RETRIEVALS OF ATMOSPHERIC AEROSOLS IN HIGH AEROSOL CONDITIONS FROM MARS CLIMATE SOUNDER MID- AND FAR INFRARED LIMB MEASUREMENTS

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Introduction: Limb sounding of thermal emission in the infrared wavelength range is a powerful technique for measuring dust and water ice aerosols in the martian atmosphere. It provides vertical profile information and, due to the long optical path, typically has a higher sensitivity compared with nadir viewing measurements. However, the limb path might become opaque in high aerosol conditions, preventing a limb sounding measurement from penetrating the atmosphere. Atmospheric opacities of aerosols in the far IR are typically lower than in the mid-IR, allowing atmospheric retrievals in conditions of higher aerosol opacity.

Here we present atmospheric profile retrievals of dust and water ice from Mars Climate Sounder (MCS) limb measurements that include radiances in the far IR. We use empirically derived extinction efficiencies for dust and water ice to convert extinctions obtained in the far IR to the mid-IR. In dust profile retrievals the use of the 32 μm channel of MCS (channel B1) extends the retrievable altitude range in dust storm conditions typically by about a scale height. In water ice retrievals the use of the MCS 42 μm channel (channel B2) extends the available vertical range in conditions of thick water ice clouds typically by at least a scale height as well. In cloudy conditions with low levels of dust, such as in the aphelion cloud belt at nighttime, the 32 μm channel can additionally be used for water ice, allowing retrievals down to the lowest scale height in most conditions. The increased vertical range of the retrieved profiles, which often extend to the lowest scale height, allows us to report aerosol column quantities derived from these profiles by extrapolation to the surface.

MCS Instrument and Retrievals: The Mars Climate Sounder [1] is a passive infrared radiometer onboard Mars Reconnaissance Orbiter (MRO), which views the martian atmosphere in limb, nadir, and off-nadir geometries. It has 5 mid-IR, 3 far IR, and one broadband visible/near-IR channels. Each spectral channel uses a linear detector array consisting of 21 elements, which provides -10 to 90 km altitude coverage with 5 km vertical sampling when pointed at the Mars limb.

Profile retrievals from MCS radiance measurements use a modified Chahine method together with a Curtis-Godson approximation in the radiative transfer [2] and employ a single-scattering approximation to account for scattering in the limb radiative transfer [3]. The retrieval algorithm employs two-dimensional radiative transfer for both temperature and aerosol retrievals in limb-viewing geometry in order to correct for lateral inhomogeneities along the line-of-sight of limb measurements [4]. Retrievals of temperature profiles use the MCS mid-infrared channels A1, A2, and A3 that cover frequencies within the 15 μm gaseous absorption band of CO_2. Water ice extinction retrievals are based on limb measurements of an absorption feature in channel A4 with a center frequency of 843 cm^{-1}. Water ice extinction is represented in the MCS radiative transfer through particles that follow a modified gamma-distribution with an effective radius of 1.41 μm [3] and spectroscopic parame-

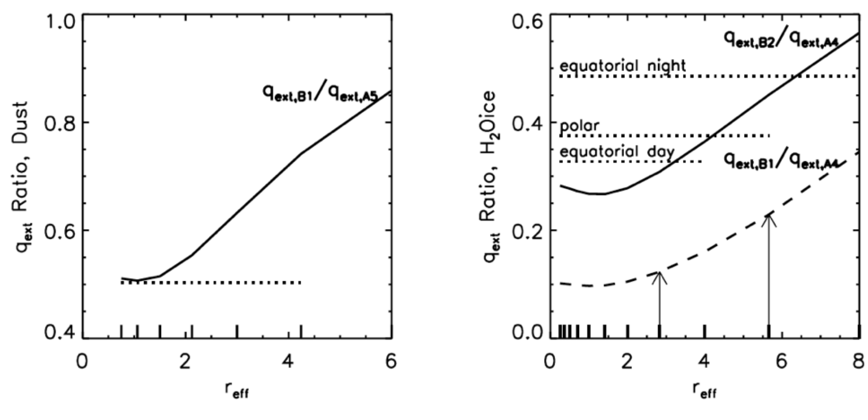

Figure 1: Ratio between extinction efficiencies for dust in the MCS channels B1 and A5 (left, solid line), and for water ice in the MCS channels B2 and A4 (right, solid line) and B1 and A4 (right, dashed line) as calculated by Mie theory for various particle sizes following a geometric series (dashes on x-axis). Dotted horizontal lines indicate empirical extinction efficiency ratios derived for dust (left, B1/A5) and water ice (right, B2/A4). Arrows indicate the theoretical extinction efficiency ratios adopted for water ice in channel B1 in case this channel is used for water ice retrievals.

ters by Warren [5]. Dust extinction is retrieved from limb measurements using an absorption feature in channel A5 with a center frequency of 463 cm^{-1}. Dust extinction is represented through particles that follow a modified gamma-distribution with an effective radius of 1.06 µm [3]. Dust spectroscopic parameters are based on Wolff et al. [6] in the mid-infrared.

A challenge for the use of far IR radiances in the retrieval process is the conversion of retrieved extinctions to the nominal MCS wavelengths in the mid-IR. We use extinction efficiency ratios derived empirically from MCS limb measurements to accomplish this task [7]. Figure 1 (left) shows a graphical representation of the empirically derived dust extinction efficiency ratio between channels B1 at 32 µm and channel A5 at 22 µm in comparison with theoretical extinction efficiency ratios calculated by Mie theory for various particle sizes following a geometric series. The empirical extinction efficiency ratio agrees very well with the ratio for the nominal particle size of 1.06 µm used in MCS retrievals. We note this result does not strongly depend on particle size such that the agreement is similarly good for slightly smaller (0.75 µm) and larger (1.5 µm) particle sizes. Only for particle sizes above ~2 µm the ratios start to differ significantly.

In the right panel of Figure 1 a graphical representation of the empirically derived extinction efficiency ratio with theoretical extinction efficiency ratios calculated by Mie theory between channels A4 at 12 µm and B2 at 42 µm is shown. Due to significant variability in observed ratios in terms of latitude and local time, three different values were derived for equatorial latitudes on the day and night side, respectively, as well as north polar latitudes. Extinction efficiency ratios between A4 and B2 suggest particle sizes of order 3 µm on the dayside and 6 µm on the nightside. We note that this analysis is weighted towards the altitude in which water ice tends to become opaque 12 µm in a limb view. The average altitude where a cloud becomes too opaque for a on the nightside is about 13 km while on the dayside in the equatorial belt this altitude is around 28 km. So the smaller particles on the dayside are associated with higher clouds than the larger ones on the nightside. This behavior is consistent with results from limb observations by the CRISM instrument, which find decreasing particle sizes with altitude and a typical particle size of 2-3 µm at 20-30 km in the daytime aphelion cloud belt [8].

We use these derived extinction efficiency ratios separately in retrievals for the north polar region (applied north of 50°N) and the equatorial region

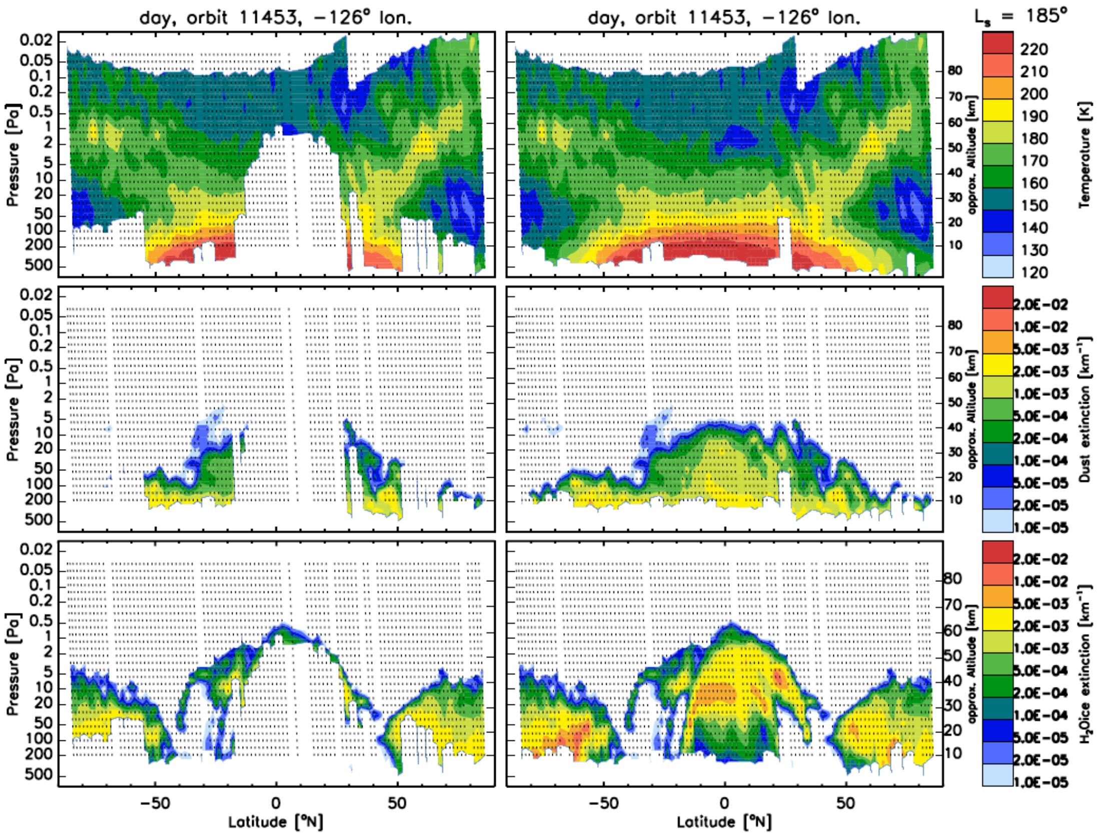

Figure 2: Temperature (top), dust extinction (center) and water ice extinction profiles (bottom) retrieved from MCS measurements during the dayside part of one MRO orbit around northern fall equinox in the standard retrieval version (v5.2) using only mid-IR channels (left) and in the new retrieval version using a combination of mid- and far IR channels (right). Dashed lines indicate the locations of the individual profiles.

(applied south of 40°N). In addition, daytime and nighttime measurements are considered separately in the equatorial region. Results of this analysis were not robust enough to derive empirical extinction efficiency ratios between channels A4 and B1 for water ice. For the use of B1 in water ice retrievals, which is only considered within the equatorial cloud belt, extinction efficiency ratios are based on theoretical values calculated by Mie theory (dashed line in Figure 1) at particle sizes that are part of a geometric series (2.83 μm and 5.66 μm, arrows in Figure 1), which are closest to the empirically derived sizes.

Results:

Aerosol profiles: Figure 2 shows a comparison between the original retrieval and the new retrieval using far IR channels along a transect of the daytime part of an orbit at L_s=185°. Although after what is considered the aphelion season, the atmosphere in the equatorial region is still dominated by substantial cloud occurrence. Clouds are present between about 20°S and 30°N and reach as high as 50-60 km. The opacity of the clouds is sufficient to prevent limb retrievals that use the mid-IR channels only (left panel in Figure 2). Because aerosol is not retrieved up to middle-atmospheric altitudes, temperature is not reported either over this altitude range.

The right panel in Figure 2 shows retrievals of the same measurements with the new algorithm, using a combination of mid-IR and far IR channels for aerosol retrievals. Retrievals are now possible from the middle atmosphere down to about 10 km altitude for nearly all measurements. This extension in vertical coverage is largely enabled by the use of channel B2 for water ice retrievals. The resulting aerosol profiles show that the equatorial region is dominated by thick water ice clouds between 20 and 50 km altitude that overlay a dust layer. The equatorial cloud structure is roughly bell-shaped, with the clouds reaching highest at the equator. They fall off in altitude towards higher latitudes, forming tendrils that reach down to 10-20 km altitude around 20°S and 35°N. Due to the successful aerosol retrieval also temperature is now reported down to altitudes near the surface based on retrievals from combined limb and on-planet observations in the 15 μm CO_2-band.

Aerosol columns: The extended vertical range of aerosol profile retrievals using combinations of mid-

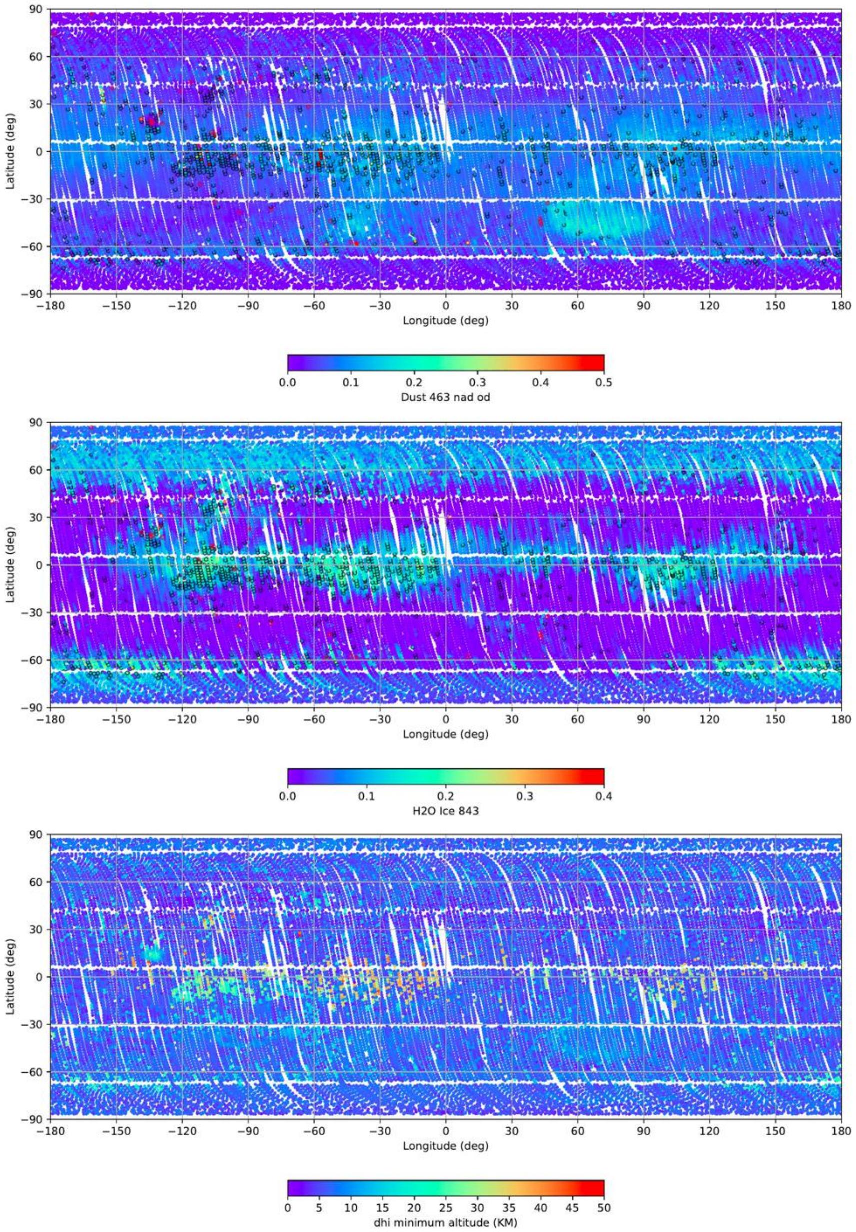

Figure 3, top: Dust column optical depths from MCS daytime measurements in January 2009 (L_s=184°-201°), derived from retrieved dust profiles, extrapolated homogeneously mixed from the lowest retrievable altitude to the surface. Center: Daytime water ice column optical depths derived from retrieved water ice profiles for the same time period. Invalid column derivations are marked by black and red circles in both panels. Bottom: Lowest retrievable altitudes for aerosol profile retrievals used to derive column quantities.

and far IR limb views allows the derivation of aerosol column quantities. For dust, extinction profiles are extended homogeneously mixed from the lowest retrievable altitude to the surface and vertically integrated in order to derive a column. For water ice the retrieved extinction profile is integrated directly to derive a column. Column quantities are typically reported if aerosol profiles reach down to 15 km altitude or below.

The top and center panels of Figure 3 show dust and water ice columns, respectively, derived from profile retrievals on the dayside in January 2009. Slight enhancements in dust are visible in the equatorial region as well as in the Hellas and Argyre basins due to their low surface elevations. Water ice clouds are present in the equatorial region, centered at three longitudes around 110°W, 30°W, and 100°E. In addition, the emerging polar hood is visible north of 50°-60°N. The south polar region exhibits a partial annulus of clouds around 70°S that reaches from about 120°E to 120°W.

The bottom panel of Figure 3 shows the minimum altitudes for daytime aerosol profile retrievals that were achieved in January 2009 using combined mid- and far IR limb measurements. Typically, retrievals reach altitudes of 10-15 km. Only in the equatorial region a few retrievals still cut off at significantly higher altitudes due to the large ice opacity.

Summary and Outlook:

We presented new atmospheric profile retrievals of dust and water ice from Mars Climate Sounder (MCS) limb measurements that include radiances in the far IR. Empirically derived extinction efficiencies for dust and water ice are used to convert extinctions obtained in the far IR to the mid-IR. Dust profile retrievals use the 32 μm channel of MCS while water ice profile retrievals use the 42 μm channel and occasionally also the 32 μm channel in conditions of the aphelion cloud belt. The use of the far IR channels extends the retrievable vertical range in high aerosol conditions typically by at least a scale height. The extended vertical coverage of the profile retrievals enables the derivation of dust and water ice columns through vertical integration. In addition, the improved representation of aerosols allows a more accurate estimate of atmospherically corrected surface temperatures from on-planet views. It is planned to re-retrieve the complete MCS dataset, spanning the time period from September 2006 to the present, with this new retrieval version (v6). The updated retrievals will be re-delivered as a revised version of MCS Level 2 data to NASA's Planetary Data System, where it will be made publicly available. This new version of Level 2 data will also include dust and water ice column quantities.

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