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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.

1. Introduction

Vortical flows are associated with some of the most dramatic and destructive weather phenomena on Earth—tornados 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-borne 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

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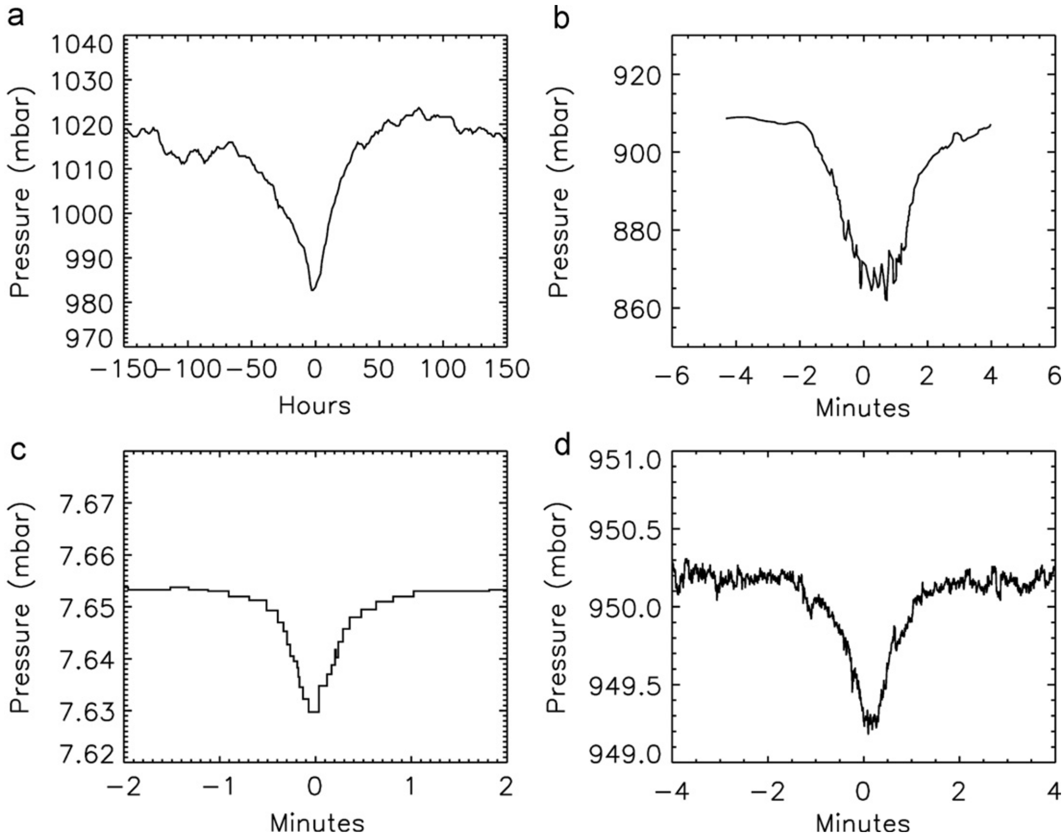

Fig. 1. Pressure drop profiles for various vortex phenomena. (a) Passage of Hurricane Irene, a large and destructive tropical cyclone, observed from Glen Burnie, MD, near the author's residence in August 2011 (b) *in-situ* measurement by a hardened 'E-turtle' instrument platform of close passage of an 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 mbar or ~4%), but very different timescales. The dust devil pressure drops shown are ~0.5% and 0.05% of ambient, respectively.

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 >0.3 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 tornados—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 ~3 encounters per day, thus a mean interval of say 2 h, it is