EXI f320 band) to retrieve the water ice clouds optical depth  $\tau_{\text{cld}}$ . The EXI data used in this study have been acquired in the so-called XOS-1 mode with a  $2 \times 2$  binning, giving a spatial resolution of 4–8 km per pixel at nadir, and processed to level 2A. Information about the EXI data products is provided in the Data Availability section.

We use the DIScrete Ordinate Radiative Transfer (DISORT) code (Stamnes et al., 1988, 2017) through the *pyRT\_DISORT* Python module (Connour and Wolff, 2023) to perform the retrievals. In terms of the model parameters, we employ the following, based on Wolff et al. (2019, 2022):

- Surface: Hapke reflectance model, with the values of the parameters listed in Table 1 and the  $w$  value from Wolff et al. (2019), scaled to be adjusted to EXI radiometric calibration (Wolff et al., 2022).
- Atmospheric dust: vertically uniform distribution of 1.5  $\mu\text{m}$  dust particles from the surface to 100 km (or alternative upper altitude derived from ACS-MIR observations), with respect to the gas density (Wolff et al., 2019). Dust properties are computed assuming asymmetric hexahedral shapes with a sphericity of 0.78 and an effective variance  $v_{\text{eff}}$  of 0.3 (Saito et al., 2021), and refractive indices from Wolff et al. (2010);

**Table 1**

Hapke parameters for the surface modeling used in this study, from Wolff et al. (2019, 2022).

Parameter	Value
$b$ (asymmetry parameter)	0.27
$c$ (forward scattering fraction)	0.70
$\bar{\theta}$ (roughness parameter)	15°
$B_0$ (strength of the opposition surge)	1.0
$h$ (width of the opposition surge)	0.06

Connour et al. (2022). The total column optical depth  $\tau_{\text{dust}}$  is extracted from a contemporaneous dust climatology constructed from the EMIRS observations (Smith et al., 2022; Edwards et al., 2021).

- Pseudo-spherical atmosphere geometry: as ACS-MIR profiles are acquired close to the terminator (see section 2.3), they are associated with high incidence and potentially with large emergence angles as well. We use the pseudo-spherical correction introduced in DISORT 3 (Stamnes et al., 2017) instead of the classical plane-parallel representation, allowing for an explicit treatment of planetary/atmospheric curvature.
- Water ice clouds: extinction and scattering properties of water ice particles are computed assuming droxtals shapes, a gamma size distribution (Hansen and Travis, 1974) with an effective variance of 0.1 (e.g., Wolff et al., 2019, and reference contained within).

Typically, these kinds of retrievals assume a vertical profile of the water ice aerosols defined by a cloud bottom around 20 km and a constant volume mixing ratio above this altitude (e.g., Wolff et al., 2019, 2022). In the present study, we will compare the optical depth values retrieved using this cloud vertical profile on some examples, with results using alternative vertical structures (altitude, ice particle sizes) from ACS-MIR coincident observations.

### 2.3. Cross-observations

While EXI offers column-integrated cloud optical depths over the illuminated Martian disk, ACS-MIR will provide locally detailed information about the vertical distribution of the water ice particle properties. Due to the SO observing geometry, ACS-MIR can only acquire atmospheric profiles near the morning and evening terminators (local times  $\sim$  06:00 and 18:00).

To perform optical depth retrievals in nadir geometry, the vertical distribution of the aerosols in the atmosphere is one of the main assumptions that must be made. Usually, one uses a uniform distribution of one size distribution with the base of the cloud starting at the same altitude (e.g., Wolff et al., 2017, 2019, 2022).

Even though no coordinated observations between the EXI and ACS instruments (or the EMM and TGO probes) have been explicitly planned, they are both looking at the Martian atmosphere from their respective orbits. Thus, we

searched for observations from both instruments that observed of the same coordinates within one hour between February 2021 and January 2023, which include the whole MY 36. We identify 31 observations from each instrument that match these criteria, spanning from  $L_s = 76^\circ$  to  $L_s = 359^\circ$  (MY 36) and covering all latitudes from  $86^\circ\text{S}$  to  $86^\circ\text{N}$ . Table 2 gives the list and coordinates of the observations used in this study.

## 3. Results and Discussion

The retrievals of water ice cloud optical depth are performed on the 31 EXI pixels associated with an ACS-MIR profile (cf. Table 2). For all of them, we run the retrieval algorithm assuming the same typical uniform cloud profile (3  $\mu\text{m}$  between 20 and 100 km) and profiles adjusted with inputs from ACS-MIR observations (altitude, size). In Section 3.1 we discuss the impact of the altitude of the clouds on the retrievals, and in Section 3.2 we also introduce a size gradient for the ice within the clouds.

Regarding the dust, we run the retrievals with uniform profiles of 1.5  $\mu\text{m}$  particles uniformly distributed (with respect to the gas density) from the surface to two alternative altitudes: either 100 km as it is usually the case in such studies (e.g., Wolff et al., 2017, 2019, 2022), or, when using cloud altitudes from ACS-MIR profiles, the highest altitude without water ice detection below the clouds in the ACS-MIR profiles. Indeed, previous studies have shown that the dust in the atmosphere is essentially present below the higher water ice clouds (Smith et al., 2013; Luginin et al., 2020; Liuzzi et al., 2020; Stolzenbach et al., 2023). This is particularly important to consider for low-altitude clouds (in the polar regions) because the higher amount of dust particles at low altitudes will have a stronger impact on the  $\tau_{\text{clld}}$  retrievals: more dust at the cloud altitude will "hide" the water ice, resulting in higher  $\tau_{\text{clld}}$  in the retrievals.

In the following, even though some ACS-MIR profiles can exhibit multiple cloud layers (Stcherbinine et al., 2020, 2022), we will consider only one continuous cloud layer per profile for the retrievals, with the bottom and top altitudes corresponding respectively to the lowest and highest ice detections in the ACS-MIR atmospheric profile. However, if a profile exhibits multiple layers of water ice, we will consider that the maximum altitude for the dust is below the upper layer. Below this altitude, we will have a mix of dust and water ice particles, which is representative of what can be observed by the orbiters.

### 3.1. Cloud altitudes

Figure 2 shows the difference (panels a & b) and relative difference (panels c & d) between EXI water ice clouds retrievals performed with the same typical cloud profile of 3  $\mu\text{m}$  water ice particles uniformly distributed between 20 and 100 km, and with profiles whose altitudes are taken from contemporaneous ACS-MIR observations. Results are presented as a function of the minimum cloud altitude derived from the ACS-MIR observations (panels a & c) and the latitude of the observation (panels b & d). For the blue

**Table 2**

List and coordinates of the 31 EXI and ACS-MIR observations used in this study.

EXI (XOS-1 – f320)	ACS-MIR	Longitude [°E]	Latitude [°N]	$L_s$ [°]	MY
20210724T220055	ORB016367_N1	72.2	-61.4	76.4	36
20210830T063840	ORB016809_N2	-133.7	-48.0	92.3	36
20211124T202544	ORB017868_N1	-146.9	-66.4	132.2	36
20211129T120020	ORB017925_N1	22.2	-65.7	134.4	36
20211201T132848	ORB017950_N1	28.4	-64.6	135.4	36
20211204T223121	ORB017991_N2	-9.9	40.8	137.1	36
20211206T172533	ORB018013_N2	70.2	30.4	138.0	36
20211208T130036	ORB018035_N1	132.9	-43.8	138.8	36
20220107T191342	ORB018403_N1	-103.4	-63.0	154.1	36
20220121T212521	ORB018576_N1	113.9	68.1	161.6	36
20220303T020711	ORB019068_N1	61.4	-86.6	183.7	36
20220307T100322	ORB019121_N1	-21.5	-83.9	186.2	36
20220323T024006	ORB019312_N1	-110.0	-68.6	195.3	36
20220407T071615	ORB019498_N1	-61.4	-22.9	204.3	36
20220424T012729	ORB019701_N2	32.8	-0.1	214.5	36
20220429T075125	ORB019766_N1	120.2	66.4	217.7	36
20220501T204754	ORB019797_N1	-52.0	66.9	219.3	36
20220515T082017	ORB019962_N1	-113.4	66.3	227.7	36
20220517T101316	ORB019987_N1	-110.8	65.9	229.0	36
20220531T055303	ORB020155_N2	6.2	-40.1	237.7	36
20220801T045738	ORB020913_N1	40.0	-12.2	276.9	36
20220805T165821	ORB020968_N1	-109.3	9.7	279.7	36
20220811T143523	ORB021039_N2	-167.2	20.9	283.3	36
20220812T064308	ORB021048_N1	98.3	37.2	283.8	36
20220818T212312	ORB021129_N1	-81.6	52.6	287.8	36
20220822T161908	ORB021174_N1	-113.0	-27.3	290.1	36
20220906T211836	ORB021361_N1	84.1	63.7	299.4	36
20220918T043109	ORB021499_N1	94.0	62.9	306.1	36
20220925T092024	ORB021587_N1	135.8	-14.5	310.3	36
20221213T193446	ORB022556_N2	-135.3	-15.8	353.6	36
20221223T220315	ORB022680_N1	93.5	83.5	358.8	36

crosses, the bottom and top altitudes of the clouds are taken from ACS-MIR data but the upper altitude for the dust is still 100 km, and for the red crosses the dust is only present below the water ice clouds (with the minimum and maximum altitudes from ACS-MIR data).

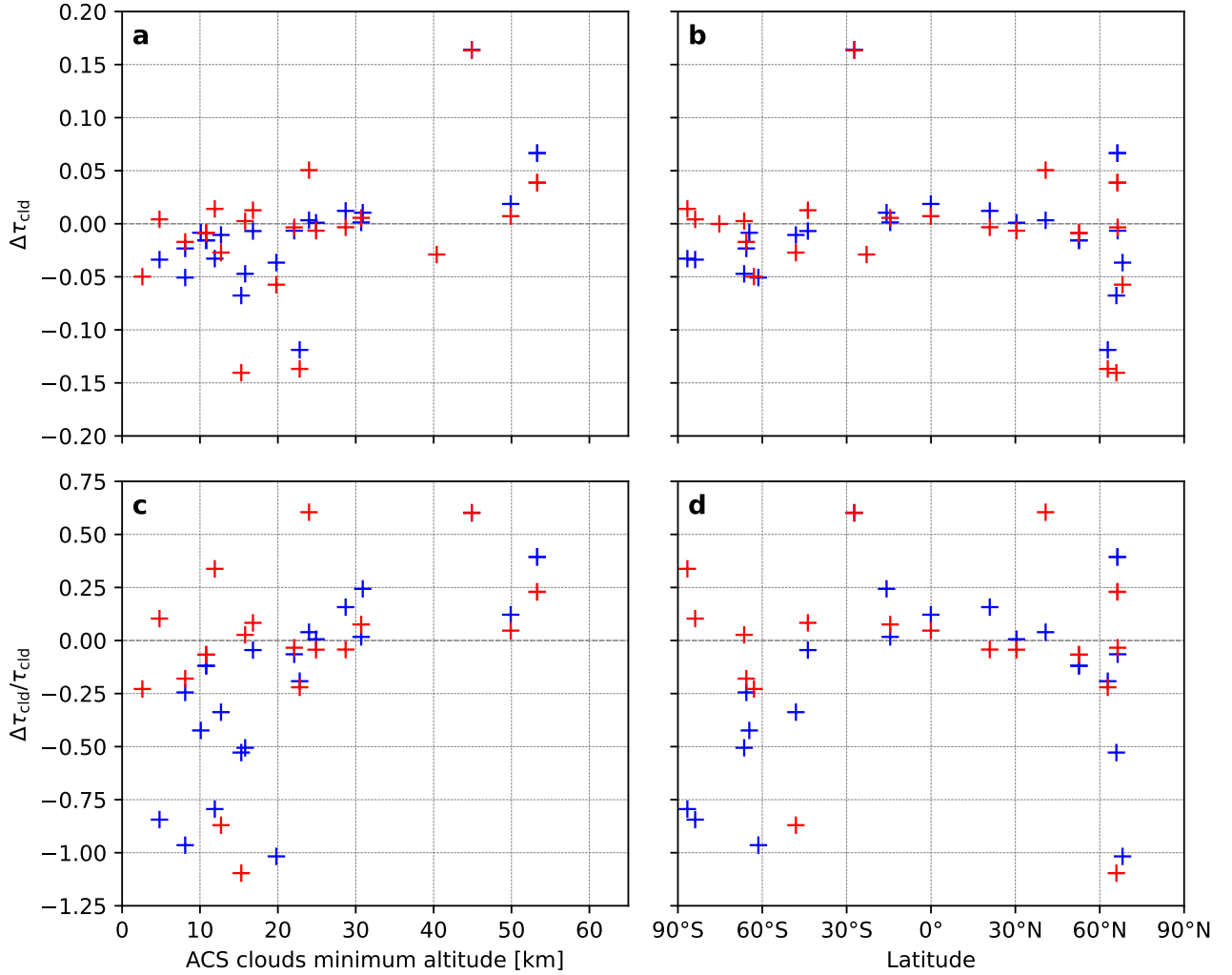
We can see that the retrieved value of  $\tau_{\text{cld}}$  depends on the altitude of the cloud provided in the model: for a given set of atmospheric and surface parameters, the value of  $\tau_{\text{cld}}$  increases when the minimum altitude of the cloud decreases. Thus, the retrieval algorithm will underestimate the optical depth of the low-altitude clouds and underestimate it for the high-altitude clouds (relative to the bottom altitude assumed in the model, i.e.,  $\sim 20$  km). For clouds starting below  $\sim 10$  km,  $\tau_{\text{cld}}$  will be underestimated by 25 % (up to 0.05 in absolute value), and similarly, for clouds with a bottom altitude between 40 and 60 km the  $\tau_{\text{cld}}$  will be overestimated up to 50 % (cf. Figure 2 a & c). We also observe on Figure 2 that, as expected, the retrievals are more affected by the dust profile for clouds with a minimum altitude below  $\sim 20$  km, and that the retrieved values of  $\tau_{\text{cld}}$  decrease when the dust is capped by the water ice clouds.

The altitude of the clouds varies significantly with the latitude (Forget et al., 1999; Heavens et al., 2011; Jaquin

et al., 1986; Montmessin et al., 2006; Smith et al., 2013; Stcherbinine et al., 2022), which is visible in Figure 1. Stcherbinine et al. (2022) reported that the typical altitude of the clouds is 20–40 km higher around the equator than in the polar regions, and that variations of the same order of magnitude also occur between summer and winter for both hemispheres. In our dataset, the minimum altitude of the clouds ranges from 3 km to 53 km. However, we do not have enough data here to discuss the impact of seasonal variations of the clouds.

As a consequence of the latitudinal variations of the cloud altitudes, the EXI nadir retrievals will tend to underestimate the  $\tau_{\text{cld}}$  in the polar regions (up to  $\sim 25$  % if also decreasing the maximum altitude of the dust;  $\sim 50$  % otherwise) and slightly overestimate it around the equator (up to  $\sim 10$  % if also decreasing the maximum altitude of the dust;  $\sim 25$  % otherwise) if assuming the same uniform vertical profile between 20 and 100 km for all clouds (cf. Figure 2 b & d). We can see that the amplitude of the variations in  $\tau_{\text{cld}}$  when adjusting the altitude of the clouds is lowered if adjusting the dust profile as well to keep it below the clouds. One should also note that the largest relative discrepancies between the retrievals observed in the polar





**Figure 2:** a. & b. Difference between the  $\tau_{\text{cld}}$  values retrieved from EXI observations assuming water ice clouds with particle size of  $3 \mu\text{m}$  from 20 km to 100 km and the ones retrieved using top and bottom altitudes from ACS-MIR profiles and dust with particle size of  $1.5 \mu\text{m}$  from 0 km to 100 km (blue), or dust only contained below the clouds (red). c. & d. Same but normalized by the  $\tau_{\text{cld}}$  values retrieved with clouds uniform between 20 km and 100 km (i.e., no ACS input). Results are displayed as a function of the clouds' minimum altitude from the ACS-MIR profiles (a & c) and the latitude of the observation (b & d).

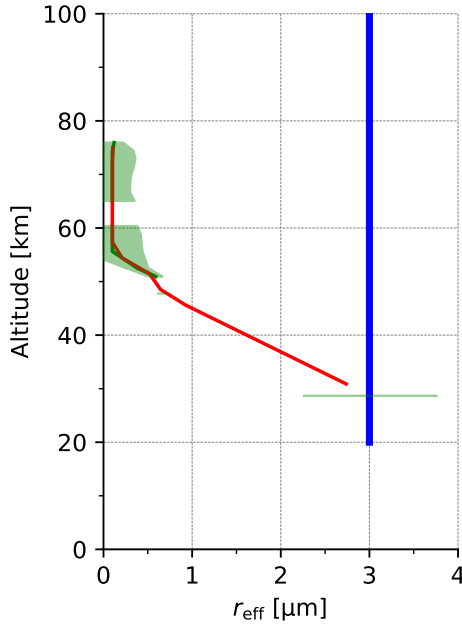
regions are associated with absolute differences in the  $\tau_{\text{cld}}$  values smaller than 0.05. The presence of optically thinner clouds in these regions contributes to enlarging the relative differences between the retrievals with and without taking into account the clouds and dust altitudes, but even the absolute variations  $\Delta\tau_{\text{cld}}$  are still higher under polar latitudes as shown on Figure 2b.

The sensitivity of  $\tau_{\text{cld}}$  with the cloud altitudes is related to the presence of dust in the atmosphere. At low altitudes, the higher concentration of dust particles in the atmosphere will hide a larger fraction of the light scattered by the clouds. Thus, more water ice is required to reproduce the radiance observed from the orbit, which leads to thicker clouds in the retrievals. This explains the higher  $\tau_{\text{cld}}$  values retrieved close to the poles when using the ACS altitudes for the clouds in the retrieval algorithm, where they are observed

down to altitudes lower than 20 km. Also, as the density of dust particles decreases with the altitude (with respect to the gas density) the distribution of the ice particles at high altitudes (typically above 50–60 km) will have a more limited impact on the  $\tau_{\text{cld}}$  retrievals. This explains why can observe such large variations in the retrieved  $\tau_{\text{cld}}$  in the polar regions between computations with the dust altitude ranging up to 100 km, or only below the clouds. For instance, if we look at the two clouds  $87^\circ\text{S}$  and  $84^\circ\text{S}$ , their ACS-MIR profiles report water ice between  $\sim 10$  km and  $\sim 35$  km, with the upper water ice layer starting from  $\sim 15$  km. So at these altitudes where the particle density is higher, a few kilometers of dust mixed with water ice will have a strong impact on the retrievals by hiding the light reflected by the water ice particles.

### 3.2. Clouds particle sizes

We discussed in the previous section the impact of the altitude of the clouds on the EXI retrievals for a fixed value of  $r_{\text{eff}}$ , here we use the altitude of the clouds as observed by ACS-MIR to focus on the impact of the size of the ice particles on the retrievals. More specifically, we focus on the vertical variations of the particle size within the cloud, rather than the choice of 3  $\mu\text{m}$  as the default reference size for  $r_{\text{eff}}$ . Indeed, observational profiles of the Martian clouds by ACS-MIR have shown that they exhibit a decrease of the  $r_{\text{eff}}$  when the altitude increases, with sizes typically ranging from 2-3  $\mu\text{m}$  at the bottom to 0.1  $\mu\text{m}$  at the top (Stcherbinine et al., 2022, Figure 4).



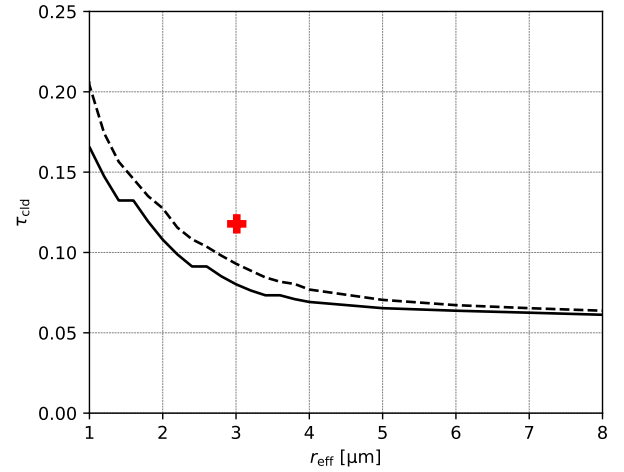
**Figure 3:** Vertical  $r_{\text{eff}}$  profile of a Martian cloud derived from ACS-MIR observation ORB021039\_N2 (see Table 2) with the associated uncertainties (green) and sampled on the altitude grid used in the DISORT retrieval algorithm (red), compared to the constant default profile (blue).

Figure 3 shows the comparison between a cloud profile obtained from ACS-MIR observations (ORB021039\_N2) and the typical default for  $\tau_{\text{clid}}$  retrievals in the literature, i.e., constant size of 3  $\mu\text{m}$  from 20 to 100 km. We can see that if  $r_{\text{eff}}$  is similar at the bottom of the cloud (although ACS-MIR reported a cloud starting from 29 km only), it decreases quickly in the observations to reach 0.1  $\mu\text{m}$  at 56 km and remain like so up to the top of the cloud at 79 km. In this section, we will discuss the impact of using different kinds of  $r_{\text{eff}}$  profiles for the clouds in DISORT on the retrieved  $\tau_{\text{clid}}$ :

- Constant profile:  $r_{\text{eff}}$  remains constant regardless of the altitude, this is the assumption usually made for such nadir retrievals.
- Linear gradient profile: previous studies (e.g., Stcherbinine et al., 2020, 2022; Luginin et al., 2020; Liuzzi

et al., 2020) have shown that the particle size within the clouds typically decreases down to  $\sim 0.1 \mu\text{m}$  when the altitude increases. Thus, we implemented an alternative  $r_{\text{eff}}$  profile where the water ice particle size decreases linearly when the altitude increases, ranging from a given value at the bottom altitude of the cloud to 0.1  $\mu\text{m}$  at the top.

- ACS-MIR profile: here we use the actual  $r_{\text{eff}}$  profile obtained from the correspondent ACS-MIR observation, resampled in the altitude grid used in the retrieval algorithm (cf. Figure 3). As stated above and for simplification purposes, we consider the potential multiple layers that may be present in the ACS-MIR data as one single cloud layer, starting from the lowest altitude where water ice has been detected, and ending at the higher altitude with water ice.



**Figure 4:** Variation of the retrieved  $\tau_{\text{clid}}$  value as a function of the water ice particle size within the cloud (EXI observation 20220811T143523) for a cloud with a constant particle size (solid line) or using a linear gradient from  $r_{\text{eff}}$  at the bottom of the cloud to 0.1  $\mu\text{m}$  at the top (dashed line). The boundary altitudes of the cloud are taken from the corresponding ACS-MIR observation (ORB021039\_N2), i.e., from 29 to 76 km, as well as the maximum altitude for the dust, set to 63 km. The red cross shows the result obtained using the actual ACS-MIR cloud profile shown in Figure 3 (red line).

Figure 4 shows the  $\tau_{\text{clid}}$  values retrieved from the EXI observation 20220811T143523, using the cloud's altitude from ACS-MIR observation ORB021039\_N2 (from 29 to 76 km), as a function of the water ice particle size assumed in the retrieval algorithm. These computations have been performed for both constant and linear gradient profiles, as well as using the actual ACS-MIR  $r_{\text{eff}}$  profile. We can see that the retrieved value for  $\tau_{\text{clid}}$  depends on the assumed size of the water ice particles at the bottom of the cloud (either for the constant or the linear gradient case), especially for  $r_{\text{eff}}$  between 1 and 4  $\mu\text{m}$ . It goes from  $\tau_{\text{clid}} = 0.166$  for  $r_{\text{eff}} = 1 \mu\text{m}$  to  $\tau_{\text{clid}} = 0.069$  for  $r_{\text{eff}} = 4 \mu\text{m}$  with the constant profile, and

respectively from  $\tau_{\text{cld}} = 0.204$  to  $\tau_{\text{cld}} = 0.077$  with the linear gradient. For larger ice particles, from 4 to 8  $\mu\text{m}$ , it became more stable:  $\tau_{\text{cld}}$  goes from 0.069 to 0.061 for the constant profile, and from 0.077 to 0.064 for the linear gradient one.

We also observe that the difference between the constant and linear gradient profiles is more pronounced when only smaller ice particles are present in the cloud: the  $\tau_{\text{cld}}$  values retrieved with the linear gradient profile are 10 % to 20 % larger than the results with the constant profile for  $r_{\text{eff}} \leq 4 \mu\text{m}$ , but the difference becomes smaller than 5 % when  $r_{\text{eff}}$  at the bottom of the cloud is larger than 6  $\mu\text{m}$ .

Smaller water ice particles in the clouds result in more reflective and less absorbing cloud layers in the atmosphere, which leads to thicker clouds retrieved in order to match the I/F measured values. Thus, introducing smaller particles in the upper part of the cloud with the linear gradient profile leads to an increase of the retrieved  $\tau_{\text{cld}}$ . However, we can see that the increase of  $\tau_{\text{cld}}$  due to the transition to a linear gradient profile is of lower magnitude compared to the decrease of  $r_{\text{eff}}$  at the bottom of the cloud. This can be explained by the fact that the density of particles in the atmosphere is higher at low altitudes, so the lower layers (also filled with more absorbent larger water ice particles) will dominate the column-integrated nadir optical depth of the clouds.

Figure 4 also shows the  $\tau_{\text{cld}}$  retrieved using the actual ACS-MIR profile as a matter of comparison (red cross). As we can see in Figure 3, the ACS profile exhibits a decrease of  $r_{\text{eff}}$  from 3  $\mu\text{m}$  at 29 km to 0.1  $\mu\text{m}$  at 56 km, then the particle size remains at 0.1  $\mu\text{m}$  up to the top of the cloud at 76 km. So, the proportion of very small water ice particles is higher in the ACS-MIR profile compared to the linear gradient one. Consequently, the value of  $\tau_{\text{cld}}$  retrieved with this profile is larger than with the linear gradient profile for the same  $r_{\text{eff}}$  (3  $\mu\text{m}$ ):  $\tau_{\text{cld}} = 0.118$  for the ACS-MIR profile versus  $\tau_{\text{cld}} = 0.093$  for the linear gradient one (and  $\tau_{\text{cld}} = 0.080$  for the constant profile). And so, even though it is not perfect, the use of a linear gradient instead of a constant profile for  $r_{\text{eff}}$  in the clouds retrievals improves the retrieved  $\tau_{\text{cld}}$  by bringing it more than 40 % closer to what can be obtained using the actual cloud profile.

## 4. Conclusion

In this paper, we use the combination of quasi-concomitant observations of the same region of the Martian atmosphere by the TGO/ACS-MIR and EMM/EXI instruments to study Martian water ice clouds, and discuss the impact of the refinement of the vertical structure of the clouds in radiative transfer models on optical depth retrievals performed from nadir imagery. The vertical distribution and properties of the aerosols and clouds in the atmosphere are two of the main hypotheses that have to be made in order to perform retrievals from nadir observations using radiative transfer algorithms. But this information can be retrieved from observations in different geometries, especially in Solar Occultation. Thus, we use cloud profiles (altitude and  $r_{\text{eff}}$ )

obtained from ACS-MIR observations to perform optical depth ( $\tau_{\text{cld}}$ ) retrievals from EXI nadir images at 320 nm, and compare the results to the values obtained with a constant cloud profile typically used in this kind of study.

First, we show that not accounting for the variation of the clouds' altitude with the latitude that can be up to 40 km between the poles and the equator (Stcherbinine et al., 2022) leads to an underestimation of  $\tau_{\text{cld}}$  up to 25 % under polar latitudes, and an overestimation of about 10 % at the equator if assuming a bottom altitude of 20 km for all the clouds.

Then, we show that the accounting for the variation of  $r_{\text{eff}}$  with the altitude in the clouds (with very small water ice particles at the top) also significantly affects the retrievals but to a lesser extent than altitude or the size of the ice particles at the bottom of the cloud. The retrieved values of  $\tau_{\text{cld}}$  are dominated by the size of the larger water ice particles at low altitudes, but the impact of the very small ones at the top of the clouds is not negligible.

Thus, from the results presented in Section 3, we formulate two recommendations to improve the representation of Martian water ice clouds in radiative transfer models, and thereby the performed optical depth retrievals from nadir observations in future studies:

- Adjust the boundary altitudes of the clouds with latitude and season, from typical ranges that can be extracted from recent clouds' climatology, such as presented in Stcherbinine et al. (2022), and adjust the maximal altitude for the dust so it remains below the water ice clouds.
- Use of a non-constant  $r_{\text{eff}}$  profile for the clouds. For instance, a profile ranging from  $\sim 2\text{--}3 \mu\text{m}$  at the bottom to 0.1  $\mu\text{m}$  at the top would provide a better representation of the vertical structure of the clouds and thus more accurate results, even if it is not perfect either.

This study is the first collaboration between the EMM and TGO/ACS science teams and paves the way for future synergies between these two active missions currently looking at the Martian atmosphere. And beyond that, it highlights the huge potential in developing more synergies between different spacecraft and instruments to study the Martian water ice clouds.

## Data availability

Data from the Emirates Mars Mission (EMM) are freely and publicly available on the EMM Science Data Center (SDC, <http://sdc.emiratesmarsmission.ae>). This location is designated as the primary repository for all data products produced by the EMM team and is designated as long-term repository as required by the UAE Space Agency. The data available (<http://sdc.emiratesmarsmission.ae/data>) include ancillary spacecraft data, instrument telemetry, Level 1 (raw instrument data) to Level 3 (derived science products), quicklook products, and data users guides (<https://sdc.emiratesmarsmission.ae/documentation>) to assist in the

analysis of the data. Following the creation of a free login, all EMM data are searchable via parameters such as product file name, solar longitude, acquisition time, sub-spacecraft latitude & longitude, instrument, data product level, etc.

Data products can be browsed within the SDC via a standardized file system structure that follows the convention: /emm/data/<Instrument>/<DataLevel>/<Mode>/<Year>/<Month>

Data product filenames follow a standard convention: emm\_<Instrument>\_<DataLevel><StartTimeUTC>\_<OrbitNumber>\_<Mode>\_<Description>\_<Kernel-Level>\_<Version>\_<FileType>

EXI data and users guides are available at: <https://sdcr.emiratesmarsmission.ae/data/exi>

Raw ACS data are available on the ESA PSA at <https://archives.esac.esa.int/psa/#!Table%20View/ACS=instrument>.

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