

**MASS EJECTED FROM MARTIAN DUST DEVILS AS A FUNCTION OF HEIGHT AND DUST DEVIL MORPHOLOGY.** N. W. Hall<sup>1</sup> and M. T. Lemmon<sup>2</sup>, <sup>1</sup>Dept. of Atmospheric Science, Texas A&M University (nhall@ariel.met.tamu.edu), <sup>2</sup>Dept. of Atmospheric Science, Texas A&M University (lemmon@tamu.edu).

**Introduction:** An important question in the study of the Martian atmosphere is how much dust is added to the atmosphere by dust devils. In this study we examine images of dust devils from the Mars Exploration Rover (MER) mission to determine the upward mass flux of dust in the Martian atmosphere, due to dust devil activity, as a function of height. Thus, we find expressions for both the quantity of dust lifted from the surface by dust devils and the height distribution of its exit from the vortices. We also examine the morphology of dust devils imaged by the rovers to determine whether it correlates significantly with upward dust mass flux or the height distribution for dust devil mass loss to the atmosphere.

**Discussion:** *Data and observations.* The data set is comprised of images taken by the *Spirit* and *Opportunity* cameras between sols 455 and 715. Each imaged dust devil is examined by hand to find its width at three points: its intersection with the ground, the horizon, and the top of the visible disturbance, all in pixels. The height of each dust devil, as well as all observed dust devil genesis and dissipation events are also recorded. Each continuous dust devil is numbered so that the resultant data can later be sorted by individual dust devil identity or any of the measured characteristics. The distance of the dust devil from the camera is estimated by use of landmarks in the surrounding terrain as described by Greeley et. al. [1]. Given the distance from the camera, all the lengths measured above in pixels can be given in meters.

*Analysis of dust devil geometry.* This information is fitted to an assumed quasicircular shape passing through the three heights at which dust devil width is measured, generating a unique estimated geometry for each dust devil observation. The geometry of each dust devil is parameterized by deviation from that of a cylinder with the same height as the dust devil and the same diameter as the observed width of the dust devil at the surface.

*Estimation of dust devil mass and vertical velocity distributions.* Material in dust devils usually appears lighter than the material on the ground and darker than the background radiance of the Martian sky. The optical depth of the dust may be determined by comparison to these background states. While the optical properties of dust particles are likely to vary somewhat with the terrain over which a dust devil

passes, estimates are available for the relationship between the optical depth of a pixel and the mass of dust interposed between the camera and the edge of the atmosphere, or the ground, respectively.[1] In our study, these optical depths are averaged horizontally and evaluated vertically. This process yields a continuous vertical distribution of dust devil mass at the time of each examined photograph, running from the ground to the top of the disturbance—a plot of  $M$  against  $z$ .

Renno et al. [2] and Ferri et al. [3] have modeled the updraft velocities within Martian dust devils to be near 15 m/s and 20 m/s respectively. Greeley et al. have subsequently described a process for determining vertical velocities in Martian dust devils by tracking the progress of identifiable features from one image to the next.[1] We use a variation on this idea. For this analysis, we simplify the situation by assuming that the dust particles are small enough that they follow the flow in which they are embedded, and that the upward velocity in each dust devil is constant. When subsequent images of the same dust devil are available, we perform the analysis described above to get a second snapshot of the vertical mass distribution. The vertical mass distribution at each time should have irregular peaks and valleys which move upward within the disturbance at some constant speed. This information, together with knowledge of the time elapsed between images, would allow for an estimation of upward velocity in an observed dust devil by charting the progress of such irregularities in the curve. Rather than rely on a few specific identifiable features, however, we take advantage of the fact that our mass distribution is continuous by simply displacing the mass distribution from the latter image downward until it is in best agreement with that of the former. The length of the displacement needed to achieve this yields the vertical velocity. From the vertical velocity and mass distribution, we may determine the vertical mass flux through any horizontal cross section of the dust devil. We can also find out the quantity of ‘new mass’ that has entered the dust devil between images, which is just the mass contained in the dust devil below the height given by the applied displacement.

*Determination of mass ejected from the vortices per unit time as a function of height.* It is expected that mass enters dust devils near their bases and exits them at higher altitudes. Thus their vertical mass

distributions tend to attenuate with height. For each dust devil there is some attenuation function that describes mass loss through the sides of the dust devil column into the atmosphere. We use the conservation of mass to determine this function, given vertical velocities and at least two images for each dust devil.

Suppose that a dust devil is imaged at times  $T1$  and  $T2$ , yielding vertical mass distributions  $M1$  and  $M2$  and vertical velocity  $V$ . Since mass is conserved, the mass flux to the atmosphere between  $T1$  and  $T2$  is the difference between the observed mass distribution  $M2$  and the mass distribution that would have obtained if no loss to the atmosphere had taken place,  $M2^*$ .  $M2^*$  may be determined by simply shifting  $M1$  upward along the z-axis a distance  $V \times (T2-T1)$ . The mass flux through the side of the dust-devil column over the time interval is then found by subtracting  $M2^*$  from  $M2$  (after integrating the distributions over z to get total mass rather than a mass distribution).

In our measurements we have already averaged mass horizontally, so changes in optical depth due to widening or narrowing of the dust devil column, either with height or over time, are accounted for. However, even assuming constant overall vertical velocity within the dust devil, there is likely to be some relaxation in the mass distribution with height due to diffusive forces. A corrective factor may be applied to  $M2^*$  to account for this.

With multiple successive images of the same dust devil, it is possible to use this technique to reconstruct the rate of mass ejection as a function of height. This is done by observing a selected region of the dust devil as it proceeds upward over several time increments. After calculating the vertical velocity, we can then determine the mass lost over each time interval by the method described above. Since we know the height of the selected region at the time of each measurement from the vertical velocity, we also know over what interval in vertical space the mass was lost. The uncertainty of this result depends on the number and frequency of images used.

*Correlation of mass loss to cylindrical and non-cylindrical morphologies.* It is possible that the height distribution of dust devil mass loss to the atmosphere is related to the geometry of the dust devil. To investigate this possibility, the dust devils examined in this study are characterized by their deviation from the cylindrical shape. We determine the degree of correlation between deviation from a cylinder and vertical velocity, as well as the mass attenuation factor.

**Summary:** Numerous Martian dust devils are analyzed to determine their size, morphology and density distributions. The vertical velocity of dust

particles in dust devils is estimated. The conservation of mass is utilized to develop an expression for the density distribution of dust leaving Martian dust devils and entering the general atmosphere as a function of height. These results are compared to other estimates of the dust distribution due to dust devils. An analysis is also carried out to determine whether dust transport varies as a function of dust devil morphology in terms of deviation from the cylindrical shape. A data set containing dust devil heights, geometries, and optical contrast levels is provided for future work in the field.

**Future Work:** *More complete analysis of the morphology dependence.* The categorization of dust devil geometry only in terms of deviation from a cylindrical shape is probably too imprecise to fully express the dependence of the mass transport characteristics of dust devils on their morphologies. Dust devils vary not only in overall shape, but in mass and velocity distributions within the bounds of the observed shape. Further studies may attempt a more more rigorous analysis of dust-devil morphology and how it changes.

*Determination of settling velocities.* Once the amount of dust entering the atmosphere due to dust devil activity is determined, the next logical question is how long it takes for the dust to settle out. Future studies may use the optical properties of dust devils, along with an analysis of the source regions of their particles, to estimate the settling velocities of particles ejected from them. Once good estimates of mass transport and settling rates are available, the concentration of dust in the Martian atmosphere due to dust devils may be determined.

**References:** [1] Greeley, R., P. L. Whelley, R. E. Arvidson, N. A. Cabrol, D. J. Foley, B. J. Franklin, P. G. Geissler, M. P. Golombek, R. O. Kuzmin, G. A. Landis, M. T. Lemmon, L. D. V. Neakrase, S. W. Squyres, and S. D. Thompson (2006), Active dust devils in Gusev Crater, Mars: observation from the Mars Exploration Rover, Spirit, *J. Geophys. Res.*, doi:10.1029/2006JE002743. [2] Renno', N. O., A. A. Nash, J. Lunine, and J. Murphy (2000), Martian and terrestrial dust devils: Test of a scaling theory using Pathfinder data, *J. Geophys. Res.*, 105(E1), 1859-1866. [3] Ferri, F., P. H. Smith, M. Lemmon, and N. O. Renno' (2003), Dust devils as observed by Mars Pathfinder, *J. Geophys. Res.*, 108(E12), 5133, doi:10.1029/2000JE001421.