Planetary and Space Science 93-94 (2014) 54–64

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Dust deflation by dust devils on Mars derived from optical depth measurements using the shadow method in HiRISE images

D. Reiss [a,*], N.M. Hoekzema [b], O.J. Stenzel [b]

[a] Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany
[b] Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

ARTICLE INFO

Article history:
Received 6 November 2013
Received in revised form
15 January 2014
Accepted 17 January 2014
Available online 31 January 2014

Keywords:
Mars
Dust devil
Dust devil track
Erosion
Deflation

ABSTRACT

We measured the optical depth of three separate dust devils and their surroundings with the so called "shadow method" in HiRISE images. The calculated optical depths of the dust devils range from 0.29 ± 0.18 to 1.20 ± 0.38. Conservative calculations of the minimum and maximum dust loads are in the range of 4–122 mg m^{-3}. Assuming reliable upper and lower boundary values of vertical speeds within the dust devils between 0.1 and 10 ms^{-1} based on terrestrial and Martian studies we derived dust fluxes in the range of 6.3–1221 mg m^{-2} s^{-1} (PSP_004285_1375), from 0.38–162 mg m^{-2} s^{-1} (ESP_013545_1110), and from 3.2–581 mg m^{-2} s^{-1} (ESP_016306_2410) for the three dust devils. Our dust load and dust flux calculations for the three dust devils are in good agreement to previous studies. Two of the analyzed dust devils left continuous dark tracks on the surface. For these dust devils we could calculate how much dust was removed by using the minimum and maximum dust fluxes in combination with measured horizontal speeds of these dust devils. Our results indicate that a dust removal of an equivalent layer of less than 2 μm (or less than one monolayer) is sufficient for the formation of dust devil tracks on Mars. This value might be used in future studies to estimate the contribution of dust devils to the global dust entrainment into the atmosphere on Mars.

1. Introduction

Dust devils are whirlwinds (i.e., vertical vortices) that lift dust from the surface and thus become laden with airborne dust. Such whirlwinds occur on both Earth and Mars (e.g., Balme and Greeley (2006)). On Earth, dust entrainment by dust devils usually occurs in semi-arid and arid regions and its significance is not well constrained. Koch and Renno (2005) estimated that dust devils and convective plumes contribute about 35% to the global amount of airborne mineral dust (almost 15% of the global aerosol budget). Dust devils are probably even more important on Mars because it is a hyperarid desert planet. The Martian atmosphere contains a global haze and Whelley and Greeley (2008) estimated that as much as half of this haze consists of dust that was lifted into the atmosphere by dust devils. This global haze has a strong influence on the Martian climate because it largely determines how much solar insolation is absorbed in the atmosphere and how much reaches the surface, and what fraction reaches the surface in a direct beam and what fraction reaches it as a diffuse illumination from the reddish Martian sky. The global reddish haze has a strong influence on the observed colors and it reduces contrasts in space images. Furthermore, the frequent occurrence of dark surface tracks caused by passing dust devils significantly lower the surface albedo of larger regions (e.g., Balme et al. (2003), Geissler (2005), Whelley and Greeley (2006)) which affects large-scale weather patterns and recent climate change on Mars (Fenton et al., 2007).

There are many parameters that have to be determined with some accuracy before one can estimate how much dust devils contribute to the global dust entrainment compared to other processes such as dust storms. Obviously, their contribution depends on dust fluxes, size–frequency distributions, and durations. None of these parameters are well known, although many recent studies have improved our knowledge (e.g., Greeley et al. (2006, 2010), Lorenz (2009, 2011, 2013), Pathare et al. (2010), Reiss et al. (2011a)). The dust load of a dust devil can be estimated from its optical depth. Thomas and Gierasch (1985), Cantor et al. (2006), and Towner (2009) measured such optical depths from satellite images of Mars while Metzger et al. (1999) and Greeley et al. (2006, 2010) used rover images acquired on the surface. Dust fluxes are calculated by multiplying the dust load with the vertical speed of the dust devil. However, vertical speeds of dust devils are difficult to constrain without in situ measurements. So far, only estimates of the minimum speeds were obtained for about 100 dust devils by tracking the motion of small "dust clots" within individual dust devils in sequential rover camera images on Mars (Greeley et al., 2006, 2010).

* Corresponding author. Tel.: +49 251 83 39068; fax: +49 251 83 36301.
E-mail address: dennis.reiss@uni-muenster.de (D. Reiss).

0032-0633/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2014.01.016

Another way to measure the global dust entrainment by dust devils on Mars is the statistical analysis of dust devil tracks (Balme et al., 2003; Whelley and Greeley, 2008). The passage of a dust devil can leave a continuous track of decreased albedo on the surface. However, in some cases the low albedo track is characterized by a cycloidal pattern suggested to be formed by redeposition of sands (Reiss et al., 2013) or the albedo increases (bright tracks) (e.g., Malin and Edgett (2001), Reiss et al. (2011b)). Most dust devil tracks on Mars show a continuous, dark track and such albedo changes may happen when the passing dust devil removes the topmost layer of dust and thus exposes a darker substrate as proposed by Grant and Schultz (1987) and Malin and Edgett (2001). In situ studies of such dust devil tracks by the MER rover Spirit in Gusev crater on Mars (Greeley et al., 2005) and on Earth (Reiss et al., 2010) indicate that dust devils cleaned away most of the topmost layer consisting of fine dust, thus exposing a coarser grained substrate (coarse sands). This changes the photometric properties of the surface, hence the albedo. Balme et al. (2003) used dust devil track densities from two regional mapping areas to estimate the contribution to the global dust entrainment on Mars based on dust devil parameters from previous studies of Metzger et al. (1999). Whelley and Greeley (2008) used global track densities in combination with calculated dust fluxes from Greeley et al. (2006) to estimate the global dust entrainment.

In this study, we measured the optical depth of three separate dust devils with the so called "shadow method" (Hoekzema et al., 2011). 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. The vertical speeds are based on terrestrial measurements and measurements from the Martian surface. Two of the analyzed dust devils left continuous dark tracks on the surface. For these dust devils we could calculate how much dust was removed by using dust fluxes in combination with the horizontal speeds that we measured for these dust devils. The ranges that we found for the dust fluxes and the thicknesses of the removed surface layer can be used in future studies to estimate the contribution of dust devils to the global dust entrainment on Mars.

2. Methods and background

2.1. Optical depth derivation

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 and behind cliffs in the rims of small fresh craters.

The shadow method was used for the first time by Markiewicz et al. (2005). The concept is simple: under a clear sky there is a large brightness difference between sunlit regions and shadowed ones, but with increasing optical depth of the overlying atmosphere this difference gets smaller. The conversion of this difference in brightness into an optical depth is what we name the "shadow method". Petrova et al. (2012) demonstrated that it is sometimes possible to do this conversion accurately. However, this is not at all trivial. One needs to know: the albedo, the bidirectional reflection properties of the surface, the local surface topography, the distribution of diffuse illumination from the sky, which part of the sky is visible in the shadow and which part is visible in the sunlit comparison region. For most available images of Mars many of these parameters are not known.

Therefore we here use a simple version of the shadow method. It only requires more readily available inputs because it makes several rough assumptions. The shadow method that we use is in the first order a fit that gives an empirical relation between optical depth and the difference in brightness between sunlit and shadowed regions. Hoekzema et al. (2011) found that the absolute accuracy of each good measurement is probably around ±15% (or ±8–10% in ideal cases) for images taken in colors between yellow and red. Most of this error is systematic; usually the relative error appears to be smaller. The shadow method can thus be used to map variations in optical depth of more than 5–10% within a good image.

For the simple version of the method we make several assumptions: (i) the surface is Lambertian; (ii) the atmosphere has the same scattering properties above shadowed and above sunlit comparison regions; (iii) all pixels in an analyzed pair of shadowed and sunlit comparison regions receive the same amount of diffuse radiation from the sky; (iv) the albedo of the surface is approximated with the measured TOA albedo (Top Of Atmosphere albedo); (v) the atmosphere has the same optical depth above all pixels of an analyzed pair of shadowed and sunlit comparison regions.

Using the above approximations Hoekzema et al. (2011) derived

$$\tau_{shad} = -\frac{\mu_0\mu}{\mu_0+\mu}\ln\left(\frac{\Delta I}{\mu_0(F/\pi)R_S}\right), \quad (1)$$

where μ is the cosine of the emission angle, μ_0 the cosine of the solar incidence angle. $\Delta I = I_{sunlit} - I_{shadow}$ in which I_{shad} and I_{sunlit} are the average intensity of the analyzed pixels in a given shadow and in its sunlit comparison region, respectively. F is the direct solar flux onto the surface, and R_S the Lambert albedo of this surface.

To work with the above equation one needs the surface albedo R_S. However, this is usually not accurately known. As mentioned above under point (iv) we therefore approximate the Lambert albedo (R_S) of the surface with the measured TOA albedo

$$R_S = \frac{\pi I_{sunlit}}{\mu_0 F}. \quad (2)$$

It is clear that this approximation of R_S cannot be generally correct because it neglects the atmospheric influence.

Because of the previous mentioned assumptions, there is a difference between the real optical depth τ and the shadow method estimate of the optical depth τ_{shad}. Hoekzema et al. (2011) found that if the analyzed space images are taken in colors between yellow and red then these are (close to) proportional, but that τ_{shad} is considerably smaller than the real optical depth τ. Their work indicates that $\tau = \tau_{shad}/C_S$, with $C_S = 0.63 \pm 0.09$. They concluded that the results are much less reliable for images that are observed in bluer colors and that maybe the shadow method should not be used for these.

For each estimate of the optical depth we used a pair of lines on the surface; one line of pixels inside a shadow and one that was sunlit for comparison. The difference between the average intensity of the line in shadow and a line in sunlit yield an estimate of τ_{shad}, and the spread around these averages is used to estimate the 1σ error. Note that this 1σ error tells about the spread of the measurements, but very little about the largely systematic errors that are introduced by the several rough approximations; these are compensated by dividing τ_{shad} by the factor C_S=0.63 ± 0.09.