Irregular dust devil pressure drops on Earth and Mars: Effect of cycloidal tracks

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ABSTRACT

In a survey of dust devil activity at a desert playa using continuous monitoring by a pressure logger, we have detected a number of pressure drops with complex structures: simple and symmetric drops make up only 25–30% of the total. In contrast to the simple, symmetric single-dip profiles expected for single-cell vertical vortices gliding past the pressure sensor, many profiles have an asymmetric shape, double dips, or ‘shoulders’ where a broad shallow dip is superposed on a narrow deeper one. A double dip in Mars Phoenix data was attributed in prior work to a near-simultaneous encounter with two dust devils, while laboratory experiments with two-cell vortices find a local peak in pressure at the center, also yielding a double dip in a transect profile. However, we suggest instead that a likely explanation for many complex pressure profiles measured in the field and on Mars is in fact the trochoidal path of a dust devil across the terrain, rather than the straight-line constant-speed path usually assumed. Images of the Martian surface show that many dust devil tracks have such a trochoidal or cycloidal path, which can be parametrically described. A model of the pressure profile driven by this parametric path description can reproduce observations.

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1. Introduction

Vortical flows are associated with some of the most dramatic and destructive weather phenomena on Earth—tornadoes and hurricanes. Dust devils are smaller vortices, driven by dry convection due to strong solar heating rather than by moisture as in those phenomena, which can be rendered visible, and perhaps are enhanced in intensity, by lofted dust. In all of these phenomena, the centripetal acceleration in the rotating flow can be related to a radial pressure gradient, such that the centers of these features have a pressure drop compared with ambient. Some example pressure drops are shown in Fig. 1: the depth of the pressure drop relates to the air density and the wind speed, while the duration of the drop scales with the size of the structure and its propagation speed. Hurricanes (tens of mbar) are therefore associated with hours–days, while tornados (tens of mbar) and dust devils (a few tens of microbar on Mars, about one mbar on Earth) are typically seconds–minutes.

Although sporadic instrumental records of terrestrial dust devil pressure drops have existed since (Wyett, 1954) in fact only a modest number of such traces have been published, since typical meteorology data is only recorded with a cadence of the order of 10 min to 1 h, too slow to capture most dust devil events. As discussed in Lorenz (2012b), the available terrestrial database of fixed-station records (that of Lambeth (1966)) is too small to make a statistical comparison of the amplitude distribution (whether power law or exponential or some other skewed function) with that of Mars, where the Pathfinder (Murphy and Nelli, 2002: see also Schofield et al., 1997) and Phoenix landers (Ellehoj et al., 2010) have recorded some 83 and 502 pressure drops, respectively. The Curiosity rover carries a meteorology package, and so we may expect additional Mars data in coming years. There is, therefore a need to acquire systematic data on terrestrial dust devils to address this data imbalance.

A field measurement campaign has therefore been initiated to remedy this data gap. The measurement approach has used small commercial data loggers using precision (1 Pa=0.01 mbar resolution) absolute pressure sensors with flash memory adapted to use higher-capacity battery power (Lorenz, 2012a) to perform 2 Hz or faster measurements over periods of months. This fixed-station approach is readily-scalable and avoids the sampling biases associated with ‘storm chasing’ measurements with vehicle-deployed instrument platforms (e.g., Metzger et al., 2004, 2011) and the vibration effects and irregular miss-distance profiles associated with vehicle-born instruments (such as those of Sinclair (1973), Tratt et al. (2003)). Although it leads to fewer encounters per station per unit time than a directed mobile platform, it is much more representative of the measurement
approach employed at Mars, where a fixed lander (or near-fixed rover) simply records pressure over long periods and post-hoc analysis detects dust devils as brief pressure drops.

A very large number of dust devil encounters is being harvested with this technique and a full statistical analysis is underway and will be reported in future work. It has been noticed, however, that a number of the pressure drops observed do not have the ‘classic’ single-dip structures shown in Fig. 1, but instead have multiple dips, or significant changes in slope—see Fig. 2. A brief inspection of the most obvious vortex signatures (those with pressure drops of $\pm 0.3 \text{ mbar}$) in measurements with three independent stations at El Dorado Playa over a 24 day period in summer 2012 reveals the data in Table 1: vortices were detected at a rate of 1.2–2.6 per day, and only 28–33% of them were simple and symmetric. 42–48% were single-dip but asymmetric, and 18–28% were double-dipped, multi-dip or otherwise complex. Thus at this location and time at least, non-simple signatures form a significant proportion of the total and merit an explanation. It may be that other locations and/or seasons favor a higher proportion of simple profiles.

Stations P28 and P11 were near the center of the playa and have a similar number of total vortices; station P10 is near the south end of the playa where fewer devils appear to form (or, perhaps, if they are spawned upwind – in general south – of the playa, a similar number of devils form, but have had less time to grow above the detection threshold.) Further discussion is beyond the scope of the present paper, but it is of interest that despite the variation by a factor of 2 in the total number of devils between the P28/P11 location and P10, the proportion of asymmetric or complex signatures is the same for both datasets.

The present paper aims to explore possible explanations for this diversity of profiles.

2. Pressure drop structure

Although it is conventional in interpreting pressure records (e.g., Ellehoj et al., 2010) to assume that a dust-devil is a single-celled vortex, with pressure drop being a smooth function of distance, vortical flows in general (including dust devils) can have much more complex structures.

In particular, two-cell vortices are not uncommon, wherein a central downdraft exists in the vortex. Thus near the ground there is a toroidal flow (leading to two loops or cells in cross-section). Laboratory simulations of such flows (Snow et al., 1980) yield horizontal surface pressure profiles which have a double-dip (Fig. 3), with the central pressure somewhat higher than the pressure at a small radial distance from the center.

In fact, multiple vortices can form in dust devils (e.g., Balme and Greeley, 2006): such structures are also seen in tornadoes—e.g., Winn et al. (1999) document a six-cell vortex associated with the tornado profiled in Fig. 1 and a double-dip pressure record is seen in a tornado encounter with a fixed station in Fig. 11d of Karstens et al. (2010). So far, few examples of complex pressure drops have been reported on Mars. Ellehoj et al. (2010) note one vortex with a double-dip (see Fig. 4) which they attribute to an encounter with multiple dust devils, which a simple calculation shows is rather improbable (i.e., with only $\sim 3$ encounters per day, thus a mean interval of say 2 h, it is

![Fig. 1. Pressure drop profiles for various vortex phenomena. (a) Passage of Hurricane Irene, a large and destructive tropical cyclone, observed from Glen Burnie, MD, near the author’s residence in August 2011 (b) in-situ measurement by a hardened ‘E-turtle’ instrument platform of close passage of an F3 tornado (Winn et al., 1999) at Allison, TX in June 1995 (c) dust devil on Mars recorded by the Phoenix lander on Sol 90 (Ellehoj et al., 2010) (d) dust devil on a Nevada playa in June 2012, recorded by a compact pressure logger (Lorenz, 2012a). Note that the tornado and hurricane have comparable pressure drops ($40 \text{ mbar or } \sim 4\%$), but very different timescales. The dust devil pressure drops shown are $\sim 0.5\%$ and 0.05% of ambient, respectively.](image-url)
The laboratory work (e.g., Snow et al., 1980) shows that two-cell vortices tend to form for high \( S \), which measures the relative strength of radial inflow and vertical throughput. \( S \) is usually defined as \( S = \frac{r_0 \Gamma}{Q h} = \frac{\Gamma}{2Qa} \), with \( r_0 \) the radius of the updraft, \( \Gamma \) is the circulation at \( r_0 \), \( Q \) is the volume flow rate per axial length or the volume flow rate across the updraft, \( h \) is the inflow depth, and \( a \) is the internal aspect ratio: \( h/r_0 \).

### Table 1
Classification of El Dorado vortex passage events (\( > 0.3 \text{ mb} \)) June 18–July 11, 2012.

<table>
<thead>
<tr>
<th>Station</th>
<th>Total events</th>
<th>Single symmetric</th>
<th>Single asymmetric</th>
<th>Double or multiple</th>
</tr>
</thead>
<tbody>
<tr>
<td>P28</td>
<td>54</td>
<td>18</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>P11</td>
<td>64</td>
<td>18</td>
<td>29</td>
<td>17</td>
</tr>
<tr>
<td>P10</td>
<td>28</td>
<td>8</td>
<td>12</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 2. Example ‘irregular’ pressure drop traces recorded at Eldorado Playa in Nevada in June/July 2012. The points are individual measurements (in most cases data are recorded at 2 Hz) while the line is a 5-point running mean. (a) A classic ‘double dip’ that might be interpreted as a dual-core vortex. (b) A dip with ‘shoulders’, wherein the outer slopes are distinctly shallower than a central core; this example has a slight secondary dip before the main drop (c) an asymmetric double-dip (d) a symmetric double dip—here as in (a) the ingress and egress slopes are slightly different (e) another asymmetric double dip, this time with sharper dips. Note that the maximum pressure drop (dot) exceeds that of the smoothed curve by ~20%, indicating a small and/or fast-moving vortex, for which a time resolution of 1 s or poorer would not have characterized well. (f) A triple (or possibly higher-number) dip signature.
While such a structure might explain some symmetric double-dip observations, it does not, however, explain the more complex multi-dip profiles seen. It is possible that multiple vortices can form (which can occur for swirl ratios $c_1$). However, another possibility deserves to be investigated.

3. Dust devil trajectories—Not always straight

The association of time in a pressure record with spatial position explicitly relies on the trajectory of the dust devil across the ground. This is invariably assumed to be at a uniform velocity, equal to the (assumed constant) ambient wind. This assumptions is not unreasonable: Flower (1936) provides data from field observation that show that dust devils in general do move at close to the ambient wind speed and Balme et al. (2012) confirm this general impression using stereogrammetric tracking of dust devils in two field locations.

Apart from the observation by Flower (1936) that many paths are somewhat curved, to date there is little documentation of dust devil paths (which anecdotally can sometimes have a somewhat circular character in cases of low ambient wind—supported by inspection of movies on the video sharing site ‘Youtubef’. However, it may be noted that vortical wind systems in general can follow trochoidal paths: due to the damage inflicted by tornadoes and hurricanes, there is considerable interest in predicting their paths. Arakawa (1952) notes the generally cycloidal paths of whirlwinds such as tornadoes. The longer duration of hurricanes and typhoons has allowed their sometimes trochooidal paths to be more systematically documented, and many papers in the hurricane literature discuss observations of these paths (e.g., Hong and Chang, 2005; Jordan and Stowell, 1955; Lawrence and Mayfield, 1976).

On Mars, although no dust devil path has been directly observed with a cycloidal path dust devils themselves sometimes draw their paths for us. In some locations and seasons on Mars dust devils leave prominent tracks on the ground (e.g., Edgett and Malin, 2000; Balme et al., 2003). Almost invariably these are dark trails, presumed to be generated by the removal of bright dust from the surface. Similar tracks have been detected at a few locations on Earth (Rossi and Marinangeli, 2004), and have been documented in situ (Reiss et al., 2010). Occasionally bright tracks are present (e.g., Hoffer and Greeley, 2010) and might be produced by a related mechanism (e.g., Reiss et al., 2011).

Balme et al. (2012) in their tracking study at El Dorado playa (the same location as our pressure records, although conducted at a different time) find ‘most of the dust devils followed straight paths on the 500 m scale We did not observe curlicue paths as seen on Mars nor a majority of severely curved paths, as reported to be dominant on Earth’. However, the 500 m scale is a very large one for Earth (where dust devils appear smaller than at Mars). Furthermore, inspection of individual tracks (Balme et al’s Fig. 5), which are defined by straight-line segments of $\sim 30–100$ m, reveals about 10 ‘kinks’ with appreciable change in direction among the $\sim 50$ tracks reported (similarly, they report that 9 out of 52 records have more than 30 degree difference between devil

Fig. 3. Double-dip profile of a two-cell laboratory vortex. The laboratory data of Snow et al. (1980) extend horizontally only from $-0.25$ radii to $+1.5$: in this plot we have reflected the data about the centerline to yield a symmetric curve with a local high pressure in the center as is familiar from field measurements.

Fig. 4. Double-dip of a Martian vortex recorded by the Phoenix lander: Ellehoj et al. (2010) suggest two dust devils close together as the explanation.

Fig. 5. An MRO/HiRISE image (PSP_004038_1255) showing the remarkably curly tracks left by Martian dust devils. Some notably arcuate examples are arrowed.
motion and ambient wind). Balme et al. (2012) acknowledge that tighter sampling ‘might produce a different result’—in fact, it is a geometrical certainty that better sampling would revise the sinuosity of tracks upwards: adding points on a curve cannot possibly make it straighter. The profiles we have recorded correspond to miss distances of only a few to a few tens of meters, and thus the actual fraction of sinuous tracks on that scale may exceed the 20% implied above for > 100 m scales and may well be consistent with the ~70% implied by the pressure data. Martian tracks are not, in general, perfectly straight either—and in some cases can be remarkably tangled (see Fig. 5). Their paths have to date been described by a single parameter (sinuosity, the ratio of along-track length to straight line end-to-end length). Verba et al. (2010) note in a survey of some thousands of dust devil tracks that the mean sinuosity of tracks in a given image had a range of 1.02–1.19 in images of Gusev crater, and 1.2–1.45 in images of Russell crater. They also noted that for the Russell crater tracks, at least, the sinuosity was anticorrelated with length. This is an important clue: this relationship is consistent with a constant lateral movement. Similarly, the Russell crater tracks are in aggregate shorter (mean length 2.6 km vs. 4.7 km at Gusev). A model that would produce this relationship is that there is some intrinsic length scale over which a dust devil may ‘wander’ in zero wind. This might well be a somewhat circular path, on which is superposed a linear drift due to a constant wind. The observed data on both length and sinuosity would be consistent with dust devils having similar durations at both Gusev and Russell, but with ambient winds being weaker at the latter location. In any case, these data show that tracks have a ‘typical’ sinuosity of 1.1–1.3.

In at least some instances, the track shape appears trochoidal, the path made by a point at a distance from the center of a circle of radius rolling on a fixed line. A trochoid has parametric equations $x = A \theta - B \sin(\theta)$, $y = A - B \cos(\theta)$, where $\theta$ is a measure time (and, since angular velocity is constant, an angle) and $A$ and $B$ are the radius of the circle and the point’s distance from center. If $B < A$ the trochoid is known as a curtate cycloid and resembles a wave; if $B = A$, it is a (classic) cycloid with vertical asymptotes; and if $B > A$, the curve has loops and is a prolate cycloid. Since the term cycloid is familiar in planetary science (via the cycloidal cracks on Europa) we may use this term even when it may be more formally correct to refer to the more general term ‘trochoid’.

Whereas a body on a straight path will have a distance from a fixed point that monotonically declines to a closest approach and then monotonically increases, a body on a cycloidal trajectory may have multiple local distance minima. Since the amplitude of the pressure drop of a dust devil gets weaker with distance, a cycloid could produce multiple dips in a pressure profile (or equivalently, multiple peaks in a wind record.) We now examine quantitatively the shape of the resultant profiles.

4. Modeling—VEMOOSE

A major obstacle to deriving a consistent picture of the evolution of individual dust devils, and the ensemble behavior of the dust devil population as a whole, is the incomplete nature of observations. The available data, from very sporadic imaging, or from isolated in-situ measurements (often with measurement gaps) make it difficult to fully understand the population—e.g., what is the probability that a dust devil seen in two images is the same devil? These difficulties have challenged efforts to characterize the similarities and differences between the Mars and Earth dust devil populations. Accordingly we have begun an effort we term ‘VEMOOSE’ (vortex evolution model with observation operations simulated explicitly) that simulates a population of dust devils in a simulation arena, and observation processes such as point pressure records, or optical observation of all or part of the arena (with a spatially-varying detection threshold). By combining quantified detection efficiencies with trial values of population parameters, it is possible to rigorously compare measurements acquired under very different conditions, and to thereby estimate the underlying parameters.

Fig. 6. Simple Lorentzian pressure drop that declines with distance from the center of a dust devil moving at a constant velocity yields a symmetric pressure drop.

\[ v = 0.200 \text{ m/s} \quad r_0 = 0.00 \text{ m} \quad p_0 = -3.00 \text{ mbar} \]

\[ y_0 = 0.000 \text{ m} \quad 0 = 5 \text{ m} \quad a = 0.000 \text{ m/s} \quad b = 1.200 \]

\[ w = 0.060 \text{ m/s} \quad Q = 0.000 \text{ m/s} \]

\[ v = 0.200 \text{ m/s} \quad r_0 = 0.00 \text{ m} \quad p_0 = -3.00 \text{ mbar} \]

\[ y_0 = 10.00 \text{ m} \quad 0 = 5 \text{ m} \quad a = 0.000 \text{ m/s} \quad b = 1.200 \]

\[ w = 0.060 \text{ m/s} \quad Q = 0.000 \text{ m/s} \]
The effort described in the present paper, that uses information from dust devil tracks to describe the path of dust devils which are measured by pressure sensing, is a first step in this effort. Future work will expand this approach and will allow, for example, the ratio of straight and cycloidal paths (or perhaps a continuous distribution of A/B) to be compared with a set of pressure records—e.g., how many double-dip vs. single-dip profiles are seen.

It is conventional to assume that a dust devil is a radially-symmetric structure, most commonly described by the Rankine vortex model, wherein solid body rotation occurs from the center to the wall radius \( r_w \) (\( =d_0/2 \) where \( d_0 \) is the observed diameter), with the circumferential speed \( u \) proportional to distance from the center \( l \), i.e., \( u=u_0(l/r_w) \), and speed falls off with inverse distance beyond the wall, i.e., \( u=u_0(r_w/l) \). A cyclostrophic balance is further assumed, such that (neglecting vertical and radial

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**Fig. 7.** A trochoidal trajectory yields a variety of pressure profile morphologies. If the loop or cusp occurs at the closest approach of the overall trajectory, then the profile can remain symmetric, but with a wider shape or even a central peak. A trajectory with a loop before or after closest approach can yield profiles with different ingress and egress slopes, or even a flat shoulder on one or both sides.
velocity) the pressure drop outside \( r_w \) varies as \( u^2 \), i.e., \( \Delta P = \Delta P_0 (r_w/l)^2 \). Ellehoj et al. (2010) model dust devil passage with a Lorentzian function—essentially an inverse square with an added constant term, i.e., \( \sim (r_w + l)^2 \). Other analytic vortex formulations have been investigated for tornados (e.g., Winn et al., 1999), incorporating vertical velocity terms, but the overall shape is broadly similar (notably, a smooth monotonic variation with distance) and so we retain the simple and familiar Rankine/ Lorentzian formulation here. We will note in passing that Tratt et al. (2003) have recorded a single dust devil encounter wherein \( u \) fell off more slowly with distance (as \( (x/r)^{0.4} \), such that in cyclostratic balance \( \Delta P \) would fall off inversely with distance rather than as the inverse square.

To simulate an encounter, we choose a central pressure drop \( \Delta P_0 \) (the label we use in the plots that follow: we ignore the interior of the vortex) and calculate the observed pressure at a fixed point as a function of time, with \( \Delta P \) proportional to the inverse square of normalized distance (i.e., distance divided by \( d/2 \)). Because VEMOOSE aims to physically simulate the growth, decay and motion of dust devils as entities, we adopt a set of physical parameters to describe the path as a function of time, even though a smaller set of parameters would describe the geometry alone.

We place the \( x \)-axis of a horizontal coordinate system along the general direction of motion driven by wind speed \( v \): the time-mean \( x \)-position simply varies as \( v \times t \) and is zero at an arbitrary time \( t=0 \). Supered on this linear path is a circular motion described by an angular velocity \( w \) with an initial angle \( Q \) and a radius \( R \). Thus \( x(t) = -x(0) + v \times t + R \sin(wt + Q) \) and \( y(t) = y(0) + R \cos(wt + Q) \). This defines a continuous trochoidal curve. In order to spatially localize the excursions, we introduce two decay parameters \( a \) and \( b \), and substitute \( R = R_0 \exp(a \times \text{ABS}(t-0)/b) \). Other formulations would yield equivalent results.

First, the effect of miss distance (previously noted for pressure drops and wind direction by Ringrose et al., 2007 and Tratt et al., 2003) is illustrated in Fig. 6 by setting \( R_0 = 0 \). An increase in miss distance (in this case, equal to \( y_0 \)) yields a broader and shallower pressure dip.

When, however, \( R_0 > 0 \), trochoïdal trajectories emerge, and depending on how the parameters are chosen (the parameter values are not of particular importance in that the solution is unique—multiple parameter sets could yield acceptable fits to a given pressure profile) the observed pressure dip can be narrow or broadened or can have shoulders (Fig. 7). Furthermore, multiple dips, whether symmetric or asymmetric, can be generated by cycloidal paths with multiple loops (Fig. 8). In symmetric encounters, the effect of the spatial localization parameters \( a \) and \( b \) is in general quite small, in that weakening of pressure drop with distance has the same spatial filtering effect. However, to develop asymmetric signatures, the timing (i.e., rotational phase) of the circular path with respect to the closest approach becomes important and these parameters are needed to secure the fit.

Desirably the dust devil trajectory will be known. For Mars this may occasionally be possible if imaging from a lander or rover observes a nearby dust devil passing by, or if imaging from an orbiter identifies a dust devil track which can be associated with an \( \text{in-situ} \) measurement record. On Earth, contemporaneous time-lapse imaging may provide the geometric context for meteorology data. Another approach, to be explored in future work, is to exploit simultaneous pressure or other \( \text{in-situ} \) data from multiple stations. Winn et al. (1999) perform a simple analysis of data from two stations supported by some imaging context information to investigate the radial pressure field around a tornado: a more general method is to forward model the observed signatures as in our VEMOOSE approach described in Section 4.

The significant number of arcuate dust devil tracks on Mars, and the possible indication in pressure records that many terrestrial dust devils have trochoïdal paths, begs a related question: what causes these paths? Is the large-scale wind field itself rotating and pushing the devil in such a trajectory, or does the
vorticity in the devil itself somehow introduce a cycloidal motion? An investigation of the possible correlation of path sinuosity or the relative frequency of multi- versus single-dip pressure profiles with ambient weather conditions (such as wind speed) may prove fruitful in addressing this issue. It seems plausible that if the characteristic circular motion of a devil has an invariant distribution with expected value $\langle v \rangle$, then in general a stronger ambient wind $u$ may tend to lead to straighter tracks, with a deviation angle of the order of arcsin $\langle v \rangle/u$. On the other hand, if the cycloidal motion relies on vorticity extracted from the ambient wind field, then $\langle v \rangle$ and $u$ may be correlated, and the straightness or otherwise may be independent of $u$. It would furthermore be interesting to learn whether cycloidal trajectories emerge in large eddy simulations (LES) of dust devils, and if so, how their straightness varies with ambient conditions.

5. Conclusions

We have shown that multi-dip and asymmetric pressure histories can be generated by simple, single-core dust devil vortices following trochoidal paths along the ground that are consistent with observations of dust devil tracks. Thus interpretation of such histories should be cautious in identifying double-core or multiple dust devils, although such features may indeed exist. Careful analysis will be required to disentangle combined effects of multiple cores and trochoidal movement, and by analogy with hurricane observations, these factors may be correlated.

This work highlights the influence of miss distance on recorded pressure drops and underscores the utility of resolving the position/size ambiguity in single-station pressure-only data. Consideration of the analogous hurricane and tornado-track literature suggests these questions are rather general ones. Furthermore, the trochoidal paths of these systems may also be connected with the presence of multiple cores. Measurements of dust devils using multiple stations, and theoretical and/or numerical modeling, may be fruitful areas of future enquiry.

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