

THE EFFECT OF DUST ON THE MARTIAN HADLEY CELLS.

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Introduction

General circulation modeling (GCM) studies have shown that the Martian Hadley cells are asymmetric in many ways. First, at equinox the rising branch of the Hadley cell is located southward of the equator, when based on the solar zenith angle alone, the rising branch should be located at the equator (in the zonal mean). As a consequence, the southern cell is weaker than the northern cell. Several modeling studies have independently concluded that the north-south dichotomy in topography is the cause for the asymmetry and not the L_s of perihelion (Richardson and Wilson, 2002) nor the surface albedo or surface thermal inertia (Takahashi et al., 2003). Zalucha et al. (2010) connected the results from the Martian version of Massachusetts Institute of Technology GCM to the analytical Hadley cell theory of Lindzen and Hou (1988) and found that they were in agreement.

Other modeling studies have noted characteristics at the solstices. Joshi et al. (1995) found that when the solar forcing was held constant between the two solstices, a factor of 1.5 difference in Hadley cell intensity was still present. Basu et al. (2006) showed that at $L_s=270^\circ$, as dust loading increased, the Hadley cell strength increased, while at $L_s=90^\circ$, the strength also increased but by a larger amount. That is, the asymmetry between the solstices became less pronounced as dust loading increased. The contribution from the north-south slope apparently diminished as dust loading increased. Here the study of the effect of dust on the Martian Hadley cells at both equinox and solstice is continued, specifically by looking at the zonally averaged cell strengths and boundaries in the latitude-height plane.

Model

For this study, the NASA Ames GCM v23 r0007 is used (PI Jeffery Hollingsworth; Tim Michaels private communication). The model uses a vertical sigma coordinate with 24 layers. The horizontal resolution is 5° in latitude and 6° in longitude. The radiative transfer scheme (described by Shaeffer, 2011) assumes that the dust is vertically distributed following a Conrath- ν distribution (Conrath, 1975). The dust is not transported, and the dust loading is defined by a single parameter τ_{tot} representing the visible dust column opacity at a reference pressure of 6.1 hPa.

The radiative transfer (RT) scheme is based on the two-stream approximation, via quadrature at short wave-

lengths and hemispheric mean in the IR. The code includes CO_2 and H_2O gas opacity and aerosol optical properties for dust. The water ice cloud option is not used, for simplicity and because cloud microphysics is not in the model. The RT scheme uses correlated-k opacities; for each spectral interval there are 17 Gauss points. The RT equation is solved throughout the entire atmospheric column for each Gauss point in each spectral interval. There are 7 visible channels and 5 IR channels. The code calculates visible and IR fluxes, which are added together and differentiated with respect to pressure to obtain a heating rate. This heating rate is then fed into the Mars GCM (note that the heating rate is a function of latitude, longitude, and season).

Owing to simplicity, we have chosen to use the older Conrath- ν distribution rather than the Mars Global Surveyor Thermal Emission Spectrometer data. Using the Conrath- ν distribution will enable us to more transparently see the effects of dust on the Hadley cell, since the dust optical depth is constant with latitude and longitude (at a given pressure) and the only variable is the reference optical depth. We however do use the current Mars Orbiter Laser Spectrometer (MOLA) topography dataset (Smith et al., 1999). The volatile cycle is included.

Results and Discussion

The GCM was run for two Martian years to ensure the volatile cycle was equilibrated and the dynamics were spun up. Results are presented for the second year. A low dust case (equivalent to non-dust storm conditions) was run with a dust optical depth of 0.3 at the reference pressure of 6.1 hPa as well as a high dust case (equivalent to elevated dust loading but weaker than the strongest observed global dust storms) of 1.0 at the reference pressure. Runs in which the topography was the MOLA (actual) Martian topography and flat topography were also performed.

Figure 1 shows the zonally and time averaged (over 5° of L_s) mass stream function. In the top panel, with low dust loading and MOLA topography, the northern cell is stronger and the latitude of the rising branch (indicated by the zero mass stream function contour) is shifted southward. In the panel second from the top, the topography is flat, and the dust loading has not been changed. These two panels simply repeat the results of Richardson and Wilson (2002), Takahashi et al. (2003), and Zalucha et al. (2010).

In the third panel from the top, the topography is

Table 1: **Hadley Cell Strengths** (10^8 kg s^{-1})

Configuration	$L_s=90^\circ$	$L_s=270^\circ$
MOLA topography, low dust	134.25	56.56
Flat topography, low dust	163.35	91.40
MOLA topography, high dust	198.17	110.14
Flat topography, low dust	191.97	118.76

again the MOLA topography but the dust optical depth has been increased to 1.0. Although there is some noise near the surface, the rising branch of the Hadley cell appears to have been shifted *northward*, though there is some latitudinal dependence of the rising branch with height. In any case, the *southern* cell is now stronger.

Several effects may be at play here. First, the increased dust loading scatters incoming solar light and makes the near surface air cooler than it would be in the low dust loading case. Zalucha et al. (2010) explained that the specific mechanism for how topography effects the Hadley cells is that air (in radiative equilibrium) over an elevated surface is warmer than the air at the same altitude over a lower surface. Thus, when the near-surface temperature gradient is removed due to scattering of sunlight by dust, the asymmetry about the equator ought to disappear. However, the deeper column to the north of the equator could be generating more absorption of sunlight (i.e. total column heating), hence shifting the upwelling branch northward.

In the bottom panel of Fig. 1, the topography is flat and the dust loading is high. Strangely, there are two weak near-surface cells that circulate in the opposite direction of a theoretical Hadley cell. This may indicate that the region of peak heating is located above the surface but is otherwise a puzzling result.

Figures 2 and 3 show the equivalent figures for $L_s=90^\circ$ and $L_s=270^\circ$. While the topography and dust loading do not appear to affect the boundaries of the single cell, the strengths do vary, as previous authors have found. Table 1 shows the maximum absolute strengths for the different model configurations. Dust increases the strength of the cells (as found by Basu et al., 2006), even when topography is flat. This behavior is likely due to the larger amount of solar energy absorbed by the increased dust loading.

Open Questions

How does keeping the insolation constant (i.e. having a zero eccentricity orbit) affect the Hadley circulation? What is the effect of higher dust loadings? What can be learned by using different analytical dust mixing ratio as a function of height specifications?

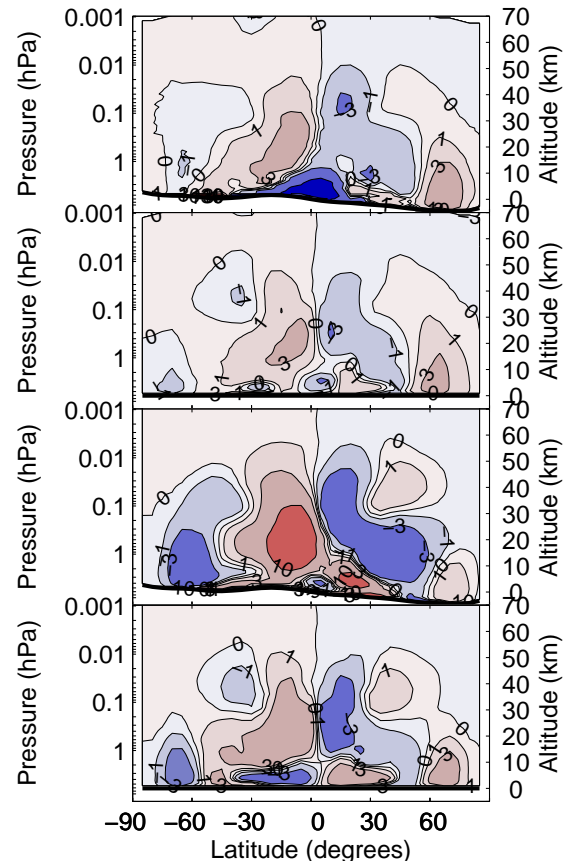


Figure 1: Zonally averaged stream function (10^8 kg s^{-1}) at $L_s=0$ (time averaged over 5°). Positive contours are counterclockwise. From top to bottom, the panels are: MOLA topography, low dust; MOLA topography, high dust; flat topography, low dust; flat topography, high dust.

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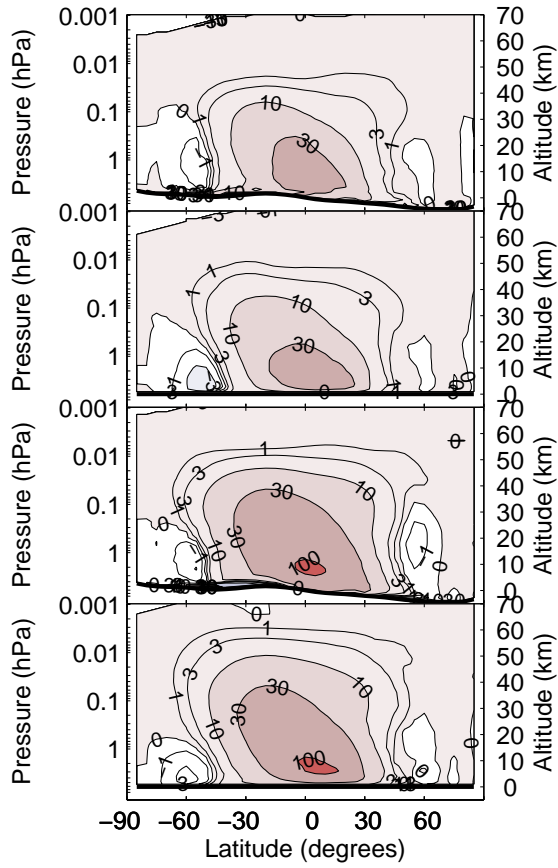


Figure 2: Same as Fig. 1 but for $L_s=90^\circ$.

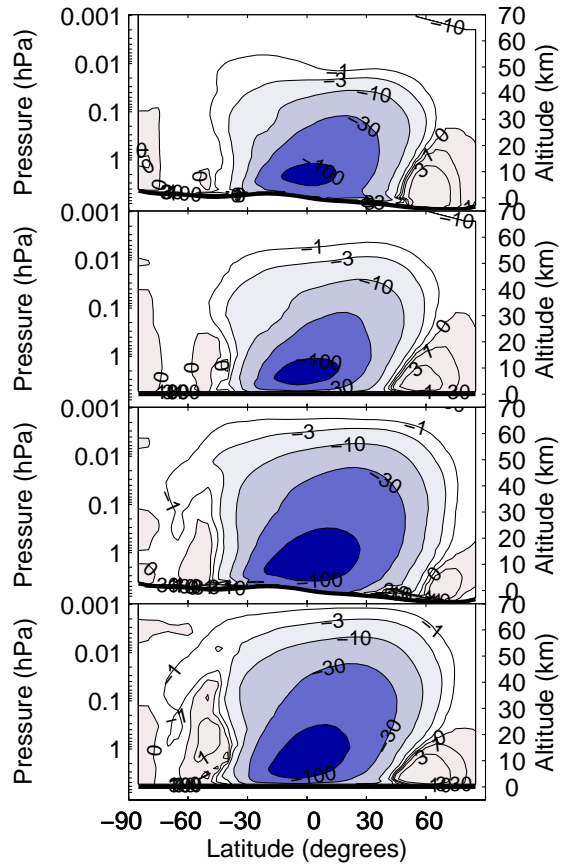


Figure 3: Same as Fig. 1 but for $L_s=270^\circ$.

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