Martian Mesospheric Cloud Observations by IUVS on MAVEN: Temperature Tides Coupled to the Upper Atmosphere

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Abstract. We report observations of Martian mesospheric ice clouds by the Imaging Ultraviolet Spectrograph on NASA's Mars Atmosphere and Volatile Evolution mission. The clouds are observed between 6 and 8 local time using mid-UV limb observations between 60 and 80 km tangent altitude, where ice clouds that scatter sunlight can appear as detached layers. Many of the clouds are confined to the equatorial region between 20° S and 20° N latitude, consistent with previous observations. The longitudinal distribution shows populations of clouds near -110° E and -10° E as well as a newly reported population near 90° E, together indicating a wave 3 pattern of temperature oscillations near 70 km. Scale heights 100 km above the clouds derived from concurrent IUVS observations also reveal a wave 3 longitudinal structure, suggesting that the temperature oscillations enabling the formation of mesospheric clouds couple to the upper atmosphere.

1. Introduction

Martian mesospheric clouds between 60-80 km altitude were first reported by Clancy and Sandor [1998] using Mars Pathfinder camera images obtained from the surface. Although they argued that the clouds were composed of CO_2 ice based on separate temperature observations [Schofield *et al*., 1997], the first unambiguous identification of Martian mesospheric CO_2 ice was by Montmessin *et al*. [2007] using near-IR imaging spectra. Because average ambient temperatures near 70 km are typically 10-15 K higher than the CO_2 frost point, these clouds are valuable diagnostics for quantifying temperature variability in the Martian mesosphere [Clancy and Sandor, 1998].

More recent satellite observations helped to define the seasonal and geographic distributions of mesospheric clouds [*e.g*. Clancy *et al*., 2007; Määttänen *et al*., 2010; Scholten *et al*., 2010; Vincendon *et al*., 2011; Määttänen *et al*., 2013a; Sefton-Nash *et al*., 2013] such that climatologies could ultimately be compiled [*e.g*. Määttänen *et al*., 2013b]. These climatologies revealed that the clouds primarily form near the equator between about 20° S and 20° N distributed between about -130° E and 30° E. In addition to this, there is a seasonal dependence such that the equatorial clouds appear between about L_s = 0-150°, although some observations indicate that the season could start as early as L_s=330° [Määttänen *et al*., 2010].

Mid-UV (MUV; 180-340 nm) limb radiances in the Martian mesosphere are bright and often the result of strong Rayleigh scattered sunlight or solar scattering from dust and aerosols. This bright background obscures the identification of ice particles in the upper mesosphere. As a result, very few observations of dust or cloud layers have ever been reported there from MUV solar scattering in a fully illuminated atmosphere [Rannou *et* *al*., 2006]. By contrast, solar scattering MUV limb observations of terrestrial mesospheric clouds is a well-established technique [*e.g*. Thomas and Olivero, 1989; Bailey *et al*., 2005; Petelina *et al*., 2006; Stevens *et al*., 2009; Robert *et al*., 2009].

Here we report solar scattering MUV limb observations of Martian mesospheric ice clouds between 60-80 km from the Imaging Ultraviolet Spectrograph (IUVS) on NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission. We also report concurrent scale height observations ~100 km higher derived from IUVS dayglow measurements and diagnostic of thermospheric temperatures. We present a possible link between these datasets by using concurrent mesospheric temperature observations from the Mars Climate Sounder (MCS) on the Mars Reconnaissance Orbiter (MRO).

We describe the IUVS observations in Section 2 and the spectral analysis as well as cloud identification in Section 3. We present the results in Section 4, including the complementary IUVS scale height observations. In Section 5 we discuss the implications for these results and summarize the findings.

2. The IUVS Limb Observations in the Mesosphere

The IUVS instrument [McClintock *et al*., 2015] on NASA's MAVEN mission [Jakosky *et al*., 2015] has been observing the Martian upper atmosphere since October 2014. MAVEN orbits Mars about five times a day and near periapsis IUVS scans the limb using two channels: a MUV channel and a far-UV (110-190 nm) channel. At the lowest tangent altitudes (below 100 km), solar scattered light typically appears in the MUV limb spectra which occasionally includes excess solar scattering from mesospheric ice particles. From 13 October through 19 December 2015 (L_s = 54°-83°) IUVS observed the limb during the mesospheric cloud season, covering all longitudes between 27° N and 72° S latitude.

Unlike many previous satellite observations of Martian mesospheric clouds, MAVEN can sample all local times (LT). Near the equator, the LT precesses about 4 h over two months of observations. For our first observations on 13 October the equatorial crossing is ~9 LT whereas for the last observations on 19 December it is ~5 LT. The scans therefore sample the morning hours just after sunrise, when the temperature minimizes over the diurnal cycle in the upper mesosphere during the cloud season [Kleinböhl *et al*., 2013]. These early morning data complement the more limited set of mesospheric cloud observations reported between 8-11 LT from Mars Express by Määttänen *et al*. [2010].

The 0.06° × 11° IUVS field of view is binned into seven horizontal segments (1.6° each) for each of 12 limb scans, allowing for up to 84 separate profiles for analysis each orbit. The vertical resolution of the IUVS data varies depending on which scans are considered, because those at periapsis are closer to the tangent point. Furthermore, the IUVS field of view can be tilted a small amount with respect to the horizon [McClintock *et al*., 2015; Jain *et al*., 2015], further affecting the resolution. Overall, the vertical resolution varies between 8-17 km in the mesosphere, depending on which scan is analyzed. We use IUVS Level 1b (L1b) calibrated "periapse" limb radiance profiles from the v07 release.

We note here that MAVEN is designed to investigate the upper atmosphere rather than the mesosphere. As a result, the vertical range for each upper atmospheric limb scan varies such that not every scan extends down to 60 km tangent altitude, which is the lowest altitude considered for cloud detection. We furthermore only use scans for which the solar zenith angle (SZA) is less than 95°. For the 68 days considered, 10,009 limb scans (~50%) extend down to 60 km with SZA<95° and we focus on these fully illuminated mesospheric scans.

3. Spectral Analysis: Mesospheric Cloud Detection

The detection of mesospheric clouds relies on the brightness and spectral shape of the sunlight scattered from the ice particles. IUVS periapse scans are typically analyzed using a multiple linear regression (MLR) technique that fits the observed limb spectra using the spectral shape of known Martian UV emissions [Stevens *et al.*, 2015; Schneider *et al.*, 2015a; Schneider *et al.*, 2015b; Evans *et al.*, 2015; Jain *et al.*, 2015; Lo *et al.*, 2015]. The shape of the prominently bright CO_2^+ Ultraviolet Doublet (UVD) near 289 nm is used to determine the IUVS MUV wavelength registration for each orbit.

To a good approximation, the spectral shape of the signal from mesospheric ice particles resembles the solar spectrum. For the detection of mesospheric clouds, the IUVS operational algorithm is modified so that only the CO Cameron band system [*e.g.* Stevens *et al.*, 2015] and the solar spectral shape are included in the fit. We use an IUVS observation of backscattered sunlight from the Martian disk as a template for the solar spectral shape. For the tangent altitudes of interest here, the solar scattered contribution can be so bright that it saturates the detector. We therefore only fit the spectral region between 185-205 nm, which is at long enough wavelengths to yield a detectable solar scattered signal but at short enough wavelengths to avoid saturation. At these wavelengths only the solar scattered light contributes significantly to the limb spectra, with only a small contribution from the CO Cameron bands.

Figure 1 shows IUVS limb spectra near 63 km tangent altitude for two different parts of the IUVS aperture from a scan on 6 December 2015. The tangent altitudes are at the same longitudes and 1.0° (60 km) apart in latitude. One spectrum is about eight times brighter than the other, indicating the presence of a mesospheric cloud along the line of sight. Both spectral fits are good and demonstrate the reliability of the approach for detecting solar scattered light in the Martian mesosphere, either with or without a mesospheric cloud present. Figure 2 shows the radiance profiles associated with the two limb spectra in Figure 1. The mesospheric cloud detection at 63 km is well above the measurement uncertainty and we identify it as a detached mesospheric cloud.

The IUVS spectral binning varies depending on the allocated data rate during the two-month time period considered here. For some orbits the binning is finer than in Figure 1 and in other cases it is coarser. The MLR templates are calculated with the line spread function appropriate to the spectral binning so that the identification of the solar scattered signal in the observed spectrum is not compromised.

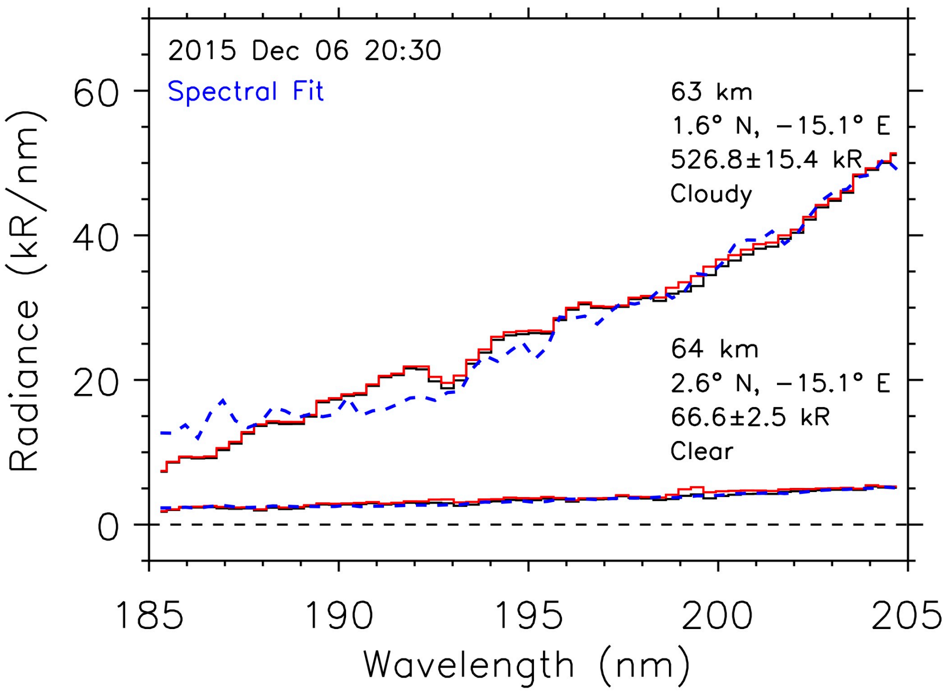

Figure 1. Limb spectra from IUVS scans between 63-64 km tangent altitude. The observed spectra (red) include a small contribution (~10 kR) from the CO Cameron bands. The solar scattered contribution is overplotted (black) along with the spectral fit (blue dashed.). The two observations are separated by 60 km at the tangent point. The indicated radiance is calculated by integrating over the passband shown.

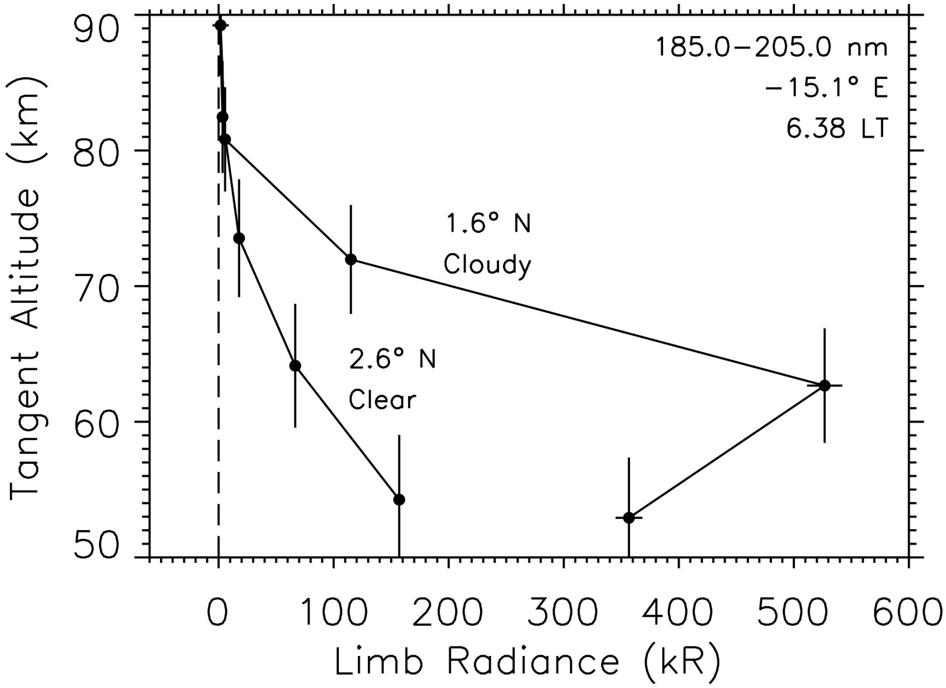

Figure 2. Limb radiance profiles associated with the spectra shown in Figure 1. The statistical uncertainties (horizontal lines) are those returned from the MLR and the vertical lines associated with each spectrum represent the vertical resolution of the measurements.

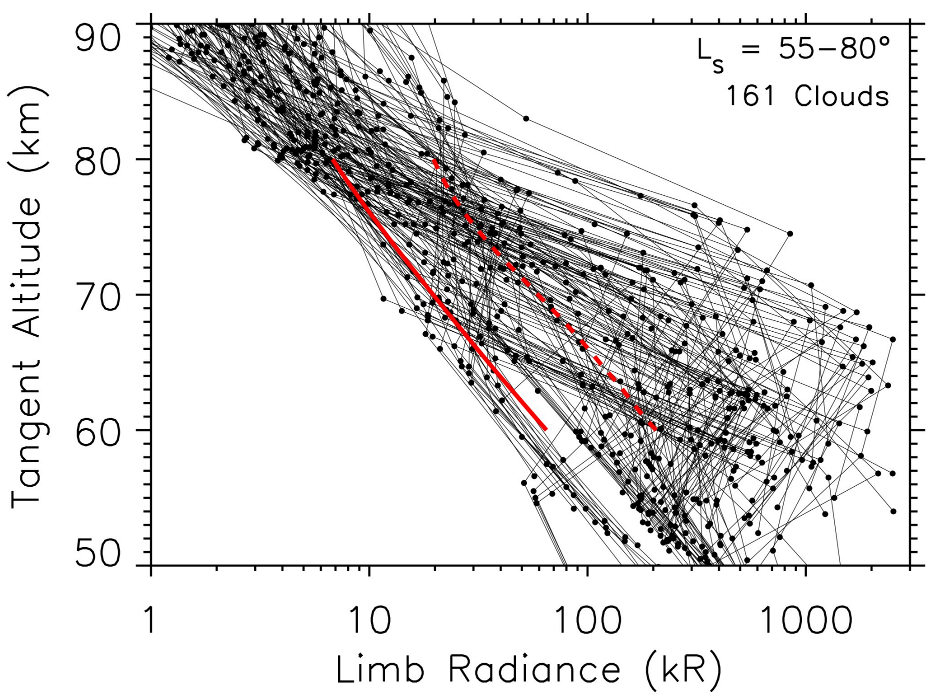

Figure 3. Mesospheric profiles of solar scattered radiance for all mesospheric cloud scans identified in this study. The average of all IUVS profiles is shown (solid red, see text) and the 5σ threshold calculated from the scatter at each altitude is overplotted (dashed red).

Figure 3 shows the radiance profiles of the solar scattered component for all identified cloud scans. An average radiance as well as a standard deviation (σ) is calculated at each altitude based on the observed scatter of measurements and we choose a 5σ threshold to identify mesospheric clouds. The 5σ threshold is chosen subjectively and conservatively to be high enough to ensure no false detections and is the same as that used for early studies of terrestrial mesospheric clouds [Thomas and Olivero, 1989]. Using this threshold, we identify 91 mesospheric clouds in the complete dataset. However, in order to reduce the positive bias on the threshold due to the brightest clouds, we iterate once more after removing these 91 scans with clouds identified. On the next iteration, we identify 70 more scans with clouds for a total of 161. Another iteration does not yield any more cloud detections. Many of the identified scans in Figure 3 show a detached cloud layer. Those clouds not identified as detached may nonetheless be so because the IUVS vertical resolution may not be high enough to resolve the separation from the background signal. The figure shows that there is an unambiguous difference between the average clear air profile and those containing clouds.

4. Results: Coupling to the Upper Atmosphere

We assemble the cloud detections geographically in Figure 4. There is a small population of clouds near 45° S and 160° E, which has been observed before during this season [Sefton-Nash *et al*., 2013]. However, in this study we concentrate on the large number of clouds in a narrow ±20° latitude band around the equator [Clancy *et al*., 2007;

Määttänen *et al*., 2010; McConnochie *et al*., 2010; Vincendon *et al*., 2011]. The equatorial clouds cluster in geographic longitude such that many are near -110° E and -10° E, consistent with previous observations. A third equatorial population is detected near 90° E, which does not have a clear precedent. The IUVS equatorial cloud observations were made from 6 to 8 LT, which is much earlier in the day than most of the previous observations. Although OMEGA observed some equatorial clouds from 8 to 11 LT [Määttänen *et al*., 2010], most others reported to date were observed from 13 to 18 LT [Clancy *et al*., 2007; Määttänen *et al*., 2010: Sefton-Nash *et al*., 2013].

During the IUVS mesospheric cloud observations, MCS was measuring mesospheric temperatures [McCleese *et al*., 2007; Zurek and Smrekar, 2007; Kleinböhl *et al*., 2009] early in the morning near the equator. Figure 5a shows MCS temperatures as a function of longitude at 75 km. The temperature minima in Figure 5a are at nearly the same longitudes as the concurrent IUVS equatorial cloud observations in Figure 4, even though the MCS observations are 2-3 h in LT prior to the IUVS cloud observations. This indicates that the longitudinal temperature structure in Figure 5a contributes to the observed mesospheric cloud structure. Figure 5a also shows the CO_2 frost point [Meyers and Van Dusen, 1933] calculated from the same MCS observations. The frost points show that additional downward temperature excursions of 20-30 K are required to enable mesospheric cloud formation. Identifying the source of this additional variability is beyond the scope of this work but may be related to local wave activity [*e.g*. Spiga *et al*., 2012; Yigit *et al*., 2015].

Following the approach of Lo *et al*. [2015] who reported the observation of nonmigrating tides in the Martian upper atmosphere, we fit the equatorial temperature data in Figure 5a with a series of harmonics. We assume that the observations are fixed in LT and fit the tidal components in a least-squares sense using the function

$$T(\lambda) = T_0 + A_k\cos(k\lambda - \delta_k) \qquad (1)$$

where λ is longitude, T_0 is the average temperature, A_k is the amplitude of wave component k, δ is the phase of component k, and k=1, 2, or 3 represents the wave 1, 2 or 3 contributions. The best fit solution to the fit is overplotted in Figure 5a, where the wave 3 amplitude is the largest (A_3=5.6 K), followed by the wave 1 amplitude (A_1=4.5 K), and the wave 2 amplitude (A_2=3.2 K).

Based upon previous observations and model results [*e.g.* Bougher *et al*., 1993; Forbes *et al*., 2002; Withers *et al*., 2003; Kleinböhl *et al*., 2013; Moudden and Forbes, 2014; Liu *et al*., 2017], it is plausible to expect that the temperature perturbations affecting the mesosphere propagate to the upper atmosphere. IUVS measures the scale heights in the upper atmosphere from radiance profiles of the CO_2^+ Ultraviolet Doublet [Lo *et al*., 2015], which are diagnostic of temperature variations between 150-180 km [Bougher *et al*., 2017]. These results are shown in Figure 5b for the same L_s as the MCS observations in Figure 5a. To reduce the scatter of the data, we include an average over 20º longitudinal bins, which suggests a strong wave 3 contribution. A fit using Equation (1) reveals that wave 3 is the strongest component (5%), followed by wave 2 (4%), and wave 1 (3%). The wave 3 contribution is therefore prominent in both the thermosphere [Liu *et al*., 2017] and mesosphere. We expect the relative contributions of these components to vary with LT and latitude [England *et al*., 2016].

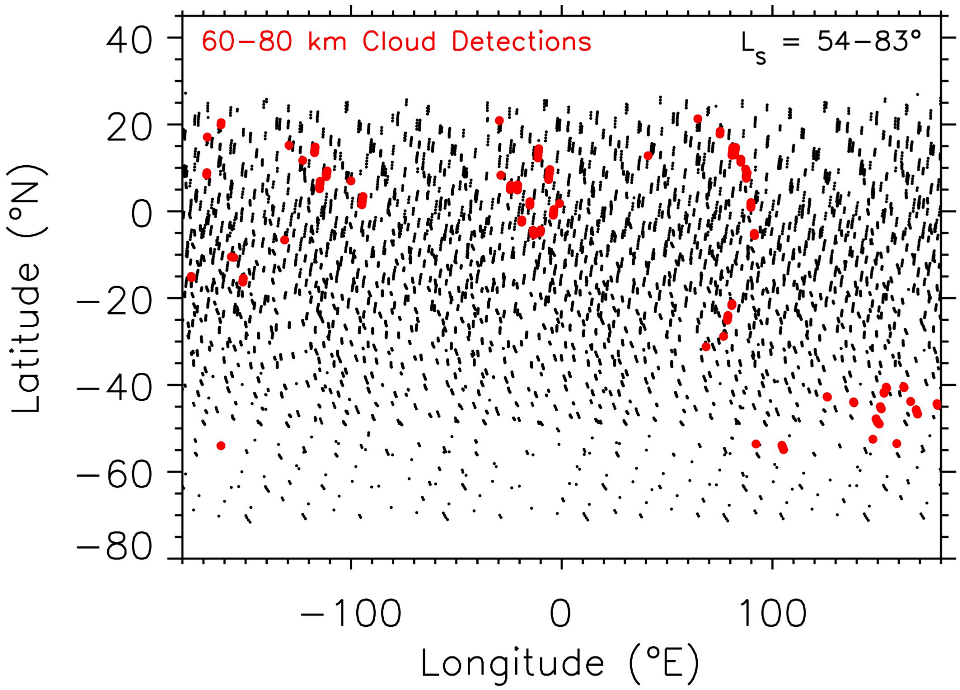

Figure 4. The geographic distribution of all the mesospheric limb scans used in this work. The cloud observations from Figure 3 are overplotted in red and show three groups near the equator, which are observed between 6-8 LT.

We note that the wave 3 IUVS scale height oscillations are out of phase with the MCS mesospheric temperature oscillations. The quantitative relationship between the thermospheric and the mesospheric wave 3 structure requires additional information on the vertical wavelength, the phase, and the amplitude variation of the oscillation with altitude and LT, which is beyond the scope of this work. Nevertheless, Figures 4 and 5 together provide a strong suggestion that the oscillations enabling mesospheric cloud formation concurrently propagate all the way to the thermosphere.

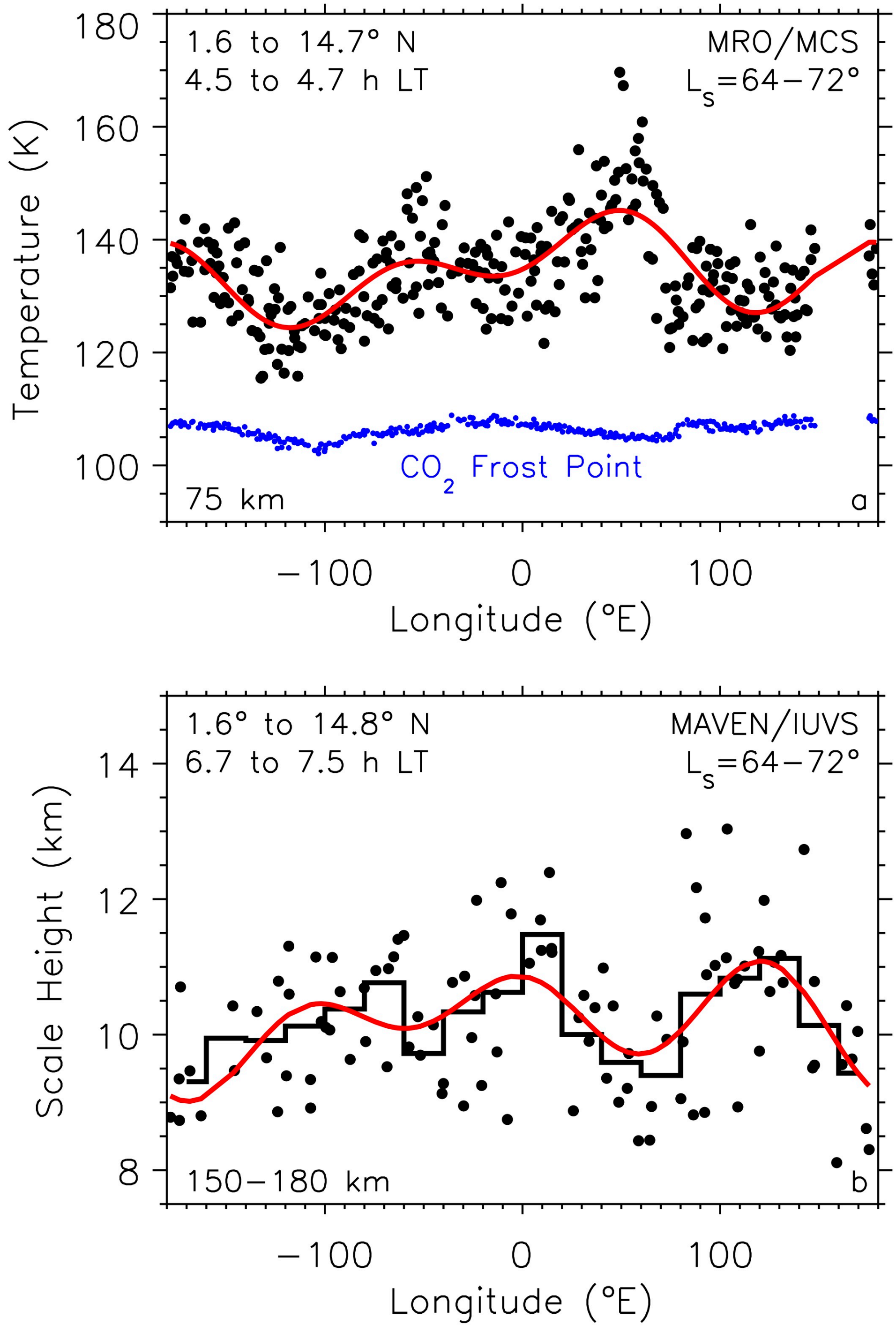

Figure 5a. MRO/MCS temperature observations at 75 km altitude between 6-23 November 2015 for the indicated latitudes and LT (black dots). Statistical uncertainties for each measurement are 11 K on average. The red solid line is a harmonic fit to the data, showing a strong wave 3 component (see text). The equatorial IUVS mesospheric clouds are observed near the temperature minima (*cf.* Figure 4). The CO_2 frost points are overplotted in blue.

Figure 5b. MAVEN/IUVS thermospheric scale heights (black dots) derived for the same time period as the MCS temperatures in Figure 5a. LT are 2-3 h after the MCS observations. The black histogram is an average over 20º bins, suggesting a strong wave 3 component. The red solid line is a harmonic fit to all the data.

5. Summary

We report the observation of detached Martian mesospheric clouds between 60-80 km from MUV daytime observations by IUVS on MAVEN. The latitudinal distribution of the clouds is consistent with previous mesospheric cloud observations, with many of them detected near the equator. Longitudinal clustering of the equatorial clouds near -110° E and -10° E is also consistent with previous observations, although we report an additional population near 90° E. All three populations correlate in longitude with temperature minima observed by MCS and indicating a strong wave 3 component.

We also report IUVS derived scale heights ~100 km higher and concurrent with the cloud observations. These data also show that a wave 3 component is strong, but 180º out of phase with the mesospheric observations. This suggests that the same tidal variability enabling cloud formation between 60-80 km propagates to altitudes 100 km higher. The IUVS mesospheric cloud and scale height observations together show that the clouds reflect changes throughout the atmosphere and provide new constraints to General Circulation Models.

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