DETECTION OF NORTHERN HEMISPHERE TRANSIENT BAROCLINIC EDDIES AT GALE CRATER MARS

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Introduction: The Rover Environmental Monitoring Station (REMS) on the Mars Science Laboratory's (MSL) Curiosity rover has been operating in Gale Crater Mars (4.5°S, 137.4°E) for over 2 Mars years. Analysis of its pressure data, which have a precision of ~0.2 Pa (see Haberle et al., 2014; Harri et al., 2014), reveal temporal oscillations in its seasonally de-trended daily averaged pressures at some seasons with 2-5 Pa amplitudes that have periods similar to those observed at the Viking Lander 2 (VL-2) site (48.3°N, 134.0°E) several decades ago. As illustrated in Fig 1 there are clear peaks in the variance at a frequency f~ 0.45 and 0.06 sol^{-1} for the fall season of Mars Year (MY) 31, and at f~0.15 and 0.06 sol^{-1} for MY 32. These frequencies correspond to periods of 2.2, 6.7, and 16.7 sols, and are very similar to those observed at VL-2 (Fig 2, and see Barnes, 1980).

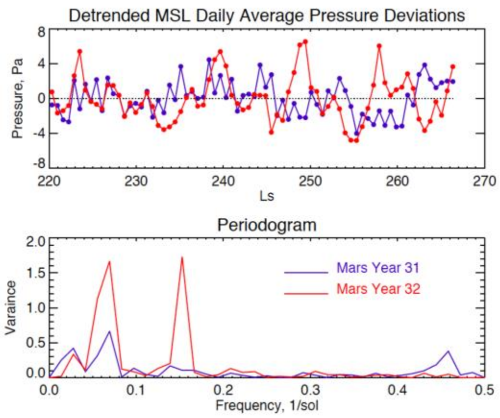

Fig 1. Top: Fall daily average pressure deviations for MY 31 (blue) and 32 (red). Bottom: Periodogram of the pressure variance per unit angular frequency interval.

Since orbital imaging data show dust frontal systems associated with eastward traveling baroclinic eddies that occasionally cross the equator (Wang et al., 2003), these findings suggest that MSL may be seeing their signature in its pressure data. To make this case we show that (a) the spectral peaks in the MSL are not only similar to those at VL-2, they have the same seasonal variation, (b) at least for some seasons the peaks are statistically significant and not likely due to random noise in the data, and (c) Global Circulation Model (GCM) results from the Ames GCM support this interpretation.

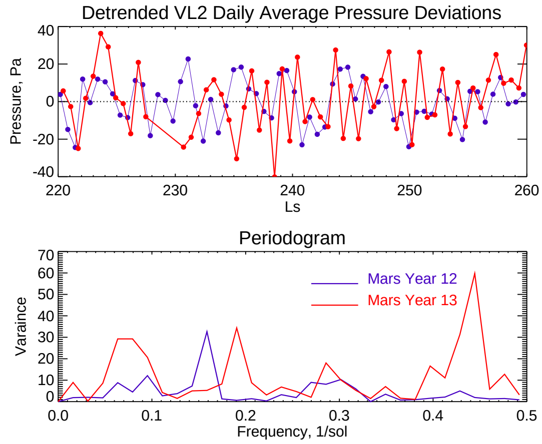

Fig 2. Same as Fig 1 but for VL-2 during MY 12 and 13.

Methodology: The basic approach to analyzing the data is to apply standard Fast Fourier Transforms (FFTs) to daily averaged pressure data. The intervals chosen were long enough (> 30 sols) to allow for at least 5 cycles of the longer period ~6 sol waves observed at VL-2. In some cases we also applied FFTs to low-pass filtered hourly-binned data in order to better resolve frequencies between 0.5 sol^{-1} (the Nyquist limit with daily averaged data) and 1.0 sol^{-1} (the diurnal frequency). The FFTs produce periodograms of the spectral variance per unit angular frequency interval with units of Pa^2 sol.

For the GCM part of our analysis we use output from the Ames GCM for a standard simulation using MY 24 TES dust maps and radiatively active water ice clouds. The model runs for two Mars years and we sample output from the second year.

Seasonal Variations: Seasonal variations in the power of the prominent synoptic periods at MSL and VL-2 are shown in Fig 3. In this case, we use a 64 Sol running window and apply the FFTs only in those cases where there are at least 43 Sols within the window that have daily averaged data (some Sols do not have enough measurements to compute a daily mean). As can be seen in Fig 3 seasonal variations at MSL and VL2 are closely correlated. At both sites eddy activity ramps up during northern fall and winter and is virtually absent during summer. This latter fact indicates that southern hemisphere wintertime eddies do not extend into Gale Crater. Furthermore, the short period eddies (~2 sols) so prominent during fall and winter at VL-2 during MY 13 and at MSL during MY 32 each exhibit a "pause" in activity around the winter solstice. During this pause, the longer period eddies (6-8 sols) increase in prominence at both sites. This transition from shorter to longer period power near the solstice is similar to the behavior of the eddies in the re-analysis simulations of Lewis et al. (2015).

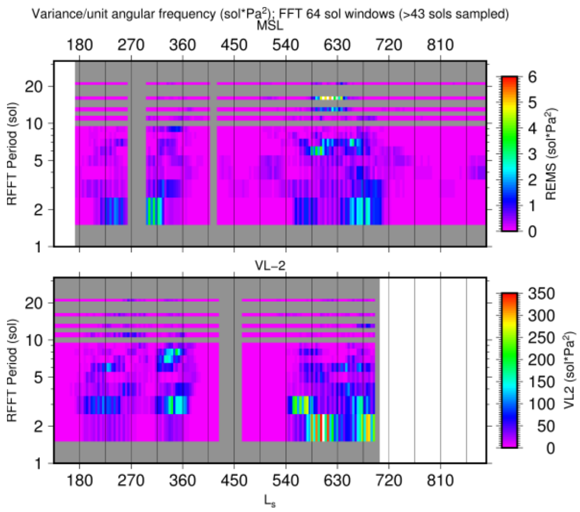

Fig 3. Seasonal variation in the variance of daily averaged pressures at MSL (top) and VL-2 (bottom). Variance is plotted as function of Ls and Period. Note that at global dust storm occurred during MY 12 in the Viking data.

The short period eddies are not much in evidence during MY 12 at VL-2 as this was a year with a global dust storm that had a significant damping effect on the eddies (see also Fig 2). However the ~3 sol waves at VL-2 are evident in both MY 12 and 13 in Fig 3 and they are also present in Fig 3 at MSL during MY 31 and 32. More importantly they follow the same seasonal pattern: at VL-2 their cycle is advanced with respect to the 2 Sol waves and this is also the case at MSL. Finally, the longer period 6-8 Sol waves appear in both data sets at roughly the same seasons. Thus, the frequencies and seasonal variations in the eddy variances at MSL are very similar to those at VL-2, though the magnitudes are much reduced as would be expected if these are the southern extensions of northern hemisphere midlatitude baroclinic eddies.

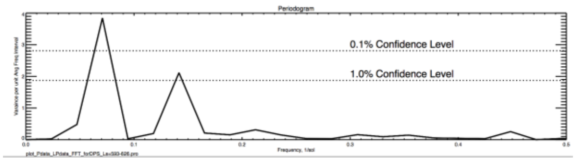

Fig 4. Periodogram of the detrended low-pass filtered pressure data for the fall of MY32. Filter response function is 1 at f=0.5 sol-1 and 0 at 1.0 sol-1. Statistical confidence levels based on total variance of frequencies < 1.

Statistical Significance: Given the very low amplitudes of the observed waves at MSL we performed statistical analysis of the data to determine the significance of various spectral peaks in the data. A result for the MY 32 fall season is shown in Fig 4. For this part of the analysis we ran a low-pass filter through the full diurnal data and used a standard chi-square test based on the total variance of frequencies less than 1 (to exclude the large diurnal cycle). As can be seen Fig 4, the f~0.15 sol^{-1} peak is significant at the 1% level, while the f~0.06 sol^{-1} peak is significant at the 0.1% level. Thus, at least for this season the peaks are not likely random noise. However, not all seasons show significance at these levels since the total variance can be spread out among multiple peaks. But the fact that we know a-priori what peaks to expect and that at least for some seasons the peaks are significant lends support for the hypothesis that REMS is seeing equator-crossing northern hemisphere transient eddies.

GCM Results: The signature of northern hemisphere baroclinic eddies can also be seen at the grid points closest MSL in the Ames GCM. Fig 5 compares the periodogram at VL-2 to MSL where it can be seen that the two sites have significant power at f~0.15 and ~0.4 sol^{-1}, though the relative distribution is reversed between the two sites. The f~0.3 sol^{-1} wave evident at VL-2 is not present at MSL for this seasonal interval. This pattern is also seen in the observations (e.g., compare Figs 1 and 2). Thus, the GCM results are consistent with our interpretation that MSL is seeing equator-crossing northern hemisphere baroclinic eddies. It also suggests that different wave modes have different abilities to cross the equator.

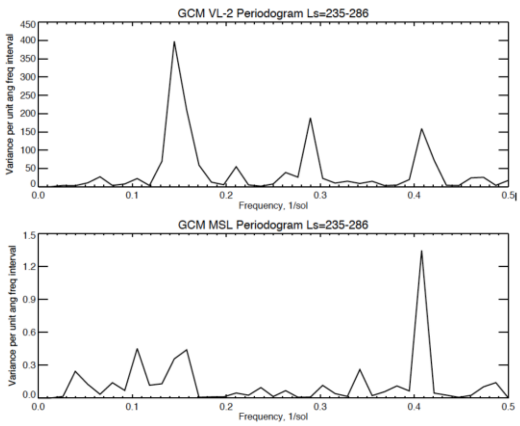

Fig 5. Periodograms of GCM pressure output at the grid points closest to VL-2 (top) and MSL (bottom) for a fall period.

The spatial structure of the simulated transient eddies for a given day in late fall is shown in Fig 6. It is clear that the perturbation pressure fields associated with these systems have a very broad meridional extent and that their signatures should appear nearly simultaneously as would be expected for two sites located at roughly the same longitude.

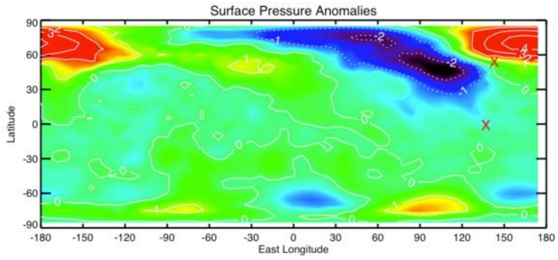

Fig 6 GCM simulated daily average surface pressure anomalies at Ls=249 expressed as a normalized % departure from a fit to the seasonal mean. "X" marks the location of VL-2 and MSL.

Furthermore, the zonal mean rms surface pressure variance from the model (shown in Fig 7) indicates that the northern hemisphere systems may penetrate as far south as 30°S during early northern fall just before the beginning of the "solsticial pause" (see Lewis et al. 2015). Again, these results support the notion of equator crossing northern hemisphere baroclinic eddies.

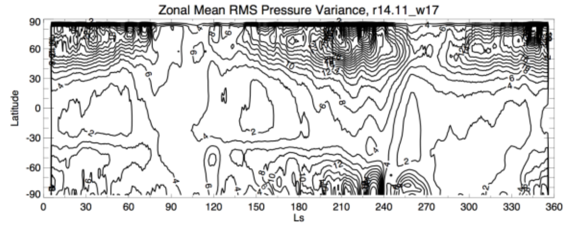

Fig 7. Simulated zonal mean rms pressure variance as a function of latitude and Ls.

The Very Low Frequency Wave. The very low frequency power seen at MSL especially during MY 32 (i.e., the f~0.06 sol^{-1} seen in Figs 1 and 4, and the P~17 sol in Fig 3 at Ls~630) may be a member of the deeper, longer period transient eddies that develop during the "solsticial pause" season (see Lewis et al. 2015). We speculate that these eddies (and pause onset) are sensitive to the starting times and intensities of the "A" storms described by Kass et al. (2016).

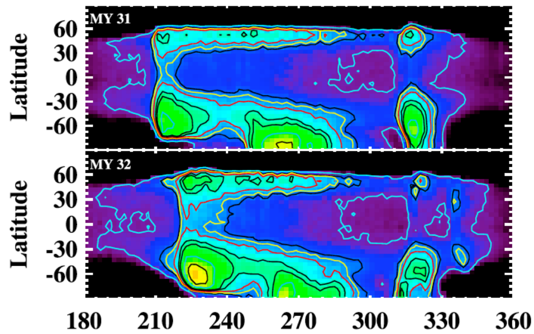

Fig 8. Daytime MCS zonal mean temperatures as a function of Ls at 50 Pa for MY 31 and 32. From Kass et al. (2016).

The MY 32 A storm started later and was stronger than in MY 31 (see Fig 8) possibly accounting for the difference in very long period power between the two years. If correct, a very weak A storm could account for the lack of power at VL-2 during MY 13. Further modeling is needed to confirm these speculations.

Conclusions. The synoptic period surface pressure oscillations at VL2 and MSL have the same frequencies and seasonal variations, though the power at MSL is greatly reduced compared to VL2. There is no evidence in the REMS data for southern hemisphere wintertime baroclinic eddies extending into Gale Crater. This accentuates the known hemispheric asymmetry between baroclinic eddies on Mars. Similar results are found in GCM simulations. The most likely explanation for the REMS oscillations is that MSL is seeing equator crossing northern hemisphere transient eddies even though it is located in a longitudinal corridor that experiences fewer equator crossing systems, at least as revealed in orbital imagery. These results raise questions about the dynamics of Martian equator crossing systems, which appear to have no counterparts on Earth.

Finally, we note that this discovery would not be possible had the REMS pressure sensor had the same precision as the Viking sensors (~9 Pa). Thus, sensor resolution (as well as accuracy) is very important. Future lander missions considering pressure sensors should keep this in mind. NASA's Insight Lander will carry a pressure sensor with even better precision than MSL. Given that its nominal landing site is very close to MSL, there is an opportunity to further characterize the nature of equator crossing systems on Mars, especially if the two missions operate simultaneously.

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