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Dust devil height and spacing with relation to the martian planetary boundary layer thickness

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ABSTRACT

In most remote and unmonitored places, little is known about the characteristics of daytime turbulent activity. Few processes render the optically transparent atmospheres of Earth and Mars visible; put more plainly, without clever instruments it is difficult to "see the unseen". To address this, we present a pilot study of images of martian dust devils (DDs) testing the hypothesis that DD height and spacing correlates with the thickness of the planetary boundary layer (PBL), *h*. The survey includes Context Camera (CTX) images from a $580 \times 590\ \text{km}^2$ area (196–208°E, 30–40°N) in northern Amazonis Planitia, spanning ~3.6 Mars Years (MY) from $L_s = 134.55°$, MY 28 (13 November 2006) to $L_s = 358.5°$, MY 31 (28 July 2013). DD activity follows a repeatable seasonal pattern similar to that found in previous surveys, with a distinct "on" season during local summer, beginning shortly before the northern spring equinox ($L_s = 0°$) and lasting until just after the northern fall equinox ($L_s = 180°$).

DD heights measured from shadow lengths varied considerably, with median values peaking at local midsummer. Modeled PBL heights, constrained by those measured from radio occultation data, follow a similar seasonal trend, and correlation of the two suggests that the martian PBL thickness is approximately 5 times the median DD height. These results compare favorably to the limited terrestrial data available.

DD spacing was measured using nearest neighbor statistics, following the assumption that because convection cell widths have been measured to be $\sim 1.2 \pm 0.2h$ (Willis, G.E., Deardorff, J.W. [1979]. J. Geophys. Res. 84(C1), 295–302), a preference for DD formation at vertices of convection cells intersections could be used to estimate the PBL height. During local spring and summer, the DD average nearest neighbor (ANN) ranged from ~1 to 2*h*, indicating that DD spacing does indeed correlate with PBL height. However, this result is complicated by two factors: (1) convection cell spacing estimates indicate that the observed DD distributions undersample the possible grid of cell vertices in each CTX image, and (2) comparison of the ANN with a random distribution shows that the most closely-spaced DD distributions exhibit some clustering; we propose that this clustering demonstrates that many of the observed DDs are located along convection cell walls, in addition to cell vertices.

1. Introduction

The association of the height of dust devils with the depth of the PBL has been recognized for two millennia: the Roman poet Lucan, writing about campaigns in Libya in his epic poem Pharsalia (Lucanus, 65) observes that smoke plumes and dust devils are capped at the same height "*There is no rain in the cloud of whirling dust which it drives furiously in circles; most of the land is lifted up by it and is suspended in the air, as the eddying motion is continuous. The needy Nasamonian sees his possessions flying in the wind and his dwelling blown to pieces; the Garamantian is laid bare, and his hut, beginning with the roof, is snatched away and flies aloft. Fire does not carry what it seizes to a greater height: as high as smoke may rise up and mar the face of day, so great is the dust that fills the air.*"

The Earth's PBL is the region of the atmosphere adjacent to the surface that responds directly to surface forcing by frictional drag, sensible heat, and volatiles with a timescale of approximately an hour or less (Stull, 1988). The height *h* of the PBL (sometimes referred to as a depth or thickness), and in particular, that of the daytime convective boundary layer (CBL), is a key quantity describing the vigor of convective activity. For example, the convective velocity scale w_* (i.e., Deardorff velocity), which describes the

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turbulent flux of virtual potential temperature near the surface, and is generally of the order of updraft speed in convective thermals, can be written as $w_* = \left(\frac{gh}{\overline{\theta_v}}\left(\overline{w'\theta'_v}\right)_s\right)^{1/3}$, in which g is gravitational acceleration, $\overline{\theta_v}$ is the mean virtual potential temperature, and $\left(\overline{w'\theta'_v}\right)_s$ is the mean vertical kinematic eddy heat flux at the surface (Stull, 1988). The CBL is composed of structured turbulent eddies, containing vortices that form in narrow updrafts at the intersections of convection cells (e.g., Willis and Deardorff, 1979; Hess and Spillane, 1990; Kanak et al., 2000). When dust-laden, these vortices are rendered visible and called "dust devils", although both water droplets and snow can play the same role, creating "steam devils" and "snow devils". Because convective cell intersections correspond with thermals that can reach to the top of the CBL, DDs have been proposed to be integrally related to convective circulation, potentially influencing CBL processes (e.g., Goody and Gierasch, 1974; Kanak, 2008). For example, Kurgansky (2006) predicted that DD heights are related to their horizontal rotational velocity and the vigor of associated convective updrafts. In sparsely-instrumented locations, such as remote locations on Earth and nearly all locations on Mars, readily observable physical characteristics of DDs have the potential to provide information about local CBL conditions in lieu of more direct measurements.

Using a laboratory convection tank, Willis and Deardorff (1979) found that vortices analogous to dust devils could reach from the surface to the top of the tank's mixed layer. Several field studies have indicated that convective activity can raise dust to altitudes greater than one kilometer, in some cases even reaching to a few kilometers (e.g., Flower, 1936; Morton, 1966; Bell, 1969; Ansmann et al., 2009), suggesting that the same pattern holds in the boundary layer on Earth. Many field studies found that DDs grow in height as the CBL deepens during late morning (Sinclair, 1969; Snow and McClelland, 1990; Metzger, 1999; Ansmann et al., 2009; Kurgansky et al., 2011), from which one may infer that dust devil heights have a monotonic relation to the height of the CBL. However, few studies to date have simultaneously measured the heights of both DDs and the CBL or PBL (see Table 1). Hess and Spillane (1990) performed the only known systematic study, reviewing observations from pilots and concluding that DDs reached two characteristic heights of $0.09h$ and $0.51h$. However, this relationship was based on only twenty-five measurements (17 from their own study and 8 from Bell (1969)) spanning the entire country of Australia, measuring only the highest plume of any observed, and assuming a constant mixed layer height. In fact, their data are also compatible with a scenario of a skewed distribution, for example an exponential with an e-folding length of ~40% of the CBL height (see Fig. 1a).

More recently, Ansmann et al. (2009) used polarized lidars to detect the structure of convective plumes in Morocco over 5 days of observations. They showed that most dust-laden convective plumes among their sample of 61 (some of which presumably contained DDs) reached to ~0.3 the height of the Saharan dust layer height (DLH, the top of the mixed layer), although occasional plumes penetrated farther (the maximum reported was 0.69DLH). In fact, quantitative comparison shows the Ansmann et al. (2009) and Hess and Spillane (1990) studies to be broadly compatible. Plotted as cumulative probabilities, they broadly agree with each other, and an exponential function. The median value in a sample (i.e., the 50th percentile) appears to correspond in both datasets to ~0.2 times the CBL/DLH.

Table 1
Measured dust devil height with respect to CBL height (h).

Study	DD height	Max DD height	DD ht/CBL ht
Willis and Deardorff (1979)	n/a	n/a	~0.33–1.0h
Hess and Spillane (1990)	~0.3–0.7 km	~0.8 km	0.09h, 0.51h
Ansmann et al. (2009)	<1 km	2.9 km	~0.3h

Although many martian DDs observed by landed spacecraft appear to be similar in size to those observed on Earth (e.g., Greeley et al., 2010), those found in global-scale surveys in lower resolution images from orbital spacecraft indicate a prevalence of DDs larger than those typically reported on Earth (although comparable surveys from terrestrial orbital images are lacking in the literature). The heights of martian DDs were first measured in Viking Orbiter images by Thomas and Gierasch (1985), who used shadows to estimate typical heights ranging from 1.0 to 2.5 km and a maximum height of 6.8 km. Since then, several studies using orbital imagery have also found DDs > 2 km, particularly during local summer in the northern hemisphere lowlands of Amazonis and Arcadia Planitia (Fisher et al., 2005; Cantor et al., 2006; Stanzel et al., 2006, 2008; Reiss et al., 2014). Fig. 2 shows a particularly large DD in Amazonis Planitia that was imaged by both the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2010) and CTX (Malin et al., 2007) on the Mars Reconnaissance Orbiter (MRO) on March 14, 2012, or MY 31, $L_s = 83°$. (MYs are numbered using the system proposed by Clancy et al. (2000), such that MY 1 began on 11 April, 1955; L_s corresponds to the solar longitude of Mars' orbit, in which 0° corresponds to the northern spring solstice.) The DD height from its shadow length was estimated to be 20 km (http://www.uahirise.org/ESP_026394_2160), although winds aloft may have spread out the dusty plume at the top of this vortex, giving it a long shadow that led to an overestimate of its height. However, it seems likely that martian DDs have the potential to extend through a significant portion of the CBL.

The low thermal inertia of the thin martian atmosphere and high levels of turbulent activity during the day on Mars lead to CBL heights ~3× higher than those observed on Earth (e.g., Sutton et al., 1978; Petrosyan et al., 2011). The available martian PBL height measurements (many of which are listed in Table 2) have been inferred from either lander measurements (e.g., Sutton et al., 1978; Tillman et al., 1994; Sorbjan et al., 2009; Komguem et al., 2013) or from the heights of convective clouds (e.g., Briggs et al., 1977), or measured from temperature profiles obtained either during the descent of landed spacecraft (Seiff and Kirk, 1977) or from radio occultations of orbiting spacecraft (Hinson et al., 2008, 2009, 2011). The most extensive study has been that of Hinson et al. (2008), who used 38 measured PBL heights scattered around the martian globe to find a consistent correlation of PBL height with elevation and, to a lesser degree, surface temperature. Atmospheric modeling has reproduced these trends (Spiga et al., 2010; Hinson et al., 2011) and shown that three-dimensional mesoscale circulations, largely driven by topography, also have a strong impact on local PBL height (e.g., Tyler and Barnes, 2013; Moores et al., 2015).

Willis and Deardorff's (1979) convection tank study produced open convective cells with a mean spacing of $\sim 1.2 \pm 0.2h$. Because DDs most commonly form at the walls and vertices of intersecting cells, it is therefore plausible that the horizontal spacing of DDs is related to the CBL height. Indeed, many field surveys have reported an apparent quasi-periodicity in DD or vortex activity on timescales ranging from 20 to 60 min (Sinclair, 1969; Carroll and Ryan, 1970; Snow and McClelland, 1990; Oke et al., 2007; Kurgansky et al., 2011; Lorenz and Lanagan, 2014; Lorenz and Christie, 2015), which Spiga (2012) and Lorenz and Lanagan (2014) attribute to passage of advecting CBL updrafts over the field equipment. Renno et al. (2004) reported a periodicity in surface heat flux, which they attributed to a negative feedback of surface solar forcing being suppressed by lofted dust, although no explanation was offered for the hysteresis required to make this system oscillate; it seems more likely that the periodic structure in the