TOPOGRAPHIC CIRCULATIONS ON MARS: SURFACE PRESSURE, CONVECTIVE BOUNDARY LAYERS AND NETWORK IMPLICATIONS

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Introduction:

To improve and validate models of the Martian atmosphere, surface pressure is an incredibly useful observation. As proposed by *Haberle and Catling* (1996), a network of stations providing simultaneous surface pressure observations would be of great value to the modeling community. Thus, it becomes crucial to understand how a network of surface pressure observations provides information about both the global atmospheric thermal tide (global forcing) and topographically excited slope-flow circulations (local forcing). The later has been shown to be important through the mesoscale modeling of *Tyler and Barnes* (2013, 2015).

Mars is indeed the slope-flow planet, and these flows exist across a very wide range of scales. At minimum, slope-flows tend to dominate the local diurnal cycle of surface winds. When slope-flows excite a vigorous convergent or divergent flow at the surface (dependent on the topography), vertical motion is excited in a circulation that modifies the vertical profile of air temperature. This holds true whether the topography is concave (a crater or basin) or convex (a hill or volcano), and by itself the dynamics of this is fairly straightforward. The circulation modifies the diurnal cycle of the local air temperature profile from what is typical for the region, where the typical vertical structure of air temperature above a region on Mars is a function of height AGL (*Webster*, 1977), quite different from that on Earth. By modifying the air temperature profile, topographic circulations can significantly modify the diurnal surface pressure cycle as well as the depth of the convective boundary layer (CBL).

Thus, the global tide and convergent/divergent topographic circulations both modify the local air temperature profile (the pressure scale height profile), the mass column and the diurnal surface pressure cycle. To most effectively use surface pressure data from a network of stations on Mars, these two mechanisms, which both modify the local surface pressure cycle, must be considered.

In a study of OMEGA surface pressure data, *Spiga et al*. (2007) noted sizable inconsistencies between the observations within craters and outside of them. Based on hydrostatic calculations using the known depth of craters, the expected differences were inconsistent with the observations, and these differences were believed too large to be caused by instrument errors. Using mesoscale model results from work performed for the Mars Science Laboratory (MSL) landing in Gale Crater, *Tyler and Barnes* (2013) predicted a much larger percentage diurnal surface pressure range at the landing site than the Global Climate Models (GCMs) were predicting (where Gale Crater was not resolved). As described by *Haberle el al*. (2013), this large range in surface pressure was indeed observed by the Remote Environmental Monitoring Station (REMS, *Gomez-Elvira et al*., 2012). As argued by *Tyler and Barnes* (2013), a crater circulation modifies the air temperature profile over the floor of the crater, causing it to become much deeper/warmer during the late afternoon and much deeper/cooler during the early morning. This modification of the air temperature profile is the reason the percentage diurnal surface pressure range becomes significantly larger than a GCM would predict for the location of Gale Crater.

The explanation of *Tyler and Barnes* (2013) was met with some criticism, with *Rafkin et al*. (2016) suggesting that the effect is simply a consequence of the atmospheric thermal tide. However, in a study of idealized crater circulations, *Tyler and Barnes* (2015) had completely eliminated the thermal tide from the simulation, such that with no crater there was no diurnal surface pressure cycle, only the diurnal expansion/contraction of the atmosphere vertically. When a Gale Crater analog was introduced, a surface pressure cycle developed at the floor of the crater, with a range of ~4%, and importantly with no range away from the crater. This ~4% total surface pressure range at the crater floor (due to the crater circulation) is in excellent agreement with the enhancement that *Tyler and Barnes* (2013) had seen by comparing their mesoscale model results for MSL both inside and outside Gale Crater.

This issue can also be explored using very high-resolution GCM simulations, as was done by *Wilson and Murphy* (2015). Using model surface pressure data, the global surface pressure tide is constructed and removed from the surface pressure cycle at all locations on the planet, leaving a residual diurnal surface pressure signal. At the season of MSL landing, the amplitude of the residual at the floor of Gale Crater was found to be in very good agreement with the estimates of *Tyler and Barnes* (2013, 2015). Upon examining craters across Mars, the phase of the residual is found to vary only minimally, in very good agreement with the surface heating (as expected for a topographic circulation), whereas the phase of the dominant diurnal mode of the tide is not nearly as constant. Typically, the phases of the two are close, although the phase of the tide can be such that the effect of a crater circulation actually diminishes the total amplitude of the surface pressure cycle, clear evidence that the enhanced amplitude cannot simply be the tide.

Eventually, when we become rich in network meteorological data from Mars, processing that data into a coherent synoptic picture will require consideration of the local/regional topographic circulations that modify the surface pressure cycle. Here, we review the dynamics of these circulations, and show that they can have a role across a wide scale range.

Using Normalized Surface Pressure:

For Mars, the use of normalized (or percentage) variations in surface pressure to track meteorological disturbances is the analog of using sea level pressure on Earth. On Mars, the vertical structure of air temperature profiles for a region/season differs from that on Earth (temperature typically follows height AGL on Mars versus pressure levels on Earth). Because of this, normalizing surface pressure (using the local diurnal mean) is a useful diagnostic technique for Mars, whereas extrapolation to sea level pressure (removing the effect of topography) is best for Earth. For quantifying the effect crater circulations have on surface pressure this normalization is most useful, as shown mathematically by *Tyler and Barnes* (2015) in supporting information. This normalization is the typical/historical method for examining the tide.

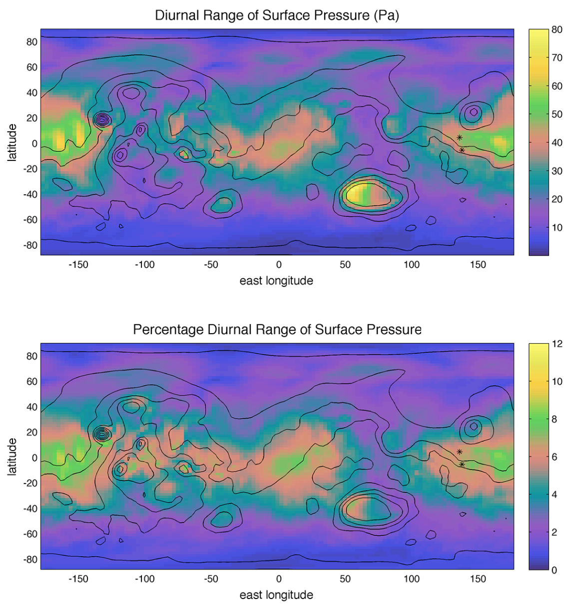

Figure 1. For $L_s\sim5^o$ (Mars 2020 landing), the mean diurnal range of the surface pressure cycle is shown for a 2^ox3^o run of the NASA Ames GCM. The upper panel shows the data in Pa, while the data in the lower panel is normalized with the diurnal mean value (and shown in percentage).

For examining the diurnal range of surface pressure, normalization provides a far more useful depiction of the spatial structure of the dominant diurnal mode. At $L_s\sim5^o$, the diurnal range is shown in Fig. 1 (both in Pa and normalized) from a 2^ox3^o run of the NASA Ames Mars GCM. In the upper panel a correlation between the diurnal range and the surface elevation is seen, although not seen in the lower panel, revealing that the dominant diurnal mode can indeed be quite constant across large changes in topography (when normalized). Thus, when there are sizable variations in the local percentage diurnal range compared to the regional norm, an explanation other that the global tide is needed, one that modifies the typical diurnal and vertical structure of air temperature versus height AGL for that region.

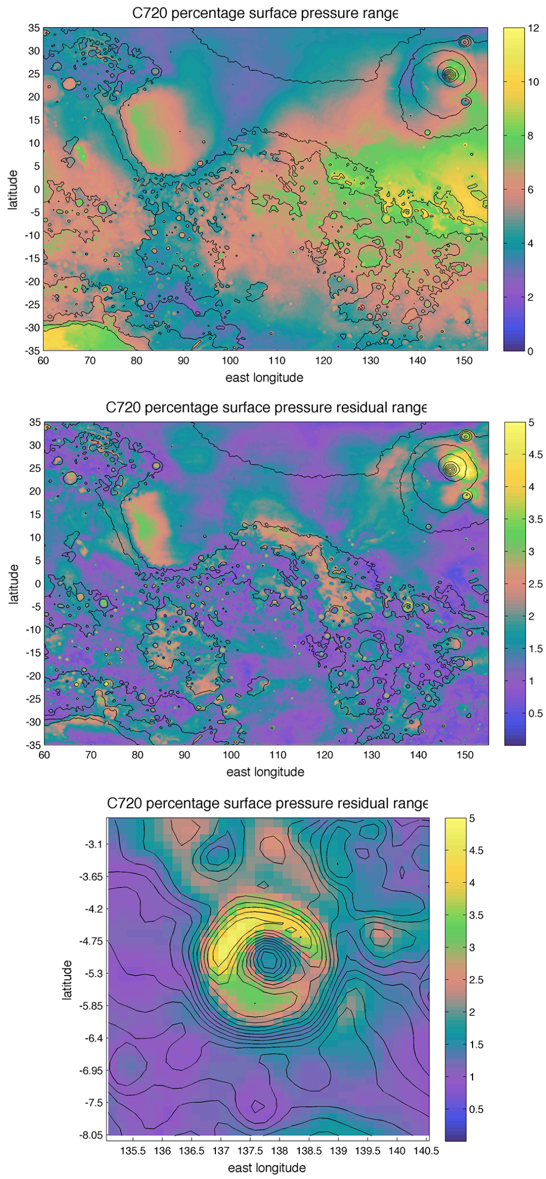

Figure 2. For $L_s\sim188^o$, a subset of the percentage diurnal surface pressure range is shown in the upper panel for the 0.125^o high-resolution run of the GFDL GCM (*Wilson et al.*, 2017), the residual after removing the global tide for the same region (middle panel), and a zoom to show Gale Crater (lower panel).

When we examine the very high-resolution GCM results of *Wilson et al.* (2017), for the eastern hemisphere subtropics at $L_s\sim188^o$, local structures begin to emerge in the percentage diurnal range as shown in Fig. 2 (upper panel). When the global tide is removed, and the percentage diurnal range of the residual (middle panel) is examined, local signals associated with craters emerge. Finally, zooming-in on Gale Crater (lower panel), the maximum range of the residual is ~5%. For the subsolar latitude at L_s~188°, an equatorial crater circulation would be somewhat stronger than during MSL landing (L_s~151°), whereas seasonal differences in the dust opacity at L_s~5° explain why the percentage diurnal range in Fig. 1 for the region near Gale Crater is smaller.

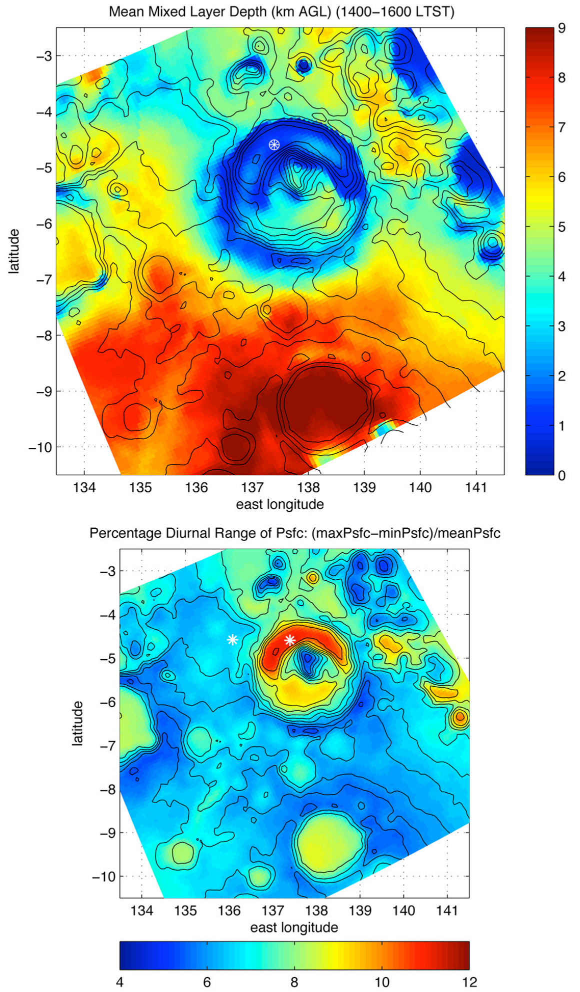

Figure 3. The depth of the CBL (upper panel) and the percentage diurnal surface pressure range (lower panel) are shown for Gale Crater at MSL landing (L_s~151°).

Dynamics of Topographic Circulations:

The slope-flows associated with topographic circulations produce a convergent/divergent flow that modifies air temperatures. In a crater, growth of the CBL can be strongly inhibited by the adiabatic warming of subsidence (daytime convergence aloft with divergence at the ground). Over convex features such as the dormant volcanoes, a vertical plume deepens the CBL. By comparing opacity measurements from the navigation cameras onboard MSL Curiosity, *Moores et al.* (2015) provided evidence that CBL growth in Gale Crater is inhibited. And, with a shallow CBL, the formation of dust devils is far less likely (*Moores et al.*, 2015; *Spiga et al.*, 2016). A large percentage diurnal range of surface pressure at the floor of a crater is itself a consequence of the air temperature profile having been modified, so a very good correlation is expected between suppressed CBL depths and the locations where the percentage range of surface pressure has been modified. At MSL landing (L_s~151°), this correlation can be seen in Fig. 3, two panels taken from *Tyler and Barnes* (2013).

For crater circulations, subsidence warms the air above the crater floor and inhibits growth of the CBL, producing a much deeper warm layer in the late afternoon (less mass in the air column, lower surface pressure). At night, katabatic flow into craters fills them with cold air (cold pooling), leading to a much deeper cold layer at night (more mass in the air column, increased surface pressure). These dynamics are described in greater detail by *Tyler and Barnes* (2013, 2015). At the respective times of maximum and minimum surface pressure, the cold morning air is deepest and the warm afternoon air is deepest, as seen in Fig. 4. The isotherms of air temperature at these times tend towards horizontal, more like on Earth. This poses some important scale questions for further investigations.

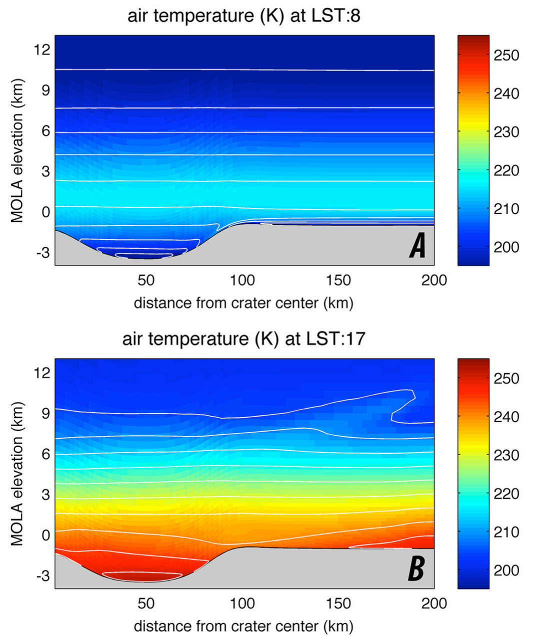

Figure 4. The mean radial air temperature structure is shown at the times of maximum (A) and minimum (B) surface pressure for the idealized Gale Crater analog of *Tyler and Barnes* (2015). The top of the central mound of the crater is the left edge of both panels.

Air mass is removed from the crater during the day due to the heat the crater circulation adds to the atmosphere over the crater floor, meaning it must go someplace. As the crater circulation expands radially, mass is removed from the crater in a "surge". This evolving structure, in the temperature and wind fields, is readily seen in the animations of *Tyler and Barnes* (2015), and may indeed be commonplace across Mars. When the radial mass flux at the rim of the crater is calculated, the connection to the surface pressure cycle becomes clear: maximum surface pressure occurs at the instant mass begins to flow out of the crater in the morning and the minimum occurs when it begins to flow back into the crater in the late afternoon. The timing of this is seen in the two panels of Fig. 5 for the Gale Crater analog of *Tyler and Barnes* (2015). The transitions in this circulation are driven by surface heating and thus the slope-flows along the crater walls, not due to the larger scale atmospheric tide.

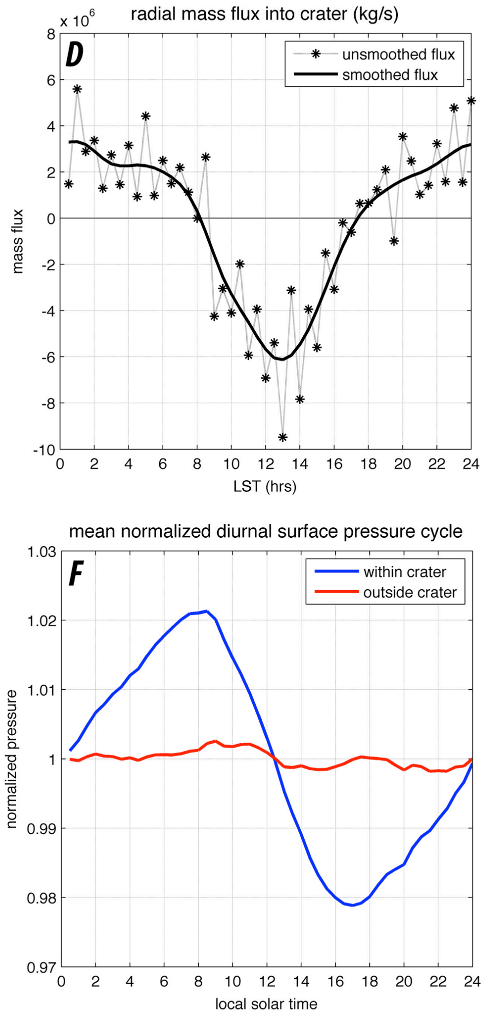

Figure 5. For the Gale Crater analog of Tyler and Barnes (2015), the flux of mass into the crater (upper panel) and the normalized surface pressure within and outside the crater (lower panel) are both shown.

Network Implications:

As the middle panel of Fig. 2 suggests, topographic circulations can be important for the surface pressure across a wide range of scales. The depth of the CBL is an important diagnostic that can help us better understand this widespread phenomenon. We see in Fig. 2 that Isidis Planitia (a semi-closed basin) has a sizeable residual, and modeling shows the CBL is also suppressed there. Modeling also suggests that Valles Marineris has a circulation with similar dynamics (*Tyler and Barnes*, 2015). These features deserve further study as we move towards a surface pressure network, and gain the ability to begin numerical weather prediction for Mars, an inevitable development towards human exploration.

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