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6 **Annual and diurnal water vapor cycles at Curiosity from observations and column modeling**
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19   Abstract
20   Local column precipitable water contents (PWC) for more than a martian year from 113 Curiosity
21   ChemCam passive-mode sky scans were used to force a column model with subsurface adsorption.
22   ChemCam volume mixing ratios (vmr) and T, RH and vmr from REMS-H were compared with
23   model results. The REMS-H observations point to decrease of vmr (i.e. depletion of near-surface
24   water vapor) during every evening and night throughout the year. The model's pre-dawn results are
25   quite similar to the REMS-H observations, if adsorption is allowed. The indicated porosity is about
26   30% and the night depletion ratio about 0.25. If adsorption is not allowed, RH and vmr become
27   excessive during every night at all seasons, leading to ground frost between Ls 82°-146°; frost has
28   not been observed. As brine formation is unlikely along the Curiosity track, adsorption thus appears
29   to be the depleting process.
30
31   During daytime the ChemCam vmr is in general close to surface values from the Mars Climate
32   Database (MCD) vmr profiles for the Curiosity site when those profiles are scaled to match the
33   ChemCam PWC. Our simulated daytime surface-vmr is in turn close to the ChemCam vmr when
34   moisture is assumed well-mixed to high altitudes, whereas a low moist layer (15 km) leads to
35   overestimates, which are worse during the warm season. Increased TES-like regional PWC also
36   leads to large overestimates of daytime surface-vmr. Hence the crater appears to be drier than the
37   region surrounding Gale and the results support a seasonally varying vertical distribution of
38   moisture with a dry lower atmosphere (by Hadley circulation), as suggested by MCD and other
39   GCM experiments.
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41   Keywords: Mars, climate   Mars, surface   Meteorology

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1. Introduction

The martian water cycle has been the object of intense research through orbit observations and general circulation model experiments (GCM), reviewed recently by Montmessin et al. (2017). Martinez et al. (2017) reviewed all surface-based observations. Among the less well-known aspects of the water cycle are the surface interactions and the vertical distribution of moisture, both being difficult to observe. This article is an attempt to study them via the Mars Science Laboratory (MSL) observations onboard the Curiosity rover in the Gale crater. We use the ChemCam passive-mode sky scans for column precipitable water content (PWC, McConnochie et al., 2018) and the Rover Environmental Monitoring Station humidity measurements (REMS-H, Harri et al., 2014a, Gomez-Elvira et al., 2012) during more than one martian year (MY). A column model is applied to help interpret the observations.

According to GCM experiments and data assimilations (Richardson and Wilson, 2002; Navarro et al., 2014; Steele et al., 2014; Mars Climate Database (MCD, Millour et al., 2015); Montmessin et al., 2017) the equatorial latitude of Gale (4.6°S) is relatively dry near the surface throughout most of the martian year, because of transport by the large-scale Hadley circulation. High mixing ratios of water vapor would hence be expected aloft, at 10-15 km during the cool aphelion season (Ls ~71°) and at 30-40 km during the warm perihelion season (Ls ~251°), but these model predictions have been hard to prove by observations. The moist season of high PWC would occur at Gale at around Ls 180°, when the water vapor pulse from the sublimated north polar ice cap finally reaches the equatorial latitudes.

At the surface, the possible exchange of water with the surface has been debated since the Viking observations, which according to Jakosky et al. (1997) displayed depletion of near-surface water vapor each night that was not due to formation of frost. They suggested and modeled regolith adsorption as the reason. Evening depletion has been reported in the TECP data of Phoenix (Zent et al., 2016) and depletion is present in REMS-H data (Harri et al., 2014a, Savijärvi et al., 2015). Surface brine formation might also deplete air moisture (Martin-Torres et al., 2015) but this is not favored by Curiosity data (Rivera-Valentin et al., 2018). Savijärvi et al. (2016, 2017) used a column model with adsorption and frost to explain the first-sols observations of Viking and Curiosity. Steele et al. (2017) applied an adsorptive mesoscale model for the Gale region but they, too, considered just a few sols, although during the three main seasons.

Here observations and the column model with and without adsorption are used to study the diurnal and annual cycles of water vapor at Curiosity. The model is forced by the rover's strictly local ChemCam daytime PWC through more than one martian year, and the REMS-H observations and model results for diurnal temperatures, relative humidities and mixing ratios are compared at the observation height of 1.6 m. Two vertical profiles for the model's initial mixing ratio are tested. Furthermore, increased values of PWC, closer to the regional orbit retrievals by TES and CRISM over Gale, are tried for comparison.

Observations and model experiments are described in Section 2. Section 3 demonstrates the diurnal cycles during the warm season, and Section 4 respectively during the cool season (the moist season was discussed in Savijärvi et al., 2016). The full annual cycle is then considered in Section 5 and the findings are discussed in Section 6. Conclusions are given Section 7.

2. Observations and model experiments

The MSL ChemCam passive spectroscopic scans of scattered skylight can be used to provide local estimates of column precipitable water content (PWC) and the dust and water ice fractions of the

total 880 nm aerosol optical depth τ from MastCam, given the surface pressure p, which is
measured by the MSL REMS-P device (Harri et al., 2014b). The methodology and first results are
described in McConnochie et al. (2018). We use their results, which originate from 113 ChemCam
passive sky scans from MSL sols 230-1293 (Ls 291° MY31 to Ls 127° MY33). The scans are
mostly from daytime, between 10-13 Mars hours local mean solar time (LT); some are from the
morning, 07-09LT. The indicated precision for PWC is +-0.6 μm. We assume in the following that
the ChemCam values represent the strictly local conditions along the Curiosity track on the Gale
crater base.

The simultaneous measurements of PWC, τ (mostly due to dust) and p are shown in Figure 1 as
function of season. Since τ and p are not originally simultaneous with the ChemCam PWC scans,
we apply the same interpolation procedure that was used by McConnochie et al. (2018). One may
note low PWC and dustiness during the cool aphelion – southern late fall season at around Ls 71°-
90°, a moist season with high PWC and low p at around Ls 180°, and a long dusty mid-PWC period
during the warm perihelion – southern late spring, Ls 251°-270°. The few morning values are
similar to the surrounding daytime PWC retrievals, indicating little or no diurnal variation of PWC.

These local ChemCam PWC retrievals, when scaled to the traditional reference p of 6.1 mb, appear
consistently lower by 2-4 μm than the similarly-scaled regionally averaged retrievals from TES and
CRISM in McConnochie et al. (2018). The large averaging area for the orbital data sets spanned 40
degrees of longitude and 10 degrees of latitude. When CRISM averaging was restricted to a local
scale covering only the interior of the Gale crater (Toigo et al., 2013), the resulting lower PWCs
become consistent with ChemCam. This suggests that low daytime PWCs are a real feature of the
crater rather than some kind of instrumental bias. In the Steele et al. (2017) high-resolution
simulations daytime upslope winds flush the desorbed moisture out of the crater base (cf. their figs.
15h, 16f), thus keeping the crater relatively dry during all the three seasons they considered.

The MSL REMS-H device onboard Curiosity consists of a fast temperature sensor and three relative
humidity Vaisala sensors in a dust-protected cage 1.6 m above the surface (Harri et al. 2014a). We
use here the hourly 5 min averages of T and the first hourly measurements of RH of selected sols
(data from the Planetary Data System). The value for the volume mixing ratio of water vapor at 1.6
m (vmr) is calculated from the observed p, T and RH (vmr = RH·e_{sat}(T)/p; e_{sat} is the saturation
pressure of water vapor with respect to ice) as in Savijärvi et al. (2016). Because the cage is well-
ventilated, the REMS-H temperatures closely follow the free air temperature at 1.6 m. Values for
RH and vmr are most accurate at maximum RH (minimum vmr). This typically occurs daily during
nighttime, at 04-06LT (cf. Figures 3-4). During daytime RH is very small (< 2%) and the REMS-H
-derived values for vmr unfortunately become unreliable.

The column model is the same as used for MSL and described in detail in Savijärvi et al. (2016)
with two small refinements explained below. The atmospheric part is hydrostatic with constant
geostrophic wind of 10 m/s (leading to near-surface winds of about 2 m/s at nighttime and about 5
m/s during daytime). There are 29 levels from 0.3, 0.7, 1.6, 7 m … to 50 km. Parameterizations
include radiation, turbulence and interactive cloud physics. Subsurface vertical diffusion of soil
temperature and pore volume moisture with possible adsorption of moisture on regolith grains is
represented in eight levels from the surface down to 48 cm depth. Adsorption isotherm follows the
Jakosky et al. (1997; J97) formulation. Icefog, iceclouds, surface frost and pore ice form during
supersaturation and sublimate under subsaturation with the associated latent heat and radiative
effects.

The two refinements to the Savijärvi et al. (2016) regolith scheme are as follows:

    1) The coefficient D for molecular/Knudsen diffusion of water vapor in CO_2 pore volume gas,

152   which was 1 cm^2/s, is increased to 5 cm^2/s, based on test chamber experiments in martian
153   pressures, temperatures and regolith representations of Hudson et al. (2007). The diurnal
154   minima and maxima of vmr do not change by this but the late morning and early evening
155   behavior is closer to the recalibrated Phoenix TECP results of Fischer et al. (2018).
156   2) The scaled diffusion coefficient during active adsorption D´ is no longer constant but is
157   allowed to vary with the predicted regolith temperature and pore space moisture at each
158   depth. The effect of this is small as D´ and its variations with temperature and moisture are
159   quite small, D' ~ $3 \cdot 10^{-6}$ cm^2/s.

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161 In the present Curiosity simulations thermal inertia is 300 SI units, surface albedo 0.18, surface
162 roughness length 1 cm and regolith porosity 0.3 for simplicity, even though these may vary in
163 reality along the track. The model is initialized at 00LT for each Ls of Figure 1 from the observed
164 PWC, τ and p (with dust well-mixed and T 210K at the surface, lapsing 1 K/km). It is then run to
165 sol three with p and τ constant, by which time its winds, temperatures and mixing ratios have spun
166 up at all heights to a repeating diurnal cycle, which closely preserves the initial PWC (for porosity
167 of 0.3). The model values shown are from this last sol.

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169 Initialization of the unknown moisture profile to the ChemCam PWC is made using two simple
170 alternatives. The first is a high-layered well-mixed assumption ("well-mixed"), in which the water
171 vapor mixing ratio is the same at all heights up to 50 km. The other assumes a 15 km high well-
172 mixed layer, above which vmr decays to zero ("low moist layer"). This is based on GCM cool-
173 season results (e.g. Montmessin et al., 2017, fig. 11.18), in which moisture at the equatorial latitudes
174 appears concentrated nearer the surface, maximum vmr being typically at around 10-15 km height
175 with a rapid decay aloft. To obtain the same ChemCam PWC, vmr must now be about 26% higher
176 in this low layer than in the high layer case. The well-mixed assumption might be expected to be
177 better during the warm season and the low moist layer assumption during the cool season. The pore
178 volume mixing ratio is initialized to the boundary layer mean (~4 km) of the initial air mixing ratio
179 in each experiment. Cloud processes are switched off above 7 km (the well-mixed profile would
180 lead to extreme cool season supersaturations at high altitudes), but fogs and boundary layer clouds
181 are allowed to occur as in the Viking and Phoenix simulations of Savijärvi et al. (2010, 2017).
182 However, they do not occur in any of the present integrations, due to the fairly dry equatorial Gale
183 environment.

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185 Two further experiments are made using the well-mixed initial moisture. As the strictly local
186 ChemCam results for PWC appear consistently 2-4 µm lower than the large-scale regional TES and
187 CRISM retrievals (McConnochie et al., 2018), we trace the sensitivity of our results to this by
188 increasing all the ChemCam PWC values by 4 µm. In a fourth experiment adsorption is set to zero,
189 but vertical diffusion of moisture remains active in the porous regolith. There are thus four
190 simulations for each PWC observation of Figure 1: well-mixed ("wm"), low moisture layer ("low
191 m"), increased moisture ("high pwc"), and no adsorption ("no ads").

192

193 Figure 2 displays for later reference the model's 1.6 m temperatures at 05LT and at the scan hour of
194 each observation of Figure 1. The model temperatures are practically the same in all four
195 experiments and are quite close to the respective REMS-H observations (Figures 3-4). Figure 2
196 indicates that the morning ChemCam scans are mostly from around 08LT (with one at 09:00LT and
197 one at 07:15LT). The 102 daytime observations are mostly from around 11LT and 12LT, with a few
198 around 10LT and 13LT. The cool and warm seasons are clearly visible in Figure 2 and the moist
199 season in Figure 1.

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202 **3. Diurnal comparison during the warm season**

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204 First comparisons between the REMS-H observations and the adsorptive column model results
205 were made in Savijärvi et al. (2016) for MSL sols 15-17 and 80-82 during the moist season. The
206 model was initialized at L_s 159° and 196° with an approximate PWC of 9.3 μm and 8 μm,
207 respectively. Results indicated good matches for diurnal temperatures and relative humidities at 1.6
208 m. A fair match with the REMS-H mixing ratios was obtained during the early morning hours. In
209 this section the observed and modeled diurnal cycles are similarly compared during the warm
210 season.

212 Figure 3 displays hourly REMS-H observations for three sols at around L_s 271° and the model's
213 diurnal cycle arising from ChemCam MY32 Ls 270.96° 10:20LT scan, PWC being 7.45 μm, τ 0.87
214 with dust fraction 0.83, and p 9.20 mb. The observed T (top panel) ranges between 205-273K. The
215 model's T at 1.6 m is quite close to the observations. Model's surface temperature T_s is also
216 displayed.

218 The observed relative humidities (mid panel) are small, reaching only to 6-9% near sunrise. The
219 two model experiments with the ChemCam PWC (well-mixed: thick line, low moist layer: thin line)
220 are on the low side of the REMS-H observations, whereas values from the increased-PWC
221 experiment (11.5 μm, dotted line) are here rather good. RH from the no-adsorption experiment
222 (dashed line) is clearly too high in the morning.

224 The REMS volume mixing ratios (bottom panel) decline during the late evening and night until
225 sunrise, indicating some depleting process. The three simulations with adsorption produce values
226 quite close to the observed 05-06LT minima of vmr, roughly covering the sol-to-sol range of 20-40
227 ppmv. The depleted layer of moisture is quite shallow, only 100-200 m (Savijärvi et al., 2016), so
228 the column-PWC does not change notably during the sol. In the no-adsorption simulation (dashed)
229 vmr is effectively constant during the sol, even though vertical diffusion of moisture is active both
230 in the air and in the regolith. This leads to excessively high RH and vmr at nighttime. Hence the
231 nocturnal diffusion into the soil is alone (i.e. without adsorption) not an effective remover of air
232 moisture in the diurnal timescale.

234 The mixing ratios increase after sunrise (in the model due to desorption, upward diffusion and
235 convection). The REMS-H values for vmr are unfortunately unreliable during daytime (because of
236 very small, inaccurate RH), but the ChemCam vmr (72 ppmv at 10:20 LT) provides here a kind of
237 validation. ChemCam vmr estimates come from applying a well-mixed assumption to the
238 ChemCam PWC (McConnochie et al., 2018), and they may actually be quite accurate near the
239 surface, as will be discussed in Section 6. ChemCam vmr is in Figure 3 close to the well-mixed
240 model's vmr curve (thick line), which grows to about 90 ppmv in the afternoon. The experiment
241 with a low moist layer (thin line) leads to slightly higher vmr, and the one with increased PWC
242 (11.5 μm, dotted) even higher, vmr then growing up to 140 ppmv in the afternoon. Adsorption
243 begins to strongly deplete the near-surface moisture from about 16LT onward in all the three
244 simulations with adsorption.

246 Steele et al. (2017) presented mesoscale model simulations for Gale at around L_s 321° within the
247 warm season. The TES MY26 data-assimilated initial PWC was about 10 μm over the Gale region.
248 Their results with the J97 adsorption (fig. 24) indicate at the MSL site a surface vmr of about 40
249 ppmv at 06LT and about 100 ppmv at 16LT, not too different from the above warm season
250 observations and column model results.

253 **4. Diurnal comparison during the cool season**

255 Figure 4 displays comparisons for Ls 90° within the cool season, the ChemCam-observed local

PWC being 5.31 μm with τ 0.41 (dust fraction 0.84) and p 8.44 mb at Ls 89.93°, 11:43 LT, MY32. The REMS-H temperatures for three sols around Ls 90° (top panel) are about 20K lower than at Ls 271°, with some sol-to-sol scatter. The model's T1.6m values match the nighttime and morning REMS-H observations again quite well but the afternoon T-maximum remains too cold. The three simulations with adsorption indicate here air frost points T_f below the air and ground temperatures, so no frost nor fog is expected. However, in the no-adsorption simulation, T_f does hit the surface temperature at around 02LT and ground frost is thereafter deposited until sunrise.

The observed nighttime maxima of relative humidity at 04-06LT are here in the range of 30-45% with wide sol-to-sol scatter. Adsorptive simulations with ChemCam local PWC (thin and thick solid lines) again display RH on the low side of REMS-H observations, whereas that with increased PWC (dots) appears on the high side. The same holds for the nocturnal 01-07LT mixing ratios, which are now quite low (10-15 ppmv), displaying only little sol-to-sol scatter.

The ChemCam vmr of 56 ppmv at 11:43LT is here located between the well-mixed and low moist layer simulation curves. Increased PWC (9.3 μm, dotted) provides on the other hand daytime values of vmr, which are much higher, up to 95 ppmv. In the no-adsorption experiment (dashed), formation of ground frost depletes the near-surface vmr from 02LT onward. After sunrise rapid sublimation of frost returns the deposited moisture back to the air, increasing vmr temporarily at around 08LT near the surface.

In Steele et al. (2017) the cool season simulation (their fig. 28, Ls 69°; PWC about 7 μm over Gale) indicates surface-vmr of about 20 ppmv at 06LT and 80 ppmv at 16LT at the MSL site, again rather consistent with the above observations and column model results.

5. The annual cycle

Results from the annual cycle simulations are displayed in two parts for clarity. Figure 5 shows all the ChemCam daytime vmr values for the cool season (Ls 0°-135°), together with the model's respective 1.6 m vmr at the ChemCam observation time, and at 05:00LT (the typical hour of minimum vmr). The two model daytime values are from the ChemCam PWC-forced simulations with adsorption, for the well-mixed and low moist layer assumptions. Simulations with increased PWC produced quite high vmr values (not shown), which are consistently about 50 ppmv above the ChemCam vmr, as was demonstrated in Figures 3-4.

In Figure 5 the lowest values of daytime ChemCam vmr occur at around Ls 30°-70°, as discussed in McConnochie et al. (2018), and not during the coldest sols, which occur around Ls 90° (Figure 2). The ChemCam vmr then increase toward Ls 135°. Well-mixed model's vmr values (*) are typically slightly lower than the ChemCam vmr, whereas the low moist layer experiments (+) tend to overestimate for higher vmr. At 05LT the model's vmr values are consistently quite low, due to depletion by adsorption in a shallow layer near the surface, as were the REMS-H observations in Figure 4.

Frost did not form in any of the simulations with adsorption, not even with increased PWC. However, when adsorption was switched off, frost did occur every night during Ls 86°-142°. Frost has not been observed so far along the Curiosity track (Martinez et al., 2016, 2017), giving further support to the adsorption assumption for the nocturnal depletion.

Figure 6 similarly covers the warm season, Ls 135°-360°. It is rather unfortunate that the probably most humid period at around Ls 160°-190° did not have any ChemCam sky scans. After about Ls 210° the vmr values stay rather steady at 50-100 ppmv with a weak decline toward Ls 360°. The

308 well-mixed model's values of vmr at 1.6 m are here close to the ChemCam vmr, whereas the low
309 moist layer experiments produce values, which are higher by 20-40 ppmv, and the increased PWC
310 simulations (not shown), by about 50 ppmv.

312 The model's 05LT vmr values are consistently much lower than vmr at 10-13LT in Figures 5-6. The
313 respective night depletion ratio R = vmr(05LT)/vmr(daytime) is plotted in Figure 7, using the
314 ChemCam and model's 10-13LT vmr. It is seen that R is nearly constant and about 0.25 throughout
315 the martian year, with lowest values during the cool season and highest values during the moist
316 season. Excessive values of model-R (e.g. at Ls 82° and at Ls 315°) may partly be due to the early
317 ChemCam scans (around 10LT, Figure 2), when desorption has not yet been operating for long in
318 the model. Hence the model-vmr at 1.6 m is about 20% lower at 10LT than it will be during midday
319 (Figures 3-4), whereas the ChemCam vmr is based on the column-PWC, which does not display
320 strong diurnal variation (Figure 1).

6. Discussion

325 In Figure 4 from the cool season there are considerable sol-to-sol variations at 00-05LT in the
326 observed high and thus relatively accurate REMS-H relative humidities. They are anti-correlated
327 with the respective sol-to-sol variations in the temperatures (e.g. at 00LT and 05LT). The low
328 volume mixing ratios exhibit on the other hand only little sol-to-sol variation in this season in
329 Figure 4 (and in Martinez et al., 2017), mainly because the anti-correlated variations of RH and T
330 tend to compensate each other in the evaluation of vmr. One may thus suspect that the low
331 nocturnal absolute humidity at Curiosity is much the same from sol to sol during the cool season.
332 Therefore any sol-to-sol changes in temperatures (perhaps due to weak local advection effects) are
333 immediately carried on to the relative humidities. This also implies that REMS-H is measuring air
334 temperatures and relative humidities independently and fairly accurately during the night.

336 In contrast, during the warm season the observed hourly 01-06LT temperatures (and thus $e_{sat}(T)$) are
337 much the same from sol to sol, by Figure 3. Hence the large observed sol-to-sol variations in the
338 high vmr during the warm season lead to relatively large sol-to-sol variations around the small RH,
339 as seen in Figure 3 and in Martinez et al. (2017).

341 In general the REMS-H observations display a clear depletion of near-surface absolute moisture in
342 the evening and night during all seasons along the Curiosity track, by some process or processes.
343 This prevents frost. Our column model with adsorption is on the other hand close to the ChemCam-
344 observed daytime vmr and to the pre-dawn much smaller REMS-H-observed vmr, whereas the no-
345 adsorption experiments produce too high vmr at night. Hence adsorption is likely at Gale
346 throughout the year.

348 When adopting higher PWC mimicking the large-scale TES and CRISM retrievals for Gale (Mc
349 Connochie et al., 2018), both our column model and the Steele et al. (2017) mesoscale model
350 appear to produce higher but still reasonable RH and vmr at Curiosity during the night, but
351 somewhat too high vmr during the day compared to the ChemCam and local CRISM vmr results.
352 This may mean that the air within the crater is locally dry during daytime. On the other hand, if
353 adsorption is switched off in these models, RH and vmr remain much too high during the night.
354 Furthermore, this leads to formation of frost at the MSL site during the cool season, by both models.
355 Frost has not been observed along the Curiosity track so far (Martinez et al., 2016, 2017).

357 We next discuss the vertical structure of moisture at Gale. Figure 8 displays the midday vmr profiles
358 for the MSL site from MCD at Ls 90° and 270° (scaled by a constant factor (0.38, 0.54) at all
359 heights to match the local ChemCam-observed PWC of Figures 3-4). Shown are also the respective

360 'well-mixed' and 'low moist layer' vmr profiles. At Ls 270° the GCM-based MCD indicates warm-
361 season moisture well mixed to high altitudes, displaying a broad maximum at about 35 km height.
362 In contrast, at Ls 90° a sharp cool-season maximum of moisture is seen at about 10 km height, with
363 rapid decay aloft. Most importantly, in both seasons the MCD profiles display relatively low values
364 of vmr near the surface. These low values are due to Hadley circulation, which near the surface
365 transports the dryness of the respective winter hemisphere to the equatorial latitudes (e.g. Fig.
366 11.18, Montmessin et al., 2017). According to MCD data the near-surface dryness dominates
367 throughout the year at the MSL site, except at the peak of the moist season (which was not sampled
368 by the present ChemCam sky scans).

370 Some interesting matters can be deduced from Figure 8. Assuming that the MCD profiles are close
371 to truth, at Ls 270° the well-mixed assumption is relatively valid for vmr. At the surface it gives an
372 estimate just 6% higher than MCD. On the other hand the low moist layer assumption is clearly no
373 good during the warm season; at the surface it leads to a large overestimate of about 35%. For Ls
374 90° during the cool season, the low moist layer profile appears at first sight better in general than
375 the well-mixed one. However, at the surface it does overestimate MCD by about 20%, whereas the
376 well-mixed profile is again quite good at the very surface, underestimating MCD there by only
377 about 5%.

379 Thus, due to the fortunate Hadley cell effect, the simple assumption of vertically fully well-mixed
380 moisture manages to produce a fairly good estimate for midday surface-vmr at the MLS site (but
381 note that this is only valid due to the equatorial latitude!). Therefore the ChemCam well-mixed vmr
382 is probably not far from the true daytime surface vmr at Curiosity throughout most of the martian
383 year. Our well-mixed model's daytime vmr (*) is in turn fairly close to the ChemCam vmr (the
384 filled circles) in Figures 5-6, especially during the warm season. In contrast, the low moist layer
385 simulations (+) produce large overestimates to the ChemCam vmr during the warm season, being
386 closer to them during the cool season. Hence our idealized modeling results and the REMS-H and
387 ChemCam observations give support to the seasonally varying vertical distribution of moisture and
388 a dry lower equatorial atmosphere as predicted by the GCM experiments.

391 **7. Conclusion**

393 The local column precipitable water contents from MSL ChemCam passive sky scan retrievals
394 (McConnochie et al., 2018) were used to force a local atmosphere-subsurface column model. The
395 113 scans covered more than a martian year. ChemCam estimates for the water vapor volume
396 mixing ratio (assuming well-mixed moisture) and REMS-H hourly observations of air temperature,
397 relative humidity and vmr at 1.6 m height were compared with model results. The sol-to-sol PWC-
398 conserving porosity of the regolith turned out to be about 30% in the present model framework.

400 The REMS-H observations point to a decrease of vmr (i.e. depletion of near-surface water vapor)
401 every evening and night throughout the year. The same was observed at the polar Phoenix site in
402 summer (Zent et al., 2016), suggesting a global process. If adsorption is allowed, the model's pre-
403 dawn results are quite similar to REMS-H values of T, RH and vmr throughout the year. The
404 indicated night depletion ratio is about 0.25 at all seasons. If adsorption is not allowed, RH and vmr
405 become excessive during every night at all seasons compared to the REMS-H values, leading to
406 surface frost every night between Ls 82°-146°. Frost has not been observed. As brine formation has
407 been shown to be unlikely along the Curiosity track, adsorption hence appears to be the main
408 depleting process.

410 The REMS-H vmr values are unfortunately unreliable during the day but the daytime ChemCam
411 vmr estimates are available. They appear to be close to the midday surface-vmr from the GCM-

based Mars Climate Database profiles for the MLS site (scaled to the ChemCam PWC) during all seasons. The well-mixed model's daytime near-surface vmr is in turn close to the respective ChemCam vmr throughout the year, whereas simulations with a low moist layer (15 km) lead to large overestimates during the warm season, being nearer to the ChemCam vmr during the cool season. Higher TES/CRISM-like regional PWC leads to even larger daytime overestimates throughout the year, although the nighttime values for RH and vmr remain reasonable. Hence the crater appears drier at daytime than the surrounding areas, and the results support a seasonally varying vertical distribution of moisture with a dry lower atmosphere, as suggested by GCM experiments.

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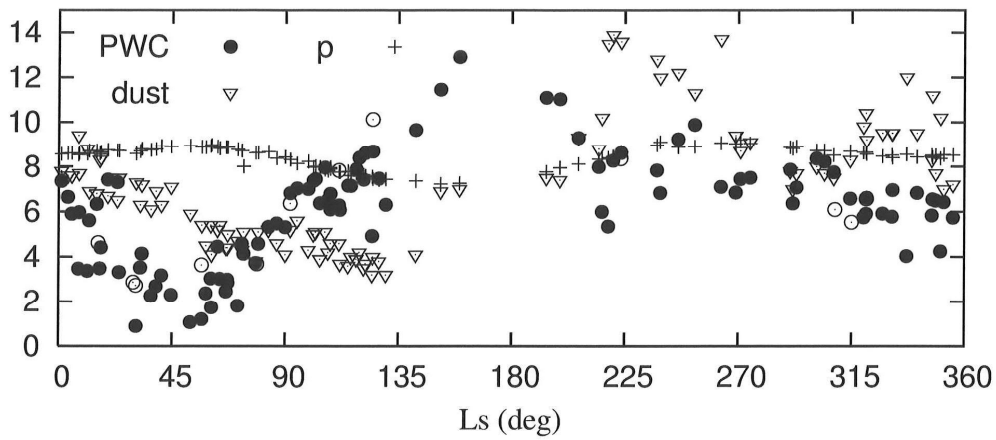
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514 Figure 1. Column precipitable water content (PWC, in μm) from MSL ChemCam passive sky scans
515 (filled circles from daytime, open circles from morning), column total opacity, mostly by dust
516 (τ multiplied by 10) from MSL MastCam, and surface pressure (p, in mb) from MSL REMS-P.
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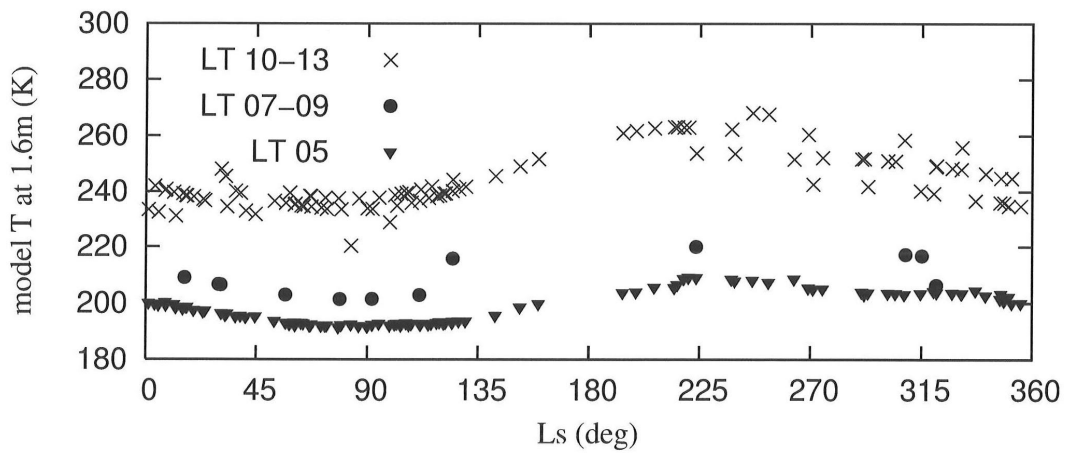
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522 Figure 2. Model 1.6 m temperatures at 05:00LT and at the nearest hour (e.g. 11:00LT) for each
523 ChemCam PWC observation of Figure 1.
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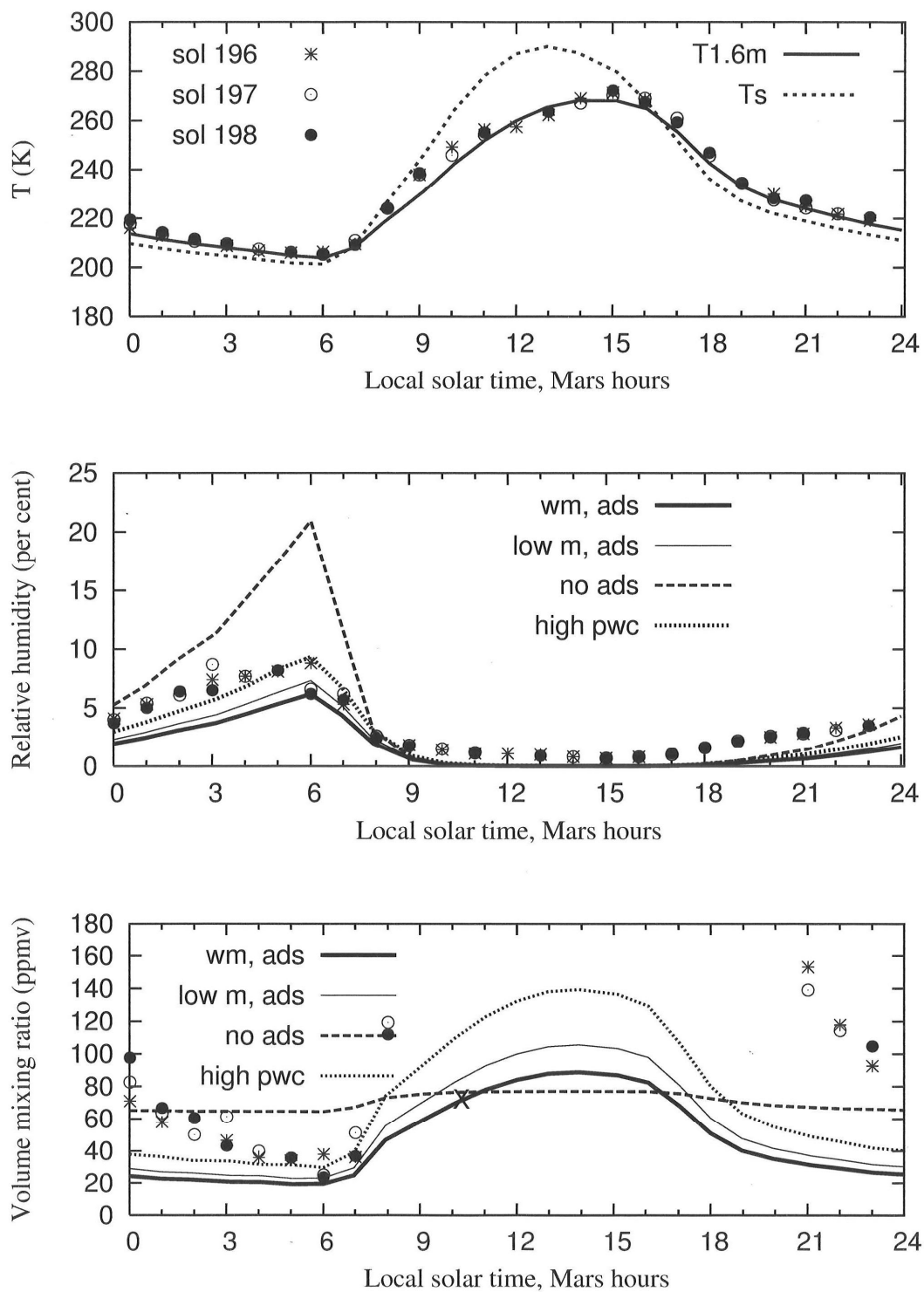
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528 Figure 3. Hourly REMS-H observations (marks) for three sols at around Ls 271° during the warm
529 season, and model results in the four experiments (lines). Top panel: T1.6 m and Ts. Mid panel:
530 Relative humidity at 1.6 m. Bottom panel: Volume mixing ratio at 1.6 m; X is the ChemCam vmr
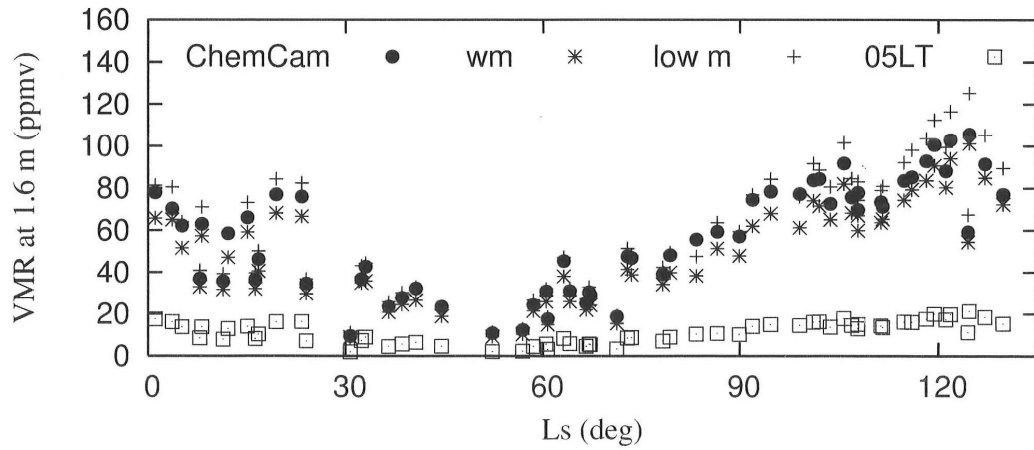531 observation. REMS RH and vmr values are considered unreliable during 08-21LT due to low RH.
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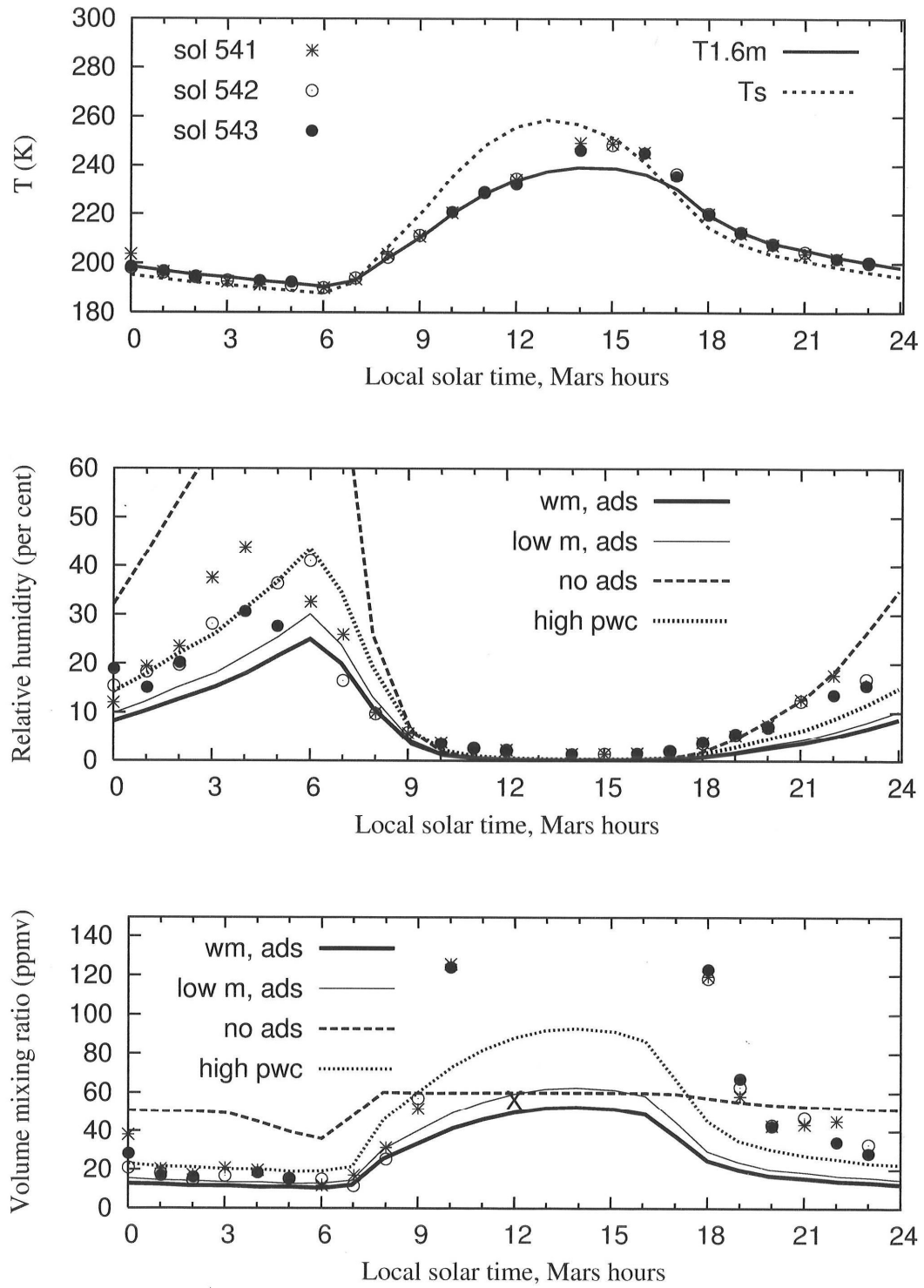
Figure 4. As Figure 3 but for the cool season, at around Ls 90°.

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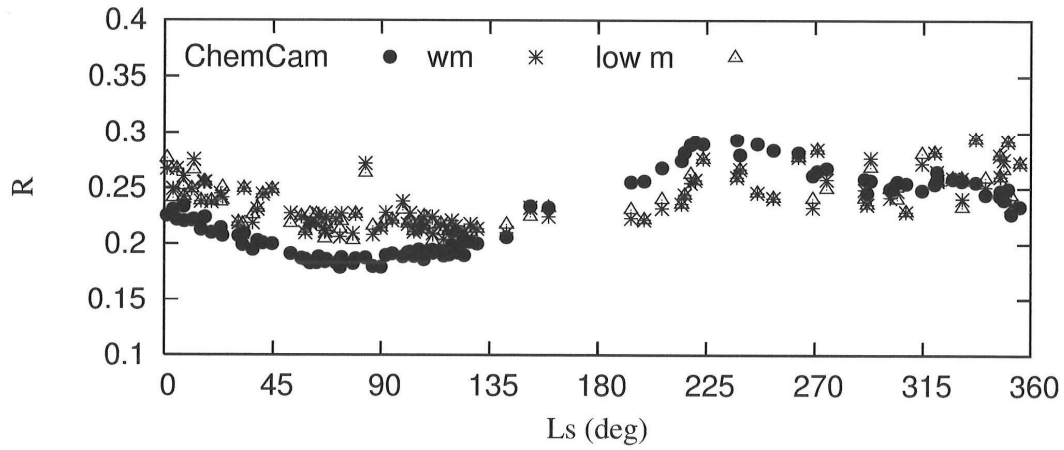Figure 5. The cool season (Ls 0°-135°) volume mixing ratios from all ChemCam daytime scans (filled circles); model 1.6 m vmr at the scan time (well-mixed simulation *, low moist layer simulation +), and at 05LT (squares). The Ls 90° case was shown in Figure 4.
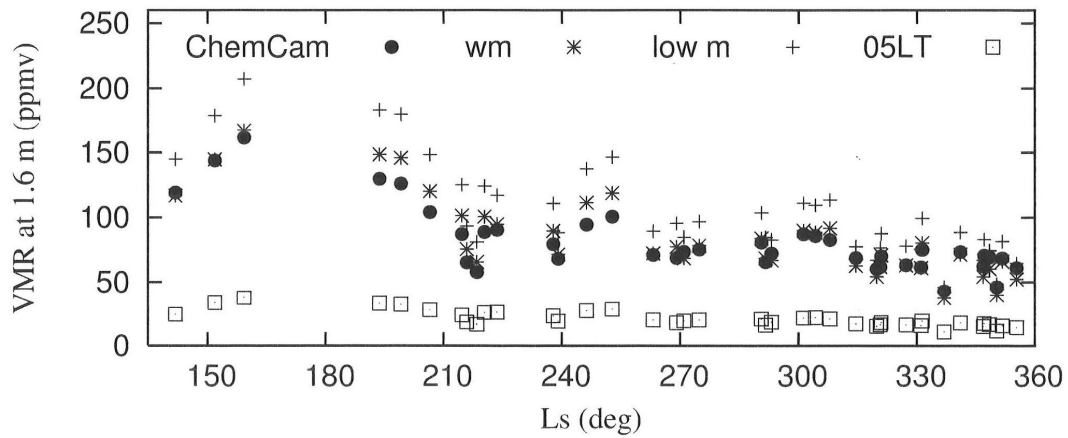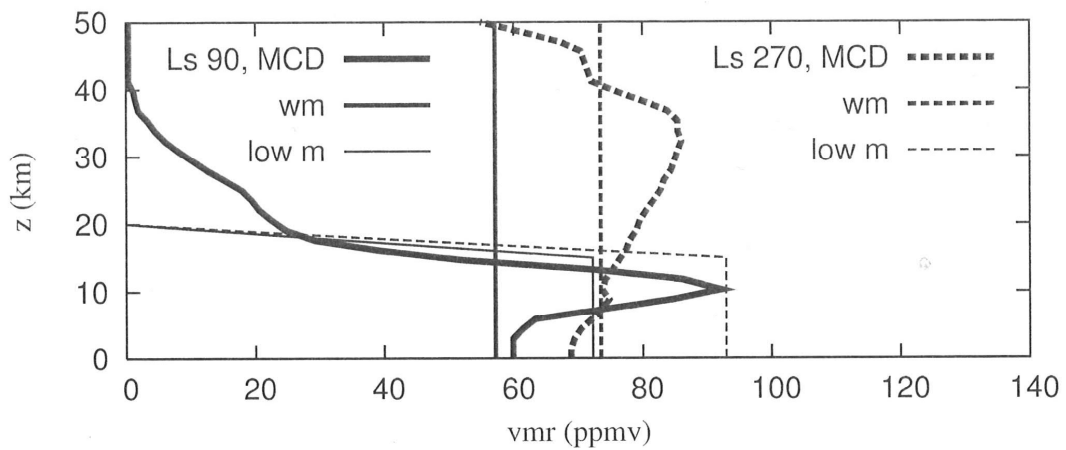

Figure 6. As Figure 5 but for the moist and warm seasons, Ls 135°-360°. The Ls 271° case was shown in Figure 3.

Figure 7. The night depletion ratio R (vmr(05LT)/vmr(daytime)) using the ChemCam vmr and the model 1.6 m vmr from Figures 5-6 (well mixed simulation: stars, low moisture layer simulation: triangles). The 05LT value for ChemCam R is from the well-mixed simulation.

Figure 8. 12LT volume mixing ratio profiles (scaled to ChemCam PWC) at the MSL site for Ls 90° and Ls 270° from the GCM-based Mars Climate Database (MCD), and the respective same-PWC profiles for the well-mixed (wm) and low moist layer (low m) assumptions.