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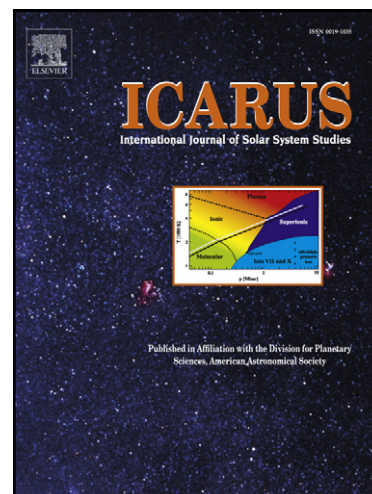
In-Situ Measurements of Particle Load and Transport in Dust Devils

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IN-SITU MEASUREMENTS OF PARTICLE LOAD AND TRANSPORT IN DUST DEVILS

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ABSTRACT

In-situ (mobile) sampling of 33 natural dust devil vortices reveals very high total suspended particle (TSP) mean values of 296 mg m⁻³ and fine dust loadings (PM10) mean values ranging from 15.1 to 43.8 mg m⁻³ (milligrams per cubic meter). Concurrent three-dimensional wind profiles show mean tangential rotation of 12.3 ms⁻¹ and vertical uplift of 2.7 ms⁻¹ driving mean vertical TSP flux of 1689 mg m⁻³s⁻¹ and fine particle flux of ~ 1.0 to ~ 50 mg m⁻³s⁻¹. Peak PM10 dust loading and flux within the dust column are three times greater than mean values, suggesting previous estimates of dust devil flux might be too high. We find that deflation rates caused by dust devil erosion are ~ 2.5 to 50 μm per year in dust devil active zones on Earth. Similar values are expected for Mars, and may be more significant there where competing erosional mechanisms are less likely.

1. INTRODUCTION

Dust devils are small-scale, particle loaded convective vortices driven by sensible heat flux (e.g., Ives, 1947; Sinclair, 1969; Balme and Greeley, 2006). They are common on both Earth and Mars and their visibility indicates that they can carry a substantial airborne particle load and must therefore be an effective aeolian erosion mechanism. On Earth, dust devils threaten air quality in arid regions through a local enhancement of airborne aerosols (Gillete and Sinclair, 1990; Mattsson et al., 1993). Kok and Renno (2006) further suggest that such aerosols might have a more global effect through the absorption and scattering of radiation (Myhre and Stordal, 2001) and as cloud or ice nucleation sites (DeMott et al., 2003). On Mars, models suggest that dust devil activity might support the persistent dustiness in the atmosphere (Basu et al., 2004), although spacecraft observations appear to rule out the possibility that Mars' global dust storms are triggered by dust devil activity (Cantor and Edgett, 2002; Balme et al., 2003a; Cantor et al., 2006). Whelley and Greeley (2008) estimate that martian dust devils lift $2.3 \pm 1 \times 10^{11}$ kg annually, approximately half as much material as local and regional dust storms. This report offers field observations critical to such concerns.

The transport of fine particles into the upper atmosphere by dust devils is an important but poorly understood part of both the terrestrial and martian climates. Dust devils lift material by their intense swirling winds (Balme et al., 2003b) and perhaps also by a suction effects at the cores (Greeley et al., 2003; Balme and Hagermann, 2006). To estimate the effect of dust devils on the climate requires data describing their size frequency distribution, and describing the amount of dust that they lift. Measurements of

particle load within dust devils have received little attention in the literature, despite being their most distinctive signature (and the one that distinguishes a dust devil from a simple convective vortex). Such measurements are also a necessary prerequisite for estimating the upwards flux of dust within the dust devil,. There have been measurements of wind speed, rotation sense, size and even the electrical properties of dust devils (see, for example, the review of Balme and Greeley, 2006) but very few of particle loading. For the Earth, the peer-reviewed data are limited to preliminary LIDAR observations at ~100 m height (Renno et al., 2004) and *in-situ* aircraft sampling at ~140 and ~300 m height (Gillette and Sinclair, 1990). The LIDAR measurements show a $\sim 10^3$ enhancement compared to ambient dust loading, and allowed Renno et al. (2004) to estimate an actual dust load of $\sim 100 \text{ mg m}^{-3}$. Gillette and Sinclair (1990) only presented estimated vertical particle flux results but the actual particle-loading data they used to calculate their flux data have not been published and so cannot be verified. Oke et al, (2007) presents measurements of size-frequency distributions of samples particles but does not relate this to particle loading or flux. More attempts have been made to estimate dust load for martian dust devils using estimates of optical depth from orbit (Thomas and Gierasch, 1985) and the surface (Metzger et al., 1999; Greeley et al., 2006; Greeley et al., 2010). Thomas and Gierasch (1985) measured a dust load of $\sim 30 \text{ mg m}^{-3}$; Metzger et al. (1999) found a range from 10 to 100 g m^{-3} . Greeley et al. (2006) published data only for estimated flux and again particle loads cannot be estimated from their data without attempting to back-calculate particle loads based on cited average vertical wind speeds and flux data. Greeley et al. (2010) presented data from three seasons of dust devils

observations by the Spirit Rover and found dust loads of 0.002 to 250 mg m^{-3} for season one, 0.8 to 45 mg m^{-3} for season two, and 0.04 to 77 mg m^{-2} for season three

Over the past ten years we have performed *in-situ* sampling and analyses of over 100 dust devils (e.g. Metzger, 1999; Balme et al., 2003b; Metzger et al., 2004). These penetrations produced data such as wind speed, temperature, pressure, and dust or total particle load. Here we present both a discussion of observations relevant to particle loading and dust lifting in an example dust devil encounter, and a summary of dust loading and flux data for all measurements we have made between 1995 and 2005. These are the first *in-situ* dust devil dust and particle loading measurements presented in the literature and provide reference data that can be directly applied to models and parameterizations of dust devil particle lifting. Such data are certainly needed: for example, Neakrase et al. (2010) state that “The need for more published field data to compare to laboratory and model results, has never been more apparent.” and “Without simultaneous measurements of sediment flux at different heights and the pressure profile within the dust devil, expansion of laboratory experiments and modeling will be difficult.”

2. APPROACH

2.1 Instrumentation. The *in-situ* sampling technique used is based on a mobile, instrumented platform, advancing the pioneering work of Sinclair (1966). To address the importance of near-surface processes the system has evolved from a single height sensor cluster fixed to a 4WD vehicle, through a profiling instrument platform deployed from

the back of a truck, to the current incarnation – termed ‘DASHER’ – which features a five meter vertical meteorology mast held in front of the vehicle (fig. 1).

Correct placement of any survivable instrumentation into the path of these dynamic phenomena over rugged terrain is a non-trivial exercise, given that dust devils are fast moving, difficult to predict and that the hot dusty conditions are often detrimental to the longevity of the instrumentation. Furthermore, few instruments are available whose design is directly intended to manage the conditions involved, especially response time. Thus sensor selection has been an evolving exploration (e.g., Metzger et al., 2004). Wind regime has been characterized using a variety of cup and propeller anemometers, and 3D and 2D sonic anemometers. The current system uses Gill™ 3-component anemometers with uniaxially responsive (1 m distance constant) helicoidal propellers at 1 m and 4.6 m height. 3-component wind speeds are presented as U (radial) V (tangential) and W (vertical) components. Pressure and temperature are sampled at various heights and video cameras within the truck cab documents sampling position relative to the vortex. Site characterization, vehicle orientation relative to the dust devil's track, and ambient weather data are immediately recorded following an encounter.

We have used a variety of commercially produced and custom-built sensors to sample particle loading in dust devils. These include upwards-looking UV sensors developed for use at the martian surface as part of the Beagle 2 mission (Patel et al., 2002; Towner et al., 2004), Piezoelectric saltation impact detectors (Sensit™ and PVDF, polyvinyl difluoride film, Towner et al., 2004), total suspended particle load (HiVol™) and suspended particle load in the 0.1 to 10 μm diameter range (particulate matter

PM10). PM10 measurements used either active DustTrak™ or passive HAM™ (Handheld Aerosol Monitors) sensors, both of which rely on measuring the angular patterns of light scattered by a cloud of small particles (Mie scattering).

The standard deployment method for DASHER involves outrunning the dust devil to then stop and position the vehicle symmetrically into the path of the approaching vortex, lowering the instrument array to ground level, and allowing the column to cross the array. Data logging continues for several minutes after the encounter to capture ambient conditions. The current version of DASHER is the end product of over 10 years of refinement in terms of both design and implementation, and includes the potential to repeatedly sample the same dust devil. These vortices are highly turbulent flows with dust entrainment that is dictated by the surficial material over which they pass, the ambient wind that push them, and the strength of convection that power them, so they are dynamic systems that fluctuate second-to-second laterally and vertically. Thus a mobile sampling system that can re-sample the same dust devil in the case of a “near-miss” is a great advantage over any kind of static sampling strategy.

2.2 Field locations Investigations were conducted in three field sites in the USA. The primary study program was established in 1995 in ‘Eldorado Valley’ (EV), a closed playa basin outside Boulder City, in southern Nevada (Metzger and Lancaster, 1996; Metzger, 1999; Metzger, 2001) where climate is arid, hot and with frequent, strong insolation. The playa itself covers 13 km² and is flat, hard and dry, with zones of fine and coarse surficial material, providing a surface well suited to vehicular use. Additional chase campaigns were conducted on the Rosamond Lake Bed (RO) contained within the western portion of

Edwards Air Force Base, in the Mohave desert, and on agricultural fields south of Eloy (EL), in the basin and range province of south central Arizona. EV and EL both offer arid surfaces (although with some vegetation in local areas) while EV and RO provide expanses of simple, natural geologic environments, including martian analogs, on which high speed pursuits can safely be conducted.

3. RESULTS

3.1 Concurrent measurements of sediment and wind field: an example encounter

Beginning in 2002 we developed the capability to investigate how wind structure relates to particle load and flux by simultaneously sampling 3-dimensional wind components, UV occultation, saltation, and dust loading in a single dust devil. Figure 2 summarizes an example EV encounter using data collected in 2005 from a dust devil presenting an opaque 15 m wide dust column, a broad sand ejecta apron with visible turbulence, a height exceeding 300 m, and a duration of 10 minutes. In terms of airborne sediments, both the PVDF saltation impact detector (which detects sand grade material at 0.3 m height.) and the aerosol monitor (HAM PM10 which detects dust grade material at 4.5 m height) detected their respective size classes at the same moment, immediately following the passage of the leading core wall, as marked by the first peak in the total horizontal wind speed 'H' measured at 4.8 m height. The saltation sensor saturated as the core center passed, remaining flat for the rest of the encounter. The measured UV intensity (1.14 m height) diminished a few seconds before the detection of airborne sediment,

possibly due to shadowing of the sensor by the approaching dust column. The maximum suspended aerosol concentration, as measured by the PM10 sensor, was 33 mg m^{-3} just before the trailing core wall, then tapering rapidly to ambient ($< 0.1 \text{ mg m}^{-3}$).

The double peaks in horizontal wind speed (H) exceed 15 ms^{-1} , and the time between the peaks matches the width of the aerosol dust column almost exactly. However, H begins to rise well before the dust column, and remains above ambient for almost 20 seconds after the visible dust column has passed. The tangential wind speed, V, shows the classic signature of a dust devil vortex passing directly over the instruments, including a noisy indication of strong buffeting at the front wall of the dust devil, which is matched by the strong fluctuation in vertical wind speeds, W, at both heights. The lower vertical wind speed data (at 0.6 m height) oscillate around zero with upwards and downwards maxima of about 1 ms^{-1} but with a narrow, strong 3 ms^{-1} upwards peak near the center of the vortex. The upper vertical winds (at 4.3 m height) peak slightly earlier, indicating the tilt of the vortex, with downdrafts before and after the central core.

We have performed many such *in-situ* samples of dust devils and in each case have obtained a suite of datasets similar to the one described above. For every encounter where the relevant data were available, we have combined the mean and peak vertical wind with mean and peak aerosol data to estimate peak and mean dust flux within the dust devil. The bounds of these data were taken to be the width of the dust column, given by the rise/fall in aerosol dust loading. These data are shown in Table 1.

3.2 A summary of *in-situ* dust devil sediment loading measurements: 1996-2005.

Table 1 presents the results from 33 dust devil encounters. Airborne particles were collected or measured during the 1996, 2000, 2002 and 2005 EV, and 2005 EL field seasons. Vertical wind speeds were also measured in some of these studies. In addition to aerosol measurements, during 1996 a vacuum collection system captured total suspended sediment (TSP) at 2 m height, collecting dust, silt, sand and mud flakes of all sizes up to 15 mm diameter. Flow rate and collection duration were used to determine the TSP mass flux (Metzger, 1999). Peak and mean aerosol and W measurements presented here are only for within the dust column defined as described in section 3.1. Flux is calculated simply as vertical wind speed multiplied by particle load. When defining the column in this manner a flux of less than zero is possible given downdrafts within the dust devil core. This may explain the erosive efficacy of a vortex laden with abrasive particulates capable of wearing away surface crusts and dispersing aggregates into puffs of dust.

Neither peak nor mean PM10 or TSP correlate strongly with time of day, peak H , peak W , or dust devil diameter, suggesting that local dust lofting conditions are separate from the larger scale turbulence that generate the dust devil columns. Mean PM10 correlates well with peak PM10, however, and indicate that the maximum dust loading in a dust devil is about three times the mean dust loading across the column.

4. DISCUSSION

4.1 Peak vs. mean flux. The well-documented 2005 EV_16-06-05/1543 event shown in Figure 2 had a surface footprint of $\sim 176 \text{ m}^2$ and lasted over 10 minutes. Given this dust devil's mean flux of $7.5 \text{ mg m}^{-2}\text{s}^{-1}$, such an event would loft about 0.8 kg of PM10 material, but with a maximum flux of $98 \text{ mg m}^{-2}\text{s}^{-1}$, it may have yielded up to 10.3 kg of respirable dust – a substantial amount of airborne material. Most previous authors have simply multiplied peak vertical wind speed by peak dust load to obtain flux but we believe the mean values for PM10 concentration and mean values for W (given a dust column width defined by either UV or PM10 profiles) are more valid data for flux calculations, as they describe the whole vortex. The mean 'peak PM10' concentration for 21 encounters was 43.8 mg m^{-3} ; the mean 'mean PM10' concentration across the column for 13 encounters where concurrent 3-dimensional wind data was available was 15.1 mg m^{-3} . For near-surface measurements, flux calculations with these data give values of 43.3 to $56.6 \text{ mg m}^{-2}\text{s}^{-1}$ maximum flux, and 0.9 to $7.5 \text{ mg m}^{-2}\text{s}^{-1}$ mean flux. Thus the mean flux in the column can be from $\sim 1/50^{\text{th}}$ to $\sim 1/10^{\text{th}}$ of the peak value, depending on the variability of the vertical wind.

4.2 PM10 vs. TSP loading in dust devils. Dust devils entrain particles ranging from fine dust and silt to granule or even pebble-sized clasts. Not all this material is transferred into the atmosphere. For example, the 1996 season *in-situ* measurements (Metzger, 1999) of TSP and vertical wind speed gave total particle flux of ~ 600 to $4300 \text{ mg m}^{-2}\text{s}^{-1}$. Combined with observations of average dust devil diameters of 7 to 15 m and lifetimes of about five minutes, this suggests that these dust devils (re)moved up to $> 200 \text{ kg}$ of

material from the surface. Subsequent field campaigns over the same EV surfaces focusing only on the PM10 dust component of the columns show much lower flux values ($< 150 \text{ mg m}^{-2}\text{s}^{-1}$ for peak values and $< 30 \text{ mg m}^{-2}\text{s}^{-1}$ for mean values). From all encounters, the mean values for TSP (296 mg m^{-3}) exceeded maximum PM10 (43.8 mg m^{-3}) by about 7 times and the mean PM10 (15.1 mg m^{-3}) by about 20 times, suggesting ~85 to 95% of the basal sediment load is coarse grained and unlikely to be transported to significant heights or distances downrange, forming instead the observed sand ejecta aprons. This is reinforced by measurements made of sediment size distribution in the bottom two meters of dust devils in Australia by Oke et al. (2007), who found that total numbers of particles are greatest in the bottom 10-20 centimeters of a dust devil, and that 200 – 600 μm sized particles dominate the basal distribution but are increasingly rare higher in the column.

4.3 Comparison with other dust events. In our studies, vortices were visible with as little as 4 mg m^{-3} PM10 load (only 30 times ambient levels) whereas maximum dust loading events exceeded 150 mg m^{-3} . By way of comparison, several authors have reported ambient levels and dust transport events in terrestrial arid regions that are 2 to 4 orders of magnitude less intense (Metzger, 1999) than the dust devils we have measured. For example, in terms of dust storms, Song et al. (2007) defines severe dust storms in Asia as $\text{TSP} \geq 6 \text{ mg m}^{-3}$ and $\text{PM10} \geq 5 \text{ mg m}^{-3}$ with wind speeds $\geq 10 \text{ ms}^{-1}$. These data are three orders of magnitude less than our TSP measurements in dust devils and about one order of magnitude less than most of our PM10 measurements. Dust devils are clearly extremely efficient erosional mechanisms. This is partly explained by the wind structure of dust devils, which often produces the strongest rotation along the trailing core

wall, including high wind speeds reaching the ground (see, for example, Metzger et al., 2004, and figure 6 in Balme and Greeley, 2006). Consequently, much of the soil erosion is likely to take place there along an arcuate path.

4.4 Comparison with other dust devil studies. Our terrestrial results give the first detailed *in-situ* measurements of dust devil particle load and include several examples with maximum flux of 100 - 120 mg m⁻²s⁻¹, with a mean flux across the typical dust devil column of 0.9 mg m⁻²s⁻¹ at 0.5 m height and 7.5 mg m⁻²s⁻¹ at 4.5 m height. Gillette and Sinclair (1990) estimated that a typical dust flux (< 25 µm diameter) for dust devils in the southwestern US was ~28 mg m⁻²s⁻¹ (although their method was never published). They also estimated TSP flux of 520 mg m⁻²s⁻¹. Renno et al. (2004) used LIDAR to remotely estimate a terrestrial dust devil column peak loading of 100 mg m⁻³ and peak vertical velocity of 10 ms⁻¹ to calculate a dust flux of 1000 mg m⁻²s⁻¹. Our peak flux results are consistent with the Gillette and Sinclair data and, although our PM10 measurements agree well with Renno et al. (2004), we suggest that the vertical wind speeds they use are possibly not typical (usually peak W is ~25% of peak H; Balme and Greeley, 2006) and thus their flux estimate may be too high.

Neakrase et al., (2006) and Neakrase and Greeley (2010) used a laboratory dust devil simulator and a variety of bed materials (from low density walnut shells through silica sand to high-density chromite particles) and vortex intensities to estimate sediment flux, finding values of ~10 to 10,000 mg m⁻²s⁻¹. Neakrase and Greeley summarize their experimental vortex flux data under terrestrial conditions using the expression $Q = 7.63 \times 10^{-7} (\Delta P/u_0)^{3.73}$, where Q is the flux (kg m⁻²s⁻¹), ΔP the pressure drop at the

centre of the vortex compared to ambient pressure, and u_0 the peak tangential wind speed. Using realistic field-derived values for wind speed and pressure drop ($\sim 10 \text{ ms}^{-1}$ for wind and $\sim 1 \text{ mbar}$ for pressure drop) for terrestrial dust devils gives a flux of $\sim 4 \text{ mg m}^{-2}\text{s}^{-1}$ from their equation. This result falls in the centre of our measured data range, providing reassurance that the laboratory experiments are at least a reasonable simulation of the field studies. However, we note that, at $10,000 \text{ mg m}^{-2}\text{s}^{-1}$, the upper range of their flux data is greater than even the TSP results from our field work. This is not surprising, given the laboratory peak flux results are for optimum sized (100-150 μm) particles that would likely be removed under even weak boundary layer winds in the field.

For Mars, Metzger et al. (1999) used column opacity to estimate the particle loading for a dust devil observed by the Imager for Mars Pathfinder camera. They calculated the particle load was 70 mg m^{-3} and, using an estimate of vertical wind speed of 7 ms^{-1} , calculated a vertical flux of $500 \text{ mg m}^{-2}\text{s}^{-1}$. Greeley et al. (2006) used surface imaging of Martian dust devils in Gusev crater to calculate vertical wind speeds of $0.2 - 8.8 \text{ ms}^{-1}$, a range well matched by our *in-situ* terrestrial measurements, giving maximum and mean dust flux estimates of $459 \text{ mg m}^{-2}\text{s}^{-1}$ and $21 \text{ mg m}^{-2}\text{s}^{-1}$, respectively (similar to our observations although the peak values are higher). Ferri et al. (2003) used a vertical wind speed of 20 ms^{-1} (based on the theoretical calculations of Renno et al., 1998 and Renno et al, 2000) and the dust load estimate of Metzger et al., (1999) to estimate a flux of $70 \text{ mg m}^{-2}\text{s}^{-1}$. Given that these results were not calculated from *in-situ* measurements they are still fairly closely matched to our “peak” flux measurements, although they are a much higher than our mean values. We note that the calculated vertical wind speed used by Ferri et al. (2003) is 20ms^{-1} , which seems high compared to most authors’ estimates

for martian dust devils (Balme and Greeley 2006; Greeley et al., 2006; Greeley et al., 2010).

Finally, Greeley et al. (2010) present flux data from three seasons of dust devil observations from the Spirit Rover. They found flux values of 0.004 to $460 \text{ mg m}^{-2} \text{ s}^{-1}$ in season one, 0.5 to $62 \text{ mg m}^{-2} \text{ s}^{-1}$ in season two, and 0.2×10^{-7} to $160 \text{ mg m}^{-2} \text{ s}^{-1}$ in season 3. These data agree well with our results and appear to show that martian and terrestrial dust devils have broadly similar dust fluxes within their columns. We note that almost all martian dust devil flux estimates use peak vertical wind speed and particle load estimates and so more realistic flux values, obtained from the mean wind speed and mean particle load, might give lower values that more closely match our mean (rather than peak) values. We also acknowledge that only *in-situ* measurements of martian dust devils will allow such data to be obtained and, as such, they will be challenging measurements to make.

4.5 Dust devils as a deflation mechanism. We find that dust devils such as the EV_16-06-05/1543 event can loft about 1 kg of PM10 material to heights of several hundred meters over their lifetime. Furthermore, applying the 5-15% TSP/PM10 ratio to the TSP data from the five large dust devils sampled in 1996 suggests that larger examples can deliver up to 20 kg of fine particulates to great height. Given measured dust devil frequencies of 60 - 90 dust devils per square kilometer per day (Pathare et al., 2010), this equates to an estimate of 50 to 1000 kg of material per square kilometer being lofted per dust devil active day. While this is potentially a significant quantity for air-quality degradation, it is equivalent to a surface layer of at most half a micron deep (if the density

of the surface material is 2000 kgm^{-3}), so even with a hundred active dust devil days per year this is only an erosion rate of ~ 2.5 to $50 \text{ }\mu\text{m}$ per year. Nevertheless, if the local climate remained stable over many thousands of years and dust devils were persistently active throughout that time then they could be responsible for meters of deflation. This could certainly be the case for Mars if dust devil flux rates are similar to Earth, as suggested by observations and simulations in the lab (e.g., Greeley et al., 2006; Greeley et al 2010; Neakrase et al., 2010), especially given the lack of competing erosional mechanisms.

5. CONCLUSIONS

Using a variety of mobile test bed platforms, we have reliably determined *in-situ* dust and sediment loading of dust devils and made concurrent wind data measurements. Dust devil vortices are highly effective erosion mechanisms capable of (re)moving substantial quantities of material, even from surfaces resistant to conventional turbulent shear winds. Of those total suspended particles, however, $\sim 10\%$ consists of PM10 fine aerosols that are carried well above and beyond the source area. Our encounter data suggests that mean dust loading and flux are approximately one third that of measured peak loading and flux and provides a field-based conservative measure of atmospheric aerosol contribution and dust devil surface deflation.

Our data provide important input to laboratory and theoretical studies of the effects of dust devils on the martian climate, as well as providing important data for studies of terrestrial air quality. In future work we will collect more dust loading and

higher resolution vertical wind data, concurrent with column dimensions made from stereo imaging. Furthermore, the complex wind structure within the basal inflow zone will be analyzed to understand where erosion is occurring, what role the “sand-skirt” at the base of the dust devil plays in surface erosion, and how different geological surfaces respond to such stresses.

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FIGURE AND TABLE CAPTIONS

Figure 1. Mobile test bed platforms to sample dust devils at 2.0 m (top), deployable array with instruments at heights 0.05 – 2.0 m (lower left), and 0.2 – 5.0 m meteorology mast (DASHER, lower right). Photos by S. Metzger.

Figure 2. Concurrent profiles of the EV_16-06-05_1543 encounter. The time-series cross section (top) was plotted using tangential velocities from 4 anemometers. The warmer colour represent faster wind speeds with the deep pink-red at the centre of the dust devil representing 15 ms^{-1} . Note the swirling gusts following the dust devils at 120, 170 and 225 seconds. In the dust load plot (middle left) “H hi” is the total horizontal wind (i.e. the magnitude of the horizontal component of the wind) at 4.3 m height, “UV” is output from the UV sensor output at ~ 1 m height (voltage in mV; proportional to UV flux – these sensors are not absolutely calibrated), “PVDF” is the output from the piezoelectric saltation sensor at ~ 1 m height in engineering units (in mV; proportional to impact counts per second), and “HAM hi” gives PM10 dust load at 4.5 m height. In the wind speed plot (lower left), “H hi” and “V hi” are total horizontal and tangential wind speed at 4.3 m height, “W hi” is the vertical wind speed at 4.3 m height, and “W lo” is the vertical wind speed at 0.6 m height. Upper photo by S. Metzger, 2 minutes after encounter, looking north ~ 2 km. Lower photo by B. McGee, 1 second before encounter, looking south (note pickup truck aligned with the center of the 15 m wide column).

Table 1. Dust Loading and Wind Speeds of directly sampled dust devils.

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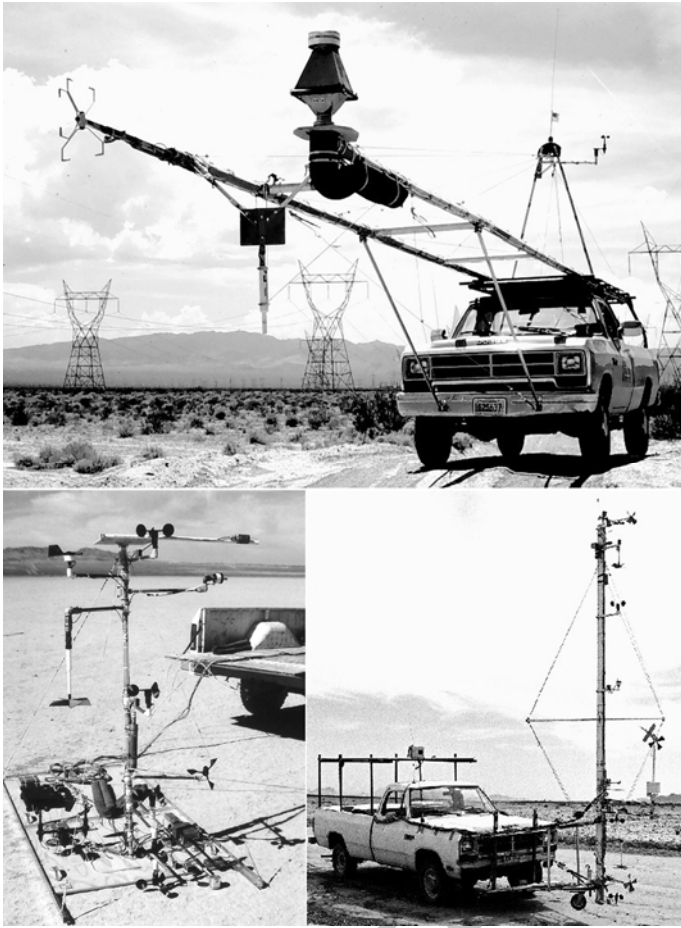
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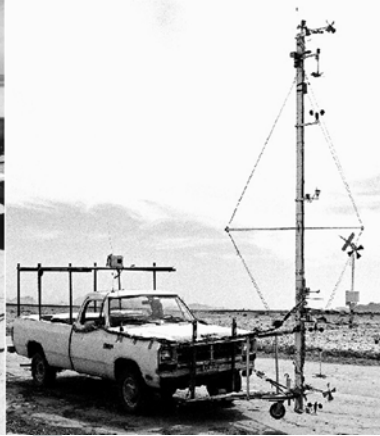
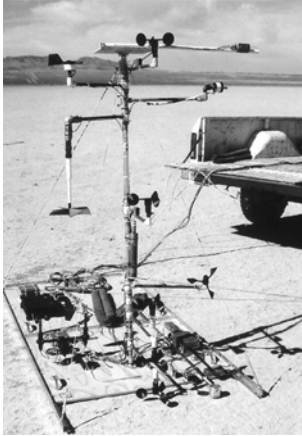
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MANUSCRIPT

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Dust Devil Identifier Code (site-date-time)	Sediment sensor height (m)	Dust Column Diameter (m)	TSP mean (mg m ⁻³)	PM10 peak (mg m ⁻³)	PM10 mean (mg m ⁻³)	Wmax (ms ⁻¹)	Wmean (ms ⁻¹)	Flux max (mg m ⁻² s ⁻¹)	Flux mean (mg m ⁻² s ⁻¹)	Hmax (ms ⁻¹)	TSP flux (mg m ⁻² s ⁻¹)
EV_25-06-96_1425	2		6.4								
EV_25-06-96_1504	2		359								
EV_25-06-96_1545	2		719								
EV_29-06-96_1412	2	15	226			7				7	1582
EV_30-06-96_1435	2	18	162			7				18	1134
EV_30-06-96_1455	2	18	199			3.8				9	756
EV_31-06-96_1245	2		127								
EV_31-06-96_1316	2		77								
EV_01-07-96_1342	2		140								
EV_01-07-96_1402	2	30	199			3				12	597
EV_01-07-96_1525	2	25	875			5				22	4375
EV_02-07-96_1159	2		463								
EV_04-07-00_1226	2			150							
EV_04-07-00_1518	2			12.3							
EV_04-07-00_1557	2			7							
EV_04-07-00_1605	2			1.5							
EV_04-07-00_~1200	2			4.7							
EV_04-07-00_~1300	2			42							
EV_04-07-00_~1400	2			45							
EV_04-07-00_~1430	2			6							
EV_23-06-02_1257	2.8	15		36	13	0.95	0.02	34.2	0.26	6.5	
EV_23-06-02_1348	2	40		2.5	1.6	0.55	-0	1.4	-0.03	8.8	
EV_24-06-02_1345	2	3.5		7.08	3.02	0.05	0	0.4	0.00	7.1	
EV_24-06-02_1351	2	30		1.33	0.84	1.65	-0.1	2.2	-0.08	15	
EV_24-06-02_1421	2	20		92	29	1.2	0.2	110.4	5.80	16	
EV_28-06-02_1351	2			68.3	20.1						
EL_10-06-05_1520	2	3		2.04	1.31	0.27	0.14	0.55	0.18	5	
EL_11-06-05_1329_q1	1.14	50		99	40.3	0.4	0.03	39.6	1.21	12	
EL_11-06-05_1335_q2	1.14	45		50	15.3	2.2	-0.3	110	<0	12	
EL_11-06-05_1340_q3	1.14	60		93.5	20.9	0.4	-0.1	37.40	<0	16	
EL_11-06-05_1343_q4	1.14	50		162	42	0.3	-0.2	42	<0	11	
EL_11-06-05_1512	1.14	7		4.1	1.1	1.6	0.3	6.4	0.3	16	
EV_16-06-05_1543	4.5	15		33	8	2.3	0	77	0	15	
	mean	26	296	43.8	15.1	2.2	0.0	38	1	12.3	1689
	St. Dev.	17	254	48.4	14.1	2.2	0.2	39	2	4.5	1385
	min	3	6	1.3	0.8	0.1	-0.3	0	0	5	597

max	60	875	162.0	42.0	7.0	0.3	110	6	22	4375
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Table 1.

ACCEPTED MANUSCRIPT

**IN-SITU MEASUREMENTS OF PARTICLE LOAD AND TRANSPORT IN DUST
DEVILS****Mezger et al.**

Research Highlights

- *In-situ* measurements of 3-D wind and particle load profiles in dust devils
- Calculation of horizontal profiles of dust devil vertical dust flux
- > 85% of sediments lifted by dust devils are coarse grained and are not transported to great heights or long distance
- Dust devils can lift 50 to 1000 kg km⁻²day⁻¹ of dust
- In active regions, dust devils might cause 2.5 to 50 μm of deflation per year