Water vapor mixing ratios and air temperatures for three martian years from Curiosity

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Abstract

The Mars Science Laboratory (MSL) Rover Environmental Monitoring Station humidity instrument (REMS-H) onboard the Curiosity rover is measuring daily minimum water vapor mixing ratios (min vmr), the respective pre-dawn air temperatures (T), and vmr at 2200LT. These are displayed for nearly three martian years (sols 10-2003) and compared with adsorptive column model simulations. The model was initialized with MSL-observed local column water contents, optical depths and surface pressures from sols 230-1291, assuming the same annual cycle outside this period.

The first two and a half MSL years present rather similar annual cycles in the REMS-H data, whereas from about sol 1800 onward the min vmr and T suddenly increase and the 2200LT vmr values get closer to the min vmr, indicating less depletion of water vapor during the nights. Model experiments with typical regolith (ground thermal inertia of 300 SI units and porosity of 30% for adsorption) match the observed min vmr and T relatively well for the first 2.5 years. However, from about sol 1800 onward, when Curiosity started to climb onto Mt. Sharp, simulations with higher thermal inertia of about 400 SI units and very low porosity of ~0.3%, suggesting exposed bedrock, provide a far better fit. Some other periods of bedrock- and dune-dominated ground can be detected from the REMS-H vmr and air-T data along the Curiosity traverse.

Keywords: Mars, climate; Mars, surface; Meteorology

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1. Introduction

The Mars Science Laboratory (MSL) onboard the Curiosity rover descended on August 6, 2012 onto the Gale crater base (4.6°S, 137.5°E), at L_s 151° of Mars Year (MY) 31. Its Rover Environmental Monitoring Station (REMS, Gomez-Elvira et al., 2012) has among other things made observations of relative humidity (RH) and surface pressure (REMS-H, REMS-P; Harri et al., 2014a, 2014b). The REMS-H instrument measures RH and air temperature T inside a dust-protected but well ventilated cage at 1.6 m height from the surface. The REMS air temperature sensor (REMS-T) and the ground temperature sensor (REMS-GTS) record ambient air and surface temperatures, respectively. The REMS-H and REMS-T measurements of air temperature are quite alike, especially during nighttime when atmospheric turbulence is weak. The REMS-GTS data has been used to chart properties of the ground along the Curiosity track. Hamilton et al. (2014) and Martinez et al. (2014) considered the first 100-150 sols (days), whereas Vasavada et al. (2017) used GTS data from two martian years (1338 sols). These authors have reported variations of ground thermal inertia and albedo along the Curiosity track as derived from the GTS measurements and column modeling, the results being consistent with the orbit retrievals and MastCam pictures of the ground around the rover. In particular, regions of low thermal inertia sand dunes and high thermal inertia exposed bedrock have been detected.

Here we concentrate on hourly REMS-H measurements of T, RH and the derived water vapor mixing ratio (vmr) of air at 1.6 m height, having data for very nearly three martian years (MSL sols 10-2003). Martinez et al. (2017) have discussed the REMS-H daily pre-dawn values of maximum RH and minimum mixing ratio (min vmr) for 1595 sols (more than two martian years), finding that the two annual cycles of daily max RH and min vmr were very similar during this period. The third year now brings a surprise in that after about sol 1800 both T and vmr are much higher during nighttime compared to values during the same season in the previous years. This is analyzed here and the possible reasons are discussed with the help of column modeling. As the near-surface air temperatures tend to stay close to the surface temperatures, it is also studied whether the sol-to-sol variations of the REMS-H air temperatures could be used to chart the apparent thermal inertia of the ground along the Curiosity traverse, thus complementing the GTS findings.

Our tool is the University of Helsinki/Finnish Meteorological Institute (UH/FMI) column model. Its subsurface scheme for adsorptive regolith was described in Savijärvi et al. (2016), having MSL data from the first 100 sols for validation of the model's diurnal cycle of moisture and temperature. The annual MSL cycle was considered in Savijärvi et al. (2019), forcing the model with the observed REMS-P surface pressures, MastCam optical depths and ChemCam passive mode precipitable water column retrievals (McConnochie et al., 2018) for sols 230-1291. The same annual forcing is applied here, assuming that it remains valid also during the third MSL year. Orbit observations (e.g. the TES and CRISM water columns) have shown little interannual variation in the Gale region apart from periods with large dust events; there were no large dust storms during the third MSL year. The three years of observations and simulations may help to explain and clarify the character of the near-surface moisture and ground properties along the 20 km long Curiosity track from the Bradbury landing site to the slopes of Mt. Sharp by sol 2003.

The observations and model experiments are described in Section 2. The diurnal cycles of REMS-H T, RH and vmr are displayed around L_s 90° in Section 3 before and after sol 1800, together with some illustrative model simulations for varied ground properties. The three-year daily observations and simulations are then considered and discussed in Sections 4 and 5. Conclusions are drawn in Section 6.

2. Observations and model experiments

We use here the hourly REMS-H observations of T and RH, and the derived water vapor volume mixing ratio vmr = RH·e_{sat}(T)/p, where e_{sat}(T) is the saturation water vapor pressure over ice, and p is the surface pressure measured by the REMS-P instrument (Harri et al., 2014a; 2014b). The hourly data (T, RH and vmr at 1.6 m height) is from sols 10-2003 (nearly three martian years of 669 sols), but we concentrate here mainly on the daily minimum values of vmr (min vmr) and the respective T at the time of min vmr (~max RH), typically during the early morning. The daytime maxima of vmr are also considered but since the measured daytime RH is very small and inaccurate due to instrument limitations, the daytime and early evening values for the vmr are unreliable. Hence the vmr at 2200LT is taken as a proxy for maximum vmr. Error bars for the nighttime RH are about +-10%. Some full diurnal cycles of the measured REMS-H T, RH and vmr are displayed in Figure 2 for 2-3 sols. The variability between the hourly observations is a measure of the typical sol-to-sol variance.

Use is also made of local column precipitable water content retrievals (PWC) from the ChemCam passive mode spectral sky scans, 880 nm total column optical depths (τ, mostly dust) from the MastCam, and p from REMS-P for sols 230-1293, as described in McConnochie et al. (2018). It was shown in Savijärvi et al. (2019) that the well mixed vmr based on the daytime ChemCam PWC is close to the midday MSL site surface vmr in the GCM-based Mars Climate Database (MCD) during all seasons. Hence the ChemCam vmr can be used as a local estimate for the daytime near-surface vmr along the Curiosity traverse.

The UH/FMI atmosphere-subsurface model and its application is here the same as in Savijärvi et al. (2019). It is a hydrostatic single column model driven by a constant geostrophic wind in assumedly horizontally homogeneous conditions (hence there are no advection terms). Wind shear- and convective-driven turbulence, radiation and cloud physics drive the evolution of wind, temperature, moisture and clouds/fogs in the atmospheric column (28 gridpoints from 0.3 m to 50 km). Thermal diffusion for temperature and molecular/Knudsen diffusion with possible adsorption of moisture onto regolith grains via the Jakosky et al. (1997) adsorption isotherm (J97) govern the evolution of soil temperature and pore volume moisture in eight gridpoints from 0 to 50 cm depth. The Zent and Quinn (1997, Z97) and Fanale and Cannon (1971, F71) adsorption isotherms were also tried, but the Z97 isotherm produces in our framework practically the same results as J97, whereas F71 exhibits excessive daytime desorption, as it did in Savijärvi et al. (2016) and Steele et al. (2017).

The radiation scheme was compared with the reference line-by-line model results in Savijärvi et al. (2005) for CO_2, H_2O and dust, leading to a fairly accurate improved delta-discrete-ordinate method (iDD) for shortwave multiple scattering in a dusty atmosphere. Values for the dust broadband single scattering albedo (0.90), asymmetry parameter (0.70), and τ_{vis}/τ_{IR} ratio (2.0) were checked by Mie calculations for Wolff et al. (2009) dust optics in Savijärvi (2012), where also the physics of the typical diurnal cycle in the boundary layer of Mars was discussed in detail, using the Spirit mini-TES observations (Smith et al., 2006) for validation. The model results have also been compared with the observations from Pathfinder (Savijärvi et al., 2004), Phoenix (Savijärvi and Määttänen, 2010) and the Viking landers (Savijärvi et al., 2018).

In the present Curiosity simulations the latitude is 4.6^{o}S and L_s defines the season. Surface roughness length is 0.01 m, albedo 0.20 and infrared emissivity 0.96. Soil thermal inertia I and porosity may vary. The model is initialized from MSL-observed values for vmr, τ and p and is run to model sol 3, by which time it has spun up to a repeating diurnal cycle of temperatures, winds and moistures. Soil porosity is 30% and thermal inertia I is 300 J m^{-2} K^{-1} s$^{-1/2}$ (SI units, omitted hereafter), unless stated otherwise. Geostrophic wind is 10 ms^{-1}, leading to surface winds of about 5 ms^{-1} during daytime and 3 ms^{-1} during the nights. The results shown are from the model sol 3.

The seasonal water ice cloud parameterization of Vasavada et al. (2017) is not used, because ice clouds are already included in the total observed optical depth τ, and the model results do not indicate any notable systematic seasonal deviations from the observations.

3. Results: REMS-H diurnal cycles around L_s 90^o at MY32 and MY34

All the available three martian year REMS-H observations (sols 10-2003) for each diurnal hourly minima and maxima of the volume mixing ratio are shown in Figure 1. The daily minima (min vmr) typically occur at about 0400-0600 local solar time (LT), when the observed relative humidity reaches its diurnal maximum (cf. Figure 2). The maxima of vmr (max vmr) are from 2200LT, as the daytime vmr values are unreliable due to the then very low relative humidity.

Figure 1 displays a repeating annual pattern, where the minima of both max and min vmr are obtained during the cool aphelion – southern late fall seasons at Gale, ie. around L_s 90^o (dashed upright lines), and the annual maxima respectively during the warm seasons around L_s 270^o (solid upright lines). The 2200LT vmr (max vmr) are always higher than the minima of vmr from the next morning. This indicates a depletion process during every night, probably by adsorption of water vapor into cold regolith grains, followed by desorption back to vapor phase after sunrise.

A striking exception to this annual pattern in Figure 1 is, however, the rapid rise in the vmr values after about sol 1800. Thereafter also the max and min of vmr tend to stay closer together, indicating less depletion during the night. For a closer look we next display the full diurnal cycles of T, RH and vmr at around L_s 90^o before and after sol 1800. The measured nocturnal relative humidities are high and most accurate during this season; hence the values of the derived vmr are also at their most accurate, although they are small. The values of min vmr around L_s 90^o are about 15-17 ppmv both at MY32 and at MY33 in Figure 1, whereas those after sol 1800 (at MY34) are much higher, around 50 ppmv; or threefold.

Figure 2 displays all the available REMS-H hourly observations of T, RH and vmr for sols 541-543 (L_s 90^o MY32) as white marks, and for sols 1880-1881 (L_s 90^o MY34) as black marks. One may note that during the night T is consistently about 5 K higher at MY34 than at MY32, and RH is also slightly higher, whereas vmr is considerably higher at MY34 than at MY32. The hourly sol-to-sol variation is notable in RH but small in the observations of T and vmr.

In order to try and explain the big L_s 90^o differences between MY32 and MY34, column model experiments are made. In Savijärvi et al. (2019) the UH/FMI atmosphere-regolith model was initialized by the sol 543 MSL observations: ChemCam PWC 5.31 μm, τ 0.41, p 8.44 mb. This L_s 90^o MY32 simulation with I 300 and porosity 30% as for typical regolith is shown in Figure 2 via solid lines. Its results match the sol 541-543 REMS-H T observations quite well (except for the turbulent early afternoon); they underestimate the nocturnal RH observations to some extent, but are quite close to the observed MY32 nocturnal vmr, matching the observed pre-dawn minimum vmr of about 15 ppmv. The model's midday vmr is on the other hand close to the ChemCam 11:43LT vmr of 56 ppmv (X in Figure 2). The depletion of the model's vmr from 1600LT onward in Figure 2 is due to downward diffusion and adsorption into the rapidly cooling soil; the increase after sunrise is due to desorption and upward diffusion from the sun-heated regolith. The regolith simulation (solid lines) matches the white MY32 vmr observations quite well during nighttime. In contrast, it does not fit at all the black MY34 observations of T and vmr.

Because the high observed nighttime temperatures and mixing ratios during sols 1880-1881 may hint at a more rocky ground with higher thermal inertia and hence smaller amplitude of the diurnal surface and near-surface air temperature cycle, model experiments were repeated by increasing I and/or decreasing porosity. The forcing (PWC, τ, p) was kept the same as for MY32, because the first two years appeared rather similar by Figure 1, and the ChemCam PWC retrievals for MY34 were not yet available. A good match with the sol 1880-1881 REMS-H observations was obtained by increasing I to 400 and setting porosity to only 0.3%, or 0.1%. These two ‘rock’ experiments are shown in Figure 2 by the dotted and dashed lines. They fit the black MY34 observations fairly well, displaying both the systematic increase of 5 K in nocturnal T and the high pre-dawn vmr values of about 50 ppmv. On the other hand, the simulation with high I and high porosity (30%; dash-dot lines) produces the high nocturnal T (all three ‘rock’ I=400 experiments displaying identical T-curves in Figure 2), but not the high nocturnal RH and vmr, because of the now active evening depletion of water vapor by adsorption.

Reduced ground porosity hence appears essential to the increased nocturnal vmr for sols 1880-1881, nearly independently of thermal inertia, whereas increased thermal inertia is responsible for the increase in the nocturnal temperatures, independently of ground porosity.

Hence we suggest that 1) the annual environmental conditions at Gale remained presumably rather similar during the three martian years. For the two first years this was the case according to Martinez al. (2017) and Vasavada et al. (2017). However, the rover encountered quite variable ground along its travel. As an example, Figure 3 demonstrates a MastCam view from sol 1812, when the rover has begun climbing up (from about sol 1800 onward) the Vera Rubin ridge at the foot of Mt. Sharp. The dark landing plane on the left is largely covered by dusty loose material (regolith) with low thermal inertia and high porosity, whereas the ridge in front of the rover is mainly higher inertia nonadsorptive solid exposed bedrock with just a hint of wind-blown adsorptive shallow dust here and there. It is therefore suggested that 2) the observed increases in REMS-H min vmr and T at 1.6 m after about sol 1800 are mainly due to the exposed bedrock encountered by the rover at the foot of Mt. Sharp.

The thermophysical properties of the ground along the rover’s traverse at Gale were analyzed in detail from the REMS GTS data for the first two MSL years in Vasavada et al. (2017). In the next sections we use the three-year REMS-H vmr and T data for the same purpose in a simplified but perhaps illuminating fashion. For this it is noteworthy in Figure 2 that the model’s L_s 90^o night temperatures match the observed temperatures almost perfectly with a suitable thermal inertia. The estimation of thermal inertia is considered in Section 4. Furthermore, as the water vapor mixing ratios are very sensitive to temperature (because of the steep $e_{sat}(T)$ relation), it is then essential for realistic vmr results and hence realistic ground porosity estimates (Section 5) that the model’s temperatures are accurate.

4. Annual experiments: REMS-H temperatures and ground thermal inertia

Annual results are here discussed for the daily 1.6 m REMS-H temperatures at the time of min vmr, and compared with the respective pre-dawn T at 1.6 m height from the model simulations. The model is initialized at L_s 45^o steps from approximate fits (connected by lines in Figure 4) to the MSL-observed PWC, τ and p from sols 230-1293 from McConnochie et al. (2018). The same annual forcing of PWC, τ and p is then used outside this range, hence assuming an unchanging annual environment at Gale. As a result, the annual model curves repeat themselves; this can be used for reference purposes. The model’s ground surface temperatures for I = 300 produce similar daily ranges to the GTS-observed T_g in Vasavada et al. (2017) and Martinez et al. (2017), ie. about 205-290K during the warm season and 185-255K during the cold season.

Figure 5 displays the REMS-H -observed T of min vmr together with the respective model-T. The three model lines correspond to ground thermal inertias I of 250, 300 and 400. The I = 300 curve (solid line) appears to give a decent overall fit for sols 10-1800 even outside the data-based MY32 forcing period (bold solid). This suggests that the annual forcing remained much the same. However, from about sol 1800 onward, the I = 400 curve gives a much better overall match, as it did in Figure 2. Generally the T observations remain within the I 250-400 model lines.

An interesting feature appears in the dotted range of sols 55-100 in Figure 5 (L_s 180°-210°, MY31), when Curiosity was parked on a loose-material sand dune region "Rocknest". Here the observed REMS-T values tend to fall below the I = 300 model curve. Martinez et al. (2014) and Vasavada et al. (2017) derived I of 295 and 250-300 for this site, respectively. Curiosity then traversed on rocky ground during sols 120-350 (L_s 225°-360°, MY31). Martinez et al. obtained I of 452 for sol 139, while Vasavada et al. indicate I of 350-450 for this high-I period. Figure 5 suggests that the REMS-H T-values stay mainly between the T-lines from the I = 300 and I = 400 simulations during this period, while some high observed values of the pre-dawn T hint to I occasionally perhaps exceeding 400 SI units.

Other high-I periods in Vasavada et al. are sols 800-900, and especially sols 1100-1170 and 1250-1350. These periods correspond to the observed REMS-H T being well above the T from the I = 300 simulation in Figure 5. Respectively, the low-I periods in Vasavada et al. during sols 500-540, and especially sols 1222-1242 (Namib Dune), are associated with the observed T being below the T from the I = 300 simulation in Figure 5. Hence the REMS-H air-T-observations appear to provide potential for the estimation of thermal inertia along the Curiosity track, thereby confirming and complementing the more direct GTS-based estimates.

5. Annual experiments: REMS-H water vapor mixing ratios and ground porosity

Figure 6 displays all the available REMS-H daily minima of vmr (min vmr) for three martian years; the respective air temperatures were shown in Figure 5. Shown are also the lines for the daily minima of vmr at 1.6 m height from two model simulations. The reference simulation (I 300, porosity 0.30, solid line) is forced by the ChemCam–based local PWC at L_s 45° steps (Figure 4). This simulation is quite good during the first two cool seasons with low min vmr. During the warm seasons with higher, less accurate and more variable min vmr it tends, however, to produce lower values than those observed. During the warm seasons the other simulation (dashed line) appears to provide a better fit. There the initial PWC is made 3 μm higher than the local ChemCam retrieval, and hence closer to the large-scale TES and CRISM retrievals for the Gale region from the orbit (McConnochie et al., 2018; Savijärvi et al., 2019). Perhaps the "flushing" large-scale winds of the warm season (Rafkin et al., 2016) are able to mix the higher moisture content of the surrounding areas into the crater. The crater appears more isolated and dominated by local circulations during the other seasons.

The Rocknest stay stands out in Figure 6 as a low min vmr period within the moist season of high observed PWC and high model min vmr. In comparison to the other two respective seasons, Figure 6 implies that the small observed min vmr during the Rocknest stay is exceptional, indicating strong adsorption during the nights, and hence presumably high porosity of the ground. Low T and low thermal inertia were also characteristic for the Rocknest period in Figure 5. Hence the ground is likely that of finely-grained sand dune -like adsorptive regolith. The MastCam pictures of Martinez et al. (2014) confirm this. The Namib Dune period (sols 1222-1242) is also associated with low T and low min vmr in Figures 5 and 6. Thus the excessively high values of T and min vmr beyond sol 1800 may indicate the opposite, ie. exposed nonadsorptive bedrock; but other possible explanations should first be ruled out.

Remarkably, the increased but still realistic moisture input (dashed line) is not able to increase the model's min vmr enough in Figure 6 to match the high observed min vmr after sol 1800. The good match of the reference simulation before sol 1800 suggests no big changes in the large-scale circulation. The observed MastCam optical depths likewise support the repeating annual environmental conditions; for instance the increase in τ due to the MY34 dust storm is observed at Gale only beyond sol 2070. The reason for the high vmr values must hence lie elsewhere. At sol 1880 (Figure 2) the rover is located about 10 km to south-west (toward Mt. Sharp) from the landing site, and has climbed about 350 m on the way. Could this change in position and altitude explain the observed increases in the pre-dawn T and min vmr? In contrast, the Gale cool season mesoscale simulations of Steele et al. (2017; figs. 26d, 28c, 30e) suggest that at 0600LT the near-surface pre-dawn air temperatures *decrease* from the landing site toward Mt. Sharp, because downslope katabatic winds have piled adiabatically heated warmer air to the crater base during the night. (This warming effect has been described for Mars in Spiga et al. (2009) and Rafkin et al. (2016), and for Antarctican slopes in Savijärvi (2011)). The 0600LT near-surface mixing ratios do increase slowly uphill in the Steele et al. simulation, but only very modestly along the 10 km distance from the MSL landing site to the sol 1880 site.

Hence the explanation lies probably in the ground properties along the track. Figure 7 displays all the observed REMS-H daily maximum and minimum values of vmr with the min vmr from two annual simulations: the reference "regolith" case with I 300 and porosity 0.30 (solid line), and the "exposed bedrock" case with I 400 and porosity 0.003 (dashed line). The regolith simulation gives a decent fit to the observed min vmr until about sol 1500, after which it fails more or less. The rock simulation is on the other hand clearly not very good for the first 2.5 years, but from about sol 1800 onward it begins to match the min vmr observations very well in Figure 7. The rock simulation (I 400) also matches the observed pre-dawn temperatures beyond sol 1800 (Figures 2 and 5). Furthermore, from sol 1800 onward the observed maxima and minima of vmr tend to stay closer together than they did before, indicating less nocturnal adsorption. Hence we suggest that the exposed bedrock at the foot of Mt.Sharp is the main explanation for the change in the behavior of the REMS-H T and vmr after about sol 1800 along the Curiosity traverse.

The maxima of vmr since sol 1800 are somewhat higher than during the previous cold seasons. Increased moisture contents above Gale could perhaps explain some of the increase. However, in Figure 6 the simulation with increased PWC was not able to increase the vmr enough. Furthermore, most of the adsorption presumably takes place during the late afternoon and early evening, as in Figure 2 (and as observed at Phoenix, Zent et al., 2016). Hence, during weak or no adsorption, as over exposed bedrock, the vmr at 2200LT is already quite close to the min vmr of the next morning.

Finally, the Rocknest and Namib dune periods stand out in Figures 1 and 7 in that the relative difference between the observed max and min vmr is enhanced compared to the surrounding sols, indicating more depletion during the night. These sites, which are dominated by loose material regolith, thus appear opposite in their behavior of vmr to the solid bedrock -dominated climb from sol 1800 onward.

6. Conclusions

The daily 2200LT water vapor mixing ratios (max vmr), the pre-dawn minimum values (min vmr) and the air temperatures (T) of min vmr from the MSL REMS-H instrument were shown for three martian years, and compared with predictions from a subsurface-atmosphere column model with adsorption to regolith grains. The model was forced at 45^o L_s steps by mean local column precipitable water contents, optical depths and air pressures based on MSL measurements from sols 230-1291, assuming the same (mainly MY32) annual cycle outside the measurement period.

The first two and a half MSL years indicate rather similar annual cycles in the observed 2200LT vmr, min vmr and T. These display low values during the cool seasons and high values during the warm seasons. From about sol 1800 onward they suddenly increase, T being about 5K above its previous values from the same season, and min vmr increasing by a factor of 3. Furthermore, the 2200LT evening values of vmr, which are always greater than the min vmr, then get closer to min vmr, indicating less depletion of near-surface air water vapor during the nights. Model experiments with ground thermal inertia of 300 SI units and porosity of 30% for adsorption, as for typical regolith, fit the observed REMS-H min vmr and T relatively well in general for the first two and a half years, but not thereafter.

Instead, from about sol 1800 onward, when Curiosity started to climb onto Mt. Sharp, the simulations with a higher I of about 400 SI units and very low porosity of ~0.3% (both as for exposed bedrock) produce a better fit. MastCam pictures from this time verify the expected bedrock scenery with very sparse and thin layers of wind-blown dust. Some other bedrock- and dune - dominated periods can be detected from the REMS-H data. These periods agree with the previous more direct REMS-GTS -based estimates of the ground type encountered along the Curiosity traverse.

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Figures:

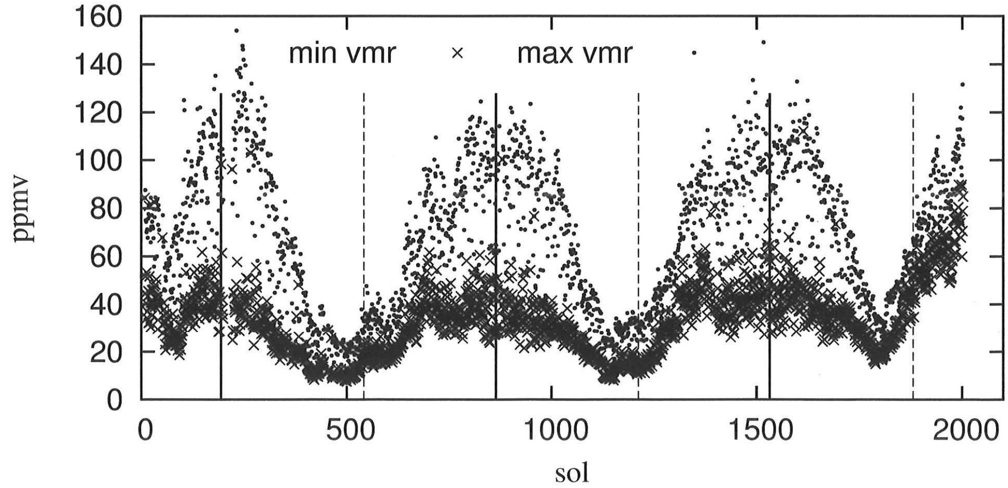

Figure 1. The daily pre-dawn minimum water vapor volume mixing ratios (min vmr; dark crosses) and the 2200LT mixing ratios (max vmr; dots) from REMS-H for MSL sols 10-2003. Solid upright lines indicate L_s 270^o (warm season at Gale), dashed upright lines indicate L_s 90^o (cool season at Gale). Temperatures at the hour of min vmr are shown in Figure 5.

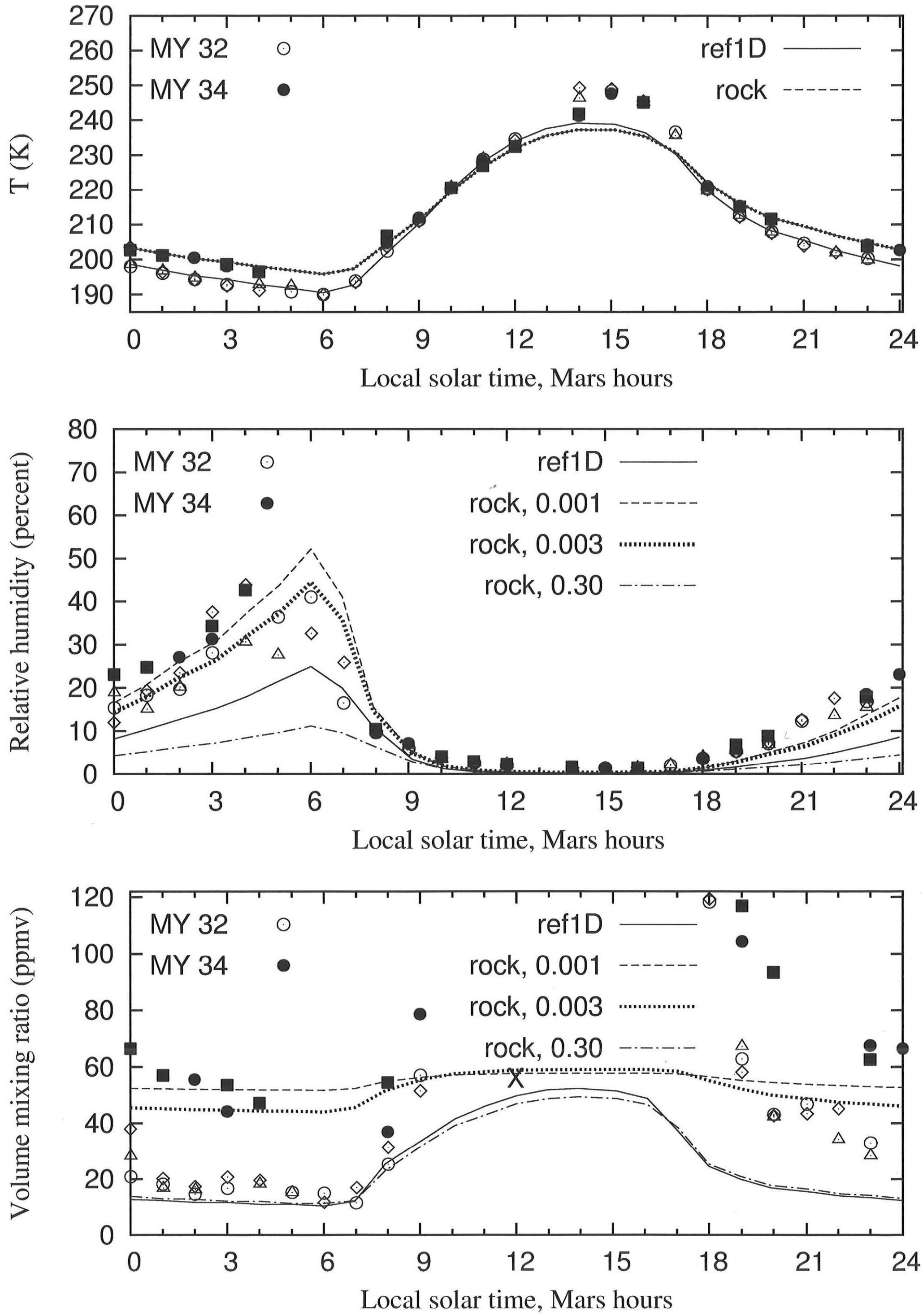

Figure 2. The hourly T, RH and vmr at 1.6 m around L_s 90° from REMS-H (MY 32 in white; MY 34 in black), and from column model simulations: "ref1D" : I = 300, porosity 0.30, solid lines; "rock": I = 400 with porosity 0.001 dashed; 0.003 dotted; 0.30 dash-dotted. Open diamonds, spheres and triangles are from sols 541, 542, 543, respectively; filled spheres and squares from sols 1880, 1881, respectively. X is the ChemCam 11:45 LT vmr observation from sol 543.

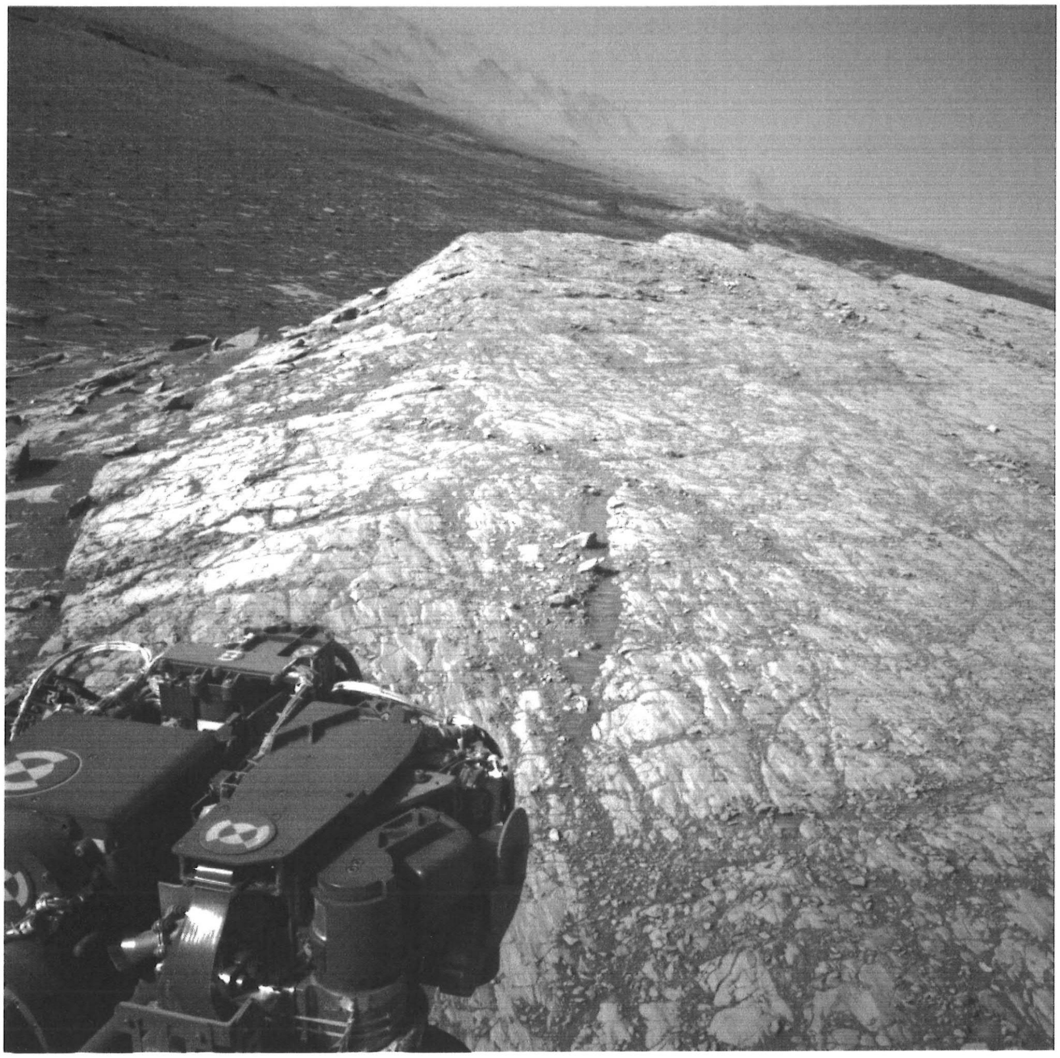

Figure 3. MastCam picture from Curiosity climbing up the rocky Vera Rubin Ridge at the base of Mt. Sharp on sol 1812. On the left the regolith-dominated crater base where the landing took place.

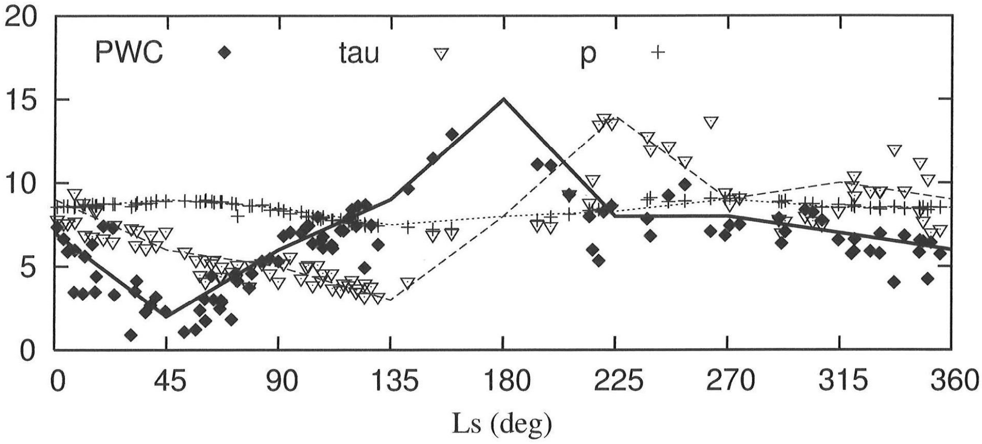

Figure 4. Column precipitable water content (PWC, in μm) from ChemCam passive sky scans, column total opacity, mostly by dust (τ multiplied by 10) from MastCam, and surface pressure (p, in mb) from REMS-P (McConnochie et al., 2018), and approximate fits to these data at L_s 45° steps (lines) for the model's annual forcing.

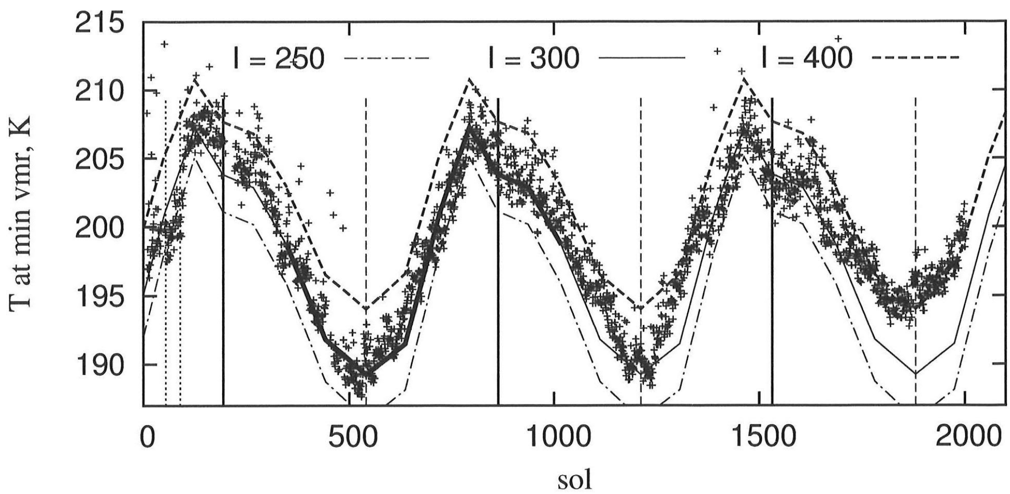

Figure 5. The daily 1.6 m REMS-H air temperatures at the pre-dawn hour of min vmr for MSL sols 10-2003, and column model 1.6 m min vmr temperatures for ground thermal inertias of 250, 300 and 400 SI units. The data-based model forcing period (MY32) is in bold in the I 300 curve. Solid upright lines indicate L_s 270° (warm season at Gale), dashed upright lines indicate L_s 90° (cool season at Gale). The Rocknest dune stay (sols 55-100) is marked by the dotted upright lines.

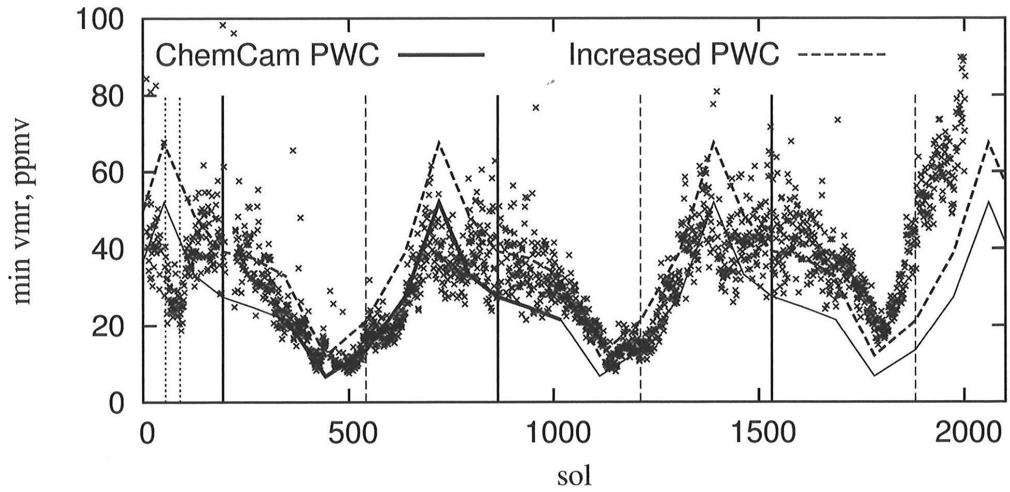

Figure 6. The daily REMS-H min vmr for MSL sols 10-2003, and the min vmr from the model (I 300, porosity 0.30) forced by ChemCam PWC, and by ChemCam PWC + 3 µm. The Rocknest dune stay (sols 55-100) is marked by the dotted upright lines.

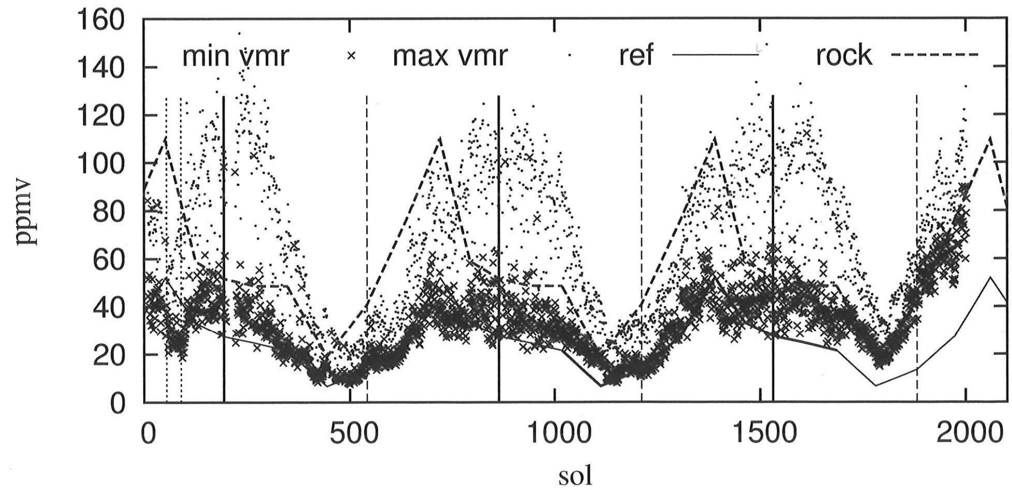

Figure 7. The daily min vmr (dark crosses) and max vmr (dots) from REMS-H, and the min vmr from two column model annual simulations: ‘reference’ with I 300 and porosity 0.30 (regolith ground; solid line); ‘rock’ with I 400 and porosity 0.003 (exposed bedrock ground; dashed line).