MARTIAN DUST STORMS, THERMAL TIDES, AND THE HADLEY CIRCULATION. R. J. Wilson, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, 08542, (John.Wilson@noaa.gov).

Introduction: Observations of the Martian atmosphere have revealed a strong annual modulation of climate that is due to the pronounced seasonal asymmetry in solar radiation and the highly variable distribution of aerosol. There is also considerable interannual variability, most notably associated with the episodic occurrence of major dust storms. Dust in the Martian atmosphere has a profound influence on the dynamics of the general circulation as a consequence of radiative effects. Numerical models have shown that winds associated with the meridional (Hadley) circulation and the thermal tides respond strongly to the evolving spatial distribution of aerosol-induced heating. In turn, the resulting circulation has a major role in determining the sources, sinks, and transport of radiatively active aerosols.

Modeling studies have generally focused on simulating major dust storms in the solstice season due to the expectation that dust is most efficiently lifted and distributed by the Hadley circulation. However, the observational record indicates that most years are characterized by pre- and post-solstice regional dust lifting. In several years (1977, 1982, and, most notably, 2001) major dust storms occurred well before the solstice, suggesting that the Hadley circulation does not necessarily play the dominant role in dust storm development. The prominent influence of diurnally varying circulations (tides) is a notable contrast with Earth.

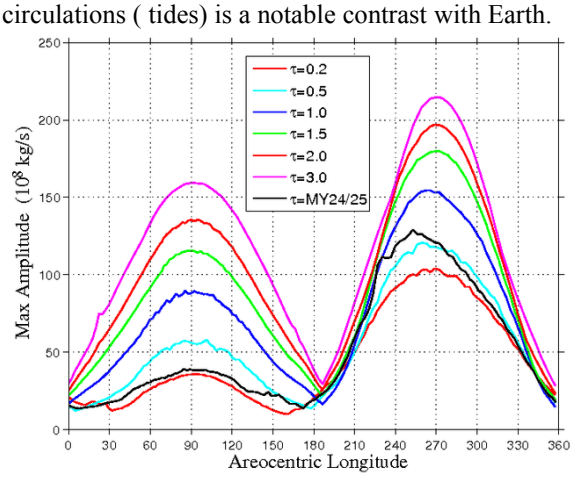

Figure 1. The seasonal variation of the maximum absolute value of the mass transport stream function for a series of simulations with specified dust optical depths. The maximum value is located in the tropics at roughly 14 km above the surface.

Hadley Circulation: Figure 1 shows the seasonal variation of the Hadley circulation intensity derived from a series of simulations with fixed dust scenarios. Due to the relatively low thermal inertia of the Martian surface, the atmosphere undergoes radiative forcing whose peak amplitude tends to track the seasonal migration of the subsolar latitude. The Hadley response is most sensitive to the displacement of thermal forcing poleward from the equator, as described by theory [*1*]. The seasonal variation is much more pronounced on Mars than on Earth, due to the absence of the moderating influence of an ocean. Interestingly, there is greater sensitivity to increased dust loading during the northern summer season, when vertically-distributed dust heating acts to reduce the suppressing effect of the cross-equatorial slope in zonal mean topography [*2*].

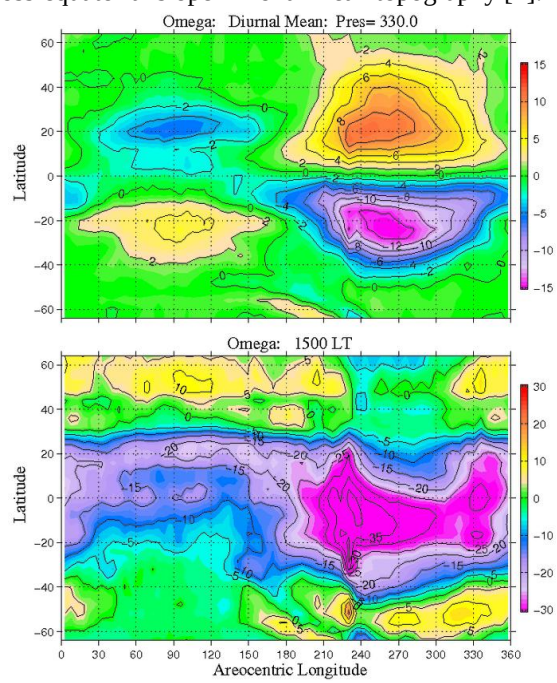

Figure 2. (a) The latitude and seasonal variation of the zonally and diurnally averaged vertical velocity (ω, in 10^{-4} Pa/s) on the 300 Pa pressure level, from a simulation using specified dust column opacity as observed by MGS TES during Mars Year 24/25. (b) As above, but for the vertical velocity at 1500 LT. The contour intervals and range of shading differ in the two panels.

Figure 2a shows the seasonal variation of vertical velocity in the simulation employing the MY24 dust scenario. The central latitude of the upward branch of the Hadley circulation roughly follows the subsolar latitude and shows a strong hemispheric asymmetry in intensity, consistent with Figure 1.

Thermal Tides: Figure 3 shows the amplitude and phase of the diurnal tide component of the zonal and meridional winds. Diurnal tide winds peak at ~ 30° latitude and are particularly prominent in the boundary layer. The tide is phased so that maximum low-level convergence occurs in the afternoon. The seasonal evolution of afternoon (1500 LT) vertical velocity is shown in Fig. 2b. The diurnally varying wind response dominates the diurnal mean (Hadley) response. Of course, there is considerable longitude structure hidden by the zonal averaging. Tide amplitudes are a strong function of dust heating so that surface wind stresses amplify with dust lifting, yielding a significant positive feedback effect for regional storm intensification. The influence of the dust lifting events in the pre and post-solstice seasons (L_s=230 and 330°) of MY24 is apparent.

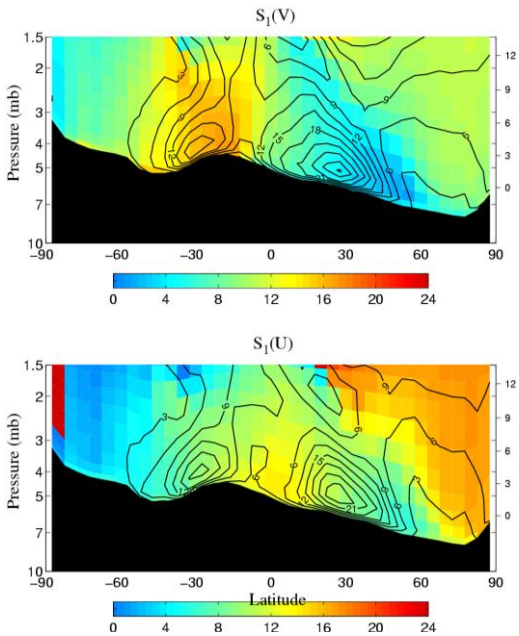

Figure 3. Latitude-height sections of the amplitude and phase of the diurnal tide component of the meridional (top) and zonal (bottom) wind. The amplitude contour interval is 3 ms^{-1} and the phase (shading) varies from 0 to 2400 LT. This simulation employs zonally averaged topography to enable a clear display of the wind structure in the boundary layer.

Figure 4 shows an afternoon cross-section of dust and meridional wind from a simulation of the 2001 global dust storm that featured an extensive region of structured dust cloud in the Claritas/Thaumasia region with a prominent boundary at 20°S. The shallow, intense equatorward flow appears to be consistent with cloud structure in spacecraft imagery of the dust storm. The flow is dominated by the thermal tide and results in strong daytime equatorial convergence and upward motion in the tropics. The strong vertical shear in the horizontal wind field may partially account for the fine "billowy" cloud top structure seen in spacecraft imagery. It is clear that there is a great deal of vertical transport of dust occurring in the simulation, even though the time-averaged vertical velocity is rather muted relative to later in the season.

Non-Local Deep Transport: Mesoscale model simulations [*4*] indicate that deep, coherent and dusty updrafts can penetrate well above the convective boundary layer, analogous to convective hot towers in the terrestrial tropics. *Rafkin* [2011] has argued that these updrafts, along with topographically-forced vertical plumes, may provide much of the required upward transport, so that net large-scale vertical transport need not be accomplished by the Hadley circulation. Current dust cycle simulations are carried out at resolutions (~3-5°) that likely misrepresent the convective updrafts present within dust storms, and so underestimate the flux of dust from the boundary layer into the free atmosphere. I am now carrying out simulations with a range of model resolutions (from 2°x2° down to 0.25°x0.25°) to investigate the consequences of increased resolution on the vertical transport of aerosol. Such transport may well be significant within the thick dust cloud present south of 20°S in Figure 4.

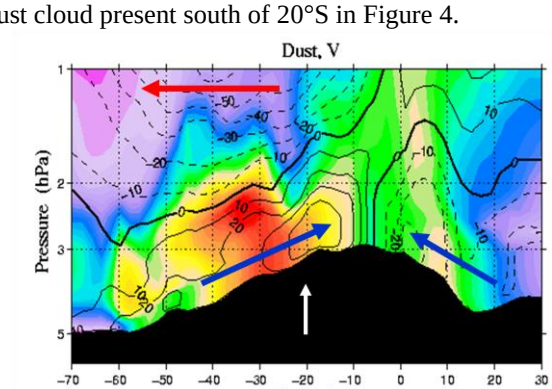

Figure 4. Latitude-height cross-section of meridional wind (contours) and dust mixing ratio (shaded) at 252° E longitude at L_s = 192.5° from a simulation of the 2001 global dust storm [*3*]. The local time is 1400.

References:

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[2] Zalucha, A.M. et al. (2010) *J. Atmos. Sci.*, 67(3), 673-693.

[3] Wilson, R.J. et al. (2008) Mars Atmosphere: Modeling and Observations Workshop, Williamsburg, VA, Abstract #9023.

[4] Rafkin, S.C.R. (2009) *J. Geophy. Res. 114* (E1), E01009.

[5] Rafkin, S.C.R. (2011) *Planet. Space Sci.*, doi:10.1016/j.pss.2011.07.015.