THE VERTICAL DISTRIBUTION OF DUST IN THE MARTIAN ATMOSPHERE AS OBSERVED BY THE MARS CLIMATE SOUNDER

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Introduction: Observations of the spatial and temporal variability and optical properties of atmospheric dust have been a part of almost every major spacecraft mission sent to Mars. One important achievement of this observational program has been the creation of multiannual datasets of dust (and water ice) column opacity with near-global coverage and repeat cycling of approximately two weeks by the Thermal Emission Spectrometer (TES) on Mars Global Surveyor (MGS) and the Thermal Emission Imaging System (THEMIS) on Mars Odyssey [*Smith*, 2004, 2009].

Dust column opacity measurements can provide valuable information about surface radiative balance and the gross structure of meteorological systems associated with dust, but the vertical distribution is more sensitive than column opacity to the mechanisms of dust lifting, transport, and removal. The vertical distribution of dust has been observed by a variety of orbital and surface landed instruments [e.g., *Conrath*, 1975; *Anderson and Leovy*, 1978; *Jaquin et al.*, 1986; *Chassefière et al.*, 1995; *Lemmon et al.*, 2004; *Montmessin et al.*, 2006; *Rannou et al.*, 2006; *Clancy et al.*, 2009], though these observations have not been as systematic (in one way or another) as those that make up the TES and THEMIS column opacity records.

The Mars Climate Sounder (MCS) on Mars Reconnaissance Orbiter (MRO) has been making global, vertically resolved observations of infrared radiance from Mars's limb, nadir, and off-nadir in nine broadband channels sensitive to dust, temperature, and other aerosol (see *McCleese et al.* [2007] for description of the instrument and observing strategy.) Simultaneous retrievals from MCS limb observations of vertical profiles of temperature, dust, and water ice are now available [*Kleinböhl et al.*, 2009]. In terms of length of record, coverage, frequency of repeat cycling, and ability to distinguish dust opacity from water ice opacity; this dataset now should be the vertical analog to the TES and THEMIS column opacity datasets.

Here, we discuss major features of the observed vertical dust distribution from the beginning of MCS science operations during early northern summer of Mars Year (MY) 28 to just after northern summer solstice of MY 30. Interested readers should consult *Heavens et al.* [2010a, 2010b] for methodological details and interpretation.

Density-Scaled Opacity (DSO): Temperature, pressure, and opacity retrievals from MCS observations can be used to calculate the density-scaled opacity (the quotient of opacity and density), which is a good proxy for both the mass mixing ratio and the heating/cooling rates per mass due to dust under optically thin conditions. Since mass-mixing ratio is the quantity conserved in transport processes, the vertical dust distribution will be reported in terms of density-scaled opacity.

Dynamic Range/Uncertainties of the Retrievals: MCS retrievals generally cut off 5—10 km from the surface (or higher), mostly due to uncertainties in modeling of the surface emission and the high likelihood that the limb is optically thick near the surface. Optical thickness of the limb effectively sets the maximum end of the dynamic range (~ $4*10^{-3}$ km^{-1}) of the dust opacity retrievals, which is equivalent to a mass mixing ratio of ~ 3 ppm at the surface of Mars, but note that the limit in equivalent mass mixing ratio increases with altitude as density falls off. So whereas nadir-looking instruments are most sensitive to order unity cloud cover near the surface, MCS limb retrievals are most sensitive to the subvisible hazes farther above the surface. The minimum in the dynamic range of retrieved opacity is set by uncertainties in modeling the radiance contribution of the wings of the instrument field of view and is ~ 10^{-5} km^{-1} (0.75 ppb at the surface), though the analyst should consult the error estimate provided with each retrieved dust opacity profile for further guidance. The presence of aerosol other than dust (such as water ice) and uncertainties in aerosol spectroscopy also will affect the vertical and dynamic range over which dust opacity is retrieved.

The High Altitude Tropical Dust Maximum at Northern Summer Solstice: At northern summer solstice, dust mass mixing ratio is significantly enhanced over the tropics, forming a layer that is 25 km above the local surface near the northern subtropic and 15 km above the surface in the southern tropics (Figures 1a-b). Prescribed forcing schemes used in atmospheric models currently do not account for such a layer (see example in Figure 1c). Models that actively simulate dust lifting and transport generally do not predict the existence of such a layer.

Longitudinal variability in this layer, called the "high altitude tropical dust maximum" (HATDM) is a mixture of wavenumbers 1 and 2. On the dayside, retrievals generally are cut off at high altitudes above the surface but often have higher dust concentrations than on the nightside (Figure 1d). Successful dayside retrievals throughout most of the tropics during this season are likely dustier than average and are likely cut off by high altitudes as limb opacity between 10 and 30 km above the surface increases due to the ascent of seasonal water ice cloud belt with the water vapor saturation level. Dust DSOs similar to those retrieved on the dayside are not retrieved on the nightside. Individual nightside profiles with resolved enhanced layers are shown in Figures 4a-b. Potential diurnal variability within and without the seasonal cloud belt is shown in Figures 4c-f.

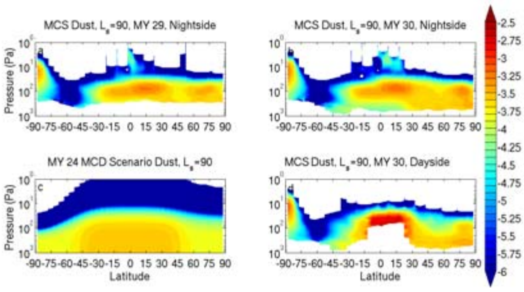

Figure 1: Log_{10} of zonal average dust density-scaled opacity ($m^2\ kg^{-1}$) as labeled.

Interannual Variability During Mid-Late Northern Summer: The evolution of the dust distribution during mid-late northern summer differed between MY 28 and 29. During MY 29, the tropics became abruptly dustier at L_s=140º, as high dust concentrations apparently spread from the southern to northern tropics. By L_s=165º, the dust haze centered over the tropics was latitudinally broader and reached higher in the atmosphere than the previous year (Figures 2a-d). The HATDM at this season during MY 29 is unambiguously narrower and higher in the atmosphere (~ 30—35 km above the surface) than on the nightside, indicating strong diurnal variability in the dust distribution in some (Figures 5a-d), but not all areas (Figures 5e-h).

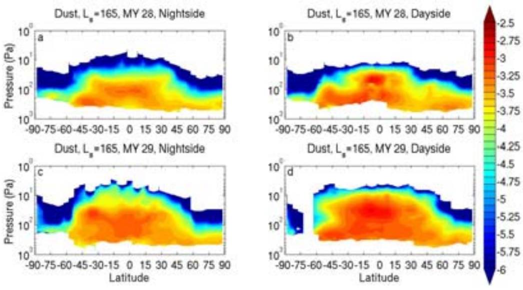

Figure 2: Log_{10} of zonal average dust density-scaled opacity ($m^2\ kg^{-1}$) as labeled.

Variability During Early to Mid Southern Summer of MY 29: As southern fall progressed during MY 29, the tropical dust distribution became more uniform. Dust concentrations at southern summer solstice were high enough that a profile of uniform DSO equivalent to the zonal average DSO at ~15—30 km above the surface would be too optically thick to be retrieved within 15 km of the surface (Figure 3a). Later in the summer, a HATDM formed in the dust distribution on both the dayside and the nightside (Figures 3b-c and 4g-h). At around L_s=315º, a maximum in dust DSO abruptly appeared. This feature peaked in magnitude over the southern extratropics but stretched to the northern tropic.

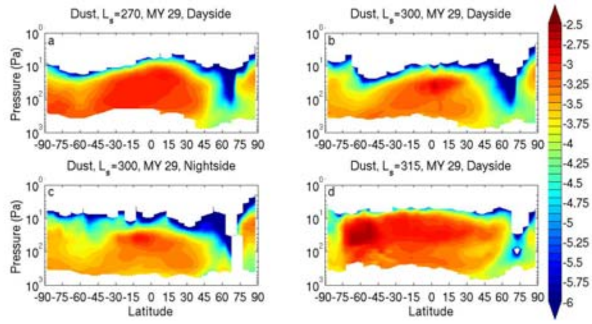

Figure 3: Log_{10} of zonal average dust density-scaled opacity ($m^2\ kg^{-1}$) as labeled.

The Aftermath of the 2007 Global Dust Storm: While conditions during the 2007 global dust storm were mostly too optically thick for successful retrieval (except in the northern extratropics), the retrievals during the clearing phase of the storm show a gradually decaying and vertically broad HATDM. Maxima in individual profiles, however, were barely resolved, suggesting that the dust distribution may have been more uniformly mixed than it appears in Figures 6a-h. These retrievals still can be used to estimate the vertical diffusivity profile of the atmosphere more exactly than *Conrath* [1975].

Summary: The vertical distribution of dust in the Martian atmosphere is highly variable. Before MCS, dust concentrations were expected to be uniform up to some height and then gradually decrease. MCS retrievals suggest that the dust distribution at some latitudes and seasons can contain significant enriched layers at high altitudes above the surface. These layers may have significant diurnal variability, particularly during northern spring and summer.

References: Anderson, E. and C. Leovy (1978), *J. Atmos. Sci.*, *35*, 723-734; Chassefière, E. et al. (1995), *JGR*, *100*, 5525-5539; Clancy, R.T. et al. (2009), *Icarus*, *207*, 98-109; Conrath, B.J. (1975), *Icarus*, *24*, 36-46; Heavens, N.G. et al. (2010a), *JGR*, in press, doi:10.1029/2010JE003692; Heavens, N.G. et al. (2010b), submitted to *JGR*; Jaquin, F. et al. (1986), *Icarus*, *72*, 528-534; Lemmon, M.T. et al. (2004), *Science*, *306*, 1753-1756; Kleinböhl, A. et al. (2009), *J. Geophys. Res.*, *114*, E10006; McCleese, D. J. et al. (2007), *JGR*, *112*, E05S06; Montmessin, F. et al. (2006), *JGR*, 111, E09S09; Rannou, P. et al. (2006), *JGR*, *111*, E09S10.

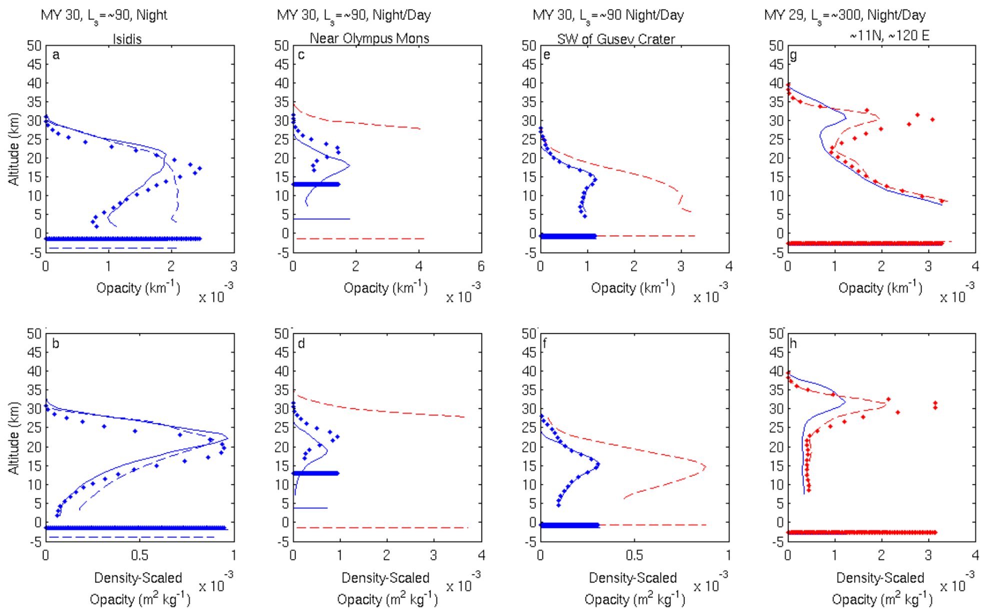

Figure 4: Dust opacity (top panels) and density-scaled opacity (bottom panels) for individual profiles vs. altitude relative to the areoid. Blue traces signify nightside profiles. Red traces signify dayside profiles. Profiles with solid traces are temporally prior to profiles with dashed traces, which are themselves prior to profiles with dotted traces. Horizontal traces with lengths equivalent to the maximum opacity/density-scaled opacity of each profile and colors/shapes corresponding to each profile trace mark the altitude of the local surface for each profile.

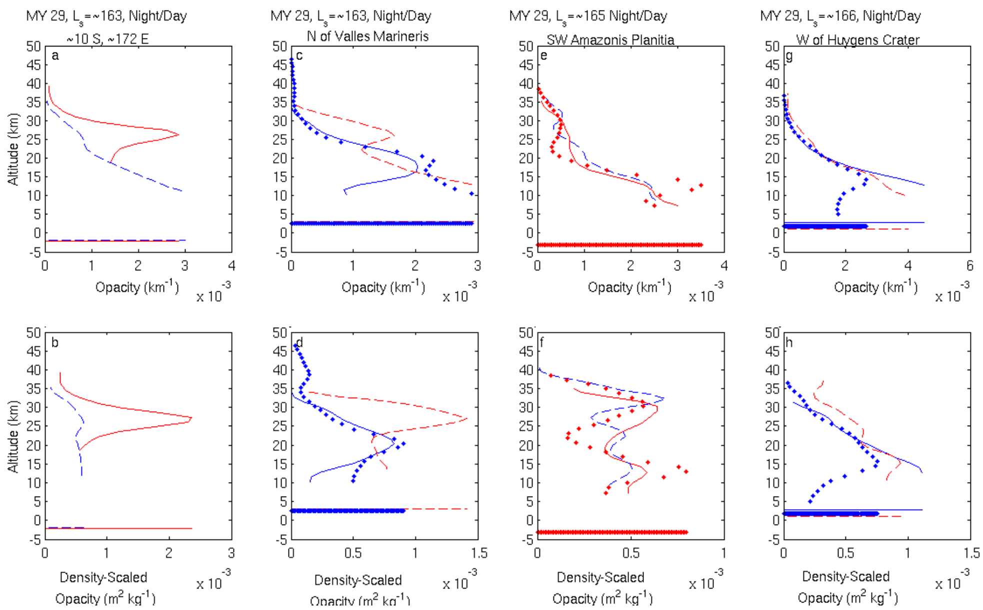

Figure 5: Dust opacity (top panels) and density-scaled opacity (bottom panels) for individual profiles vs. altitude relative to the areoid. The key is identical to Figure 4.

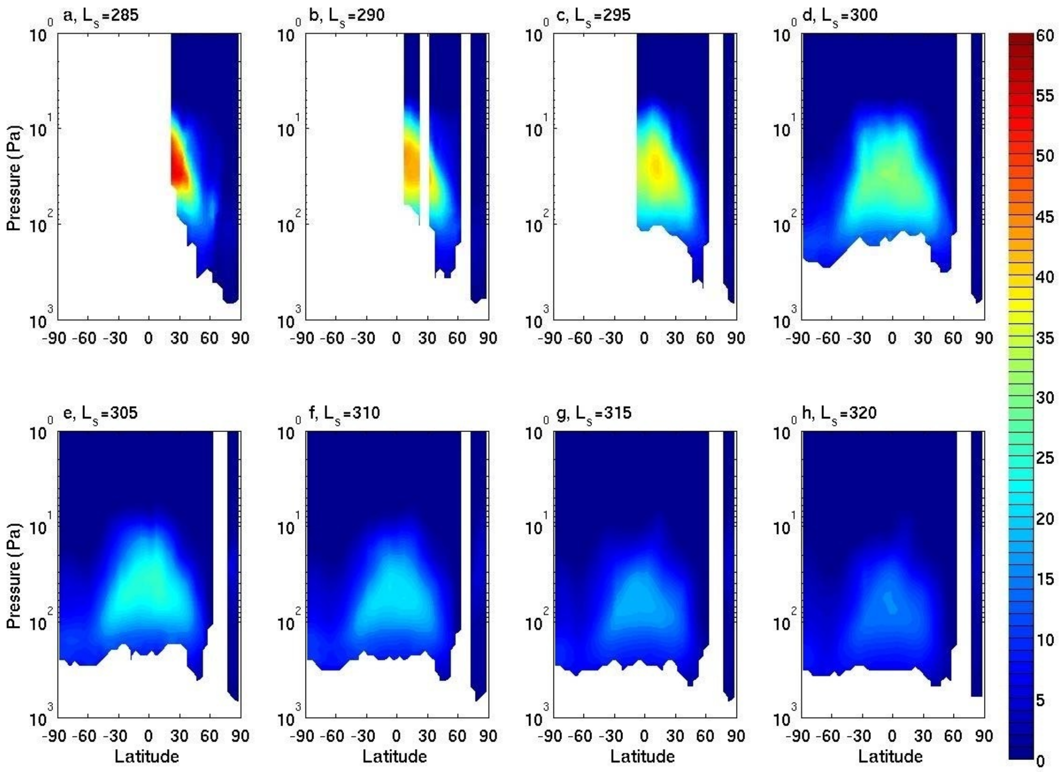

Figure 6: Estimated zonal average dust mass mixing ratio, nightside, MY 28, as labeled on the top of each panel.