The diurnal water cycle at Curiosity: Role of exchange with the regolith

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ABSTRACT

Hourly temperatures T, relative humidities RH and mass mixing ratios of moisture q at 1.6 m derived from the Mars Science Laboratory REMS-H and REMS-P measurements are shown for MSL sols 15–17 (Curiosity at Bradbury) and 80–82 (Curiosity at Rocknest). They are compared to column model simulations with and without adsorption to porous regolith. The observed mixing ratio is small at night (10–30 ppmm). It increases rapidly to 50–80 ppmm after sunrise and decreases slowly during the evening. The model gives a good account of the observed T and, with adsorption and realistic precipitable water content (PWC), reproduces the diurnal cycles of both RH and q relatively well. The suggested regolith thermal inertia is 300 tiu and porosity 35–40% for both sites. According to the simulations moisture is adsorbed and diffused to the cooling regolith in the evening from the lowest very stable air layer. It is then desorbed in the morning from the rapidly warming regolith and mixed throughout the growing convective boundary layer. Estimates of PWC based on night-time near-surface moistures (assuming an even distribution with height) might therefore be on the low side in areas of porous adsorbing regolith.

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1. Introduction

The Mars Science Laboratory (MSL) onboard the rover Curiosity landed onto the Gale crater (137.4°E, 4.6°S) on August 2012 at L_s 151°. It carries the Rover Environmental Monitoring Station (REMS, Gómez-Elvira et al., 2012), which measures, among other quantities, the surface pressure (REMS-P, Harri et al., 2014a) and relative humidity (REMS-H, Harri et al., 2014b). Hourly REMS-H and REMS-P observations for two three-sol periods, MSL solar days (sols, 88,775 s) 15–17 and 80–82, initially discussed in Harri et al. (2014b), are considered here and compared with column model (1-D) calculations, in order to better understand the diurnal near-surface moisture cycle on Mars. This article is continuation to Savijärvi et al. (2015, S15 from now on), where the same observations were used, but with a simpler model, and the background of previous humidity observations on Mars was given. This background is hence not repeated here.

Jakosky et al. (1997) drew attention to the fact that the daytime column precipitable water content (PWC) obtained from the Viking Orbiter Mars Atmospheric Water Detector was higher at the two Viking lander sites than PWC based on the two landers' nighttime observations, assuming an even vertical distribution. This indicated significant depletion of near-surface atmospheric water

vapor during every night. They suggested, supported by calculations with the Zent et al. (1993) atmosphere–regolith 1-D model, that nighttime adsorption of water vapor to porous regolith could provide the required nocturnal depletion. They pointed out that diurnal variation seen in the near-surface atmospheric water vapor density, when this would become available, could be used to determine the role of the water exchange with the regolith.

Such observations have now been provided by Curiosity. In S15 the hourly REMS-H relative humidities RH and air temperatures T at 1.6 m height were used to validate a 1-D boundary layer model at the MSL landing site. This model included, like successful models for Earth deserts, a two-layer force-restore scheme for water vapor transport in the soil and a sublimation–condensation scheme at the surface, but not adsorption. It reproduced the diurnal cycle of T fairly well and that of RH reasonably well. However, it failed to simulate the observation-indicated slow decline of water vapor mixing ratio during every evening, followed by a rapid increase after sunrise. A similar diurnal cycle is also seen in water vapor partial pressures obtained from the recalibrated Phoenix TECP data (Zent, 2014). Furthermore, the suggested PWC of 2–7 μm in S15, based on the nighttime REMS observations and model results, is lower than the typical afternoon PWC of about 10 μm indicated by many orbiter missions and data assimilations for the MSL landing site and season.

Besides adsorption, nighttime hydration of salts in the regolith has been suggested to occur at Gale, related to the diurnal exchange of water vapor with the regolith (Martin-Torres et al.,

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2015). Here we modify the S15 model to include adsorption, and show that the modified model with PWC of 8–10 μm and porosity 35–40% for the regolith is able to simulate the REMS-H-observed diurnal cycles of temperature, relative humidity, water vapor pressure and water vapor mass mixing ratio relatively well at the 1.6 m observation height during the two 3-sol periods. Some sensitivity studies are also made.

2. Observations and model algorithms

The MSL column model and the REMS-H observations were described in detail in S15, so only a brief summary is given here. The REMS-H device onboard Curiosity consists of a temperature sensor and three RH-sensitive polymer sensors within a dust-protected cage mounted at about 1.6 m above the surface on the REMS boom 2. We use here hourly surface air pressures p from REMS-P with the first hourly RH measurements (the sensors warm up during operation) and 5 min means of T (to remove effects of turbulence) from REMS-H. Values of small daytime RH < 2% (with estimated uncertainty of ±1%) are considered unreliable; error bars for the higher nighttime RH are about ±10% in the present data. The water vapor partial pressure e at 1.6 m is obtained via $e = RH \cdot e_{sat}(T)$ and the vapor mass mixing ratio q via $q = \varepsilon e/p$, where ε (~18/44) is the ratio of the molecular weight of water to that of dry air (95% CO_2) on Mars. The saturation pressure of water vapor with respect to water ice $e_{sat}(T)$ is here given by

$$e_{sat} = p_o \exp\{22.542(T - 273.16)/(T + 0.32)\}, \tag{1}$$

where p_o = 611.657 Pa. Eq. (1), also used in the model, was shown in S15 to be fairly accurate with regard to reference values in the T-range of 190–273 K relevant here.

Our atmospheric column model is a hydrostatic one without advections. It is forced by constant geostrophic wind V_g and thermal diffusion in the ground. It includes turbulence, solar and thermal radiation and moist physics with the mass mixing ratios of water vapor (q) and water ice (q_i) being the moisture predictants. The atmosphere is represented by 29 grid points up to 50 km, the lowest points being at 0.3, 0.7, 1.6, 3.7, 8.5, 20 and 50 m above the surface. The model results have been compared with e.g. MER mini-TES observations (Savijärvi, 2012a, 2012b) and with Phoenix observations (Savijärvi and Määttänen, 2010).

There are in the present experiments eight sub-surface points for diffusion of heat in the ground, at physical depths of 0, 0.4, 0.8, 3.2, 6, 12, 24 and 48 cm for the two MSL sites. The two-layer force-restore method used in S15 for transport of moisture in the porous soil is here replaced by the same diffusion scheme as is used for the soil temperatures, so the pore mixing ratios (q_s) and regolith temperatures (T_s) are available at the same eight points. As only a few sols are considered here and the diurnal thermal skin depth is about 5 cm at the MSL sites, these eight points at optimized depths (Savijärvi and Määttänen, 2010) are able to describe the diurnal behavior of the soil temperature quite well. For long integrations, the soil column should however be deeper to better catch the annual cycle and any weather-driven transients.

The mass mixing ratio q of water vapor is governed in the model mainly by the convergence of the vertical flux of moisture due to turbulence, the stability- and wind-dependent scalar exchange coefficients being the same as those for temperature. Other local sources include the possible formation and clearing of frost, fogs and clouds. At the surface the turbulent vertical flux of moisture (positive upward) from porous regolith is given by

$$\phi = f\rho C_h V(q_s(0) - q), \tag{2}$$

where $\rho(=p/(RT))$, p, T, q and V are, respectively, the air density, air pressure, temperature, mixing ratio and wind velocity at the lowest

air point, R is the dry gas constant (191 J/kg/K for Mars), and $q_s(0)$ = $q_s(z = 0, t)$ is the surface mixing ratio in the pores. The stability- and roughness-dependent scalar transfer coefficient C_h is provided by the model's Monin–Obukhov surface layer scheme and f is porosity (the relative pore volume of the ground, often assumed to be 20–50% for the martian regolith). Note that for no moisture gradient or for no pores (i.e. f = 0) the flux equals 0.

If D is the molecular/Knudsen diffusion coefficient of H_2O vapor in CO_2 gas (here $1 \cdot 10^{-4}$ m²/s, Chevrier et al., 2008) the macroscopic diffusion coefficient in the regolith likely follows the Buckingham law f^2D of consolidated porous soil (Meslin et al., 2010). For conservation of mass the vertical flux of water vapor density from the regolith must be the same as the surface flux of moisture received by the air (2). Hence

$$-f^2 D \frac{\partial q_s \rho}{\partial z}\bigg|_{z=0} = \phi, \tag{3}$$

where $q_s(z)$ is the mixing ratio in the pore space. The surface value $q_s(0)$ can be solved from the finite difference version of (2)–(3) at each time step.

Following Zent et al. (1993) and Schorghofer and Aharonson (2005) water in the regolith is assumed to exist as mass of pore vapor $fw = fq_s\rho$ and as mass of adsorbate $a = a(w, T)$. Ice is disregarded for the time being. The total mass of H_2O is hence $fw + a$. Its evolution in a unit volume of regolith is governed by vertical diffusion of vapor through the regolith. Thus one gets

$$\frac{\partial}{\partial t}(fw + a(w, T)) = f\frac{\partial w}{\partial t} + \frac{\partial a}{\partial w}\frac{\partial w}{\partial t} + \frac{\partial a}{\partial T}\frac{\partial T}{\partial t}$$
$$= -\frac{\partial}{\partial z}\left(-f^2 D \frac{\partial w}{\partial z}\right). \tag{4}$$

Denoting $c = 1 + (1/f)\partial a/\partial w$, having f and D constants and assuming that air in the pores adopts the temperature $T_s(z, t)$ of the surrounding soil but its density changes are negligible it follows that

$$\frac{\partial q_s}{\partial t} = \frac{fD}{c}\frac{\partial^2 q_s}{\partial z^2} - \frac{1}{\rho cf}\frac{\partial a}{\partial T_s}\frac{\partial T_s}{\partial t}, \tag{5}$$

which we use to predict $q_s(z, t)$. D is thus scaled by $f/(1 + (1/f)(\partial a/\partial w))$. In practice the solution of (5) is split: $q_s(z)$ is first updated at each time step by the fast and strong last term. Then a new $q_s(0)$ is obtained from (2)–(3) and the slower diffusion part of (5) is solved using $q_s(0)$ as the top boundary condition (the results remain the same with reversed order, if the time step is not too long). Initially $T_s(z)$ is the diurnally averaged surface temperature for the appropriate L_s, and $q_s(z)$ in the pores equals $q_{m,i}$, where $q_{m,i}$ is the mean initial $q(z)$ in the boundary layer (0–4 km). If there is no adsorption, $a = 0$, $c = 1$, and (5) reduces to diffusion of H_2O through the pore space CO_2.

Some form for the adsorption $a = a(w, T)$ should now be defined.

3. Adsorption of water vapor

Adsorption of water in Mars is a process, whereby air water molecules get attached onto the surfaces of the grains in the regolith via weak van der Waals forces. This is favored by low and/or decreasing temperatures, whereas during increasing temperatures the weakly attached water molecules are driven back to the air by the increasing thermal motions (desorption). Besides temperatures the processes depend on the amounts of the available water molecules, and on the mineral composition and grain structure of the regolith.

The dependence of adsorption a on the water vapor partial pressure e in CO_2 gas has been measured for some minerals at constant temperatures T. The oldest and much used "adsorption isotherm" a (e, T) for Mars is based on basalt powder measurements by Fanale