Gravity Wave Observations by the Mars Science Laboratory REMS Pressure Sensor and Comparison with Mesoscale Atmospheric Modeling with MarsWRF

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ABSTRACT

Surface pressure measurements on Mars have revealed a wide variety of atmospheric phenomena. The Mars Science Laboratory Rover Environmental Monitoring Station pressure sensor dataset is now the longest duration record of surface pressure on Mars. We use the first 2580 martian sols of measurements to identify atmospheric pressure waves with periods of tens of minutes to hours using wavelet analysis on residual pressure after the tidal harmonics are removed. We find these waves have a clear diurnal cycle with strongest activity in the early morning and late evening and a seasonal cycle with the strongest waves in the second half of the martian year (L_s = 180-360°). The strongest such waves of the entire mission occurred during the Mars Year 34 global dust storm. Comparable atmospheric waves are identified using atmospheric modeling with the MarsWRF general circulation model in a "nested" high spatial resolution mode. With the support of the modeling, we find these waves best fit the expected properties of inertia-gravity waves with horizontal wavelengths of O(100s) of km.

1. INTRODUCTION

Long duration monitoring of atmospheric pressure on Mars has allowed a cornucopia of phenomena to be identified and studied. The Viking lander pressure records serve as the foundation for understanding how CO_2 cycles into and out of the seasonal polar ice caps and how martian dust storms drive variations in atmospheric tides (Martínez et al., 2017; Rafkin et al., 2017; Zurek and Leovy, 1981; Hourdin et al., 1993). Additionally, their location in the northern

hemisphere lowlands exposed the Viking Landers to seasonal baroclinic [Barnes, 1980; Tilman, 1988; Collins et al., 1996] and barotropic traveling waves, analogous to terrestrial weather fronts and low pressure storm systems (e.g., Wilson et al, 2002). The Mars Science Laboratory (MSL) Rover Environmental Monitoring Station (REMS) pressure sensor has now measured the longest record of atmospheric pressure on Mars, complementing the Viking record due to its near-equatorial southern hemisphere location. The REMS pressure sensor has detected the seasonal CO_2 cycle and the familiar atmospheric tides [Haberle et al., 2014; Guzewich et al., 2016]. Its finer resolution compared to the pressure sensors carried by the Viking landers has even permitted the detection of distant baroclinic traveling waves, which originate at high latitudes and have very low amplitudes by the time they reach MSL's location [Haberle et al., 2018]. The 1 Hz measurement rate has also allowed the detection of much more transient phenomena, such as pressure dips associated with passing convective vortices [e.g., Steakley and Murphy, 2016; Kahanpää et al., 2016; Ordonez-Exteberria et al. 2018; Ordonez-Exteberria et al. 2020; Newman et al. 2019; Kahanpää and Viúdez-Moreiras, 2020], which if sufficiently dusty may be visualized as 'dust devils.' MSL's location within Gale Crater has also shown how the topography forces atmospheric flows that maintain hydrostatic balance [Richardson and Newman, 2018] and wavelike perturbations with periods of tens of seconds to minutes likely driven by topographic wind flows and/or gravity waves forced by the topography of Gale Crater [Harri et al., 2014; Haberle et al., 2014; Ullán et al., 2017]. More recently, the InSight lander, with a sensitive pressure sensor that obtains measurements at much higher rate (up to 20 Hz), has detected undular bores, infrasound, and gravity waves with periods of minutes [Banfield and Spiga et al., 2020].

This work is motivated, in part, by two factors. First, the visual observation of gravity wave-like behavior in water ice clouds seen above Gale Crater by Kloos et al. [2018]. These cloud patterns are consistent with temperature moving alternately above and below the water ice condensation temperature due to gravity waves, and we seek to determine whether such temperature or pressure variability is measured on the surface by REMS. Second, we aim to search for atmospheric behavior with periods of tens of minutes to hours. This is a region of the time domain that is previously not well-studied on Mars from surface meteorological stations.

Based on modeling and theory of both Earth and Mars, we suggest that atmospheric waves with periods of tens of minutes to hours should primarily be inertia-gravity waves. Inertia-gravity waves (shortened to "gravity waves" hereafter) have sufficient horizontal wavelengths to be impacted by the rotation of the planet through the Coriolis effect and have buoyancy act as the restoring force to a vertical displacement. Of course, at the near-equatorial location of Gale Crater, the Coriolis forcing is minimal. They can be caused by a variety of mechanisms under statically stable conditions including flow over topography, atmospheric convection, and wind shear near atmospheric jets and fronts (e.g., Plougonven and Zhang, 2014). On Earth, gravity waves have been detected by surface pressure sensors, from a variety of forcing mechanisms (e.g., Marlton et al., 2015), while on Mars they may have been detected in surface pressure readings from orbiting spacecraft [Spiga et al., 2007]. Furthermore, as already mentioned, perturbations possibly caused by gravity waves have been detected in the surface pressure records of MSL and InSight, albeit with shorter time scales than studied in this work [Harri et al., 2014; Haberle et al., 2014; Ullán et al., 2017; Banfield and Spiga et al., 2020]. More commonly for Earth and Mars, gravity waves are detected in limb-viewing geometries as perturbations to the vertical temperature structure [de la Torre and Alexander, 1995, 2005;

Creasey et al., 2006; Heavens et al., 2020]. As they propagate horizontally and vertically, they alter the thermal structure of the atmosphere (e.g., Creasey et al., 2006) and breaking waves deposit momentum into the circulation, slowing or speeding winds (e.g., Bretherton, 1966 and references therein).

In this work, our analysis predominantly focusesd on atmospheric pressure and temperature. Section 2 describes the REMS observations in addition to general circulation modeling using the MarsWRF atmospheric model that was performed to complement our data analysis. Section 3 presents detections of gravity waves with periods of tens of minutes to hours in REMS pressure observations and non-detections in concurrent temperature observations, Section 4 provides some contextual discussion and concludes.

2. METHODOLOGY

2.1. REMS Observations

In this work we have used REMS pressure and temperature observations from the first 2580 sols (martian solar days) of the MSL mission. Gómez-Elvira et al. (2012) and Harri et al. (2014) provide overviews of the REMS instrument and its performance. REMS takes observations at a frequency of 1 Hz during the first 5 minutes of every Local Mean Solar Time (LMST) hour, as well as during up to eight hours of "extended block" observations per sol. These extended blocks consist of (i) 1-hour observations every 6 hours, shifting an hour earlier each sol, hence covering a full diurnal cycle every 6 sols, and (ii) 3-hour observations that cover the same 3 hours for 3 sols before shifting 3 hours earlier, hence cover a full diurnal cycle in 3-hour blocks every 24 sols. The hour surrounding local solar noon is also observed on nearly every sol, due to the expected peak of UV radiation and coinciding with the maximum convective vortex activity at that time-of-day (e.g., Miller et al., 2018; Newman et al., 2019).

Newman et al. (2017) and Guzewich et al. (2019) show examples of the REMS observation cadence. We convert all observations to local true solar time (LTST) for analysis.

Harri et al. (2014) provides a thorough overview of the accuracy and precision of the REMS pressure measurements. In isolation, the resolution of the pressure sensors is ~0.2 Pa, limited by the noise level. Larger uncertainties associated with the sensor warmup period (1 s), response time (1 s), shadowing by the rover's remote sensing mast (max. 1 Pa drop), and repeatability variation (induced by hysteresis with respect to the sensor's temperature, varying on the timescale of a sol; < 1.5 Pa) are also detailed by Harri et al. (2014). We focus on searching for waves with periods of tens of minutes to hours and therefore combine individual REMS measurements into 30-second averages for our analysis. This strongly mitigates the instrumental effects of noise, response time, sensor warmup, and the "shadow effect". In nominal measurements, the REMS pressure instrument outputs readings of two Vaisala Barocap® sensor heads with different temperature hysteresis (Harri et al., 2014). We have repeated some of our analysis using data from each of these two Barocap® sensor heads independently and found no indications of the repeatability variation influencing our results. Lastly, we have removed time periods (~every 100 sols) when pressure sensor self-checks have been performed and data are not fully comparable (Harri et al., 2014). In total, we assume we are able to resolve atmospheric waves with amplitudes of 0.2 Pa.

The Curiosity rover has traversed over 20 km of horizontal distance and several hundred meters of vertical elevation during its roughly 9 Earth year/4.5 Mars year surface mission to date. We do not normalize the pressure to a single altitude as it is plausible that wave behavior could change based on elevation or horizontal position and because elevation changes are negligible within a single sol (during which we remove the pressure harmonics, see below) or even within

99 the 10-sol periods we typically analyze (see below). Our 1-10 sol analysis periods also remove
100 the signature of the martian seasonal pressure cycle, driven by the condensation / sublimation of
101 CO_2 onto / off the polar ice caps in autumn and winter / spring and summer (see figure 1 by
102 Haberle et al., 2018).

103 After combining REMS measurements into 30-second averages, our analysis proceeds by
104 fitting and then subtracting a low-order harmonic to a single sol's pressure or temperature data.
105 We select here eight harmonics for the fit, which effectively removes the low-order frequencies
106 (Figure 1) produced by the atmospheric tides (e.g., Haberle et al., 2014; Guzewich et al., 2016)
107 and the effect of the hydrostatic adjustment flows (Richardson and Newman, 2018). These
108 mechanisms are responsible for the vast majority of the daily surface pressure variability on
109 Mars, particularly at equatorial locations like Gale Crater.

110 Figure 1 shows an example of the harmonic fitting procedure. We assume the
111 atmospheric tides and other mechanisms affecting the pressure variability along the sol such as
112 the effect of the hydrostatic adjustment flows are harmonics of the solar day as in Equation 1:

113 $$p(t) = p_o + \Sigma_{k=1}^{n} A_k cos(2\pi kt) + B_k sin(2\pi kt) \quad (1)$$

114 where $p(t)$ is pressure as a function of time, p_o is the mean pressure, k is the numbered
115 harmonic, n is the total number of harmonics considered in the fit (n=8 for this study), and t is
116 time. The amplitudes of the harmonics, A_k and B_k, are found through singular value
117 decomposition of the matrix filled with the trigonometric functions.

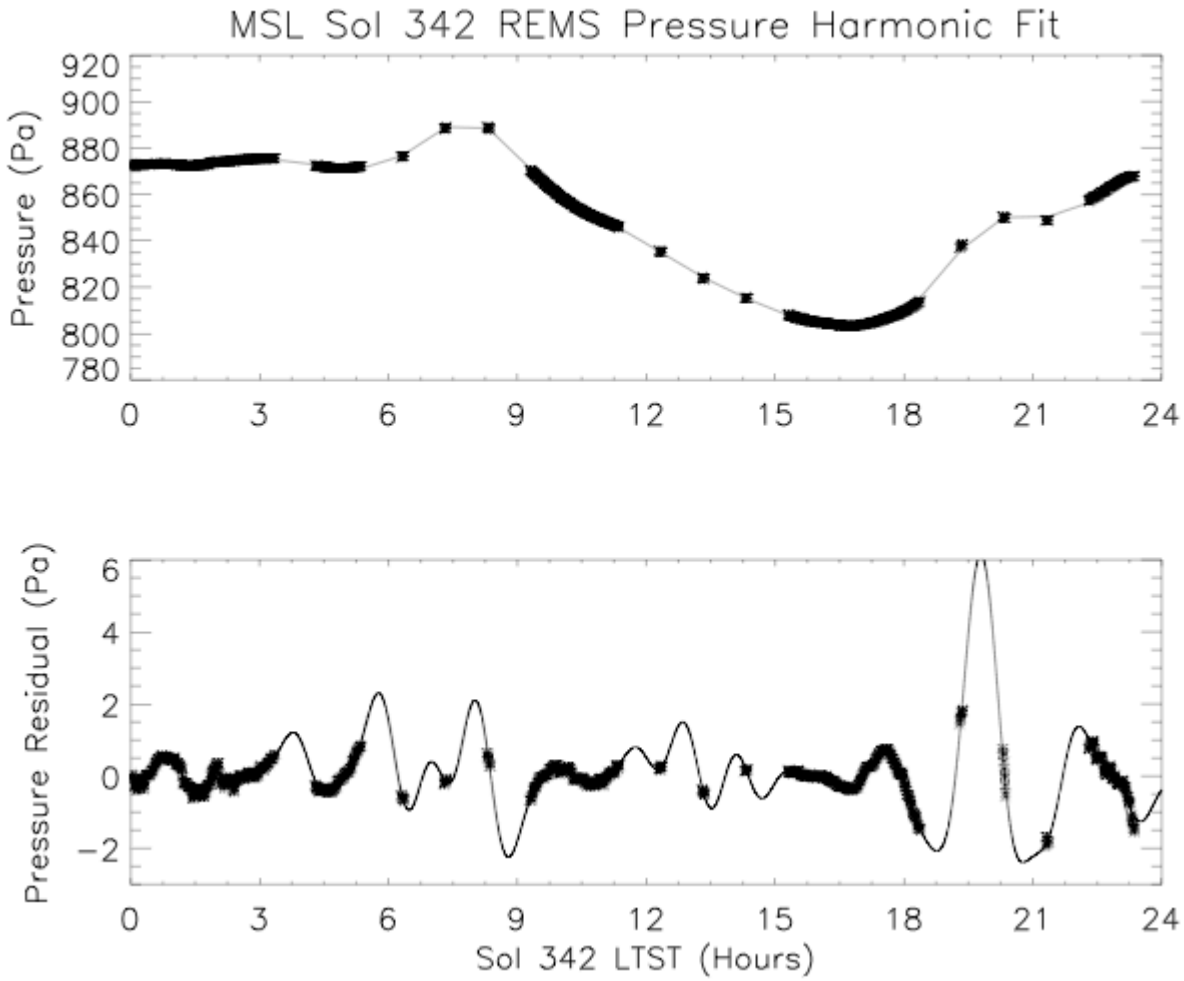


Figure 1. (Top) REMS pressure observations for MSL Sol 342 (asterisks) and low-order harmonic fit (n=8) to it (line). (Bottom) REMS pressure residual (asterisks) and a 24th order harmonic fit to it (line).

In Figure 1, the cadence of REMS hourly or multi-hourly extended blocks and 5-minute background observations can be clearly seen. Removing the harmonic fit leaves a residual pressure variation that is shown in the bottom plot of Figure 1. At this stage, multiple analysis methods are available to examine the wave behavior present.

All analysis methods shown below indicate that there are frequent waves with periods of ~1-3 hours and amplitudes of O(1-10 Pa) present in Gale Crater that are detectable by REMS.

However, we must note that two factors may bias this analysis, regardless of the method we choose.

First, our chosen harmonic fit (specifically the number of harmonics) to remove the pressure tides selects, to some degree, which wave periods remain in the residual pressure after removing the harmonic fit. Our choice of 8 harmonics effectively removes most waves with periods longer than 3 hours and hence we make the implicit choice that non-tidal waves of interest to this analysis will have periods shorter than 3 hours. Note that we do not completely eliminate the ability to detect waves with periods longer than 3 hours (as seen in Section 3.2), but the wave power or amplitude of these waves as depicted is likely weaker (perhaps much weaker) than in reality. Based on our previous analysis of tides in REMS pressure data (e.g., Guzewich et al., 2016), we know that tides up to p_6 (the 6-per-sol tide with a period of 4 hours) are clearly present with amplitude of about 3 Pa that varies with season and atmospheric dust loading and thus 6 harmonics is the bare minimum to effectively remove them. Choosing more harmonics (n=10 or n=12) fits the daily REMS pressure to such a degree that the remaining residual is dominated by variations more likely driven by turbulent boundary layer processes that are the subject of future work.

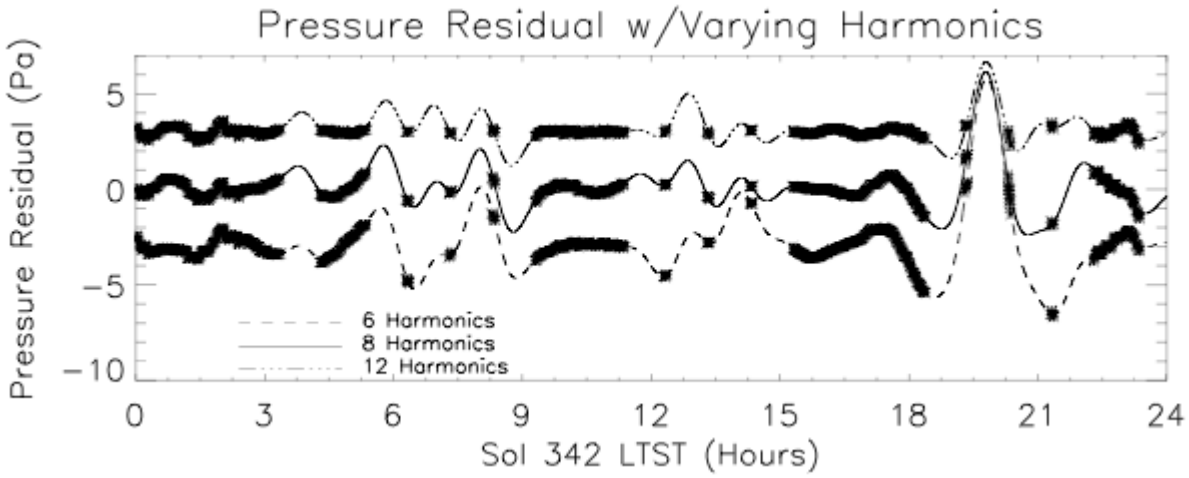


Figure 2: REMS pressure residuals (asterisks) and 24th order harmonic fits to them (lines). The residual after using n=6 in the harmonics fit is offset by -3 Pa and shown with the dashed line, the residual after fitting n=8 is shown by the solid line, and the residual after fitting n=12 is offset by 3 Pa and shown by the dashed-3 dotted line.

In Figure 2, we demonstrate how the pressure residual is modified by the choice of a n=6, 8, or 12 harmonics fit to the Sol 342 REMS pressure observations. The residual with n=6 and n=8 is generally similar, with some increased amplitude in longer-period waves in the former. However, the residual after fitting n=12 is very flat with little variation and the 24th order harmonic fit to the residual is overfit.

Second, the REMS observation cadence likely biases these results to some degree. REMS extended blocks are typically 1-3 hours in duration, with rare extended blocks of 4 or 5 hours duration. Both the harmonic analysis and the wavelet analysis have sensitivity to waves of longer periods, but may be inherently less sensitive to wave periods longer than the typical REMS extended block due to the nature of the observation cadence. We have conducted tests of our wavelet analysis (see below for a further discussion of wavelet analysis) with idealized combinations of wave amplitudes and periods observed at REMS-like cadences and found that the wavelet analysis is still able to correctly identify the wave periods, even if they are longer than typical REMS extended blocks (e.g., 6 hour wave periods) (Figure 3). In the idealized case in Figure 3 (top panel), we created a residual pressure sequence for 10 sols that represents a changing combination of waves with periods of 1, 2, and 6 hours with varying amplitudes. In the bottom panel of Figure 3, we sample that idealized pressure sequence in the same pattern that REMS observed during Sols 2020-2029. It can be seen that some wavelet power “leaks” into adjacent periods and some is aliased into both shorter and longer multiples of a given period. However, the true period is still identifiable in each case. This implies that the predominance of

observed wavelet power at periods <3 hours is real and not primarily an artefact of the REMS observation cadence and that we are able to detect wave periods longer than 3 hours.

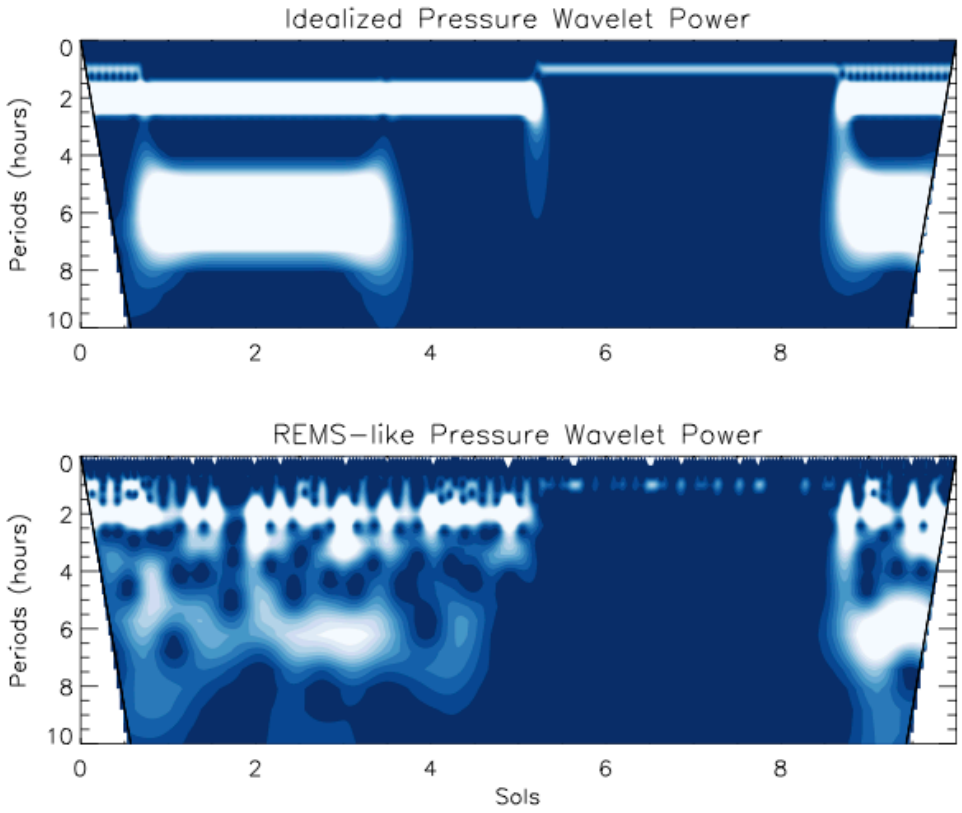


Figure 3: Wavelet power spectrum for an idealized pressure residual that represents a combination of 1, 2, and 6-hour period waves (top). (Bottom) Wavelet power spectrum for the same idealized pressure residual, but sampled at a cadence following REMS observations during Sols 2020-2029.

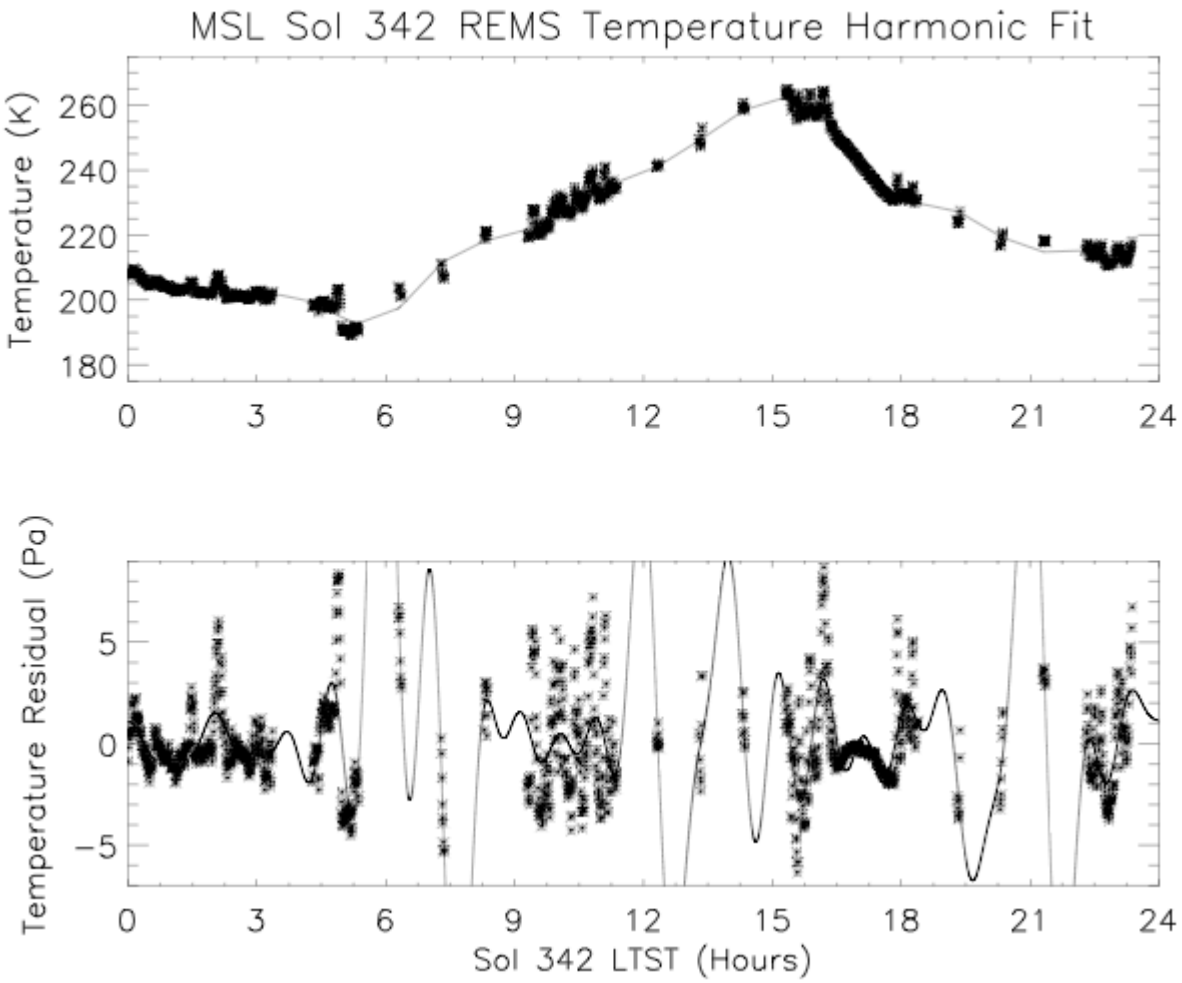


Figure 4. (Top) REMS temperature observations for MSL Sol 342 (asterisks) and 8th order harmonic fit (n=8) to it (line). (Bottom) REMS temperature residual (asterisks) and a 24th order harmonic fit to it (line).

We can conduct the same type of analysis on REMS temperature measurements. Comparing Figures 1 and 4 confirms that the residuals of pressure and temperature behave very differently, due to different physical phenomena driving their variations. Indeed, the 8th-order harmonic fit to temperature generally provides a poorer fit (Figure 4, top panel) than that for pressure (Figure 1, top panel). And while the pressure residual shows clear wavelike behavior and the 24th-order harmonic fit provides a reasonable match to this pressure residual (Figure 1, bottom panel), a 24th-order harmonic fit does not fit the temperature residual well at all. The

191 temperature variability is much higher frequency/shorter period and higher amplitude (as a
192 fraction of the mean temperature) than that of pressure. These temperature fluctuations are more
193 sensitive to changes in local radiative and topographic forcing mechanisms that drive, largely,
194 turbulence and convective processes superposing them on the underlying large-scale wave
195 forcing (Sutton et al., 1978; Schofield et al., 1997; Smith et al., 2006; Spanovich et al., 2006;
196 Martínez et al., 2009; Mason and Smith, 2021), as is also seen in Figure 5. For this reason, we
197 reserve most additional analysis of these temperature variations to future work, with the
198 exception of Section 3.1 below.
199 We employ wavelet analysis for the bulk of our analysis of REMS pressure data.
200 Wavelet analysis (Haar, 1910; Calderón, 1960) is a more flexible analysis method, and one that
201 is well-suited to the on-and-off nature of REMS observations. It is particularly advantageous for
202 transitory phenomena and makes no assumption about when a wave begins, ends, or what wave
203 periods are present. Banfield and Spiga et al. (2020) also use wavelet analysis to identify short-
204 period atmospheric waves in InSight pressure observations, although the 20 Hz sampling rate of
205 InSight's pressure sensor opens up an analysis regime that is not available to REMS. We utilize
206 a continuous wavelet transform with an assumed "Morlet" wavelet shape (Torrence and Compo,
207 1998; wavelet software available at http://paos.colorado.edu/research/wavelets/). We combine
208 REMS observations into ~10-sol groupings of 30-second average values for this analysis, which
209 enables us to detect waves with periods of up to ~48 hours in practice. The "cone of influence"
210 specifies what regions of the period-time phase space are amenable to confident wave detections,
211 and wavelet power outside the cone of influence is ignored. The 30-second periods without
212 REMS observations (i.e., most of each sol, see Figure 1) are assigned pressure perturbations of
213 zero. In essence, a wavelet analysis works by shifting the wavelet shape across the time series of

REMS pressure observations, while adjusting the amplitude and frequency of the wavelet to best fit the observations. The output can be either expressed as amplitude or, more commonly, power (e.g., Banfield and Spiga et al., 2020) as a function of period and time.

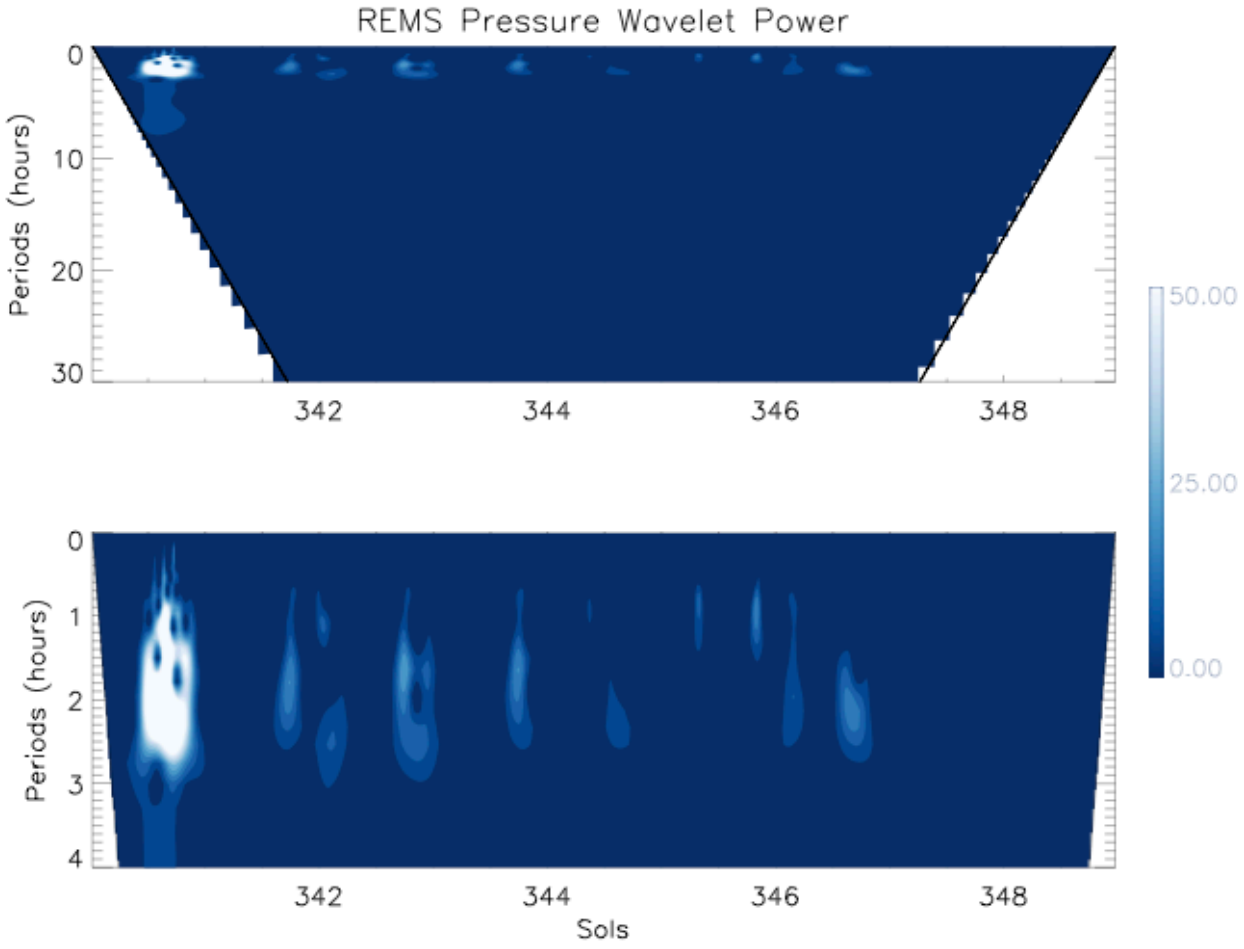


Figure 5. REMS pressure wavelet power (Pa^2) for the Sol 340-349 period. The bottom panel is zoomed in to highlight periods less than 4 hours. The cone of influence is represented by the thick black diagonal lines in each panel.

Figure 5 shows an example wavelet power spectrum for the 10-sol period including Sol 342 that has already been showcased in Figures 1 and 4. Nearly all power is contained in wave periods shorter than 3 hours, as expected given our choice of 8 harmonics to fit to the daily pressure curve. A particularly strong wave event, represented by the flame-shaped blob on the

left half of the bottom panel of Figure 5, was detected by REMS in the afternoon of Sol 340. Sol 342, which we have already analyzed in Figure 1 using harmonic fitting, shows modest wavelet power in the early morning with periods of ~2.5 hours, no wave activity in the midday, and then a stronger period of wave activity in the late evening with periods of 1.5-2.5 hours. This matches well with what was implied by the harmonic fitting of the pressure residual shown in Figure 1.

2.2. MarsWRF Simulations

We conducted a series of MarsWRF general circulation model (GCM) simulations to compare against and contextualize the REMS observations. MarsWRF has the ability to "nest" higher spatial resolution domains within a lower resolution global domain [Richardson et al., 2007; Newman et al., 2017], enabling the latter to be driven by realistic regional and global scale circulations while also capturing local dynamics, such as mesoscale flows driven by topography. We employ the simulation architecture described by Newman et al. [2017] (vertical grid "B") with a 2° horizontal resolution global domain and a series of nested domains centered over the InSight and MSL landing sites in Elysium Planitia and Gale Crater, respectively. Specifically, we use "Domain 2" and "Domain 3" to provide mesoscale regional information (see Newman et al. [2017] figure 14). For reference, Domain 3 has a spatial resolution of ~13 km at Gale Crater. We conduct 12 short-duration simulations with the nested domains, starting approximately every 30° of solar longitude and run each simulation for 10 sols. The first sol of each simulation is disregarded for analysis to allow the nest to "spin up". Meteorological variables are output every 10 minutes. For simplicity, we assume a prescribed dust distribution (the "MCD MGS scenario"; Montmessin et al., 2004; Toigo et al., 2012) and no radiatively active water ice clouds.

3. RESULTS

3.1. Standard Deviation

The most basic analysis step after removal of the low-order harmonic fit (see Section 2.1) to the daily pressure or temperature variation is to take the standard deviation of the difference between the harmonic fit and observed pressure or temperature. This provides an initial first glance at the seasonal and diurnal pressure and temperature variability, but with no information on the cause of the variability or the properties of potential waves.

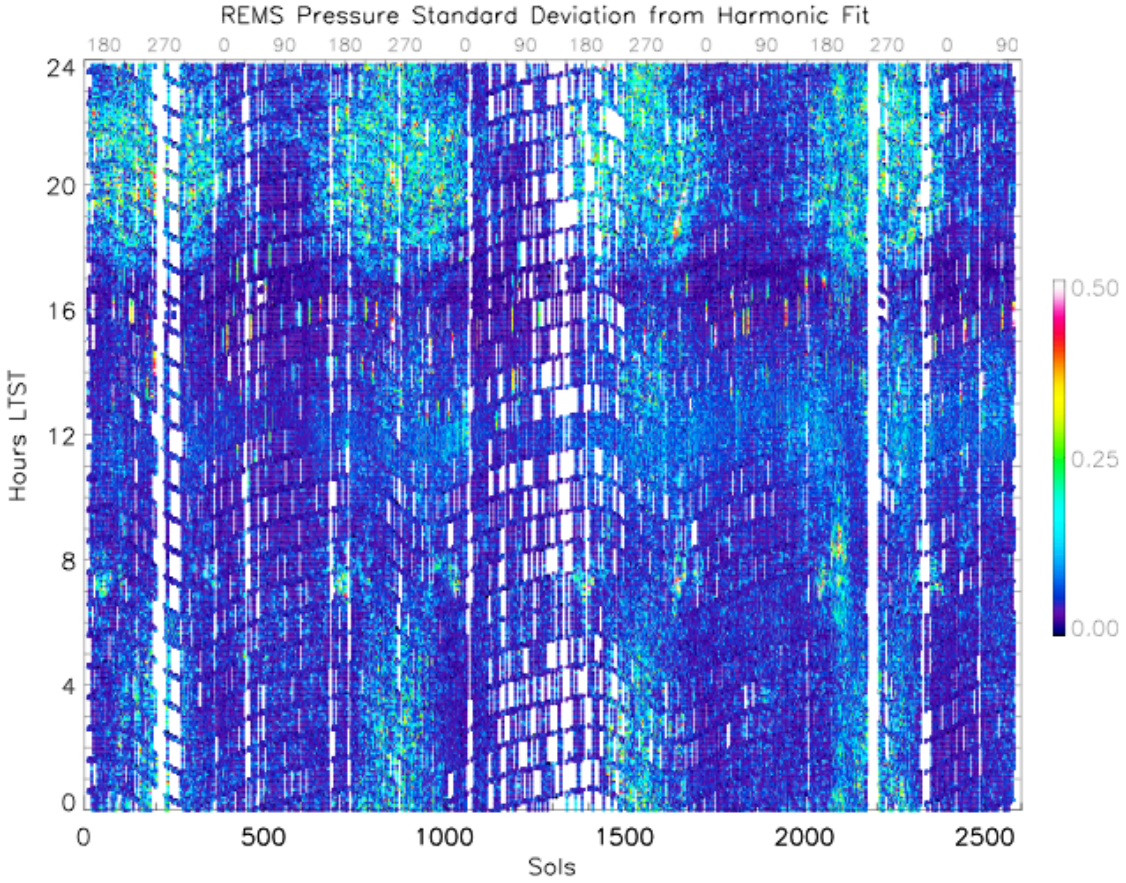


Figure 6. Standard deviation (Pa) of REMS pressure from the daily harmonic fit for the first 2580 sols of the MSL mission. The undulatory sampling in LTST is a consequence of REMS sampling in LMST units and the seasonal change when converting from LMST to LTST.

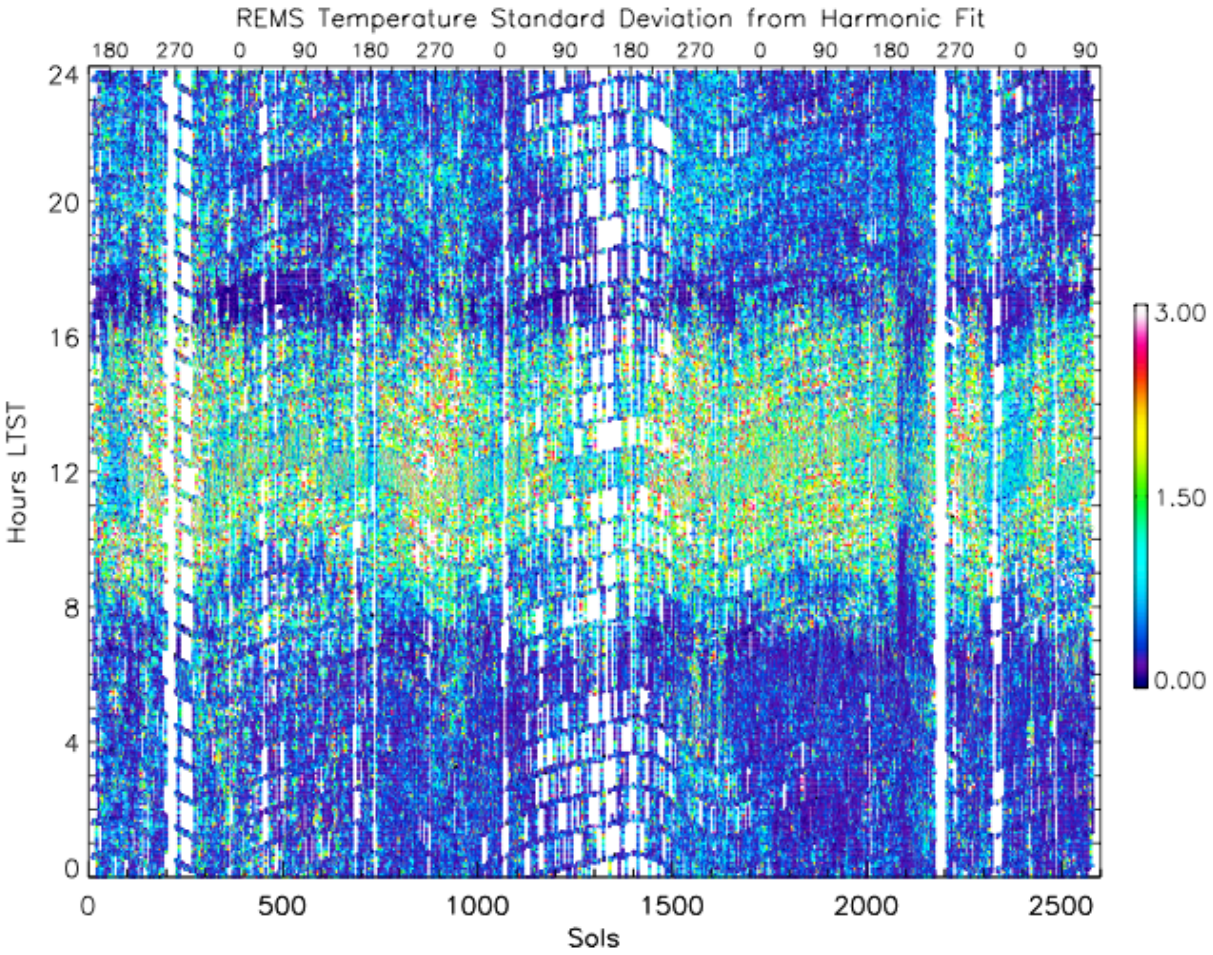


Figure 7. Standard deviation (K) of REMS air temperature from the daily harmonic fit for the first 2580 sols of the MSL mission.

It is immediately apparent by comparing Figures 6 and 7 that the pressure and temperature residuals behave very differently both seasonally and diurnally. The pressure standard deviation (Figure 6) exhibits an annual cycle of increased perturbations (particularly in the late evening, 1700-2400 LTST) beginning at approximately $L_s = 150°$ (the end of southern hemisphere winter, coincidently at the same time of year that Curiosity landed on Mars) and then extending to near or just beyond $L_s = 0°$ (the southern hemisphere autumn equinox). In between those times, pressure deviations from the harmonic fit are minimal. The primary time of day for this pressure activity is in late evening and early morning, rather than during daylight hours. The

seasonal cycle of early morning pressure deviations is similar to that in the late evening, but appears to have a somewhat narrow seasonal window with noticeable activity from approximately L_s = 220°-340°. The Mars Year (MY) 34 global dust storm (GDS, MSL Sols 2080-2160, Guzewich et al., 2019; Viúdez-Moreiras et al., 2019) altered this seasonal behavior, particularly for the early morning pressure deviations. There is also some weak pressure behavior near solar noon. In all cases, the standard deviations from the pressure harmonic fit are 0.25-0.5 Pa. This is directly comparable to the pressure perturbations shown by Harri et al. [2014], Haberle et al. [2014], and Ullán et al. [2017] believed to be driven by topographic effects including gravity waves. However, as shown below, we isolate pressure behavior with periods that are much longer than identified by those works.

As stated above, the temperature behavior is clearly distinct from pressure in most respects. The amplitude of the temperature perturbations is typically 1-3 K. Most temperature deviations occur during daylight hours, centered on or just after solar noon. There is a modest seasonal cycle to the diurnal extent of the daytime temperature perturbations, with the greatest diurnal extent (~0800-1600 LTST) near L_s = 290° each year. As with pressure, there is again some temperature activity in the evening from 1800-2400 LTST that also seems responsive to the dust cycle in a similar way to the coincident pressure cycle, suggesting that both are tied to the same physical process. Morning activity is more modest than that of the evening. Again similarly to pressure, the temperature activity was clearly impacted by the MY34 global dust storm near MSL Sol 2100. The greatly reduced diurnal variability in air and ground temperature during the storm (Guzewich et al., 2019; Viúdez-Moreiras et al., 2019) also appeared to stabilize the perturbations to temperature seen in nearly all other sols of the mission. Throughout the mission, the daytime temperature behavior is consistent with turbulent convection (Miller et al.,

297 2018) and is the expected response to radiative forcing from modeling and known from previous
298 landed missions (Mason and Smith, 2021).

299 Recently, Miller et al. (2018) and Banfield and Spiga et al. (2020) identified a previously
300 unknown atmospheric "quiet" period immediately after sunset and extending for 2-4 hours in
301 pressure and temperature data from both MSL and the InSight lander (also seen in wind
302 measurements by InSight). InSight observations indicate this quiet period has extremely stable
303 pressure observations, with very little variability. This stability is important for InSight's
304 seismometry mission and this time of day is when most of the Marsquakes observed to-date have
305 been detected (Banfield and Spiga et al., 2020). In Figures 6 and 7, we see that such a quiet
306 period is also present within Gale Crater throughout the MSL mission. The quiet period within
307 Gale Crater is most clearly seen in temperature (Figure 7) and immediately follows the turbulent
308 daytime regime with noticeably decreased temperature perturbations. Due to the comparatively
309 weak daytime pressure variability, the quiet regime is less obvious in pressure, but still present.
310

311 3.2. Wavelet Analysis

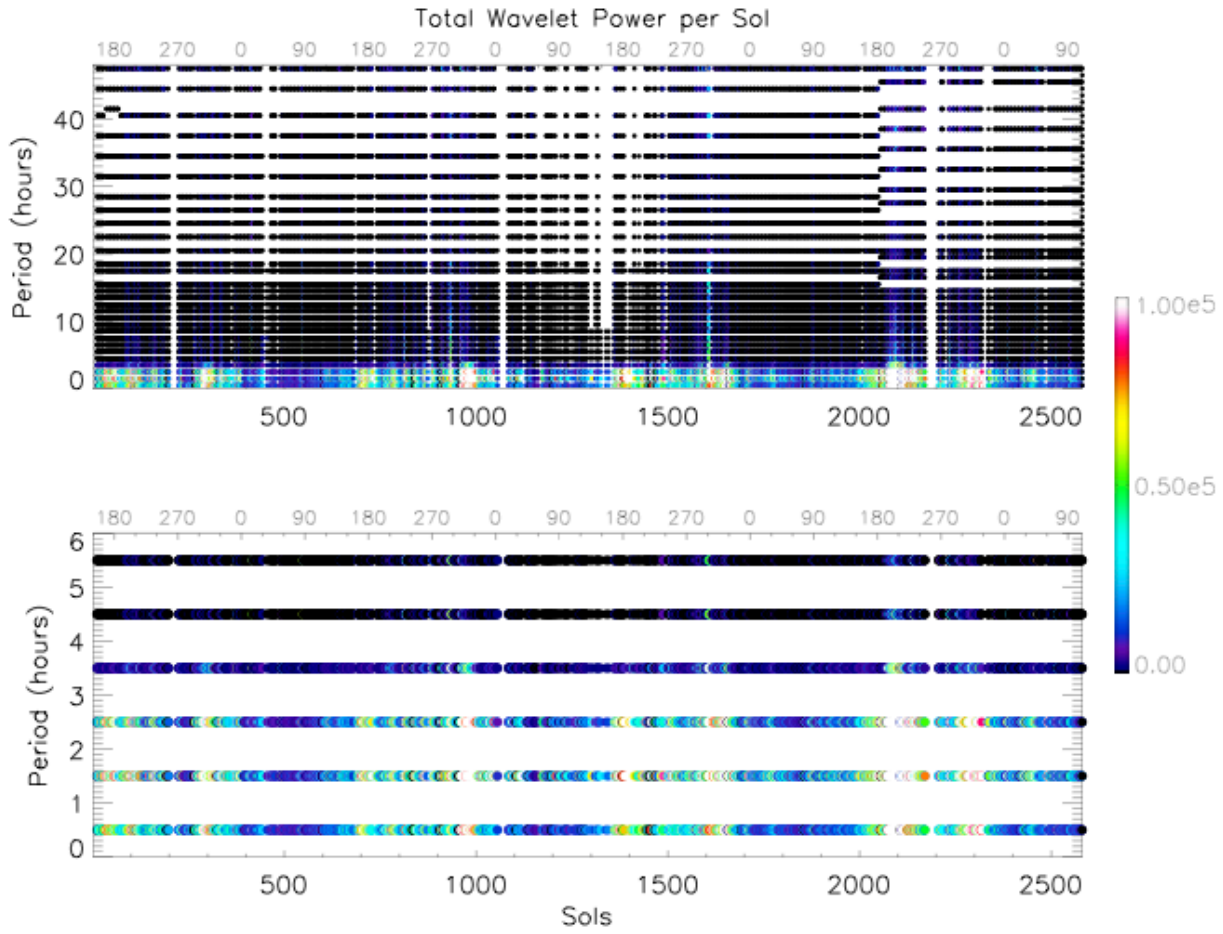


Figure 8. Total wavelet power (Pa^2) per sol for the first 2580 sols of the MSL mission as a function of period (hours). Periods are displayed as centered values in 1-hour intervals (e.g., 0.5 hour period covers periods from 0-1 hour). The bottom plot highlights periods under 6 hours.

The seasonality present in Figure 6 is clear as well in Figure 8. Wavelet power is highest during the dustier seasons (southern spring and summer), with minimal activity during the clearer southern autumn and winter seasons. The seasonality for all wave periods is approximately the same, with some minimal interannual variability present. Interestingly, wavelet power is highest on the edges of the dusty season, with modestly weaker wavelet power at the peak of the dusty season near southern summer solstice. This pattern is analogous to the "solsticial pause" seen in traveling wave behavior (Wilson et al., 2002; Lewis et al., 2016) and first noticed in pressure data by Barnes (1980) in Viking surface pressure data. The strongest waves have periods of ~2 hours, but the wavelet analysis also shows substantial power in periods

shorter than 1 hour. These short-period waves are occurring within a single REMS extended block and the wavelet analysis is ideal for identifying such waves. Some modest wavelet power is present at longer periods, typically associated with single events such as the MY34 global dust storm (see also Figure 12). On a given sol, cumulative wave power can be quite high (>10^5 Pa^2). This cumulative wave power is much higher than suggested by the harmonic analysis, largely because the wavelet analysis is better able to capture transitory, higher-frequency/shorter-period wave activity. However, as shown in Figure 5, the power in a single wavelet packet is typically much more modest (10-40 Pa^2).

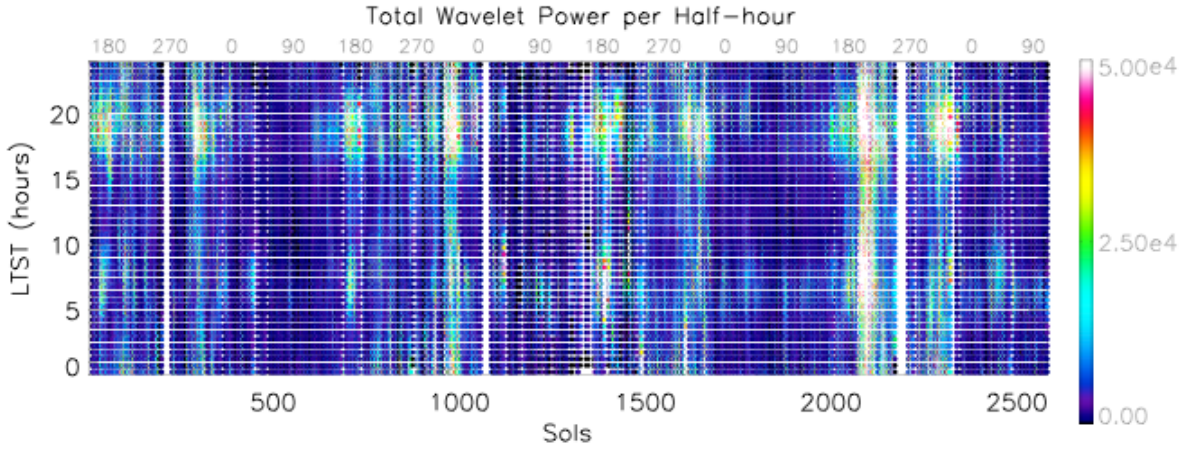


Figure 9. Total wavelet power (Pa^2) per half-hour for the first 2580 sols of the MSL mission as a function of LTST. Times are displayed as centered values in 1/2-hour intervals (e.g., 0015 LTST covers times from 0000-0030 hours).

Figure 9 presents the same data as in Figure 8, but instead shows wavelet power as a function of LTST so that the daily pattern of wave activity can be discerned. The pattern shown in Figure 9 is very similar to that in Figure 6 which showed the standard deviation of the pressure from the tidal harmonic fitting. Wavelet power is predominantly present in the late evening near 2000 LTST, with a weaker period of activity in the morning centered near 0800 LTST. The "quiet" period that was apparent in Figures 6 and 7 is less apparent in the wavelet analysis shown in Figure 9. The same seasonal cycle discussed previously is also distinct, but Figure 9 more

clearly shows isolated events of higher wave activity in the southern hemisphere autumn and winter period (L_s ~ 0-150°). The abnormally large early season dust storm in MY35 at Ls~37° (just before Sol 2500; Malin et al., 2019) shows up clearly with unseasonably high morning wavelet power. This briefly enhanced wavelet power has analogues at very similar times of year in MY 32 and 34 (MY33 had frequent data drop-outs at that time), but with weaker power values, and also with no response in the late evening as is typically seen in the dusty season.

We focus on the strongest wavelets present on each sol of the mission in Figure 10. On certain sols during the dusty season each year, maximum wavelet power exceeds 100 Pa^2, and sometimes reaches 500 Pa^2. For comparison, this is comparable to a typical semidiurnal pressure tide amplitude in Gale Crater, which is often 10-20 Pa (Haberle et al., 2014; Guzewich et al., 2016). More commonly, maximum wavelet power is <40 Pa^2, and during the southern hemisphere autumn and winter (L_s ~ 0-150°) is often <20 Pa^2.

The most quiescent period of the entire mission occurred near Sol 500 (MY 32 L_s ~ 70°) and that is also seen in Figures 6, 8, and 9. This may be simply due to interannual variability, but also could be a reflection of the changing altitude and position of the Curiosity rover within Gale Crater. Near Sol 500, the rover was still within the crater's trough, which tended to stabilize the meteorological environment in a number of ways. As the mission has progressed, the rover has climbed several hundred meters up Aeolis Mons/Mt. Sharp.

On each sol of the mission, the strongest wavelet has a period <3.2 hours with ~2 hours the most common value (Figure 10, bottom panel). The time of day of the strongest wavelet follows the previously identified pattern of evening and early morning preference, with rarer occurrence in the midday hours when the Sun is high in the sky.

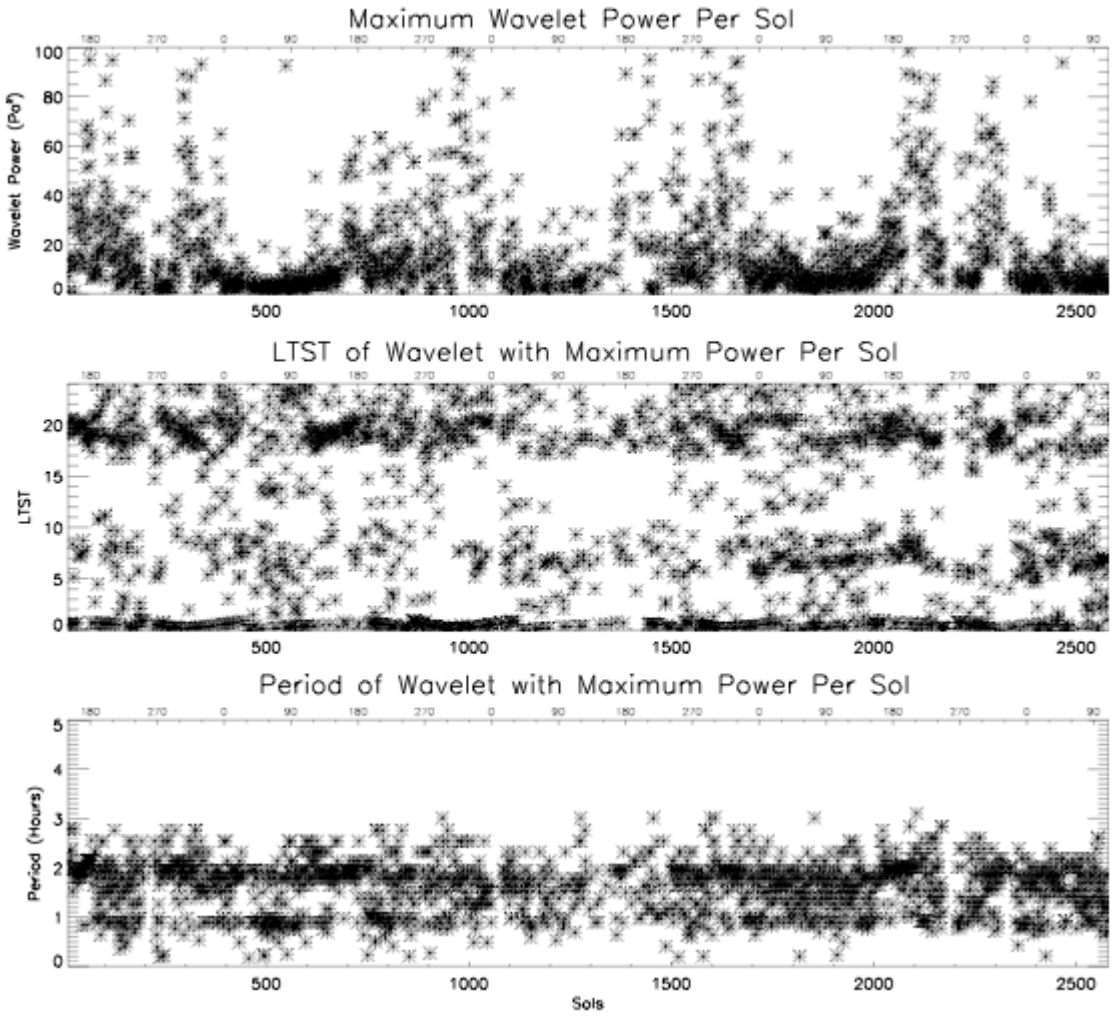


Figure 10. Maximum wavelet power (Pa^2) per sol for the first 2580 sols of the MSL mission (top panel), the LTST of the wavelet with maximum power per sol (middle panel), and the period of the wavelet with maximum power per sol (bottom panel).

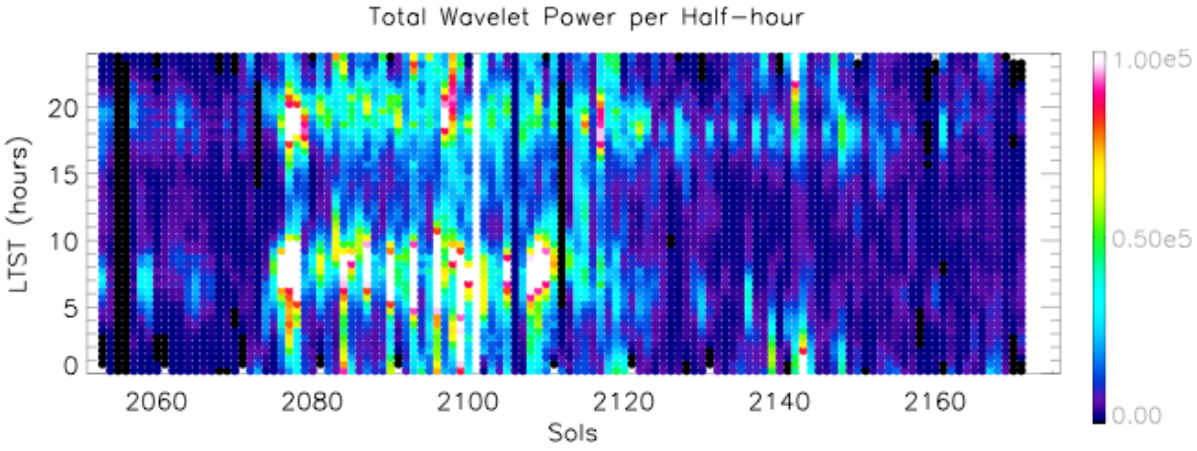
During the MY34 global dust storm, the REMS extended block cadence was doubled, leading to a 1-hour duration extended block every 3 hours versus every 6 hours under nominal operations (e.g., Newman et al., 2017; Guzewich et al., 2019). This change was implemented on Sol 2075 and Sol 2075 shows substantially higher wavelet power than Sol 2074 (Figure 11). Still, some of that change is also likely attributable to meteorological effects. The enhanced REMS cadence was continued through Sol 2164 and wave power did decline well before the

REMS cadence returned to nominal (Figure 11). The REMS cadence was also doubled for the late MY34 regional dust storm observed by InSight soon after landing (Banfield and Spiga et al., 2020; Viúdez-Moreiras et al., 2020), but produced a far less abrupt change in wavelet power over the duration of the doubled-cadence (Sols 2291-2306). Wavelet power increased starting on Sol 2285 and then began to weaken again on Sol 2296 (not shown). These examples suggest that if REMS were able to operate at all times a broader mix of wave periods and amplitudes might be detected. Actual changes in the meteorological conditions clearly still drive most of the variations in observed wave properties, however. This is relevant for considering the possible observation cadences of the Mars Environmental Dynamics Analyzer onboard the Mars 2020 Perseverance rover.

The effect of the rotating REMS extended block cadence can be seen clearly in Figure 11, particularly in the morning near 0800 LTST. When long-duration (2-3 hours or more) extended blocks were scheduled in the ~0600-1000 LTST timeframe, the wavelet analysis measures high wavelet power whereas the wavelet power is weaker on sols with reduced numbers of observations in that timeframe. This effect can be seen in the analysis of data collected according to the nominal REMS cadence before the dust storm campaign was initiated on Sol 2075, in which higher wavelet power is seen in the morning and evening on sols when REMS extended blocks observe those times. Nevertheless, since the REMS extended block cadence rotates through all local times (e.g., Newman et al., 2017), the true meteorological pattern of pressure wave activity can still be seen in Figure 11.

The MY34 GDS clearly strengthened wave activity at all times of day, with a focus on the strongest waves in the morning. We note that this is contrary to what Heavens et al. [2020] and Kuroda et al. [2020] report regarding middle atmospheric gravity wave activity in observed

403 temperatures and in modeling, respectively; however, the strengthening of waves at the surface is
404 consistent with the higher static stability during dusty periods. Upper atmospheric gravity waves
405 were also enhanced during the storm, suggesting a complex altitude-dependent response
406 [Leelavathi et al., 2020]. Wavelet power increased by an order of magnitude from before the
407 storm. During the MY34 GDS, the column opacity peaked on Sol 2085 and then steadily
408 declined afterwards (figure 1 in Guzewich et al., 2019), however the amount of dust measured
409 between MSL and the crater rim (i.e., the amount of dust within the crater rather than above it)
410 had a double-peaked structure with a secondary peak around Sol 2125 (Smith et al., 2019;
411 Lemmon et al., 2019). The wave response more closely follows the pattern of the column
412 opacity, particularly for the waves in the evening, with a peak soon after the storm arrived in
413 Gale Crater and then a long tail toward Sol 2160 as the storm decayed.



414

415 Figure 11. Total wavelet power (Pa^2) per sol for Sols 2050-2175 of the MSL mission, focused
416 on the MY34 global dust storm, as a function of LTST. Times are displayed as centered values
417 in 1/2-hour intervals (e.g., 0015 LTST covers times from 0000-0030 hours).
418

419

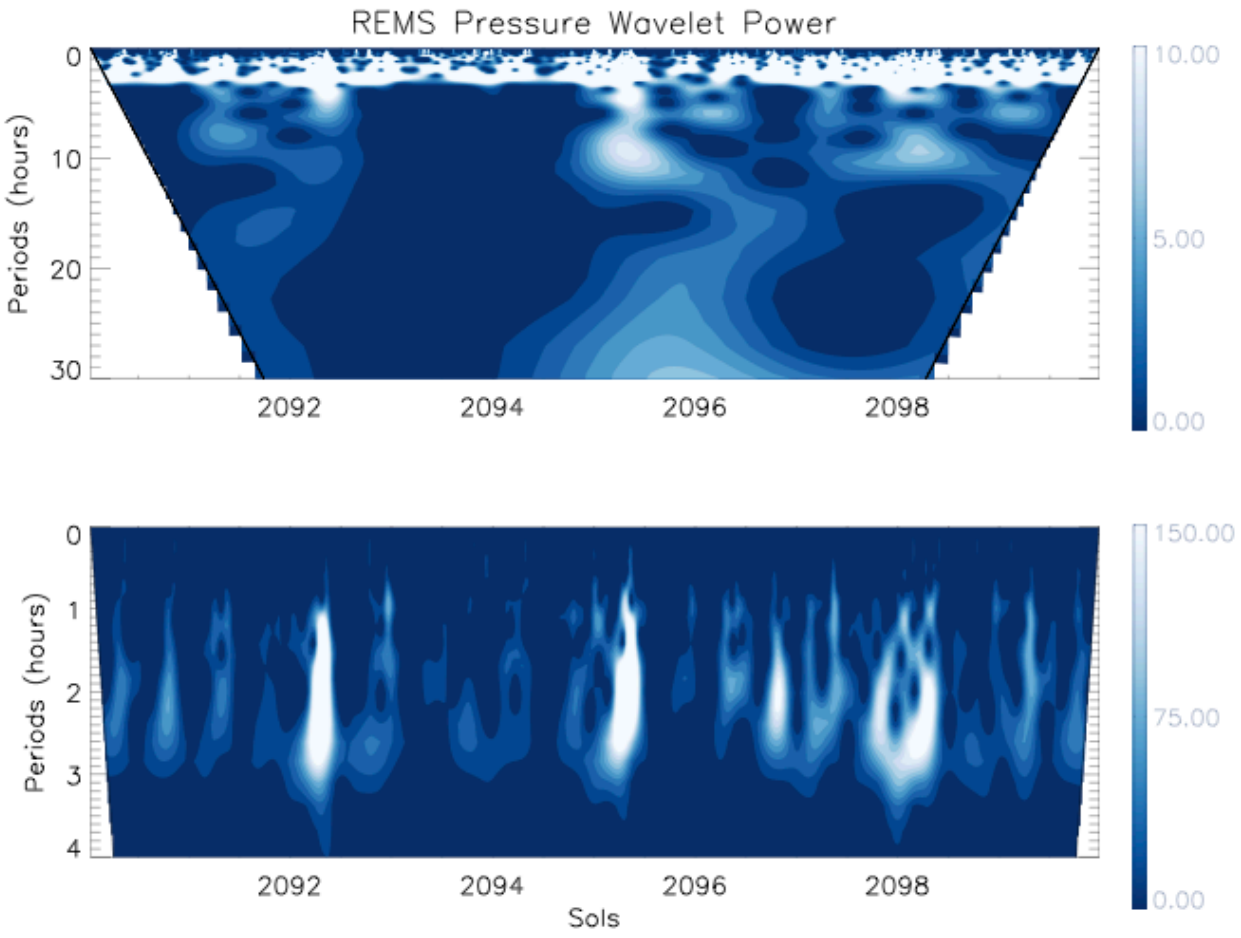


Figure 12. REMS pressure wavelet power (Pa^2) for the Sol 2090-2099 period during the MY34 global dust storm. The bottom panel is zoomed in to highlight periods less than 4 hours. The cone of influence is represented by the thick black diagonal lines in each panel. Notice the different color bars for each panel.

Figure 12 shows the wavelet spectrum at the peak of the storm (as delineated by dust opacity). Unlike almost any other time period in the entire mission, there is non-negligible wavelet power at long periods. Sol 2095, in particular, exhibits wavelet power with periods of ~9-10 hours and then an additional region of wavelet power of periods >20 hours. As discussed in Section 2, our choice of 8 harmonics (essentially filtering wave periods longer than 3 hours) likely weakens the depicted power at these long wave periods relative to reality. The bottom panel of Figure 12 focuses on the periods <4 hours. The every-3-sol repeat pattern of the

433 cadence is seen in the morning peaks of wavelet power on Sols 2092, 2095, and 2098. The peak
434 wavelet power occurs with periods of 2-3 hours.
435
436 3.3. MarsWRF Results
437 The MarsWRF GCM simulations allow us to have complete and consistent local time
438 coverage of each sol and the ability to study wave behavior at different locations near Gale
439 Crater and Elysium Planitia. Ultimately, this helps us interpret the REMS observations, as
440 single-station observations have inherent biases and limitations and can provide us with no
441 information about the cause or source of the waves detected by REMS.
442 To more directly compare with the REMS analysis, we perform wavelet analysis on the
443 MarsWRF surface pressure values at the model grid point nearest to Curiosity's landing site. As
444 stated in Section 2.2, we are using Domain 3 of the simulations defined by Newman et al. (2017)
445 which have a horizontal spatial resolution of ~13 km. Figure 13 is designed to be directly
446 compared with Figure 10, which provides an overview of wavelet analysis of the REMS pressure
447 observations.

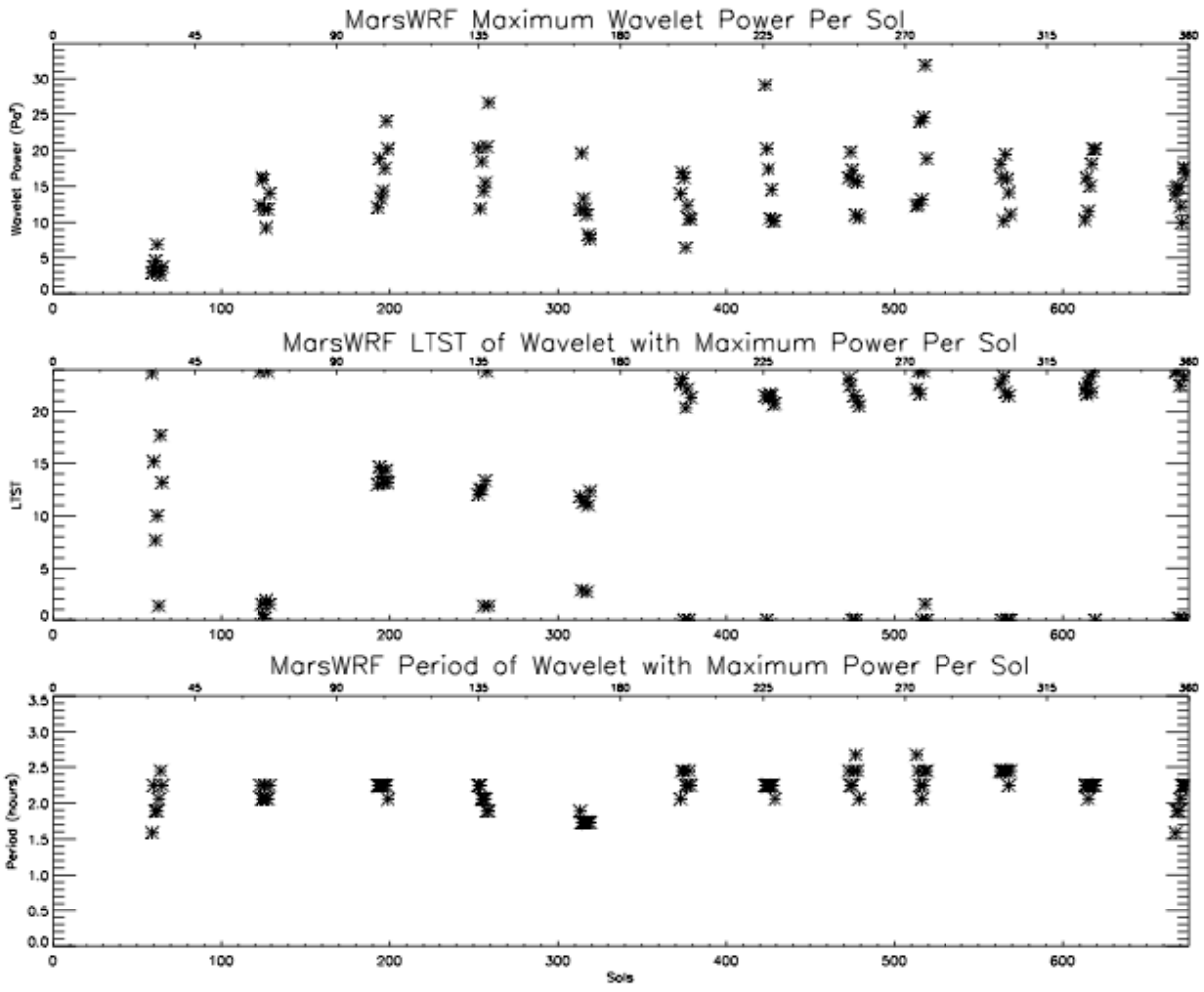


Figure 13. Maximum wavelet power (Pa^2) per sol for each MarsWRF simulation (top panel), the LTST of the wavelet with maximum power per sol (middle panel), and the period of the wavelet with maximum power per sol (bottom panel).

Like the REMS observations, MarsWRF finds that the strongest wavelets on a given sol typically have periods near 1.5-2.5 hours, with very slight seasonal variations. However, MarsWRF simulates weaker waves relative to observations, with maximum wavelet power of 10-30 Pa^2, which is a factor of 2-3 weaker than REMS observations. REMS observations also exhibited a strong seasonal cycle in maximum wavelet power, with a minimum near $L_s = 90°$ (Figure 10). MarsWRF does show distinctly weaker waves near $L_s = 30°$, but the remainder of

459 the year sees minimal variation (Figure 13). The local time of the strongest wave each sol is
460 clustered around midnight (2100-0100 LTST) during the second half of the year (L_s = 180°-
461 360°), while the first half of the year often shows midday (~1200 LTST) occurrences as well.
462 This shows some broad agreement with the REMS observations, where the first half of the year
463 (L_s = 0°-180°) also has the strongest wave occur during midday occasionally. However, the
464 frequent clustering near 1800-2100 LTST and again near ~0700 LTST seen in REMS
465 observations is entirely absent from the simulations. In brief, the MarsWRF simulations
466 underestimate the strength of these non-tidal waves, but corroborate the period and some aspects
467 of the diurnal timing of the waves.
468 Integrating over all wavelets with periods under four hours leads us to Figure 14. Figure
469 14 can be directly compared to Figure 8, which shows the comparable values from the REMS
470 observations. Of particular note are the different scales, with the MarsWRF total wavelet power
471 substantially less (by a factor of 10 or more) than that seen in the REMS observations. This
472 trend of weaker simulated waves can also be seen in Figure 13, showing the same behavior for
473 the strongest wavelet on a given sol. Guzewich et al. [2016] presented a similar situation where
474 MarsWRF simulations underestimated atmospheric tide amplitudes in surface pressure, likely
475 due to the difference between the dust opacity used in the model vs. reality and insufficient
476 spatial resolution. We have no unique explanation for why the simulated waves are consistently
477 weaker, but can suggest a couple of possibilities. Our MarsWRF simulations use a simple, and
478 modest, atmospheric dust opacity climatology. As seen in Figure 11, the higher dust loading in
479 reality on Mars leads to stronger waves and dustier conditions, likely explaining some of the
480 discrepancy. The difference in observation cadence and model output frequency may play a role
481 as well. As shown in Figure 3, the REMS observation cadence creates “leakage” of amplitude to

periods other than the true period, but in our idealized experiments this reduces rather than increases the total wavelet amplitude. The MarsWRF model's consistent output rate (every 10 minutes across all nine sols) should prevent aliasing between periods from occurring, but the net effect of the discrepancy between observation and model is difficult to directly quantify. Lastly, the model may simply lack sufficient resolution or physics to properly simulate these waves.

The simulations do corroborate the observations in the wave periods with the highest amplitudes, 1-3 hours. MarsWRF, however, underestimates the wave amplitudes in the shortest waves and the seasonal cycle is muted relative to the REMS observations. The discrepancy at the shortest periods is easier to understand as a cause of the difference between REMS observation cadences and model output frequency. REMS extended blocks allow waves with periods under 1 hour to be fully resolved (although background 5 minute hourly observations do not), relative to 10 minute output frequency in the model. At the MarsWRF resolution, short-duration fluctuations at high frequencies will be smoothed, which partially drove our selection of a 10 minute output frequency. Coupled with the horizontal resolution of the model simulations, which may mask wave forcing mechanisms that drive higher frequency/shorter period waves (see Section 4), we believe this likely explains the relative lack of short period waves in the model relative to REMS observations.

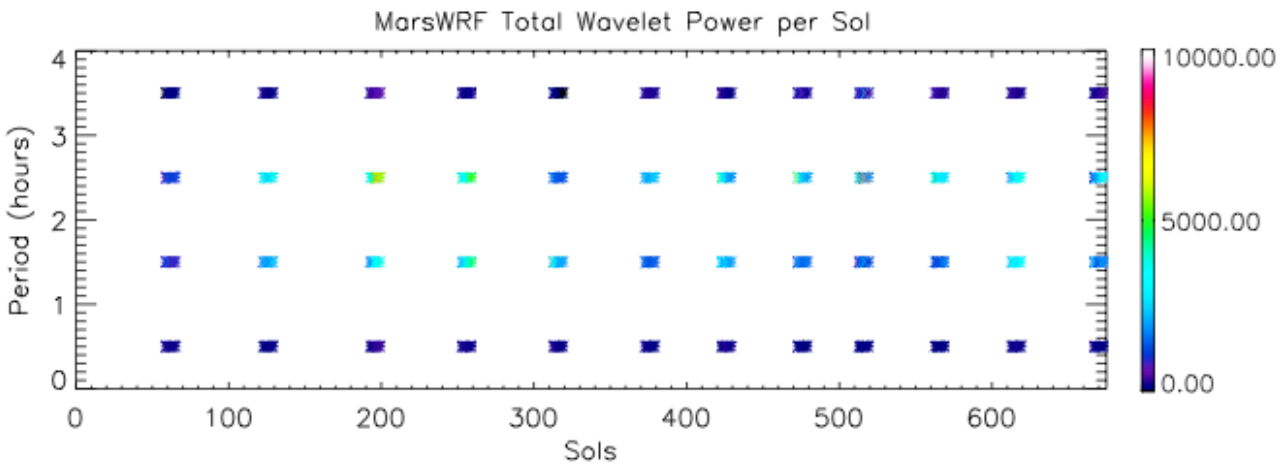


Figure 14. Total wavelet power (Pa^2) per sol for each MarsWRF simulation as a function of period (hours). Periods are displayed as centered values in 1-hour intervals (e.g., 0.5 hour period covers periods from 0-1 hour).

Most importantly, MarsWRF can help guide us to the source of these waves. To this point, we have not discussed the physical mechanism that is producing waves with periods under 4 hours in surface pressure in Gale Crater. Our assumption is that these are topographically-generated inertia-gravity waves due to their amplitudes and periods, but we can not produce any genetic connection between REMS pressure variations and the physical mechanism producing them (be it air flow over topography or something else) with the observations alone. The spatial information provided by the model allows us to determine the direction in which these waves are propagating. We employ an array analysis method that has its heritage in terrestrial seismology and is described in detail by Hedlin et al. [2018] (and references therein). In brief, the method works by examining three stations (in our case, three model grid points) and looking at the cross-correlation and lag between the pressure perturbations caused by a passing wave at each station. From this, the phase speed and azimuth of the wave can be determined. In our MarsWRF simulations, we use a variety of grid points, in addition to the grid point nearest the MSL landing

site in Gale Crater, to more robustly determine the phase speed and azimuths of the waves present in the simulations.

Figure 15 presents the results from this array analysis to identify the predominant wave azimuths and phase speeds present in the MarsWRF simulations. In all seasons, we present the two most common wave azimuths and their associated phase speeds. There is very little seasonal variation to the wave azimuths, with the majority of the waves coming from the north (352-360°) and the second most common azimuth of south-southeast, south, or south-southwest (163-188°). The standard deviations of those azimuths are shown in Figure 15 as error bars and are approximately 20-25° for most seasons. As Gale Crater sits on the topographic dichotomy boundary, these directions make sense with the assumption that these are largely topographically-driven waves. Strong jet streams or other dynamic conditions that could generate inertia-gravity waves are far from Gale Crater (typically poleward of 45° latitude). Elysium Mons is to the north and north-northeast of Gale, while the rugged terrain of the southern highlands of Terra Cimmeria is to the south. Regional analysis of the MarsWRF simulations shows Elysium Mons produces widespread and frequent gravity wave activity that propagates through the entire high spatial resolution domains and likely beyond. Waves could also be produced nearer to the Curiosity rover by the crater rim or Aeolis Mons (e.g., Rafkin et al., 2016), however we expect those to have much shorter horizontal wavelengths and shorter periods/higher frequency [Harri et al., 2014; Haberle et al., 2014; Ullán et al., 2017] than the longer wavelength waves with periods of tens of minutes to hours that we focus on. That may explain the relative lack of wavelet power with wave periods <1 hour in the MarsWRF analysis relative to REMS observations.

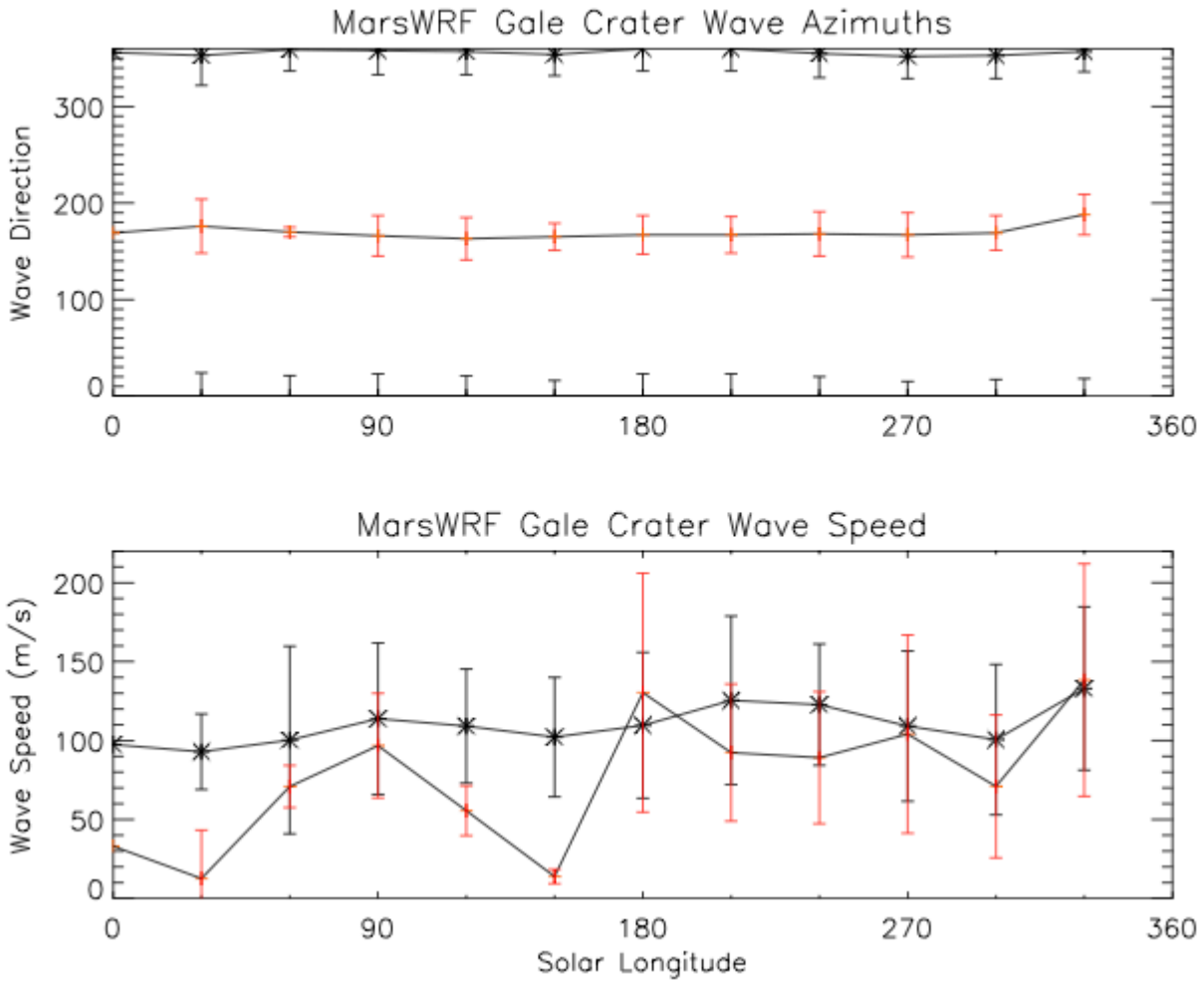


Figure 15. Predominant daily average MarsWRF pressure wave azimuths (top) and phase speeds (m/s, bottom). Black asterisks show waves propagating from a northerly direction while red crosses indicate those propagating from a southerly direction. One standard deviation around each value is shown as error bars.

The phase speeds shown in Figure 15 also aid in determining the type of waves we have identified in the simulations, and by analogy, in REMS observations. Migrating atmospheric tides, by definition, have phase speeds that are equal to the linear rotation speed of Mars: 241 m/s at the equator. Figure 15 shows that the detected wave phase speeds are well below that value and thus are not migrating tides with periods of 2 or 3 hours. These phase speeds, coupled with predominant periods of 1-3 hours, imply horizontal wavelengths of ~200-1500 km under the shallow water assumption. These values are directly comparable to those seen in Earth's

553 stratosphere and mesosphere for atmospheric gravity waves (e.g, Ern et al., 2018). Additionally,
554 shallow water theory implies that the phase speed is equal to $\sqrt{gh}$ where g is gravitational
555 acceleration and h is the "equivalent depth." Using Mars' gravitational acceleration and the
556 phase speeds shown in Figure 15, we calculate typical equivalent depths of 600 m - 6 km. These
557 values are comparable to typical daytime atmospheric boundary layer depths in Gale Crater
558 [Guzewich et al., 2017].
559
560 4. DISCUSSION AND CONCLUSIONS
561 We have searched for non-tidal pressure and temperature perturbations with periods of
562 tens of minutes to hours in REMS observations using harmonic fitting and wavelet analysis.
563 Analysis of REMS temperature observations are consistent with daytime convective turbulence
564 and show no coherent non-tidal patterns with longer periods. Detailed analysis of this turbulence
565 is reserved for future work. On the other hand, REMS pressure observations, after removing the
566 atmospheric tides, do show coherent wave-like behavior with such periods using wavelet
567 analysis. Our methods bias our detections to wave periods less than 3 hours, but occasionally
568 longer-period waves were seen.
569 We find that such waves typically have amplitudes of O(1-10 Pa) and have a distinct
570 diurnal and seasonal cycle. Waves are most clearly present in the evening (1700-2400 LTST)
571 and early morning (0400-0800 LTST) with a distinct "quiet" period near sunset that was also
572 recently identified by InSight [Banfield and Spiga et al., 2020]. Pressure wave activity detected
573 by REMS is strongest in the southern spring and summer seasons (L_s = 180-330°) with a local
574 minimum in activity near southern summer solstice (L_s = 270°), analogous to the solsticial pause
575 seen in dust storm and baroclinic wave activity across the planet (e.g., Barnes, 1980; Lewis et al.,
576 2016). The MY34 global dust storm saw the strongest activity of the entire mission with some

577 waves having amplitudes comparable to migrating atmospheric tides (e.g., Guzewich et al.,
578 2016).

579 To augment and complement the REMS data analysis, we conducted a series of high
580 spatial resolution atmospheric simulations with the MarsWRF GCM. The simulations generally
581 corroborate the patterns seen in REMS observations in terms of predominant wave periods and
582 the diurnal cycle of wave activity. However, the simulations produce wave amplitudes (or
583 power) that are typically a factor of 2-5 weaker and don't replicate the seasonal cycle seen by
584 REMS. This may be due to the prescribed dust climatology in the MarsWRF simulations. The
585 ability to simulate the entire region gives us additional information on how such waves may be
586 generated, their sources, and additional wave properties that are unknowable from a single
587 meteorological station on the surface of Mars. Analysis of the wave azimuths and phase speeds
588 in the simulations clearly show these are non-tidal waves with phase speeds and wavelengths that
589 are directly comparable to terrestrial atmospheric gravity waves, particularly those detected in
590 the terrestrial stratosphere and mesosphere.

591 We note that short-period (<1 hour) wavelet power is one particular area of discrepancy
592 between the REMS observations and the GCM. As mentioned in Section 3.3, this is plausibly
593 due to the model's spatial resolution not fully capturing wave activity (and associated forcing
594 mechanisms) that occur at scales near or below the model's resolution. Here we postulate a
595 forcing mechanism for such short-period waves based on terrestrial mountain meteorology and
596 suggest that the short period waves poorly resolved in the GCM may be produced through a
597 different forcing mechanism than the longer period waves that are simulated in MarsWRF.

598 The northwest slope of Aeolis Mons / Mt. Sharp and the walls of Gale Crater form a ~13
599 km wide valley (comparable to the spatial resolution of the MarsWRF nested domain) around the

600 study area of Curiosity, oriented WSW to ENE. The phase speed calculated in the GCM is
601 consistent with an equivalent depth of 600 m-6 km which is comparable to the extent of the
602 boundary layer and possibly the inversion layer. Therefore, an analogy to the mechanisms that
603 might be occurring is found in terrestrial mountain meteorology, starting with the scheme found
604 by Defant (1949). As the Sun sets, Gale's northern wall starts casting shadow on its own slope,
605 thus cooling down radiatively at a time when Aeolis Mons remains illuminated. Cold air near the
606 surface of the northern crater wall sinks into the valley and this downslope jet generates shear
607 that can cause internal gravity waves with some backlash as the jet reaches the southern wall and
608 bounces back. This would happen in the evening before sunset, thus explaining the standard
609 deviation increase near 1700 LTST (Figure 6). After sunset as a stable inverse thermal layer
610 develops and grows in altitude, winds cannot reach the bottom of the crater and a shear layer
611 forms above the surface (e.g. Whiteman, 2000; Sun et al., 2001). The lower altitudes remain
612 subject to the echo of these higher altitude waves that are much stronger seasonally when higher
613 altitude winds are stronger. During the dust season, high altitude winds strengthen and the
614 vertical temperature gradients decrease thus weakening the thermal inversion. A weaker thermal
615 inversion between 2000 and 0500 LTST results in lower static stability and higher sensitivity to
616 perturbations from activity/turbulence by the higher altitude winds in the dust season. In the
617 morning as the Sun rises, the nighttime inversion breaks up with the start of convection seen in
618 the ~0800 LTST temperature fluctuations. The volume of air trapped in the crater is smaller and
619 therefore heats up faster than the plains around the crater, thus producing an outflow of air from
620 the bottom of the crater up the slopes and a subsidence of air into the center of the crater. This
621 flow is also coupled with a crater internal circulation along the crater bottom as the sun-facing
622 west side of the crater starts warming up radiatively at a time when the west slopes of Aeolis

623 Mons are still shaded and remain colder. This horizontal temperature gradient east to west will
624 generate a background wind oriented nearly 90° to the upslope winds, thus creating a wind shear
625 in the morning until the east-west temperature difference has been compensated well after LTST
626 sunrise (~0700), contemporary with the morning pressure fluctuations and the temperature
627 fluctuations in Figure 9 at 0700-0800 LTST. Because of their origin, the morning short-period
628 fluctuations are a radiation-driven effect related to the direction of the solar radiation. The effect
629 should be stronger under clear skies, and decrease when atmospheric dust homogenizes the light
630 resulting in smaller east-west radiative heating differences. It is interesting that the opposite
631 effect is observed on pressure where Figure 9 shows it to be strongest right before and after the
632 dust season.

633 In combination, we interpret the waves (particularly those with periods >1 hour) detected
634 by REMS to be topographically-forced inertia-gravity waves. The wavelengths calculated in the
635 model (~200-1500 km) imply that these longer-period waves are likely not produced locally
636 within Gale Crater, but farther afield in the southern hemisphere highlands or from Elysium
637 Mons and its associated high terrain. Our work, in conjunction with that from InSight (e.g.,
638 Banfield and Spiga, et al., 2020), help extend understanding of martian atmospheric gravity
639 waves to the surface. Previous model studies (Forget et al., 1999; Kuroda et al., 2015; Gilli et
640 al., 2019?) and analysis of orbital datasets (e.g., Heavens et al., 2020) have largely focused on
641 the substantial impact that breaking gravity waves have on the atmospheric temperature structure
642 and circulation in the middle and upper atmosphere. Here we show that they are clearly
643 detectable with surface pressure stations, while not being seen in surface temperature
644 observations (at least not those taken with the frequency and cadence of REMS). Our work
645 further fills in the phase space of martian atmospheric phenomena, which extends from

convective vortices with durations of seconds, to atmospheric tides with periods of hours that are integer fractions of a solar day, to baroclinic and barotropic waves with periods of days, and to the sublimation and deposition of the polar caps with a period of a Martian year.

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