DIRECT IN-SITU MEASUREMENT OF NATURAL DUST DEVIL SEDIMENT LOADING AND FLUX. S. Metzger[1], M. Balme[1], M. Towner[2], B. Bos[3], and A. Pathare[1], [1]Planetary Science Institute, Tucson AZ (metzger@psi.edu), [2]Open University, PSSRI, Milton Keynes UK, and [3]NASA Goddard Space Flight Center, Greenbelt MD.

Introduction: Dust devils are an effective aeolian erosion mechanism of small-scale, substantially particle loaded convective vortices driven by insolation, common on both Earth and Mars. 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 pockets of hot air that power their "engine", thus they fluctuate second-to-second laterally and vertically. On Mars, dust devil activity might support the persistent dustiness in the atmosphere [1], although spacecraft observations appear to rule out the possibility that Mars' global dust storms are triggered by dust devil activity [2,3,4]. This report offers field observations critical to such concerns.

Understanding the climate influence of injecting fine particles into the upper atmosphere by dust devils requires data describing their size frequency distribution, and the amount of dust that they lift, yet few studies have attempted direct measurement of particle loading. Terrestrial LIDAR observations at ~100m height [5] show an ~10^3 enhancement compared to ambient dust loading, allowing an estimate of actual dust load of ~$0.1 gm^{-3}$. More attempts have been made to estimate dust load for martian dust devils using estimates of optical depth from orbit [6] and the surface [7,8]. [6] measured a dust load of ~0.03 gm^{-3}; [7] found a range from 0.01 to 0.1 gm^{-3}. [8] published data only for estimated flux and particle loads cannot be calculated from their data.

Over the past decade we have performed *in-situ* sampling and analyses of over 100 dust devils [e.g. 9,3,10]. These penetrations produced data such as wind speed, temperature, pressure and dust or total sediment load. Here we summarize field data made between 1995 and 2005; the first *in-situ* dust devil dust and particle loading measurements presented in the literature.

Instrumentation: The *in-situ* sampling technique used is based on a mobile, instrumented platform, advancing the pioneering work of [11], evolving from a single 2 m height sensor cluster fixed to a 4WD vehicle, through a 5 m vertical meteorology mast profiling array held well in front of the vehicle ("DASHER"). Correct placement of any survivable instrumentation into the path of these dynamic phenomena is a non-trivial challenge and few instruments are available whose design can endure the conditions involved and provide the response time required. We have utilized cup, 3-component propeller, 2D and 3D sonic anemometers as well as pressure and temperature sensors at various heights. Site characterization, vehicle orientation relative to the dust devil's track, and ambient weather data are also recorded.

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 [12], Piezo-electric saltation impact detectors (Sensit™ and PVDF, polyvinyl difluride film, [12]), 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).

Standard deployment for DASHER involves outrunning the dust devil, positioning directly into it's oncoming path, lowering the instrument array to ground level, and allowing the column to cross the array. Post-encounter data logging captures ambient conditions. The current version of DASHER follows 10 years' refinement of both design and implementation, including the capability to repeatedly sample the same dust devil.

Field locations: Investigations were conducted in three field sites in the USA. Beginning in 1995 the prime study area has been Eldorado Valley (EV), a closed playa basin (flat, hard, and dry, with zones of fine and coarse surficial material) outside Boulder City, in southern Nevada [13,9,14] where climate is arid, hot and with frequent, strong insolation. Additional chase campaigns were conducted on the Rosamond Lake Bed (RO) at 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 with vegetation roughness elements while EV and RO provide expanses of simple geologic environments on which high speed pursuits can safely be run. Additional work was conducted near the Sabancaya volcano in the Peruvian Andes and a new site is being established in the Atacama Desert of northern Chile.

Results *Concurrent in-situ measurements of sediment and wind field, 1996-2005:* Airborne particles from 33 dust devil encounters 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 acquired total suspended sediment (TSP) at 2 m height, capturing dust, silt, sand and mud flakes of all sizes up to 15 mm. Flow rate and collection duration were used to determine the TSP mass flux [9]. Peak and mean aerosol and W (vertical) measurements presented here are only for within the dust column. 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 disbursing aggregates into puffs of dust; analogous to the "beater bar" in a vacuum cleaner.

Neither peak or mean PM10 nor 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 and max PM10 correlate well, however, and indicate that maximum dust loading is ~3 times the mean dust loading across the column.

Discussion *Peak vs. mean flux:* **A** well-documented 2005 EV_16-06-05_15:43 event had a surface footprint of ~176 m^2 and lasted over 10 minutes. Given this dust devil's mean flux of 7.5 $mgm^{-2}s^{-1}$, such an event would loft 792 g of PM10 material, but with a maximum flux of 98 mgm^{-2}s^{-1}, it may have yielded 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. 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, especially once the complex vertical near-surface wind field and amount of material recycled in the base of the dust devil is understood. The mean 'peak PM10' concentration for 21 encounters was 43.8 mgm^{-3}, the mean 'mean PM10' concentration across the column for 13 encounters where concurrent 3-dimensional wind data was available was 15.1 mgm^{-3}. Flux calculation with this data indicates maximum and mean flux values of 56.6 mgm^{-2}s^{-1}and 7.5 mgm^{-2}s^{-1} at 4.5 m height. Thus the mean flux in the column can be from ~1/50th to ~1/10th of the peak value, depending on the variability of the vertical wind.

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 [9] of TSP and vertical wind speed gave total particle flux of ~600 to 4300 mgm^{-2}s^{-1}. Combined with observations of dust devil diameters of 7-15m and lifetimes of ~5 minutes, this suggests that these dust devils (re)moved up to >200kg of material from the surface. Subsequent field campaigns focusing only on the PM10 dust component of the columns show much lower flux values (<150 mgm^{-2}s^{-1} for peak values and <30 mgm^{-2}s^{-1} for mean values). From all encounters, the mean values for TSP (296 mgm^{-3}) exceeded maximum PM10 (43.8 mgm^{-3}) by about 7 times and the mean PM10 (15.1 mgm^{-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. Conversely, applying this result to the five dust devils sampled in 1996 suggests the commonplace delivery of ~20 kg of fine particulates per dust devil to at least several hundred meters height.

Comparison with other dust events: In our studies, vortices were visible with as little as 4 mgm^{-3} PM10 load, only 30 times ambient levels, whereas maximum dust loading events exceeded 150 mgm^{-3}. Comparatively, several authors have reported ambient levels and dust transport events in terrestrial arid regions that are 2 to 4 orders of magnitude less intense [9]. Dust devils are clearly extremely efficient erosional mechanisms.

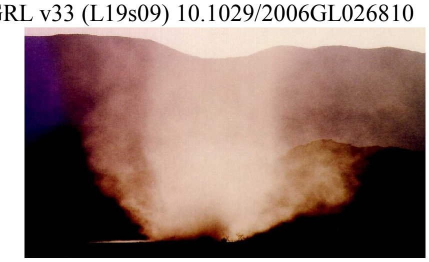
Comparison with other dust devil studies: Our terrestrial results give the first detailed *in-situ* measurements of dust devil particle load and include several columns with maximum flux of 100 - 120 mgm^{-2}s^{-1}, with a mean flux across the typical column of 7.5 mgm^{-2}s^{-1} at 4.5m. [15] estimated that a typical dust flux was ~28 mgm^{-2}s^{-1} and TSP flux of 520 mgm^{-2}s^{-1} (although their method was not described). [5] used LIDAR to remotely estimate a terrestrial dust devil column peak loading of 100 mgm^{-3} and peak vertical velocity of 10 ms^{-1} to calculate a dust flux of 1000 mgm^{-2}s^{-1}. Our peak flux results are consistent with the [15] data and, although our PM10 measurements agree well with [5], we suggest that the vertical wind speeds they use are possibly not typical (usually peak W is ~25% of peak H; [16]) and thus their flux estimate may be too high.

For Mars, [7] used column opacity to estimate the particle loading for a dust devil observed by the Imager for Mars Pathfinder camera, calculating a particle load of 70 mgm^{-3} and, using an estimate for vertical wind speed of 7 ms^{-1}, a vertical flux of 500 mgm^{-2}s^{-1}. [8] used surface imaging of Martian dust devils in Gusev crater to calculate vertical wind speeds of 0.2 – 8.8 ms^{-1}, a range well matched by our *in-situ* terrestrial measurements, giving maximum and mean dust flux estimates of 459 mgm^{-2}s^{-1} and 21 mgm^{-2}s^{-1}, respectively (similar to our observations although the peak values are higher). The vertical speeds used for estimates of vertical flux in martian dust devils by [17], 15 ms^{-1}, and [18], 20 ms^{-1}, however, were not observed *in situ* and are probably a factor of 2-4 too high. Laboratory vortex simulations at Earth and Mars atmospheric conditions [19] yield a dust flux range of 10 mgm^{-2}s^{-1} to 10,000 mgm^{-2}s^{-1}, with the upper range being greater than the field-based TSP reported here.

Conclusions: Using a variety of mobile test bed platforms, we have reliably determined *in-situ* sediment loading of dust devils, concurrent with wind data. Of those total suspended particles, however, ~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 is ~ one third that of measured peak loading and flux and provides a field-based conservative measure of atmospheric aerosol contribution.

Acknowledgements: We thank the Desert Research Institute, NV, Brent Bos & William Farrell at NASA Goddard, Ron Greeley at Arizona State University, and John Zarnecki at the Open University, UK for material & logistical support.

References: [1] Basu *et al*., 2004, JGR 109 (E11): 10.1029/2004JE002243 [2] Cantor & Edgett, 2002, AGU, 83 (47) P41A-0331 [3] Balme *et al.*, 2003, JGR 108: 10.1029/2003JE002096 [4] Cantor *et al.*, 2006, JGR 111 (E12002):10.1029/2006JE002700 [5] Renno *et al.*, 2004, JGR 109 (E07001): 10.1029/2003JE002219 [6] Thomas & Gierasch, 1985, Sci 230 (4722) [7] Metzger *et al*., 1999, GRL 26 (18) [8] Greeley *et al.*, 2006. JGR 111(E12): 10.1029/2006JE002743 [9] Metzger, 1999, PhD Dissertation, Univ. NV, Reno [10] Metzger *et al.*, 2004, AGU Fall Abs.P14A-08 [11] Sinclair, 1966, PhD dissertation, Univ. AZ, Tucson [12] Towner *et al*., 2004, Plan. Space Sci., 52 [13] Metzger & Lancaster, 1996, GSA Abs. v28, no7, p. A-109 [14] Metzger, 2001, LPSC 32 [15] Gillette & Sinclair, 1990, Atmos. Environ. Part A-Gen. Topics, 24 (5) [16] Balme & Greeley, 2006, Rev. Geophys, 44 (RG3003): 10.1029/2005RG000188 [17] Renno *et al*., 2000, JGR 105 [18] Ferri *et al.*, 2003, JGR 109 (E03004), 10.1029/2000JE001421 [19] Neakrase *et al*., 2006, GRL v33 (L19s09) 10.1029/2006GL026810



EV Back Dust Devil (Photo by S. Metzger, 2002)