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Assessing the power law hypothesis for the size–frequency distribution of terrestrial and martian dust devils

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ABSTRACT

Competing hypotheses for the diameter dependence of terrestrial and martian dust devil frequency are assessed using new field observations from two sites in the southwestern United States. We show that at diameters less than 12 m, our observed dust devil size–frequency distributions are better fit by an exponential function than by a power law formulation, and discuss the implications for larger dust devils on Earth and Mars.

1. Introduction

Dust devils, convective vortices made visible by the dust and debris they entrain (Balme and Greeley, 2006), are typically observed in arid environments where insolation causes strong vertical temperature gradients. Dust devils are common on Earth and especially Mars, where their associated dust-lifting may be responsible for the persistent dustiness of the martian atmosphere (Newman et al., 2002). Analysis of Mars Pathfinder (MPF) and Mars Exploration Rover (MER) imagery reveals the similar morphologies of martian and terrestrial dust devils (Metzger et al., 1999; Greeley et al., 2006).

As noted by Lorenz (2009), estimates of dust devil frequency derived from visual surveys conducted *in situ*—on both Earth and Mars—have varied by approximately four orders of magnitude (underscoring the need for better field data). Kurgansky (2006) proposed that terrestrial dust devil observations are best fit by an exponential function of the form

$$P(D) = \exp(-D/D_1) \quad (1)$$

where P is the probability that the dust devil size exceeds a given diameter D, and the decay parameter D_1 is approximately twice the Monin–Obukhov turbulent length scale L_0; i.e., $D_1 \sim 2L_0$. For example, the size–frequency distribution of dust devils observed in the Tucson Basin and Avra Valley by Sinclair (1966) is best fit by $D_1 = 8.3$ m, and the dust devil density observed in the Mojave Desert by Ryan and Carroll (1970) can be reproduced by $D_1 = 1.7$ m (Kurgansky, 2006).

However, Lorenz (2009) argues that such an exponential distribution does not provide a good match to MER observations of martian dust devils (Greeley et al., 2006). Instead, Lorenz demonstrates that a simple $n = -2$ power law differential size distribution better fits the MER observations (see Fig. 1 of Lorenz (2009)), the cumulative form of which can be expressed as:

$$N(D) = kD^{(n+1)} \quad (2)$$

where N is the number of dust devils per sq. km per day exceeding diameter D, and k is a constant equal to 250/km^2/day/m. The aim of the present work is to assess these competing exponential and power law hypotheses of dust devil size–frequency distributions with new observations of terrestrial dust devils.

2. Observations

In the first year of our ongoing field campaign, we conducted surveys of two locations in the southwestern United States: Eloy, Arizona, and Eldorado Valley, Nevada, both of which have been well-characterized as dust sampling sites in previous studies (e.g., Metzger, 1999; Balme et al., 2003; Renno et al., 2004). The Eloy site consists of tilled barren soil surrounded by a mixture of cultivated agricultural plots and arid desert terrain, including some shrub cover. The Eldorado Valley locale is a natural dry lakebed basin, devoid of vegetation on the playa but surrounded by sporadic sage and creosote bush. Encroaching alluvial fans, debris flow deposits, desert pavements, isolated surface rocks, and general geomorphology make this site an effective analog for Mars (Metzger, 2003). During the survey period, at least two and usually three observers were positioned at spotter stations located approximately 50 m apart, thereby allowing areas of $A = 0.83$ km^2 and $A = 0.55$ km^2 to be surveyed in Eloy and Eldorado, respectively (note that the well-defined boundaries along the rectangular Eloy tract permitted a larger survey region). Two of the spotters took simultaneous stereo photographs of dust devils that will be utilized for quantitative calculations of dust devil diameter (Balme et al., 2010), while the third spotter was tasked with making qualitative assessments of dust devil diameter and duration.

The results of our survey (shown in Table 1) are incompatible with the power law hypothesis of Lorenz (2009). We observed 150 dust devils over 5 days in Eloy and 528 dust devils over 9 days in Eldorado, resulting in respective number

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Table 1
Summary of dust devil survey observations conducted in Eloy, Arizona and Eldorado Valley, Nevada, including qualitative assessments of dust devil diameter (Tiny/Small/Medium/Large) and duration (Short/Moderate/Long). Conditions during the Eloy survey were unseasonably cloudy and windy; in contrast, skies were mainly clear during the Eldorado Valley survey.

Date (Y/M/D)	Start time	Stop time	Length (h)	Total # dust devils	Tiny (<2 m)	Small (2–6 m)	Medium (6–12 m)	Large (>12 m)	Short (<30 s)	Moderate (30–120 s)	Long (>120 s)
20090601	1114	1618	5.07	46	11	25	9	1	18	12	16
20090602	1132	1558	4.43	31	13	15	3	0	13	8	10
20090603	1124	1524	4.00	25	14	10	1	0	12	8	5
20090604	1104	1429	3.42	27	16	5	5	1	12	9	6
20090606	1104	1527	4.38	21	6	11	4	0	4	9	8
Eloy subtotals (area = 0.83 sq. km)				150	60	66	22	2	59	46	45
20090617	1215	1559	3.73	37	10	18	9	0	11	14	12
20090618	1058	1610	5.20	73	31	31	8	3	32	31	10
20090619	942	1550	6.13	71	35	24	6	6	28	27	16
20090621	1052	1415	3.38	37	5	19	9	4	11	21	5
20090622	1006	1624	6.30	71	37	23	6	5	24	31	16
20090623	1101	1620	5.32	83	29	28	17	9	32	33	18
20090624	1049	1453	4.07	58	14	25	14	5	25	20	13
20090625	1108	1218	1.17	18	6	5	3	4	4	5	9
20090626	1038	1645	6.12	80	20	41	17	2	18	46	16
Eldorado subtotals (area = 0.55 sq. km)				528	187	214	89	38	185	228	115
Combined totals (Eloy + Eldorado)				678	247	280	111	40	244	274	160

densities of $N = 40.6$ and $N = 106.7$ dust devils/km^2/day. These values are substantially less than the power-law-predicted occurrence rate of $N = 500$ dust devils/km^2/day derived from Eq. (2) assuming $n = -2$ and a minimum cutoff diameter of $D = 0.5$ m (corresponding to the dust devil detection threshold of human observers in the field: Lorenz, 2009).

Moreover, our qualitative estimates of dust devil diameter are also not consistent with a power law dependence. We visually assigned dust devils to one of four size categories: Large ($D > 12$ m), Medium (6 m < D < 12 m), Small (2 m < D < 6 m) and Tiny ($D < 2$ m). For example, at Eldorado Valley we observed 38 Large, 89 Medium, 214 Small, and 187 Tiny dust devils, which as shown in Fig. 1A means that at diameters greater than $D = 12/6/2/0$ m we surveyed $N = 38/127/341/528$ dust devils. Fig. 1A also plots the cumulative number of dust devils predicted for this 0.55 km^2 survey area by an $n = -2$ power law Eq. (2) and a $D_1 = 4.6$ m exponential function Eq. (1), the latter of which yields a much better fit to the data (Fig. 1A, caption). The relative quality of the exponential and power law fits can also be seen in Fig. 1B, which depicts the differential diameter dependence of dust devils in Eldorado Valley, expressed as a percentage of the total number of dust devils observed in each diameter bin. Fig. 1B shows that the shape of the $n = -2$ power law distribution is a poor fit ($R^2 = 0.35$) to the Eldorado observations, as it significantly underestimates the proportion of Medium and Small dust devils and dramatically overestimates the percentage of Tiny dust devils. In contrast, the $D_1 = 4.6$ m exponential fit of Kurgansky (2006) provides an excellent match ($R^2 = 0.98$) to the Eldorado field observations across all four diameter bins (Fig. 1B).

There are two main potential sources of error with our dust devil distribution observations: size estimation and durational bias. Table 1 represents our qualitative visual assessment of dust devil size, which may systematically over- or under-estimate actual dust devil diameters due to human error. We can formally assess this error by utilizing our aforementioned stereo photographs of dust devils to quantitatively calculate diameters via the parallax measurement methodology detailed in Balme et al. (2010). Based on our preliminary results—to date, this time-consuming computational technique has only been applied to 21 dust devils—we find that the majority of stereo-photographed dust devils have been qualitatively assigned to the correct diameter bin. Therefore, it is highly unlikely that our observed dust devil size estimates, which indicate an approximately equal number of Tiny and Small dust devils (Table 1), are sufficiently skewed to permit the Tiny/Small dust devil ratio of 4.0 predicted by an $n = -2$ power law (Fig. 1B).

But what if we are not observing a representative dust devil distribution within our survey areas? The most likely cause for such an error would be durational bias—i.e., dust devils in some size bins may not persist long enough on average to allow consistent detection, resulting in under-sampling. We qualitatively assigned dust devils to one of three duration categories: Long ($t > 2$ min), Moderate (30 s < t < 2 min), and Short ($t < 30$ s); overall, we observed 160 Long, 274 Moderate, and 244 Short duration dust devils (Table 1). The diameter dependence of dust devil duration is plotted in Fig. 2, which indicates that most observed dust devils larger than $D = 2$ m persist for longer than 30 s, as do more than 40% of Tiny ($D < 2$ m) dust devils. If we conservatively assume a 100% error in the detection rate for Short duration dust devils (in other words, that we only observed half of the actual distribution), and just apply this factor to Tiny dust devils (since smaller dust devils are more difficult to detect), then the "corrected" ratio of Tiny/Small dust devils is 392/280 = 1.4, which is still much less than the Lorenz (2009) power-law-predicted value of 4.0 (Fig. 1B). Therefore, we conclude that our terrestrial dust devil size–frequency observations are better fit by the exponential distribution Eq. (1) suggested by Kurgansky (2006).

3. Implications

Although our results are most consistent with an exponential diameter dependence of terrestrial dust devil density, they do not invalidate the applicability of the Lorenz (2009) power law to martian dust devils. As Lorenz (2009) noted, power laws will only apply above a certain threshold diameter. Since 93% of our observed dust devils are Medium-sized or smaller (Table 1), our results imply a power law threshold diameter of $D > 12$ m. This is consistent with the analysis of Lorenz (2009), who was able to fit an $n = -2$ power law to the Greeley et al. (2006) MER observations for diameter size bins greater than $D > 10$ m (see Fig. 1 of Lorenz (2009)) but not for the smallest-sized ($D < 10$ m) bin. Thus our results suggest that the observed "deficit" in the smallest MER dust devils (see Fig. 8a of Greeley et al. (2006)) is due not to MER detection limitations but rather to physical truncation of a power law (assuming one applies) at small diameters.

Intriguingly, Lorenz (2009) did accurately predict the frequency of our dust devil observations in Eldorado Valley and Eloy. As shown in Fig. 2 of Lorenz (2009), a simple empirical relationship

$$N_{obs} = 50/A \quad (3)$$

linking observed dust devil density N_{obs} (devils km^2/day) to survey area A (km^2) appears to apply to a wide array of terrestrial and Martian dust devil surveys, ranging from the Mojave Desert in California to Gusev Crater on Mars. Based on the survey areas of Eldorado (0.55 km^2) and Eloy (0.83 km^2), Eq. (3) predicts an observable number density of $N_{obs} = 90.9$ dust devils/km^2/day for Eldorado and $N_{obs} = 60.2$ dust devils/km^2/day for Eloy. These estimates are remarkably close to the actual values of $N = 106.7$ dust devils/km^2/day and $N = 40.2$ dust devils/km^2/day that we observed in Eldorado and Eloy, respectively (Table 1). Though note that the unseasonably windy and cloudy conditions that prevailed in Eloy at the time of our survey likely contributed to the overall lower number density of dust devils (as well as the nearly complete lack of Large dust devils) that we surveyed in Eloy (Table 1).

Lorenz (2009) suggested that the applicability of Eq. (3) to martian and terrestrial dust devils may be the consequence of an $n = -2$ power law dust devil distribution. Lorenz (2009) argued that if dust devil height and diameter (D) are correlated, and the detection threshold depends upon the solid angle subtended by the dust devil (i.e., D^2), then the observed number density N_{obs} should vary inversely with survey area A such that $N_{obs} = 50/A$ Eq. (3), which can be derived from Eq. (2) assuming $D = 0.5$ m and $A = 0.1$ km^2.

The closeness of our observed dust devil densities to the values predicted by Eq. (3) would thus appear to support the Lorenz (2009) $n = -2$ power law hypothesis. However, we argue that this correspondence is coincidental, for three reasons. First and foremost, the Lorenz (2009) power law hypothesis for dust devil frequency prediction is based on the presumption that the detection threshold diameter for an $A = 0.55$ km^2 survey area is $D = 0.5 \text{ m} * 0.55 \text{ km}^2/0.10 \text{ km}^2 = 2.75$ m. This is clearly inconsistent with our detection of 187 Tiny ($D < 2$ m) dust devils in Eldorado (Table 1). Secondly, we find that dust devil height may not necessarily be correlated with width at small diameters (as assumed by Lorenz, 2009), since we observed numerous Tiny dust devils exhibiting rapidly-spinning compact cores with heights

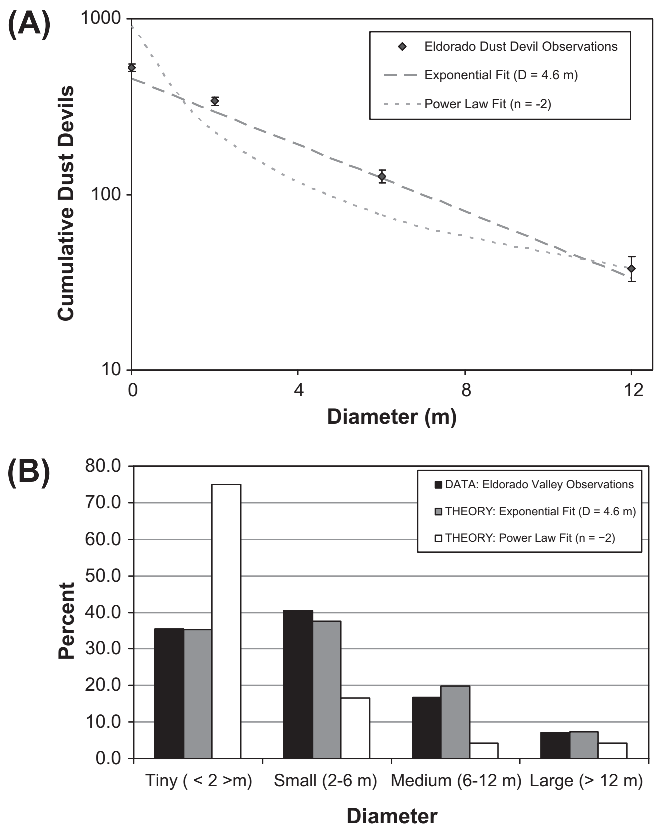

Fig. 1. (A) Cumulative number of dust devils *N* exceeding a given diameter *D*. Filled circles correspond to our survey of 528 dust devils in Eldorado Valley (Table 1): error bars represent standard sqrt(*N*) error. For the $A = 0.55\ km^2$ survey area, the cumulative form (short-dashed line, $R^2 = 0.838$) of the Lorenz (2009) power law distribution (Eq. (2)) does not fit the observations as well as the cumulative form (long-dashed line, $R^2 = 0.999$) of the Kurgansky (2006) exponential function for $D_1 = 4.6$ m (derived by multiplying *P* in Eq. (1) by *k* in Eq. (2), in order to enable direct comparison with the power law formulation). (B) Histogram showing differential dust devil size distribution, expressed as a percentage of the total number of dust devils observed/predicted in each diameter bin. From left to right (within each diameter bin) bars correspond to: Eldorado survey of 528 dust devils (Table 1); Kurgansky (2006) exponential function (Eq. (1)); and Lorenz (2009) power law (via Eq. (2)). The shape of the $n = -2$ power law distribution is a poor fit ($R^2 = 0.35$) to the data—a slightly better power law fit actually occurs at $n = -1.8$, but yields such minimal improvement ($R^2 = 0.36$) that we have elected to retain $n = -2$ as the default power law throughout this work to facilitate direct comparison with the results of Lorenz (2009). The value of the Kurgansky (2006) decay parameter that produces the best fit to the observed Eldorado differential distribution is $D_1 = 4.6$ m ($R^2 = 0.98$): this value yields an even better fit ($R^2 = 0.99$) to the Eloy differential dust devil distribution (Table 1). The exponential function of Kurgansky (2006) provides an excellent match to the Eldorado field observations across all four diameter bins.

exceeding several tens of meters. Indeed, a classic type of dust devil vortex is that of a narrow ($D = 1$–3 m), stable, tightly structured tube that extends hundreds of meters above the surface, which is quite different in morphology from shorter, thicker dust devils (Balme and Greeley, 2006). Lastly, we note that the Lorenz (2009) power law hypothesis for dust devil frequency prediction does not specify a temporal component, which may be a significant factor for field observers of dust devils at Tiny and Small diameters given the large proportion of Short ($t < 30$ s) duration dust devils in these size bins (Fig. 2).

Therefore, we suggest that below our inferred power law threshold diameter (which is approximately $D \sim 12$ m), a baseline exponential dust devil distribution is being modified by diameter-dependent detection and duration thresholds that act together to reproduce the empirical dust devil frequency relationship Eq. (3) identified by Lorenz (2009). Instruments on board the forthcoming Mars Science Laboratory (MSL) rover mission may confirm whether such a phenomenon occurs at similar diameters on Mars.

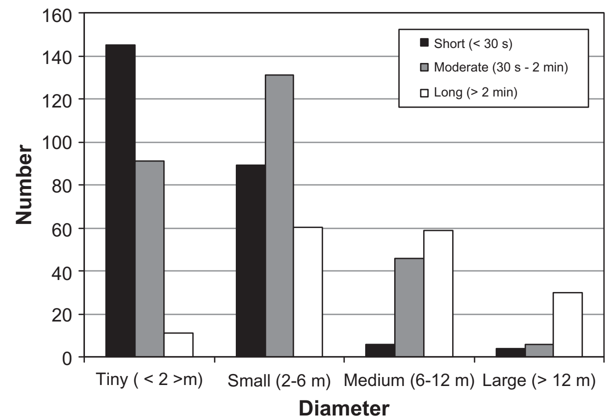

Fig. 2. Histogram showing dependence of dust devil size distribution on duration, for all 678 observations in Eldorado Valley, NV and Eloy, AZ (Table 1). From left to right (within each diameter bin), bars correspond to short ($t < 30$ s), moderate ($30\ s < t < 2$ min), and long ($t > 2$ min) duration dust devils, as qualitatively determined by field spotters.

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