Active Dust Devils on Mars: A Comparison of Data Returned from Six Spacecraft Landing Sites.

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Overview: Aeolian processes are the primary geological process currently altering the martian surface; however, it is unclear how wind-related processes vary with location. Dust devils (dust-laden convective vortices) are powered by insolation in the presence of atmospheric instability [1-3]. The formation of convective vortices and the mechanisms that allow them to entrain dust is important on Earth and Mars (reviewed by [4]). Dust devils have proven to be commonplace on Mars, although their occurrence is unevenly distributed [5] across the surface. Dust devils have been inferred from sudden atmospheric pressure drops accompanied by temperature increases and changes in the local wind vector as recorded by meteorological (MET) instruments onboard landed spacecraft [6-10]. Orbital analysis of dark tracks created from the removal of bright unconsolidated dust by the passage of dust devils is also used to determine their frequency [11-15]. Past studies of dust devil tracks show that they could lift approximately half as much dust as local and regional dust storms annually [5], making them major contributors to the background atmospheric dust haze. Hundreds of active dust devils have been analyzed in images from orbiting and landed spacecraft [9-10, 12,14,16-22] providing a means to observe changes in their morphology over their lifetimes.

Observation: Dust devils were imaged or inferred from meteorlogical measurements at all six successful Mars landing sites [Viking 1 and 2 Lander (VL-1 and VL-2), Mars Pathfinder (MPF) Lander, Phoenix Mars Lander (PML) and the Mars Exploration Rover Spirit and Opportunity], providing a unique opportunity to compare their sizes, speeds, normalized number frequencies, dust flux, and dust loading. The MER Spirit data are used as the basis of comparison because it is the most extensive data set compiled, spanning 3 martian years [18,22]. MER Spirit imaged more than 6 times as many dust devils as were imaged or detected at the other 5 landing sites combined.

Analysis: Each landed vehicle had different methods of detecting dust devil activity, making direct comparisons challenging. Dust devils imaged by MER Spirit and Opportunity were resolved in visible camera images and identified using simple contrast enhancement and frame subtraction techniques [18,22]. The rover payloads were not equipped with MET instruments so observations were mostly imaged during daytime hours when rover resources were available. A 21-frame Navigational camera dust devil movie sequence (reviewed by [18,22]) provided the means to observe variations in morphology as dust devils move across the plains. VL-1, VL-2, MPF and PML were equipped with MET instruments and measured diurnal variations in pressure, temperature, and the ambient wind vector. They detected hundreds of passing vortices; from horizontal wind speed measurements (assuming that vortices traveling at speeds that exceed the threshold to entrain dust can become a dust devil), 32 vortices were inferred to be dust-laden (19 inferred from MPF [9], 6 inferred from VL-1 [6] and 7 inferred from VL-2 [6,8]). No dust devils were imaged in VL images. Dust devils were imaged in visible images and inferred from MET data at the MPF and PML sites, although no simultaneous measurements were made for either study.

In all dust devil studies, number frequencies peaked during the warmest times of the day (between 0900 and 1600-1700 LTST) and during the warm dusty seasons (spring and summer). Insolation-driven activity supports the idea that dust devils are convective. Dust devil observations throughout the three years of study at the MER Spirit site were imaged between 0942 and 1617 LST with peaks between 1200-1600. The 38 vortices detected by MET instruments at the VL-2 site [8], were detected between 0948-1648, with peaks between 1000-1030 and 1300-1330. The early morning peak is attributed to Lander-generated turbulence because this peak is not seen in terrestrial analog studies [2], nor were they seen at the MER Spirit site [18,22]. No vortices were detected immediately following the early afternoon spike in activity.

Previous studies on Earth [1] and on Mars [18,22] predict that large spikes in dust devil frequency may mix the boundary layer, stabilizing the atmosphere and halting boundary layer convection. The atmosphere must rebuild its superadiabatic lapse rate in order for vortex formation to begin again. Because of the small sample of visible images analyzed in the MPF studies [3,9,17], a true statistical analysis of the times at which MPF dust devils occur cannot be determined. Observations consisted of analysis of image frames all centered within 45 minutes of local noon. Because of a single dust devil identified in an image taken at 1506 LST, we assume that dust devils were probably occurring at a larger range of times throughout the day.

Core diameter sizes and horizontal speeds were measured, then areas of dust devil detection and normalized number frequencies were determined. However, due to difficulties in locating the actual position of dust devils in certain visible image studies or detecting subtle variations in MET data, number frequencies and dust fluxes were derived only for a few studies.

Core diameters measured from visible ground-based images [9-10,17-18,22] tend to all be smaller than those derived from the detection of vortices in MET data [6,8,9]. They all measure less than 300m, with the exception of a single dust devil imaged at the MPF site [20]. The range of diameters measured for the three Spirit dust devil campaigns is 2-276m in Season One, 5-124m in Season Two and 5-159m in Season Three [18,22]. Dust devil diameters measured in visible images at the MPF site range from 2.3-80m in one 2-sol study for images containing the horizon [3,17] and, with the exception of a very large dust devil (573m) they range from 11-245m in a second study [9] that analyzed images containing the horizon in the entire 83-sol mission. Uncertainties in dust devil diameters at the PML site were estimated to range from 20-200m, due to the uncertainty in dust devil locations in the arctic plains [10]. Core diameters measured from the detection of vortices in VL-1 MET data range from 10-690m [6] and from 10-950m [6, 8] in VL-2 MET data. Past terrestrial studies [2] have shown a 1:10 relationship between the visible core diameter and the area of disturbance of a dust devil. Visible image studies measure the visible dusty core of a passing dust devil, whereas MET instruments detect the full area of disturbance as the vortex passes over the sensors. Therefore, the range of core diameters detected by the MET instruments may be up to a factor of 10 larger than core sizes measured in visible images.

Horizontal speeds of the dust devils imaged at the MER Spirit site were measured by tracking their locations through sequential frames of the dust devil movies and dividing the total distance traversed by the amount of time they were observed. Because the dust devil is in contact with the surface, the speed at which it moves is believed to be slightly slower than the ambient wind due to drag by surface shear stresses. Speeds for the three seasons that Spirit observed range from 0.1-12 m/s with median values ~ 2.1 m/s [18,22]. Horizontal speeds for dust devils imaged at the MPF site are between 0.5-4.6 [3,17]. To make direct comparisons of speed measured in visible movie sequences of a passing dust devil to those detected by MET wind sensors, measurements of the ambient wind speed just before and after the passage of vortices over MET sensors were compared with wind speeds at the Spirit and MPF sites. Internal components of the wind vector measured by the MET instruments (tangential, radial and vertical speeds) were ignored. At the VL-1 ambient wind speeds associated with the passage of vortices ranged from 2-12 m/s [6]; they range from 1-12 m/s at the VL-2 site [6].

Areas of dust devil detection are defined as the furthest areal extent to which visible cameras could detect dust devils. This detection area is also defined as the area surrounding the Landers over which the MET sensors could detect a disturbance from normal ambient conditions. Areas were calculated according to the techniques used in the three Spirit dust devil campaigns [18,22]. These areas of detection were then used to calculate normalized dust devil frequencies that were comparable to the way in which Spirit's seasonal dust devil frequencies were calculated [18,22]. Spirit measured frequencies of 51 dust devils/km^2/sol in Season One, 11 dust devils/km^2/sol in Season Two and 20 dust devils/km^2/sol in Season Three. The large decline in frequency from Season One to Season Two is possibly attributed the passage of a large storm that truncated the second dust devil season (reviewed in [22]). Averages over 3 seasons are 3.2 dust devils/km^2/sol at the VL-1 site [6] and 5.7 dust devils/km^2/sol at the VL-2 site [6]. Values of dust devil frequency were much lower at the MPF site where dust devils were imaged in two different studies. In the two studies [9,17] frequencies were 0.33 and 0.004 dust devils/km^2/sol, respectively. These small values are possibly due to analysis of a very small number of image frames.

Dust fluxes were derived for the two visible camera studies of dust devils at the MPF site, and they both fall within the ranges calculated at the Spirit site. Dust fluxes of 5x10^{-4} kg/m^2/s and 7x10^{-5} kg/m^2/s, are well within the ranges calculated by MER (4.0x10^{-9} to 4.6x10^{-4} during Season One, 5.2x10^{-7} to 6.2x10^{-5} during Season Two and 1.5x10^{-7} to 1.6x10^{-4} during Season Three [18,22]).

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