DUST DEFLATION BY DUST DEVILS ON MARS DERIVED FROM OPTICAL DEPTH MEASUREMENTS USING THE SHADOW METHOD IN HIRISE IMAGES.

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Introduction: Dust devils are convetive vertical vortices that lift dust from the surface and thus become laden with airborne dust [e.g., 1]. The martian atmosphere contains a global haze and [2] estimated that as much as half of this haze consists of dust lifted into the atmosphere by dust devils. In this study, we measured the optical depth of three separate dust devils with the so called 'shadow method' [3]. These optical depth measurements were used to calculate their dust loads. Then, assuming reliable upper and lower boundary values for the vertical speeds inside these three dust devils, we calculated upper and lower boundaries for their dust fluxes. Two of the analyzed dust devils left continuous dark tracks on the surface. For these dust devils we were able to calculate how much dust was removed using the calculated dust fluxes in combination with measured horizontal speeds.

Methods: The background optical depth of the Martian atmosphere is considerable, commonly in the range 0.3-1.0. Dust devils can raise the optical depth locally. Obviously, the local optical depth change that the dust devil creates can only be mapped with an optical depth retrieval method that can work on spatial scales that are smaller than the dust devil itself. Therefore we use the so-called “shadow-method” for our analysis. It can estimate optical depths from shadows if these are larger than about ten pixels. The shadow-method works best if the sun is not too high in the sky (below some 35°-45° above the horizon) and with images that have a very high spatial resolution (better than about a meter per pixel) as offered by HiRISE because in such images the Martian surface shows shadows frequently; e.g., behind large boulders. The “shadow-method” and its application for this study is decribed in detail in [3, 4]. We derived optical depths of dust devils from satellite imagery. To calculate the dust flux (F) for an individual dust devil, we used a slightly modified approach of [5] – which takes into account the vertical structure of the dust devil:

$$F = u_z V_d^{-1} M_t,$$

where

$$M_t = (2/3)\, r_{eff} A_d \rho \Delta\tau,$$

where u_z is the vertical speed within the dust devil, V_d is the volume of a conical vortex of a dust devil, and M_t is the total mass of dust lofted by a dust devil which relates mass to optical depth [6, 7], where r_{eff} is the effective particle radius ~1.5×10^{-6} m [e.g., 8, 9], A_d is the surface area of a dust devil, ρ is the dust grain density ~3000 kg m^{-3}, and $\Delta\tau$ is the measured optical depth of a dust devil minus the measured background optical depth. Most parameters used in the equations are reasonably well known or can accurateley measured. The most uncertain parameter is the vertical speed (u_z) within the individual dust devils, which cannot be measured directly from satellite imagery and has a large effect on the calculated dust fluxes. Therefore, we assumed minimum and maximum vertical speeds in the range of 0.1 – 10 ms^{-1} based on terrestrial and martian dust devil vertical speed measurements.

Results: *Optical depths.* Optical depths inside the dust devil and in its surroundings were measured using the shadow method. Fig. 1 gives an overview of the derived optical depth measurements inside the dust devils. Table 1 summarizes the dust opacity values taken from inside and outside the dust devils.

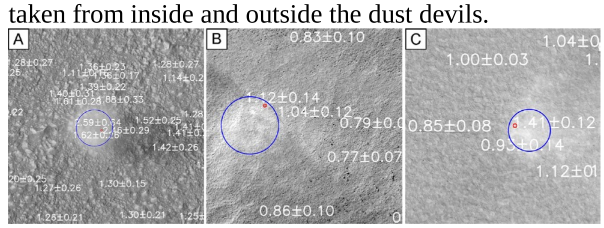

Figure1. Derived dust opacities inside the dust devils (A: PSP_004285_1375; B: ESP_13545_1110; C: ESP_016306_2410). The small red circles show the location where dust opacities inside the dust devil column were measured and used in the dust load calculations. The large blue circles indicate the diameter of the dust devils (175 m, 115 m, and 75 m, respectively).

Image ID	τ_d	τ_b	τ_{dd}
PSP_004285_1375	2.46 ± 0.29	1.26 ± 0.09	1.20 ± 0.38
ESP_013545_1110	1.12 ± 0.14	0.83 ± 0.04	0.29 ± 0.18
ESP_016306_2410	1.41 ± 0.12	0.85 ± 0.04	0.56 ± 0.16

Table 1. Used optical depths within the dust devils (τ_d) and for the background dust opacity (τ_b). Dust devil opacity (τ_{dd}) were used for the dust load calculations.

Dust loads and fluxes. Dust loads were calculated using the derived dust devil opacity (τ_{dd}) (Table 1). Based on the error of τ_{dd} we calculated minimum and maximum dust loads of the dust devils. Our calculated dust loads range from 63.4 – 122.1 mg m^{-3} (PSP_004285_1375), from 3.8 – 16.2 mg m^{-3} (ESP_013545_1110), and from 32.3 – 58.1 mg m^{-3} (ESP_016306_2410). As discussed earlier, the calculation of dust fluxes is uncertain because the vertical speed of the dust devils is unknown. Based on terrestrial and martian measurements of dust devil vertical speeds we can assume that the vertical speeds should be in the range of 0.1 – 10 ms-1. Therefore, we calculated minimum dust fluxes using minimum values of dust load and u_z of 0.1 ms^{-1}, and maximum dust fluxes using maximum values of dust load and u_z of 10 ms^{-1}. Our calculated dust fluxes range from 6.3 – 1221 mg m^{-2} s^{-1} (PSP_004285_1375), from 0.38 – 162 mg mg m^{-2} s^{-1} (ESP_013545_1110), and from 3.2 – 581 mg m^{-2} s^{-1} (ESP_016306_2410).

Dust deflation. Calculated dust fluxes in combination with the measured horizontal speeds [see 4, 10] enable us to constrain how long the dust devil needed to cross a specific point of the surface [11] hence the dust deflation of individual dust devils. Interestingly, both dust devils of which horizontal ground speeds are known left surface tracks (dust devil tracks) on the surface (Fig. 2). This gives us new insights about the amount of dust removal necessary for the formation of dust devil tracks. The dust devil in ESP_013545_1110 has a diameter of 115 m and a horizontal ground speed of 4.8 ± 1.6 ms^{-1}. It would need to cross a given spot on the surface in ~18 – 36 seconds. For the calculation of the minimum dust deflation we used the calculated minimum dust load, a minimum vertical speed (u_z = 0.1 ms^{-1}) and the maximum horizontal ground speed (6.4 ms^{-1}). To calculate the maximum dust deflation we used the calculated maximum dust load, a maximum vertical speed (u_z = 10 ms^{-1}) and the minimum horizontal ground speed (3.2 ms^{-1}). Under the assumption that the density of the surface material is 3000 kg m^{-3} the dust deflation is in the range of 0.002 – 1.94 µm. Using the same method for the dust devil in ESP_016306_2410 results in a dust deflation in the range of 0.004 – 2.24 µm. This implies that a removal of < ~2 µm of dust (or about one monolayer) from the surface is sufficient for the formation of dust devil tracks.

Discussion: Two of the dust devils that we studied left clear dark dust devil tracks and for those we found rather low dust deflation of an equivalent layer thickness of about < 2 µm. This is in agreement with the results from numerical modeling of dust devil track generation on Mars by [12], who found that around 1.5 µm was removed from the majority of the simulated dust devil track area. Furthermore, our results are in agreement with sediment deflation by dust devils on Earth where the removal within dust devil tracks correspond to an equivalent layer of 1– 2 µm [13, 14]. However, these results are not directly comparable because the removed particles on Earth had sizes in the range 4–70 µm in diameter [13], while removed dust sizes on Mars are around 3 µm in diameter (e.g., 8, 9). Nevertheless it illustrates that the removal of a very thin layer of dust can lead to albedo changes on both planets. The removal of thin dust layers leading to albedo changes are also in agreement with laboratory measurements of [15], who found that the deposition (or removal) of very thin layers of dust can change the surface albedo drastically.

Figure 2. Dust devils with associated tracks (A: HiRISE IRB image ESP_013545_1110; B: HiRISE RED/IRB image ESP_016306_2410).

Conclusions: Optical depth measurements with the shadow method in HiRISE images of three individual dust devils and their surroundings resolve horizontal variations in the optical depth on scales of only tens of meters. The shadow method can be used when the optical depth is less than about 1.5 – 2.0. Optically thick features cannot be measured with the shadow method. Conservative calculations of the dust loads and fluxes of three dust devils based on the measured optical depths are in agreement with previously measured dust loads and fluxes of dust devils on Mars and Earth. Two of the three measured active dust devils left a track behind its passages. Our calculations indicate that a removal of an equivalent layer of less than 2 µm (or less than one monolayer) can be sufficient for the formation of dust devil tracks on Mars.

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