<https://helda.helsinki.fi>

Curiosity observations and column model integrations for a martian global dust event

Savijärvi, Hannu

2020-02

Savijärvi , H , Martinez , G , Harri , A-M & Paton , M 2020 , ' Curiosity observations and column model integrations for a martian global dust event ' , Icarus , vol. 337 , 113515 . <https://doi.org/10.1016/j.icarus.2019.113515>

<http://hdl.handle.net/10138/335754>

<https://doi.org/10.1016/j.icarus.2019.113515>

cc_by_nc_nd

acceptedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.

Curiosity observations and column model integrations for a
Martian global dust event

Hannu Savijärvi, German Martinez, Ari-Matti Harri, Mark Paton

PII: S0019-1035(19)30363-X

DOI: <https://doi.org/10.1016/j.icarus.2019.113515>

Reference: YICAR 113515

To appear in:

Received date: 16 May 2019

Revised date: 12 September 2019

Accepted date: 27 October 2019

Please cite this article as: H. Savijärvi, G. Martinez, A.-M. Harri, et al., Curiosity observations and column model integrations for a Martian global dust event, (2019), <https://doi.org/10.1016/j.icarus.2019.113515>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Curiosity observations and column model integrations for a martian global dust event

Hannu Savijärvi^{1,2,*}, German Martinez^{3,4}, Ari-Matti Harri², Mark Paton²

¹Institute for Atmospheric and Earth System Research / Physics, University of Helsinki, Finland

²Finnish Meteorological Institute, Helsinki, Finland

³Lunar and Planetary Institute, Universities Space Research Association, Houston, TX, USA

⁴College of Engineering, University of Michigan, Ann Arbor, MI, USA

revised, 12 Sept 2019

Abstract

The Curiosity observations of surface pressure, optical thickness (τ), and Mars Year 32 water column values (PWC) were used to force adsorptive column model simulations around the MY34 strong dust event. Hourly ground (T_g) and air temperatures and water vapor mixing ratios were used for model validation. The diurnal amplitude of T_g drops from 90K to 30K during thick dust (τ up to 7-8.5), then increases back to 90K in the pace of τ decreasing back to seasonal average values. The model mimics the very large and rapid temperature changes quite well, strong dust downward IR emission being the dominant term in the surface heat budget during thick dust. Sensitivity tests indicate that the thick dust tends to show more solar forward scatter initially, consistent with larger particles. Water vapor mixing ratios are lower than normal before and after the event but a lot higher during it. The required local PWC at Gale is 2-3 μm lower than during the low-dust MY32 before and after the dust event, but about 7-8 μm higher during the peak of it.

Keywords: Mars, climate; Mars, surface; Meteorology

*Corresponding author at: INAR/Physics, Faculty of Science, 00014 University of Helsinki, Finland

E-mail address: hannu.savijarvi@helsinki.fi

Tel: +358-40-9380858

1. Introduction

The Mars Science Laboratory (MSL) Curiosity rover landed successfully in Gale crater (137.4°E, 4.6°S) in August 2012, corresponding to L_s 151° in Mars Year (MY) 31. It has been operating successfully for more than three martian years of 669 sols (days) and its Rover Environmental Monitoring Station (REMS; Gómez-Elvira et al., 2012) has provided interesting atmospheric and surface information. The in-situ meteorological data from Curiosity for its first 1600 sols, more than two martian years, has been included in the review of Martinez et al. (2017), which also briefly describes the many relevant instruments and observations, so this is not repeated here. The 1600 sol period was quiet in the sense that no major dust storms occurred during it. The still quiet period up to sol 2005 was considered with single column model interpretations of the diurnal and annual cycles in the near-surface temperatures and moistures in Savijärvi et al. (2019a,b). Here we continue beyond sol 2005, concentrating on Curiosity's observations and their interpretation through column modeling during sols 2085-2200 ($L_s \sim 195^\circ$ -270°), which covers the 2018/MY34 global dust event. Our tool is the University of Helsinki/ Finnish Meteorological Institute adsorptive subsurface-atmosphere column model described in the above references and in Section 2.

A major global dust event (GDE) occurred in June 2018, during the fourth year of Curiosity in Mars. The dust event, described in more detail by Guzewich et al. (2018), originated at around L_s 185°, MY34 far from Gale. It expanded rapidly to a global event, dust reaching the Gale area at around MSL sol 2075 (L_s 190°) and peaking on sol 2085 (L_s 195°), a period in which the Mastcam-observed 880 nm optical thickness (τ) suddenly jumped from 0.6 (the typical value of the L_s 180° season) to 7-8.5 (Fig. 1). Dustiness then decayed slowly in the time scale of 60-70 sols. The related REMS hourly observations of the ground and air temperatures and air moistures are presented and compared to idealized column model simulations forced by the MSL-observed optical thicknesses, surface pressures and column precipitable water contents (PWC). The latter, from ChemCam passive mode retrievals (McConnochie et al., 2018), are available only from the quiet period (mainly MY32) and hence provide here a reference for a GDE-free year.

Our main interest is here in the near-surface moisture behavior during the GDE, a novel subject not considered in Guzewich et al. (2018). Since both moisture in the air and its possible diurnal adsorption and desorption in the ground are very sensitive to the respective temperatures, we first have to validate the model's air and ground temperatures, to assure realistic simulations of moisture. We present in passing some interesting temperature-related experiments, as the major GDE provides a rare opportunity to look at and validate model results against actual martian surface observations during conditions of record-high dust thickness. Then the moisture findings are presented. In the end we derive, through model experiments, the “required” local PWC for MY34 at Gale, with which the near-surface Curiosity moisture observations can best be explained during the GDE, and compare these values with the local ChemCam-derived observed PWC during a quiet Mars year.

Previous studies have reported decreases in orbit-observed water columns in the equatorial region following a major GDE, but no big changes of PWC preceding or during it (e.g. Smith, 2004; 2018; Trokhimovskiy et al., 2015). In contrast, the Curiosity surface observations indicate strongly increased water vapor mixing ratios during the MY34 GDE (Section 5). The local and regional wind transports of water vapor in and around Gale may hence change due to a GDE. It is for instance plausible that the diurnal slope circulations are damped during thick dust, whereas the large-scale equatorial Hadley circulation may be strongly enhanced (Haberle et al., 1982; Kahre et al., 2017). Coupled GCM-mesoscale model simulations for the GDE are obviously needed to resolve these circulations and the related water transports. Meanwhile, our “required PWC” may provide a first tentative prediction for the behavior of the resulting local water column at Gale during the MY34 global dust event.

The observations and model experiments are briefly described in Section 2. The observed surface and air temperature aspects and the dust experiments are discussed in Section 3, while the model's diurnal temperature profiles and the surface heat budget for sols preceding and during the peak of the dust event are contrasted in Section 4. Moisture aspects are then discussed in Section 5 and our conclusions are drawn in Section 6.

2. Observations and model experiments

The processed MSL data are here 880 nm optical thicknesses τ from Mastcam (with reported accuracy of ± 0.03), hourly averaged ground surface temperatures T_g from the REMS ground temperature sensor (REMS-GTS, ± 1.0 K at 273 K, ± 4.5 K at 213 K), surface pressures p_o from REMS-P (± 3.5 Pa), air temperatures T (± 5.0 K) and the relative humidity observations ($\pm 8\%$ at 203 K, $\pm 2\%$ at 273 K) from REMS-H. The hourly water vapor volume mixing ratios (vmr) at 1.6 m height are derived from p_o and RH. These high confidence data have been obtained here for MSL sols up to sol 2167, following the same methodology as in Martinez et al. (2017) for the first 1600 sols. A separate dataset for the daily 2200 local time (LT) vmr (proxy for the daytime max vmr), the daily minimum value of vmr (min vmr), and T1.6m at the pre-dawn hour of min vmr (min T) from REMS-H extends to sol 2300. The accuracy of the vmr values is discussed in Section 5.

Use is also made of the passive mode ChemCam daytime retrievals of the local column precipitable water content along the Curiosity track for sols 230-1293 (mainly MY32), described in McConnochie et al. (2018). These local PWC values tend to be lower than from the simultaneous larger-scale orbital retrievals above the Gale region, indicating a normally relatively dry crater area throughout the year.

Our subsurface-atmosphere column model is hydrostatic without advections, forced by a constant geostrophic wind of 10 m/s and by the predicted ground heat flux (Section 4), which drives thermal diffusion in the ground in eight optimized grid points. The diurnal adsorption and desorption of water vapor in the soil pores is modeled as in Savijärvi et al. (2016; 2018; 2019a,b) in the same eight points as the soil temperature. Adsorption isotherms are taken from Jakosky et al. (1997). The atmospheric column consists of 29 grid points at the heights of 0.3, 0.7, 1.6, 7, ..., 50000 m above the surface. Parameterizations include radiation, turbulence (a Monin-Obukhov surface layer with a mixing layer treatment aloft), and interactive cloud physics. Solar (shortwave, SW) radiation is handled by a fast broadband delta-two-stream approach for CO₂ and dust, and thermal (longwave, LW) radiation by a fast broadband emissivity approach for CO₂, H₂O and dust. These schemes have been developed and validated by comparisons to results from a multiple-scattering spectrum resolving Crisp model (Savijärvi et al., 2005). In the comparisons it turned out that a small physically motivated change to the dust backscattering fraction of parallel solar radiation greatly improved all the candidate delta-two-stream methods. In particular the downwelling SW radiation to the surface became quite accurate, hence improving the prediction of T_g , as solar radiation is normally the dominating term in the daytime martian surface heat budget (Section 4). The dust parameters were later refined by Mie calculations with the more recent spectral data of Wolff et al. (2009) in Savijärvi (2012a,b). This confirmed the dust SW single-scattering albedo to 0.90 and the asymmetry parameter to 0.70, which are used in our reference model. The MY34 global dust event provides an opportunity to test parameter values against real martian data during high observed optical thickness, beyond the weak to moderate τ -range used in the above computational comparisons.

The model is initialized at 0000 local time (LT) for each L_s adopted, using the observed p_o , τ and PWC as in Savijärvi et al. (2019a,b). Surface and in-soil temperature is initially 225K with air lapse

rate of 1 K/km and well-mixed moisture both in the air and in the soil pores. Dust profile is given by $\tau(z) = \tau(p/p_0) \exp(-z/H)$, where τ is the visible optical thickness at the surface and H is 20 km. Dust is hence assumed well-mixed in the lower atmosphere, decaying upward more rapidly above about 10 km. The model is then run for a period of three sols (keeping p_0 and $\tau(z)$ temporally constant), by which time its temperatures, winds and moistures have spun up to a repeating diurnal cycle, which closely preserves the local PWC from sol to sol for the suggested porosities of the ground. The model values shown are from sol 3.

3. Observed and modeled temperatures

The MY34 GDE reached Gale crater at around MSL sol 2075, L_s 190°, and peaked on sol 2085, L_s 195°, a period in which τ values climbed from nominal (~ 0.6) to highest ever recorded from the surface of Mars (~ 8.5 , Fig. 1). Thereafter the dust settled down slowly in the timescale of about 60-70 sols. For the model input a fit to Mastcam $\tau(L_s)$ was made, shown in Fig. 1. The model was then applied with its standard settings (called the reference model), initializing and forcing it for each L_s with τ of Fig. 1 and PWC from the MY32 local ChemCam passive mode retrievals, Fig. 10. As in Savijärvi et al. (2019a,b), we hence assume that the local PWC is about the same during MY34 as it was during the GDE-free MY32, since the local PWCs of MY34 are not yet available. An attempt is later made to vary the PWC, to be discussed in Section 5.

The ground along the Curiosity MY34 climb on the Vera Rubin ridge toward Mt. Sharp is here assumedly exposed bedrock, with surface albedo of 0.20, roughness length of 0.01 m and ground emissivity ϵ_g of 0.96 set to the model. Thermal inertia I during the climb is set to 400 SI units and the PWC-preserving porosity 0.7% after Savijärvi et al. (2019b), except for sols 2045-2140 ($L_s \sim 175^\circ$ -230°), when the rover had temporarily descended back to the lower- I region. Here I is 300 SI units and porosity 1.5%. During sols 2045-2092, i.e. before and during the onset of the dust event at Gale, Curiosity was nearly stationary, made ready to observe the GDE at the foot of the Vera Rubin ridge. The thermal inertia remained unchanged during the GDE (Guzewich et al., 2018) but the surface albedo may have increased from 0.20 to 0.28 due to sedimentation of dust. We have made many experiments, varying model parameters systematically around their nominal values to chart the sensitivity of the results, but display here only the most informative results about the ground and air temperatures during the GDE.

Fig. 2 shows, for sols 2000-2167, the hourly ground surface temperatures T_g observed by the REMS-GTS device together with the daily maximum and minimum ground surface temperatures from four model experiments. The GTS values record a vast ~ 40 K drop in the daytime maximum T_g and a simultaneous 25-30K increase in the nighttime minimum T_g during the peak of the dust event, with a slow return thereafter to normal conditions as the dust settles. Note that during the first ten sols of the dust peak, both the maxima and minima of the observed T_g appear slightly higher than later on.

Thick lines in Fig. 2 originate from our reference simulation, where the broadband shortwave single-scattering albedo of the dust (ω_0) is 0.90 and the asymmetry parameter of scattering (g) is 0.70. Fig. 2 indicates that the reference model reproduces the daily extremes of the ground surface temperature fairly well even during the dust storm, especially after the first ten sols. Fig. 3 displays (for reference to later moisture discussion) the hourly nighttime air temperatures at 1.6 m height from the REMS-H instrument. The upward leap in the daily pre-dawn minima of $T_{1.6m}$ is very clear, about 15-18 K. The reference simulation (thick line) reproduces this fairly well. Hence the model's parameterizations appear to work overall quite well before and during the dusty period, its standard settings producing a fair simulation during the dust event, except perhaps for the first

ten sols.

We then made sensitivity tests about the dust radiative parameters. The thin lines in Figs. 2-3 represent an experiment, where the dust SW albedo ω_o is increased from the nominal 0.90 to 0.94, meaning less absorptive dust, as suggested in Wolff et al. (2009) and Määttä et al. (2009). This leads to slightly cooler air temperatures and higher daytime T_g during the dusty period by Fig. 2, as less solar radiation is absorbed by the dust. According to Fig. 2 the fit to the observed max T_g is then better during the first ten sols of the GDE but not afterwards. The daily minima of T_g are not changed much, but the minima of T1.6m (Fig. 3) are now slightly lower than in the reference simulation, as there is now less downwelling IR radiation from the cooler atmosphere. These findings are similar to those in Wolff et al. (2009). However, for the higher minimum air temperatures at 1.6 m observed during the first ten days of GDE the higher single-scattering albedo does not bring an improvement according to Fig. 3.

In another experiment (dashed lines) ω_o is 0.90 but the asymmetry parameter g is increased from the nominal 0.70 to 0.75, meaning more forward scatter by dust. This leads to higher daily max T_g during the dust event in Fig. 2 (less solar radiation is scattered around and hence more of it reaches the ground) but also to higher night temperatures in Fig. 3, as the dusty air now remains warmer at night due to the higher daytime T_g . This experiment gives the best fit to both T_g and min T1.6m for the first ten sols after the dust peak by Figs. 2-3, but thereafter the reference simulation is the best of the three experiments considered so far. As larger particles are associated with more forward SW scatter (e.g. Liou, 2002) this suggests that when the thick cloud of dust reached the MSL site there were still large and heavy particles in it that settled down in about ten sols, leaving behind the nominal smaller-particle dust. This is in accordance with Guzewich et al. (2018), where the estimated dust effective radius was 1.4 μm before the GDE, but more than 4 μm on sol 2097.

Guzewich et al. also indicate that thermal inertia of the ground remained unchanged during the GDE but the surface albedo around Curiosity may have increased from 0.20 to 0.28 due to settled dust. The double-dot lines in Figs. 2-3 hence display an experiment, where albedo was increased from 0.20 to 0.28 from sol 2085 onward. In the thick dust phase this makes almost no impact (in particular during the first ten days), because incident solar radiation is strongly attenuated by dust at that time (cf. Fig. 6). Later on the higher surface albedo simulation does produce a good match with the Curiosity temperature observations, according to Figs. 2-3.

We also experimented with the broadband dust IR emissivity/absorptivity values ε ($\tau_{\text{IR}} = \varepsilon \tau_{\text{vis}}$) used in the model. (The model's longwave scheme and handling of dust is described in detail in Savijärvi, 2012a,b). Increase of the emissivity for the downwelling flux to 0.3 from its nominal value of $\varepsilon_{\text{down}} = 0.25$ leads to consistently too high values for both T_g (Fig. 4) and min T1.6m compared to observations during the dusty period, whereas decrease of $\varepsilon_{\text{down}}$ to 0.2 leads to temperatures, which are consistently too low. Very nearly the same is obtained by increasing/decreasing the upwelling flux emissivity ε_{up} to 0.6/0.4 from its nominal value of 0.50. Hence the REMS observations of the high dust period appear to validate the above nominal values for ε . The reason for higher ε for the upwelling flux is that dust has a double effect on it: the layers of dust (if normally cooler than ground) attenuate the strong near-blackbody surface IR emission by absorbing some of it, while their own emission simultaneously adds up to the total upwelling flux. In the downwelling LW flux there is no such boundary contribution from the extremely cold space.

Luckily the REMS observations during the MY34 GDE provided an opportunity to indirectly validate the important but not well-known LW parameter $\varepsilon_{\text{down}}$ of dust, to about 0.25. The respective ε_{up} of dust has previously been constrained to around 0.5 ($\tau_{\text{vis}}/\tau_{\text{IR}} \sim 2$) via satellite IR $\sim 9 \mu\text{m}$ observations. This value is now confirmed (in the present model framework) for broadband LW.

4. Model temperature profiles and the surface heat budget before and during the dust event

Fig. 5 displays the model temperature profiles at 0600, 1000, 1600 and 2200LT just before and just after the onset of the GDE, namely at L_s 190° (sol 2075, τ 0.67, ω_o 0.90, g 0.70) and at L_s 195° (sol 2085, τ 7.0, ω_o 0.90, g 0.75). The pre-GDE profiles (thin lines) display a typical diurnal temperature variation near the surface with a strong inversion at night and an adiabatic profile to 5 km height in the afternoon. These profiles are nearly identical to the Mars Climate Database (MCD) normal dustiness T-profiles for the Curiosity site at L_s 190°. In strong contrast, the 1-D model's GDE profiles ten sols later (thick lines) reveal the highest temperatures of 265K at about 5-15 km heights in the late afternoon, due to the accumulated solar heating by strong dust SW absorption during the day. There is in fact an afternoon inversion from the surface up to 10 km. For the rest of the day the atmosphere then cools down (mainly by IR cooling to space), the near-surface temperatures being high and rather isothermal up to about 20 km. Although the thick dust is assumed to decay upward, there is still enough of it above 30 km height to drive moderate diurnal variation of temperature.

The details of the peak dust T-profiles of Fig. 5 are quite sensitive to the chosen dust profile $\tau(z)$, which is here an educated guess, pending observations. However, first estimates for the zonal mean temperatures at 40-50 km heights at 5°S by the ExoMars Trace Gas Orbiter indicate 200-220 K during the GDE (Belyaev et al., 2019). The model's GDE peak values of T at 40-50 km would seem to be the same by Fig. 5 (so the assumed dust amounts at these heights appear realistic), while the model's ground and near-surface air temperatures were close to REMS observations by Figs. 2-3. Therefore the model's surface heat budgets might be expected to be realistic.

Fig. 6 shows key diurnal surface heat budget terms from the simulations during low dust, L_s 190°, τ = 0.67, and during high dust, L_s 195°, τ = 7.0. (Fig. 5 displayed the respective diurnal temperature profiles). The low dust case (Fig. 6, top) presents a typical equatorial martian diurnal surface heat budget during low dustiness, like e.g. in Petrosyan et al. (2011), Martínez et al. (2014) and Read et al. (2017). Here the net SW flux ($SW_{down} \cdot (1 - \text{albedo})$) is clearly dominant during daytime. The net LW flux ($LW_{down} - \epsilon_g \sigma T_g^4$) is negative and fairly constant during the night, and the sensible heat flux is quite small. The sum of them, i.e. the ground heat flux G (positive downward) peaks at around 1000-1100LT to 160 W/m² and turns negative at around 1600LT, stabilizing the surface layer. The downwelling LW radiation is here small (40-60 W/m²) and nearly constant during the sol, the net LW flux being strongly negative around midday due to the high T_g (Fig. 2). In all, the SW down and LW up terms are dominant in the low-dust case energy balance.

The novel high dust case budget is strikingly different (Fig. 6, bottom). Here the midday net SW flux is attenuated to only 20% of that in the low-dust case. The net LW flux is quite small and the sensible heat flux is practically zero so the resulting ground heat flux G is small negative at night and peaks to only about 40 W/m² during midday. The dominant fluxes are here the massive downwelling LW radiation from the dusty atmosphere and the upwelling surface LW flux - $\epsilon_g \sigma T_g^4$ (not shown), such that the net LW flux remains small and negative. Dust emission from the sun-heated late afternoon air column (Fig. 5) leads to LW_{down} peaking at ~200 W/m² at 1500-1600LT in Fig. 6. The large LW_{down} in the surface heat budget during high dust explains the strong sensitivity of T_g to the LW emissivity ϵ_{down} of dust in Fig. 4.

5. Moisture aspects and discussion

The strong solar heating of thick dust, as vividly demonstrated in Fig. 5, may drive strong local or

mesoscale circulations, such as “rocket dust storms” (Spiga et al., 2013), if the dusty area is limited in size. In a global dust event, however, local and mesoscale circulations are probably quite weak, as the strong daytime heating then is similar everywhere. This tends to damp any horizontal temperature differences, which drive the local circulations. On the other hand, weakening of the normally strong slope circulations of Gale (Rafkin et al., 2015; Steele et al. 2017), together with the simultaneous strengthening of the large-scale Hadley circulation during a GDE (Haberle et al., 1982) may lead to changes in winds and hence in the moisture within the crater. Such changes might be reflected in the local REMS-H volume mixing ratios around the GDE.

Fig. 7 presents the MY32 passive mode daytime ChemCam observations of local PWC at Gale from McConnochie et al. (2018), converted to the respective volume mixing ratios (vmr) of well-mixed moisture. As shown in Savijärvi et al. (2019a), these ChemCam vmr estimates are very close to the respective daytime *surface*-vmr in the GCM-based normal dust year MCD data. We may thus assume that the ChemCam vmr values adequately represent the normal dust year daytime vmr values near the surface. We further assume that they are also mostly valid during MY34 (this will be discussed later), as the MY34 local ChemCam retrievals of PWC are not yet available. In Fig. 7 there are also the daily REMS-H vmr values at 2200LT (“max vmr”) for sols 1800-2250. These are proxies for the daytime maximum vmr, which are unavailable due to instrument limitations. Hence the REMS-H max vmr values should be about the same as the ChemCam vmr. Fig. 7 shows that during sols 1800-1970, and again after sol 2200, the ChemCam vmr and the REMS-H max vmr are indeed rather similar, but during sols 2000-2095, i.e. before the dust event, the values of max vmr are clearly lower than ChemCam MY32 vmr. This indicates that moisture at Gale was lower than normal before the dust event. During the dust event the REMS-H max vmr values then jump up and settle down in the same pace as did dustiness (Fig. 1). This would in turn indicate increased near-surface moistures within Gale during the dust event.

Fig. 7 also displays two simulations with our adsorption model. The thick line presents the midday model vmr at 1.6 m height from the MY34 reference simulations, where moistures were initialized from the available ChemCam daytime MY32 PWC. It is therefore no wonder that the thick line is within the ChemCam dots of Fig. 7 in general. An exception occurs, however, during the thickest dust, where the model-vmr (thick line) drops down. This is due to the strongly damped amplitude of T_g -variation (Fig. 2), which allows less evening adsorption and less morning desorption of moisture into/from the ground, hence leading to the smaller midday near-surface vmr from the same PWC.

The dashed line in Fig. 7 is from a simulation, where we have artificially increased the local PWC during the dust event and decreased it before and after the event, such that the model’s midday vmr better matches with the REMS max vmr proxy, and its pre-dawn min vmr simultaneously better matches with the observed REMS pre-dawn min vmr. The “required PWC” simulation (dashed) gives a better fit to the observed max vmr in Fig. 7. This will be discussed later in connection with the respective min vmr observations and simulations.

Fig. 8 presents the REMS-H pre-dawn 1.6 m temperatures during the observed daily minima of vmr (min T) for the long period of sols 1800-2250. These are typically the coldest temperatures of each sol and are thus sensitive to ground thermal inertia, L_s and dustiness but not to moisture. Fig. 8 shows, like Fig. 3, the clear upward jump in min T during the GDE. Fig. 8 furthermore shows the daily minima of $T_{1.6m}$ from reference model simulations with the GDE-free MY32 PWC (solid) and with the above “required PWC” (dashed). The two are practically equal and match relatively well with the observations, except for being too cool just before the dust event, as in Fig. 3. During the dust event the minimum air temperatures appear to be adequately simulated.

Fig. 9 displays the observed daily REMS-H max vmr (from Fig. 7) and the pre-dawn min vmr,

together with min vmr from the reference model simulations forced by the GDE-free MY32 PWC (solid line), and forced by the “required PWC” during the GDE period (dashed line). The latter is confined such that fits to both the observed daily max vmr (Fig. 7, dashed) and the observed daily min vmr (Fig. 9, dashed) are subjectively good, giving however more weight to the REMS-H min vmr observations, which are more accurate than the max vmr estimates. Figure 9 shows that during sols 1800-1950, when Curiosity had just started to climb the bedrock-dominated Vera Rubin ridge, the observed max and min vmr are close to each other. This means little adsorption during the night and hence very low porosity (0.7% in the model), i.e. fully exposed bedrock (Savijärvi et al., 2019b). From about sol 2045 onward the observed daily max and min vmr are more apart in Fig. 9, suggesting slightly more nighttime adsorption and hence slightly higher PWC-preserving porosity (1.5% in the model).

The GDE-free PWC simulation (solid) fits to the REMS-H min vmr observations relatively well in Fig. 9, except during the dusty period, when it is clearly an underestimate. This must be due to lack of moisture, since the model’s min T are about right (Figs. 3, 8), dustiness is set as observed (Fig. 1), and the rover was nearly stationary, so properties of the ground did not change. The “required PWC” simulation with increased moisture during the GDE (dashed line) gives a good fit to min vmr during the dusty period, whereas the decreased moisture just before the GDE produces a slight underestimate. The opposite was true for max vmr in Fig. 7, for which the same required PWC produced high values before the GDE but low values during it, compared to the observations. Hence our required (“predicted”) local PWC at Gale for MY34 is a compromise but it is within the respective ranges of the REMS-H observations for the daily max and min vmr.

The ‘required PWC’ of MY34 at Gale (dashed) is shown in Fig. 10 together with the MY32 ChemCam PWC observations. The solid line (a fit to the ChemCam PWC) shows the GDE-free normal-dust-year PWC. Fig. 10 suggests that before and after the dust event the typically high local PWC during the moist L_s 180° season over Gale, 10-13 μm , is low by 2-3 μm . During the dust event, however, the local PWC jumps to 18-19 μm , well above the normal value of the season at Gale, but typical for the surrounding regions from the larger-scale orbit retrievals (McConnochie et al., 2018). This might mean that, diurnal slope winds being presumably weak in Gale during thick dust, the dust-enhanced large-scale (Hadley cell) near-surface winds are temporarily able to flush the higher moisture content from the surrounding regions into the normally dry crater. Coupled GDE mesoscale simulations are, however, needed to prove this hypothesis.

6. Conclusions

The MSL observations of Mastcam optical thickness τ , REMS-P surface pressures and ChemCam MY32 PWC values were used to force adsorptive column model simulations around the 2018/MY34 global dust event at Curiosity. Hourly REMS-GTS ground surface temperatures together with observations of air temperatures and water vapor volume mixing ratios (vmr) from the REMS-H device were used for model validation. The dust storm (τ up to 7-8.5 at around L_s 195°, MSL sol 2085) is dramatically seen in the observed surface temperatures, their diurnal amplitudes initially dropping from about 90K to about 30K and then increasing slowly back to 90K in the pace of the decreasing optical thickness. The model mimics these very large and rapid changes quite well with its standard settings.

Sensitivity tests suggest that the dust SW broadband single-scattering albedo is optimally about 0.90 all the time in the present model framework. The dust broadband SW asymmetry parameter (g) is optimally about 0.70 most of the time, except for the first ten thick-dust sols of the GDE at Gale, when a higher g of about 0.75 best reproduces the slightly higher surface temperatures during this initial period. This suggests that during the first sols of the event there were still many large and

strongly forward-scattering particles in the arriving cloud of dust (the larger particles more rapidly settling down, leaving behind nominal small-particle dust), thus supporting the findings of Guzewich et al. (2018). Our tests also support their suggestion of increased surface albedo after the event, due to the freshly sedimented dust.

Experiments with the dust LW broadband emissivity values (ϵ) constrain ϵ_{down} to 0.25 and ϵ_{up} to 0.50 in the present model framework. The strong solar heating due to dust absorption leads to high model temperatures at about 5-15 km heights each afternoon during the GDE, with nearly isothermal and relatively high near-surface temperatures in the lower atmosphere for the other hours. This in turn makes the downwelling LW radiation the clearly dominant term in the surface heat budget during thick dust. According to the model, LW_{down} reaches to above 200 W/m^2 at the surface during a thick-dust (sol 2085) afternoon (from about 60 W/m^2 in a low-dust sol 2075 afternoon), while respectively the midday net SW radiation is attenuated by 80% to only about 100 W/m^2 .

Moisture simulations display a good correspondence for sols 1800-1950 between the daytime GDE-free MY32 ChemCam vmr, the REMS-H daytime vmr proxy (max vmr), and the model's daytime vmr. Just before the GDE, however, the REMS-H max vmr values appear low, and during the GDE, quite high, compared to the quiet-year ChemCam vmr. Similarly, the REMS-H pre-dawn min vmr values are low before the GDE but quite high during it. Therefore the near-surface moisture at Gale appears low before the GDE and quite high during it. Mesoscale model simulations are needed to explain this. However, we 'predicted' the evolution of the local PWC at Gale during the GDE, by defining through column model experiments with the observed τ a new PWC for each L_s , which produces a decent fit to the measured max and min vmr from REMS-H during MY34 (and a good fit to the measured temperatures). The so-obtained 'required' local PWC (Fig. 10) is 2-3 μm lower than the low-dust year MY32 ChemCam PWC before and after the dust event, but about 7-8 μm higher than the ChemCam PWC during the peak of the dust event.

Acknowledgements: The work was supported by the Academy of Finland grants 131723, 132825 and 310509. Germán Martínez was supported by JPL grant 1449038. We are grateful to the reviewers and to Tim McConnochie, who graciously provided his data for our disposal.

References:

- Belyaev D, et al., 2019. Temperature vertical profiles of Mars' atmosphere: first year of solar occultations by the ACS MIR onboard the ExoMars TGO. EGU2019-15943.
- Gómez-Elvira GJ et al., 2012. REMS: The Environmental Sensor Suite for the Mars Science Laboratory Rover. Space Sci. Rev. 170, 583-640, doi:10.1007/s11214-012-9921-1.
- Guzewich SD, et al., 2019. Mars Science Laboratory observations of the 2018/Mars year 34 global dust storm. Geophysical Research Letters, 46, 71–79. <https://doi.org/10.1029/2018GL080839>
- Haberle RM, Leovy CB, Pollack JB, 1982: Some effects of global dust storms on the atmospheric circulation of Mars. Icarus 50,322-367.
- Jakosky BM, Zent AP, Zurek RW, 1997. The Mars water cycle: Determining the role of exchange with the regolith. Icarus 130, 87-95.
- Kahre MA, et al., 2017: The Mars dust cycle. In "The Mars Atmosphere and Climate" (eds. Haberle RM, R Todd Clancy, F Forget, MD Smith, RW Zurek). Cambridge University Press, 644 p.

- Liou K-N, 2002. Radiation and cloud processes in the atmosphere. Oxford University Press, UK.
- Martínez GM et al. (2014), Surface energy budget and thermal inertia at Gale Crater: Calculations from ground-based measurements, *J. Geophys. Res. Planets*, 119, doi:10.1002/2014JE004618.
- Martínez GM, Newman CN, De Vicente-Retortillo A, Fischer E, Renno NO, Richardson MI, Fairén AG, Genzer M, Guzewich SD, Haberle RM, Harri AM, 2017. The Modern Near-Surface Martian Climate: A Review of In-situ Meteorological Data from Viking to Curiosity. *Space Sci. Rev.* pp.1-44.
- Määttänen A, et al., 2009: A study of the properties of a local dust storm with Mars Express OMEGA and PFS data. *Icarus* 201, 504-516.
- McConnochie TH, et al., 2018. Retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy. *Icarus* 307, 294-326, doi:10.1016/j.icarus.2017.10.043.
- Petrosyan A, et al., 2011: The Martian atmospheric boundary layer. *Reviews of Geophysics*, 49, RG3005, doi: 10.1029/2010RG000351
- Rafkin S, et al., 2016. The meteorology of Gale Crater as determined from Rover Environmental Monitoring Station observations and numerical modeling. Part II: Interpretation. *Icarus*, doi:10.1016/j.icarus.2016.01.03.
- Read PL, et al., 2017. Chapter 7: The Martian Planetary Boundary Layer, pp. 172-202. In “The Mars Atmosphere and Climate” (eds. Haberle RM, R Todd Clancy, F Forget, MD Smith, RW Zurek). Cambridge University Press, 644 p.
- Savijärvi H., 2012a: Mechanisms of the diurnal cycle in the atmospheric boundary layer of Mars. *Quart. J. Roy. Meteor. Soc.* 138, 552-560. doi:10.1002/qj.930
- Savijärvi H., 2012b: The convective boundary layer on Mars: some 1-D simulation results. *Icarus* 221, 617-623.
- Savijärvi H., Crisp D, Harri AM, 2005: Effects of CO₂ and dust on present-day solar radiation and climate in Mars. *Quart.J.Roy.Meteor.Soc.*, 131, 2907-2922.
- Savijärvi H, Harri AM, Kemppinen O, 2016: The diurnal water cycle at Curiosity: role of exchange with the regolith. *Icarus* 265, 63-69, doi:10.1016/j.icarus.2015.10.008
- Savijärvi H, Paton M, Harri AM, 2018: New column simulations for the Viking landers: winds, fog, frost, adsorption? *Icarus* 310, 48-53, doi: 10.1016/j.icarus.2017.11.007.
- Savijärvi H, McConnochie T, Harri AM, Paton M, 2019a: Annual and diurnal water vapor cycles at Curiosity from observations and column modeling. *Icarus* 319, 485-490. doi:10.1016/j.icarus.2018.10.008
- Savijärvi H, McConnochie T, Harri AM, Paton M, 2019b: Water vapor mixing ratios and air temperatures for three martian years from Curiosity. *Icarus* 326, 170-175, doi:10.1016/j.icarus.2019.03.020.
- Smith MD, et al., 2004: Interannual variability in TES atmospheric observations of Mars during 1999-2003. *Icarus* 167, 148-165.
- Smith MD, et al., 2018: The climatology of carbon monoxide and interannual variation of water vapor on Mars as observed by CRISM and modeled by the GEM-Mars general circulation model. *Icarus* 301, 117-131.
- Spiga A, Faure J, Madeleine JB, Määttänen A, Forget F, 2013: Rocket dust storms and detached dust layers in the Martian atmosphere. *J.Geophys.Res.Planets* 118(4), 746-767.
- Steele LJ, Balme MR, Lewis SR, Spiga A, 2017. The water cycle and regolith-atmosphere interaction at Gale

crater, Mars. *Icarus* 280, 56-79.

Trokhimovskiy A et al., 2015. Mars' water vapor mapping by the SPICAM IR spectrometer: five Martian years of observations. *Icarus* 251, 50-64.

Wolff, M. J., M. D Smith, R.T. Clancy, R. Arvidson, M. Kahre, F. Seelos IV, S. Murchie, and H. Savijärvi, 2009: Wavelength dependence of dust aerosol single scattering albedo as observed by the Compact Reconnaissance Imaging Spectrometer. *J.Geophys.Res.*, 114, E00D04, doi:10.1029/2009JE003350.

Figures:

Figure 1. The Mastcam 880 nm optical depth τ during sols 2000-2167, and the fit $\tau(L_s)$ for the model experiments.

Figure 2. The REMS-GTS hourly ground surface temperatures for sols 2000-2167 and the daily max and min T_g from the reference simulation (dust single-scattering albedo ssa 0.90, asymmetry parameter g 0.70, surface albedo a 0.20, thick lines), from simulation with ssa of 0.94 (thin lines), from simulation with g of 0.75 (dashed lines) and from simulation with a of 0.28 after sol 2085 (double dots). Dust- τ is from Fig. 1. Note the first ten sols after the sol 2085 peak in τ .

Figure 3. As fig. 2 but for the observed hourly nighttime air temperatures at 1.6 m from REMS-H for sols 2000-2167, and the model's daily minimum T at 1.6 m from the four simulations.

Figure 4. The REMS-GTS hourly ground surface temperatures for sols 2000-2167, and the model daily maximum and minimum T_g from the reference simulation (dust emissivity ϵ_{down} of 0.25, thick lines), from ϵ_{down} of 0.30 simulation (thin lines), and from ϵ_{down} of 0.20 simulation (dashed lines). Dust- τ is from Fig. 1.

Fig. 5. Model temperature profiles (1.6 m – 40 km) at 0600, 1000, 1600 and 2200LT from the low dust sol 2075 ($\tau = 0.67$, thin lines) and from the high dust sol 2085 ($\tau = 7$, thick lines).

Figure 6. The diurnal surface heat budget terms LW_{down} , LW_{net} , SW_{net} , the sensible heat flux and the ground heat flux (G) for the low dust sol (top panel) and for the high dust sol (bottom panel) of Fig. 5. Zero line (thin) is also displayed.

Figure 7. The well-mixed daytime vmr from ChemCam MY32 PWC retrievals, the REMS-H vmr at 2200LT (max vmr), and the model's midday vmr when forced by the ChemCam low dust year MY32 PWC (thick solid line), and when forced by the required PWC of Fig. 10 (thick dashed line).

Figure 8. The REMS-H air 1.6 m temperatures at the pre-dawn hour of minimum vmr (min T), and the daily minimum temperatures at 1.6 m from the two simulations of Fig. 7 (lines). The cool season occurs at Gale around sol 1880 (L_s 90°), the moist season around sol 2060 (L_s 180°) and the warm season around sol 2200 (L_s 270°).

Figure 9. The daily max and min REMS-H vmr, and the daily minimum vmr from the two simulations (the thick solid and dashed lines) of Fig. 7.

Figure 10. The annual ChemCam PWC retrievals of McConnochie et al. (2018) during GDE-free conditions (mainly MY32), the fit to them for model forcing, and the required PWC for MY34, which provides a decent fit to REMS-H observations during MY34 (dashed lines in Figs. 7-9).

Highlights of “Curiosity observations and column model integrations for a martian global dust event” by Hannu Savijärvi, German Martinez, Ari-Matti Harri, Mark Paton

- Curiosity observations during the 2018/MY34 global dust storm were used to force and validate an adsorptive subsurface-atmosphere local column model.
- The model simulated the observed surface and near-surface temperatures quite well.
- Thick dust indicates initially more forward scatter and higher surface albedo afterwards.
- Observed water vapor mixing ratios are low before and after the storm but high during it.
- The required PWC is 2-3 μm lower than normal before and after the storm, but about 7-8 μm higher during the peak of it.