ELEVATION DEPENDENT METEOROLOGY IN GALE CRATER

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Introduction: Airflow over and around Mars' extreme topography drives much of its sensible weather. On global scales, the large Argyre and Hellas impact basins of the southern hemisphere drive stationary waves [1-3]. In the northern hemisphere, the smoother and lower terrain provides channels for baroclinic and barotropic traveling waves [4-5]. Many of these massive terrain features also force vertically-propagating gravity and inertia-gravity waves [6-7]. On smaller scales, craters of all sizes produce daily- and seasonally-varying patterns of upslope and downslope winds [8-9] and hydrostatic adjustments in air pressure [10], resulting in complex aeolian activity and possibly dispersal of trace gases from localized sources [11-12].

The Mars Science Laboratory Curiosity rover landed on the floor of Gale Crater in 2012/Mars Year (MY) 31 at an elevation of approximately -4500 m below the martian datum. At the center of Gale, nearly 6 km higher, lies Aeolis Mons/Mt. Sharp. This extreme altitude variation over a short distance produces fascinatingly complicated atmospheric flows through the crater, which Curiosity has measured to some degree and has been modeled [e.g., 9]. In nearly 10 Earth years on Mars, Curiosity has climbed approximately 500 m higher on Mt. Sharp and will continue to ascend in the years ahead. This change in altitude over 5 Mars years now allows us to directly interrogate how aspects of the martian atmosphere change with altitude, a perspective that has not been previously available to Mars atmospheric science either on the ground or in orbit (due to much coarser vertical resolution of remote sensing instruments).

Specifically, we investigate two meteorological factors that are expected to be functions of altitude: the amount of dust in the atmosphere and the atmospheric pressure.

Methods: Dust opacity is measured by Curiosity through direct solar imaging by the Mast Camera (Mastcam) 880 nm neutral-density-5 extinction filter [13]. These images are typically taken every 1-3 martian sols, although particular periods have higher cadences (up to 3/sol), while periods of solar conjunction or rover faults have none for several weeks. 880 nm dust opacity ("tau" for short) throughout the mission has typically ranged between 0.3 and 1.5 with a very repeatable seasonal cycle outside of significant perturbations such as the MY34 global dust storm [14] or the recent pre-equinox MY36 regional dust storm.

To complement and extend the opacity record from Curiosity, we also use Mars Climate Sounder (MCS) retrievals of dust extinction. MCS retrieves dust extinction in the thermal infrared with a nominal vertical resolution of 5 km, but the retrievals are oversampled to output dust extinction at ~1.5 km intervals [15]. We use the two-dimensional MCS retrieval version 5.2 for this work, which provides increased sensitivity at low altitudes [15]. However, MCS retrievals frequently do not extend below 20-30 km altitude.

Other meteorological data used in this study has been collected by the Rover Environmental Monitoring Station (REMS). REMS includes sensors measuring air pressure, air and ground temperature, ultraviolet radiation, relative humidity, and wind [16]. One wind sensor was damaged during landing and the remaining one was damaged approximately 2.5 Mars years into the mission [11]. REMS measurements are collected for the first 5 minutes of every hour local mean solar time (LMST) and in rotating 1-3 hour extended observation blocks every sol [e.g., 14].

Results: We discuss each result individually.

Dust Scale Height. As previously stated, the atmospheric opacity over Gale Crater is largely repeatable each year outside of large dust storms (Figure 1).

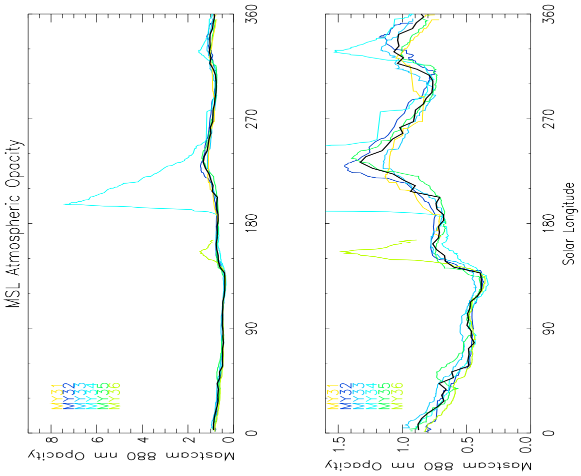

Figure 1. Smoothed 880 nm midday and afternoon atmospheric opacity measured by Mastcam over the duration of the MSL Curiosity mission for each Mars

year. The black line represents the multi-year average.

Opacity reaches a minimum each year near L_s = 120-140° before increasing during the dusty season. Two periods of higher opacity occur during the southern hemisphere spring and summer seasons, corresponding to the “B” and “C” dust storm phases [17]. The repeatability of the seasonal cycle in dust opacity, particularly in the less dusty L_s = 340-180° period, allows us to use Curiosity’s change in altitude over time to probe how dust opacity decreases with height. To best isolate dust’s contribution to atmospheric opacity, and reduce or eliminate the contribution from water ice clouds, we only use Mastcam tau measurements taken after 10 am LMST. We also remove the four most anomalous dust storms that Curiosity has experienced: the MY34 global dust storm, the MY34 large regional dust storm near L_s = 330°, the MY35 southern hemisphere autumn regional dust storm near L_s = 50°, and the recent MY36 large regional dust storm near L_s = 150°.

Then using the rover’s position information and combining the opacity measurements into 5° solar longitude bins, we can determine how opacity has changed as a function of altitude. In this binning, MY31 and MY32 measurements are frequent outliers to an otherwise robust linear trend of opacity as a function of altitude. In Figure 2, it can be seen that in the L_s=5-10° time period of MY33-36, opacity has closely followed a linear trend and implies a dust scale height of ~2 km.

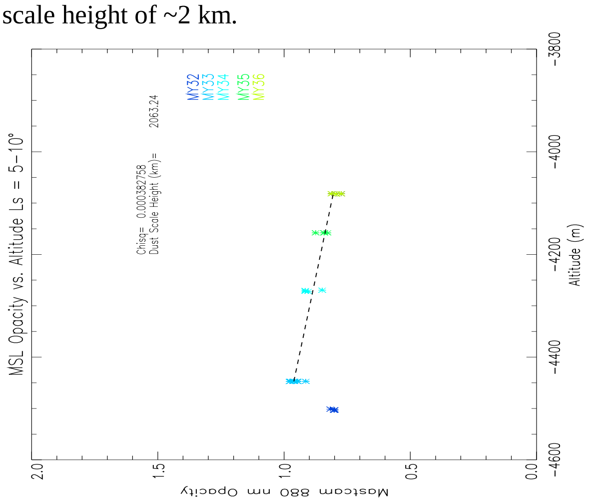

Figure 2. MSL opacity over altitude in the L_s = 5-10° solar longitude bin. The dashed line represents the linear fit to the opacity trend with altitude in MY33-36, which has a chi-squared statistic of 0.0038 and results in a dust scale height of ~2 km.

This pattern is common to most 5° L_s periods during the martian year outside of the dust storm season of L_s = 180-330°. During the dust storm season, there is frequently little or no trend in opacity over altitude, which is expected due to the variability in dust activity during this season. To make our results more robust, we only calculate dust scale height for 5° solar longitude bins that contain at least 3 Mars years with opacity measurements that fall on a linear trend line with a chi-squared statistic of less than $5*10^{-4}$.

Figure 3 presents the results for dust scale height across the entire martian year. Dust is strongly vertically confined within Gale Crater for most of the year, with dust scale heights near 2 km outside of the dust storm season. The increase to 4-6 km in the L_s = 90-120° period could either reflect a true increase in dust scale height or may be due to contamination by daytime aphelion cloud belt water ice clouds.

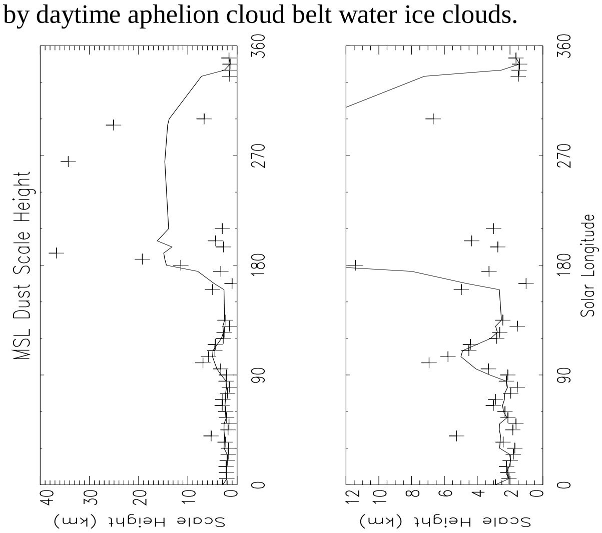

Figure 3. Dust scale height within Gale Crater determined by the change in Mastcam opacity as a function of altitude over 5 Mars years. Each 5° solar longitude bin’s value is indicated by a cross with the black line representing a smoothed running mean. Solar longitude bins without at least 3 Mars years of values or an insufficiently low chi-squared statistic are excluded.

The same process can be completed for MCS retrievals of dust extinction (converted to 880 nm opacity). Note that the lowest retrieved altitude is typically 5-10 km above the martian datum, or 9-14 km above Curiosity’s location. We find dust scale heights typically less than the pressure scale height of approximately 11 km. More typical values for MCS retrieved dust scale height are 5-8 km, but occasionally values as low as 2-4 km are seen in northern spring and summer. By extrapolating the MSL dust opacity trend line to the lowest retrieved MCS altitude, we can infer what the dust scale height would be in order for the MSL and MCS observations to be self-consistent. This follows work done in [18] to infer the vertical dust profile over Gale Crater. Connecting these two observed regions of atmosphere implies that while dust is vertically confined within Gale Crater itself, above Gale Crater, dust is well-mixed (with dust scale heights of approximately 11 km) for 1-2 atmospheric pressure scale heights.

Hydrostatic Pressure Adjustment. Surface air pressure on Mars varies widely over a given sol due to atmospheric tides [8]. The exact cycle of pressure at a given location is a combination of multiple different tides with periods that are integer fractions of a solar day. The most prominent are the diurnal (once per sol) and semidiurnal (twice per sol). Within topographic depressions such as craters, however, there is an additional enhancement to the daily pressure cycle due to "hydrostatic adjustment" [8]. Richardson and Newman [2018] describe the physics of this process in detail. Essentially, variations in surface air temperature over the course of the day drive lateral atmospheric flows to maintain hydrostatic balance across elevation. They estimate that as much as 15 Pa variations around the daily mean pressure are due to this process, which is additive to the planetary-scale diurnal tide.

Figure 4 shows how the diurnal pressure tide (representing the total diurnal period variation in pressure, *i.e.*, the planetary-scale tide plus any local hydrostatic adjustment term) has varied each Mars year in the L_s = 340-90° period. We choose this period for being largely free of any significant dust storm activity around the planet which can alter the amplitudes of the tides [19]. It can be seen that while the pattern of variation over time in each Mars year is quite similar, the amplitude of the tide does vary year-over-year. This is compared to the semidiurnal tide, which has very little year-to-year variation. Presumably, some of this is directly due to the change in mean surface pressure over ~500 m of altitude, but there should also be a change in the hydrostatic adjustment forcing.

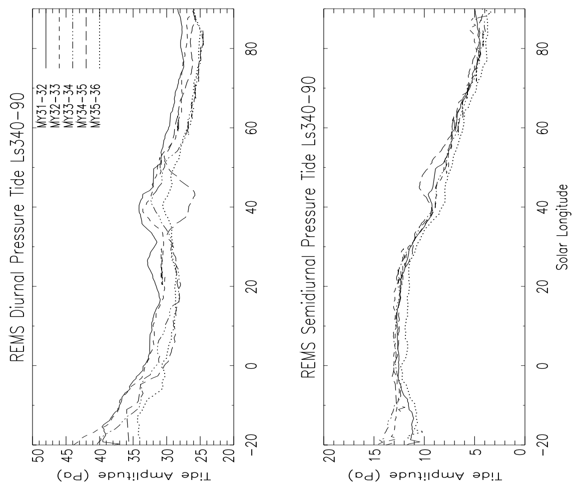

Figure 4. Diurnal and semidiurnal pressure tide amplitude (Pa) as measured by REMS in the L_s = 340-90° period of each Mars year.

We normalize the change in diurnal pressure tide change by dividing by the mean surface pressure to compute the percentage of daily range of surface pressure (PDRSP) [8]. As it is reflects the hydrostatic change in surface pressure over altitude, any change in PDRSP reflects either a change in the global-scale diurnal tide or in the changing hydrostatic adjustment term. By calculating this term in the clearer southern late summer and fall, we ideally minimize any interannual variability in the global-scale tide and assume any change in PDRSP over altitude is due to the hydrostatic adjustment forcing decreasing. In Figure 5, we plot PDRSP over altitude in two solar longitude bins as an example. The change in PDRSP falls closely to a linear trend with altitude over 5 Mars years. The slopes in these two periods are typical of the period analyzed and have slopes of ~1 %/km.

Figure 6 presents the results for each 5° solar longitude period and shows a mean change in hydrostatic adjustment forcing of ~1% of PDRSP per km of altitude. This can be directly compared to Figure 5a-b of Richardson and Newman [2018] which shows ~1% change in PDRSP over 500 m of altitude over the Curiosity traverse route.

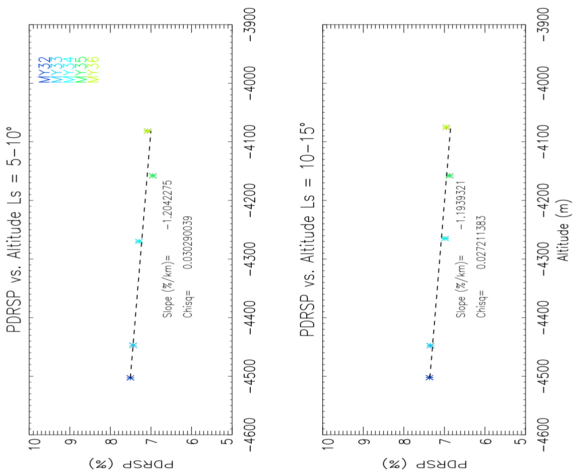

Figure 5. The change in PDRSP over rover altitude in the L_s = 5-10° and 10-15° periods for each Mars year. The linear fit is included in a dashed line with the slope (%/km) and chi-squared statistic indicated on each panel.

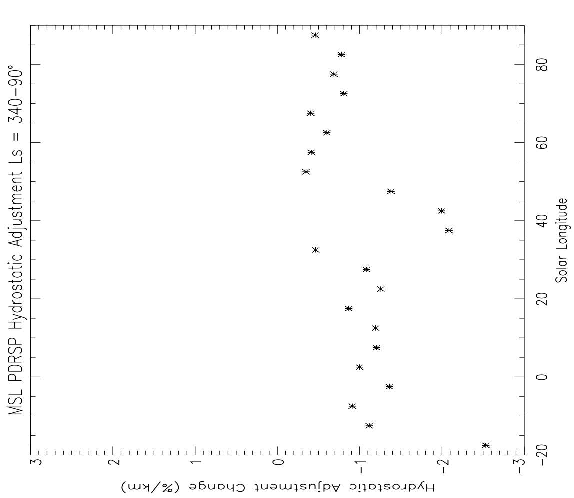

Figure 6. The change in hydrostatic adjustment forc-

ing (%/km) to the diurnal pressure range over the MSL mission in each 5° solar longitude bin from L_s = 340-90°. The mean value is ~1 %/km.

Conclusions: Curiosity's ascent up Mt. Sharp allows us to directly interrogate elevation-dependent atmospheric phenomena. We have measured the change in dust opacity and atmospheric pressure as a function of elevation over the 5 Mars year mission lifetime to-date.

We find that over much of the year, dust must be strongly vertically confined within Gale Crater, with a dust scale height of ~2 km. This is much lower than the atmospheric pressure scale height. During the dustier second half of the martian year, the dust scale height is more variable and often matches or exceeds the pressure scale height.

Second, using routine measurements of atmospheric pressure by REMS, we can isolate the change in hydrostatic adjustment forcing to the daily pressure cycle in Gale Crater. We find this factor changes by ~1%/km of elevation gain.

References: [1] Conrath, B. J. (1981), Planetary-scale wave structure in the Martian atmosphere, Icarus, 48, 246–255. [2] Banfield, D., et al. (2003), Forced waves in the martian atmosphere from MGS TES nadir data, *Icarus*, 161, 319-345. [3] Hinson, D., et al. (2003), Stationary planetary waves in the atmosphere of Mars during southern winter, J. Geophys. Res., 108(E1), 5004.[4] Barnes, J. R. (1980), Time spectral analysis of mid-latitude disturbances in the Martian atmosphere, *J. Atmos. Sci*., 37, 2002–2015. [5] Banfield, D., et al. (2004), Traveling waves in the martian atmosphere from MGS TES Nadir data, *Icarus*, 170(2), 365-403. [6] Creasey, J. E., et al. (2006), Global and seasonal distribution of gravity wave activity in Mars' lower atmosphere derived from MGS radio occultation data, Geophys. Res. Lett., 33, L01803. [7] Heavens, N.G., et al. (2020), A multiannual record of gravity wave activity in Mars's lower atmosphere from on-planet observations by the Mars Climate Sounder, Icarus, 341, 113630. [8] Tyler, D., & Barnes, J. R. (2015). Convergent crater circulations on Mars:Influence on the surface pressure cycle and the depth of the convective boundary layer. Geophysical Research Letters, 42(18), 7343-7350. [9] Rafkin, S.C.R., et al. (2016), The meteorology of Gale Crater as determined from Rover Environmental Monitoring Station observations and numerical modeling. Part II: Interpretation, Icarus, 280, 114-138. [10] Richardson, M.I., and C.E. Newman (2018), On the relationship between surface pressure, terrain elevation, and air temperature. Part I: The large diurnal surface pressure range at Gale Crater, Mars and its origin due to lateral hydrostatic adjustment, *Planetary and Space Science*, 164:132-157. [11] Baker, M. M., et al. (2022). Diurnal variability in aeolian sediment transport at Gale crater, Mars. *Journal of Geophysical Research: Planets*, 127, e2020JE006734. [12] Moores, J.E. et al. (2019). The methane diurnal variation and microseepage flux at Gale crater, Mars as constrained by the ExoMars Trace Gas Orbiter and Curiosity observations. *Geophysical Research Letters*, 46, 9430– 9438. [13] Lemmon, M. T., et al. (2019). Large dust aerosol sizes seen during the 2018 Martian global dust event by the Curiosity rover. *Geophysical Research Letters*, 46, 9448– 9456. [14] Guzewich, S. D., et al. (2019). Mars Science Laboratory observations of the 2018/Mars year 34 global dust storm. *Geophysical Research Letters*, 46, 71–79.[15] Kleinböhl, A., et al. (2017) Two-dimensional radiative transfer for the retrieval of limb emission measurements in the martian atmosphere, Journal of Quantitative Spectroscopy and Radiative Transfer ,187 , 511-522. [16] Gómez-Elvira, J., et al. (2012), REMS: The Environmental Sensor Suite for the Mars Science Laboratory, *Space Science Reviews*, 170, 583-640. [17] Kass, D. M., et al. (2016), Interannual similarity in the Martian atmosphere during the dust storm season, *Geophys. Res. Lett.*, 43, 6111– 6118. [18] Guzewich, S.D., et al. (2017), The Vertical Dust Profile Over Gale Crater, Mars, Journal of Geophysical Research-Planets, 122, 2779-2792. [19] Guzewich, S.D., et al. (2016), Atmospheric Tides in Gale Crater, Mars, Icarus, 268, 37-49.