AEROSOL PARTICLE SIZES FROM MARS CLIMATE SOUNDER OBSERVATIONS

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Introduction:

Vertical variations in aerosol particle sizes can have a dramatic effect in their net impact on the state and evolution of the Martian atmosphere. Through absorption of solar radiation, aerosols heat the atmosphere by tens of Kelvins, significantly alter the general circulation, and are a key component of the water cycle via cloud nucleation. Changes in the size of aerosol particles will significantly affect their radiative properties and change their ability to heat or cool both the atmosphere and the surface (Ebert and Curry 1992, Tomasko et al. 1999). Due to the diversity of atmospheric processes dependent on aerosol particle size, the very limited nature of current constraints on vertical size profiles represents a large problem.

Dynamical modeling of the Martian atmosphere has reached a level of sophistication such that the vertical variations in aerosol microphysical properties are recognized as fundamentally important in reproducing observed behavior (e.g., Madeleine et al., 2011; Kahre et al., 2008). Although there have been a few promising initial results from Mars Express and Mars Global Surveyor (Montmessin et al., 2006; Clancy et al., 2010), a systematic study of the vertical distribution of aerosol particle sizes is critically needed in order to constrain and validate modern dynamical simulations.

The ~5 km vertical resolution, dedicated atmospheric sounding data collected by the Mars Climate Sounder (MCS) (McCleese et al., 2007), provides the crucial systematic temporal and spatial sampling to investigate the vertical variation of aerosol particle size. The simultaneous acquisition of IR and visible wavelength data by MCS provides the necessary spectral range to constrain aerosol composition (i.e., dust vs. ice) and particle size at altitudes between 10-60 km above the surface.

Data and Methods:

MCS is a nine channel visible and infrared radiometer with limb-staring arrays optimized for atmospheric sounding. The MRO orbit (Zurek and Smrekar, 2007) allows MCS to make radiance observations from pole to pole, in both the morning (3:00) and afternoon (15:00).

The MCS IR A1, A2, and A3 channels are primarily sensitive to emission by CO_2 in the 15 µm absorption band, and thus to temperature. Two of the MCS IR channels, A4 (12 µm) and B2 (42 µm), are sensitive to water ice aerosols in the atmosphere as they are near peaks in the water ice absorption profile for cloud particles. In both channels, the ice is primarily absorbing, although there is a significant scattering contribution as well. Another two IR channels, A5 (22 µm) and B1 (32 µm) are sensitive to dust, with A5 near the peak and B1 on the shoulder of the long wavelength dust spectral feature. The solarband channel (A6) is sensitive to scattered sunlight from aerosol hazes, especially dust and water ice. The combination of A6 with A5 and B1 provides significant dust particle size sensitivity in the daytime (see Figure 1, right). A6 also provides water ice particle size sensitivity to small particles when combined with A4 and B2 (see Figure 1, left). The solarband channel has been calibrated recently by Bandfield et al. (2013) using a combination of CRISM and MARCI contemporaneous observations.

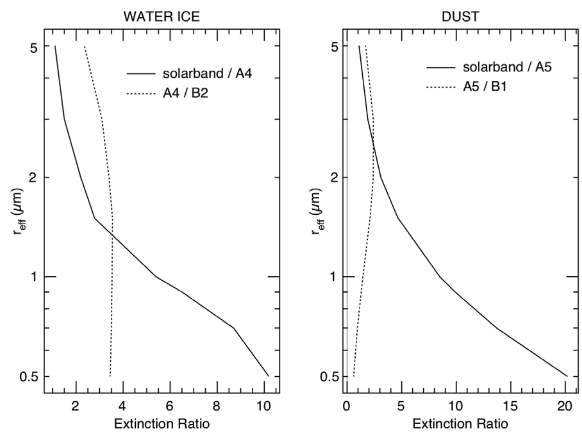

Figure 1*: (left) Water ice particle size (effective radius) vs. the ratio of extinction cross section for channels A4/B2 and solarband/A4. (right) Dust particle size vs. the extinction ratio for channels A5/B1 and solarband/A5. By using a ratio of retrieved extinction in two channels, the particle size of dust and water ice aerosols can be retrieved.*

The MCS team retrieval algorithm fails to retrieve temperature and aerosol profiles in cases of moderate to high aerosol opacity, especially during the day (Kleinböhl et al., 2009, 2011; Benson et al., 2010; Heavens et al., 2011). The absence of retrievals during dust storms and within the ACB significantly limits the ability to investigate aerosol particle size during the most relevant and interesting periods and when particle size may be the most variable. Because of this, and in order to achieve a self-consistent retrieval of temperature, aerosol, and particle size, we have developed our own independent temperature and aerosol retrieval algorithm.

Aerosol scattering is important for the MCS IR channels used for temperature retrieval and we include full multiple scattering in our radiative transfer (RT) model. In addition, the limb-viewing geometry requires that the spherical geometry inherent in the observations also be explicitly treated. A fully spherical RT code with multiple scattering is extremely computationally expensive. However, we have developed and validated a highly accurate forward RT code that fully treats multiple scattering and accounts for spherical geometry in an approximate way that allows for relatively rapid retrievals. The code has been extensively tested and validated against an "exact" Monte Carlo RT code and found to be accurate within a few percent over a wide range of conditions and viewing geometries.

The forward RT model uses the discrete ordinates method to treat scattering (e.g., Thomas and Stamnes, 1999). This is the same approach used by the popular DISORT radiative transfer package. In our code the atmosphere is divided into vertical layers, and the number of radiation "streams" can be set as high as necessary to accurately model the angular dependence of scattering. We use 100 layers, each 0.1 scale heights (~ 1 km) thick, and 4 streams (2 pairs) to describe the radiation field. Atmospheric state variables (temperature, gas abundance, aerosol abundance, aerosol scattering properties, etc.) can be specified separately for each vertical layer. Gas absorption is handled using the correlated-k approximation (Lacis and Oinas, 1991) with gas absorption coefficients taken from the most recent HITRAN database.

The forward scattering properties and phase functions are pre-computed for both dust and water ice particles as a function of r_{eff} and wavelength. The effects of particle shape are not particularly important in the thermal IR [e.g., *Wolff et al*., 2006], however, we use a droxtal to represent the shape of ice particles [Yang *et al*., 2003], and we adopt the refractive indices of *Warren and Brandt* [2008]. The size distribution is specified using a gamma distribution and the assumption of a distribution variance (v_{eff}) of 0.1 [i.e., *Wolff and Clancy,* 2003]. We employ the aerosol model of *Wolff et al.* [2009] that represents dust as a cylinder with an axial ratio of unity and refractive indices derived from a combination of MRO and Mars Express observations. The dust size distribution is a gamma distribution, with the assumption of a v_{eff} of 0.3.

Our temperature retrieval algorithm uses MCS IR radiance observations from the A1, A2, and A3 channels to determine the temperature between the surface and ~60 km. TES climatology values are used for surface temperature, which are retrieved from TES nadir spectra at the same season and location in an earlier Mars year. We use a TES climatology atmospheric temperature profile as a first guess. The retrieval finds the model parameters (atmospheric temperature profile, aerosol extinction profiles, and surface pressure) that provide a "best fit" in a chi-squared sense between the observed data (radiance as a function of height above the limb) and the radiance computed from the forward RT model.

We employ a three-stage retrieval process in order to determine the aerosol particle sizes. First we iterate between dust, water ice, and temperature using the MCS IR channel radiances to retrieve a self-consistent temperature profile and dust and ice extinction profiles. We then use those retrieved quantities to calculate the "best-fit" to the MCS solarband channel. Finally we use the ratio of the solarband-IR optical depths to derive the particle size.

Results:

Figure 2 shows a comparison of temperatures retrieved using the retrieval method described here (BSW-Benson, Smith, Wolff - retrieval) to those of the MCS team retrieval. The BSW retrieval in this figure includes no aerosol in the temperature retrieval. Even in this case, the agreement between the BSW retrieval and the MCS retrieval is quite good in most places. Using the BSW retrieval method, we are able to fill in the regions of critical interest where the MCS team retrieval is unsuccessful. The most noticeable temperature difference between the two retrievals occurs near the surface at night (top panels), where the MCS temperatures are higher than the BSW temperatures by about 10 K. However, inclusion of aerosols in the BSW method accounts for this discrepancy and the overall agreement is improved, as seen in Figure 3. The black profiles in Figure 3 include no aerosol in the temperature retrieval, corresponding to the top left panel in Figure 2. The red profiles include both dust and ice aerosol in the temperature retrieval. The blue profiles show the MCS team retrieved profiles at the same location.

Figure 4 shows the model fit to the MCS radiances from A5, B1, and A6 using the retrieval methodology described above for an observation at Ls=3°. The data from Figure 4 are converted to optical depth per unit length (extinction). Figure 5 shows the retrieved dust extinction as a function of height for the A5 and A6 channels. Using the ratio A6/A5 along with the calculations shown in Figure 1 enables particle size to be retrieved. Here we find a gradient in dust particle size from 0.8 μm at 30 km to 2 μm at 10 km.

We will present additional results of the application of our particle size retrieval scheme for dust and water ice.

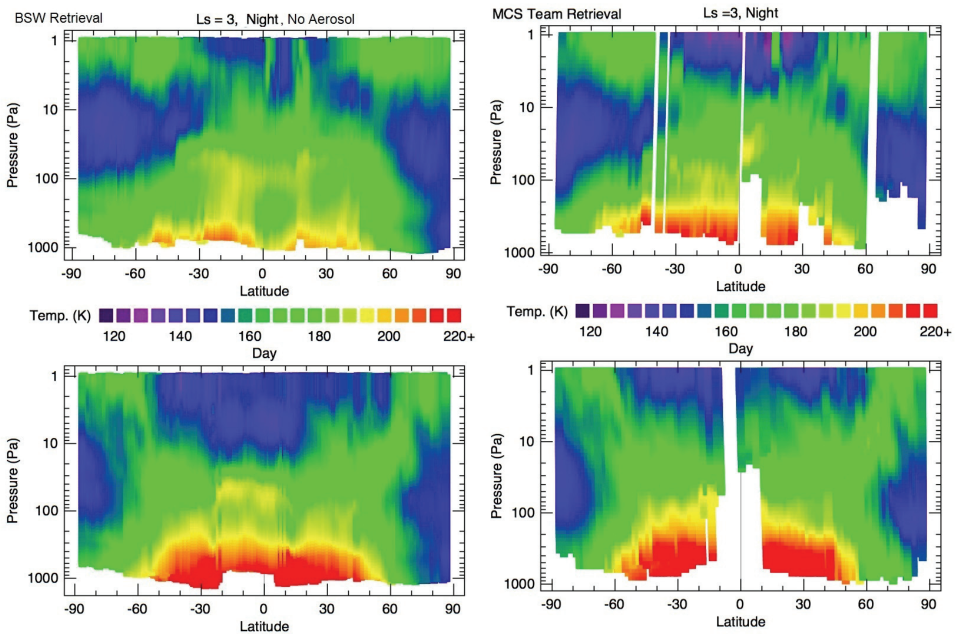

***Figure 2**: Temperature cross-sections as a function of latitude and pressure at L_S=3°. **Left**: BSW (Benson, Smith, Wolff) retrieval at night (top) and day (bottom). **Right**: MCS team retrieval. Because we include full multiple scattering, our (BSW) retrieval fills in the regions of critical interest(daytime equatorial) where the MCS team retrieval is unsuccessful.*

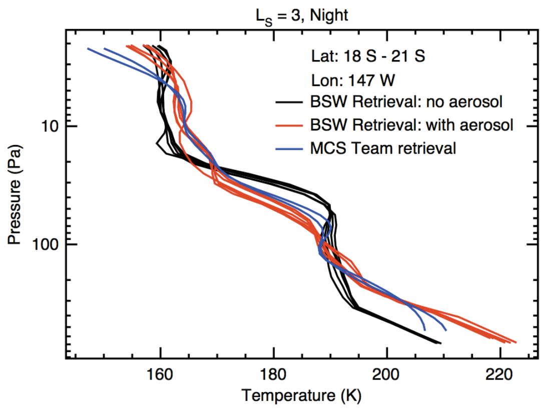

***Figure 3**: Temperature profiles retrieved using the BSW method at L_S=3° at night. **Black**: Temperature profiles with no aerosol included in the BSW temperature retrieval, corresponding to the top left panel of Figure 2. **Red**: Temperature profiles with aerosol included in the BSW temperature retrieval. **Blue**: MCS team retrieved temperature profiles in the same location. The overall agreement between the BSW method with aerosol and the MCS Team is quite good.*

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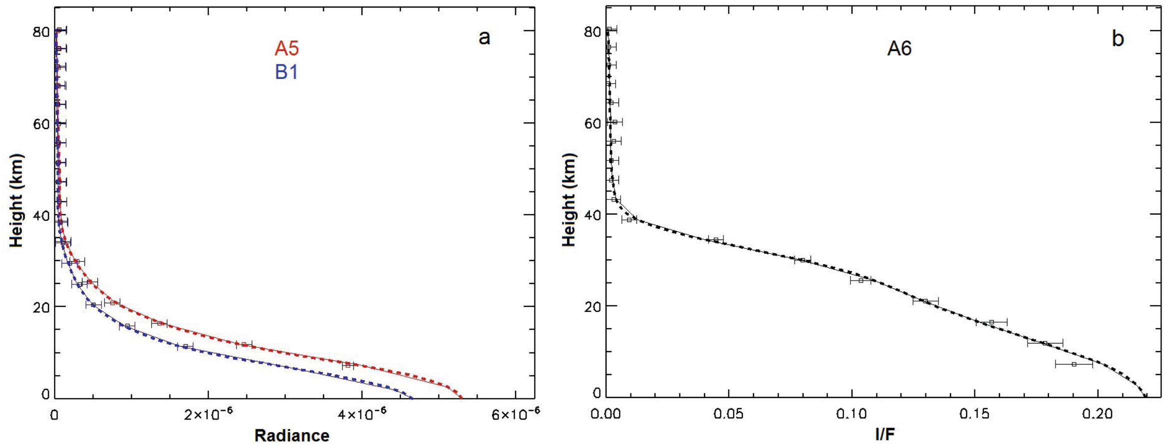

Figure 4*: Fit to the MCS radiances. The points are the MCS observations and the dotted lines are the model fits sampled at observation heights. Observation at L_S=3° (day), 29° N, 45° E. (a) A5 (red) and B1 (blue) radiance and best fit as a function of height. (b) A6 solarband I/F and best fit as a function of height. Our retrieval is able to provide excellent fits to the observed MCS data.*

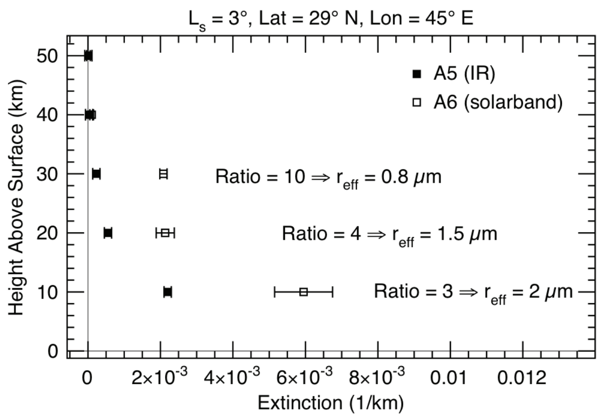

Figure 5*: Retrieved dust extinction as a function of height (km) at L_S=3° (day), 29° N, 45° E.* ***Filled box****: retrievals with A5 (22 μm) using the BSW method.* ***Open box****: retrievals with A6 (solarband) using the BSW method. The ratio A6/A5, with the calculations shown in Fig.1, enables particle size to be retrieved.*