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Chapter #10:

PARTICLE LIFTING PROCESSES IN DUST DEVILS

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Abstract

Particle lifting in dust devils on both Earth and Mars has been studied from many different perspectives, including how dust devils could influence the dust cycles of both planets. Here we review our current understanding of particle entrainment by dust devils by examining results from field observations on Earth and Mars, laboratory experiments (at terrestrial ambient and Mars-analog conditions), and analytical modeling. By combining insights obtained from these three methodologies, we provide a detailed overview on interactions between particle lifting processes due to mechanical, thermal, electrodynamic and pressure effects, and how these processes apply to dust devils on Earth and Mars. Experiments and observations have shown dust devils to be effective lifters of dust given the proper conditions on Earth and Mars. However, dust devil studies have yet to determine the individual roles of each of the component processes acting at any given time in dust devils.

1.0 Introduction

Dust devils are vertical convective vortices that are intense enough to erode surficial particulate materials and perhaps even weakly-indurated sediments. They are of scientific interest because of their potential to lift considerable amounts of surface material into the atmosphere. In contrast to regular boundary layer winds, dust particles ($D_p < \sim 63 \mu\text{m}$) are more easily removed from the surface by dust devil action than by boundary-layer wind shear alone (Greeley et al., 2003). This has been proposed to be due to a combination of influences dubbed the “ ΔP -effect” by Greeley et al. (2003), in reference to the idea that the low-pressure core of a dust devil might “suck up” material.

Understanding this effect is important for Mars because of the many dust devils seen there (e.g., Metzger et al., 1999; Cantor et al., 2006; Greeley et al., 2006; 2010), and the likelihood that the low atmospheric density makes the lifting of small particles by boundary layer winds alone difficult (Greeley and Iversen, 1985). The dust cycle on Mars (Kahn et al., 1992; Zurek and Martin, 1993; McKim, 1996; Newman et al., 2002) dominates much of the weather on Mars, and has many sources and sinks responsible for regulating the global movement of fine-grained material. The martian dust cycle includes interactions between multiple drivers of dust entrainment into the atmosphere (such as dust storms, dust devils, polar outflow, etc.) and dust removal processes (primarily, dust settling out from the atmosphere over time). Dust devils and dust storms are the major contributing sources for atmospheric dust on Mars (e.g., Newman et al., 2002; Kahre et al., 2006). Beyond understanding the nature of martian weather, the dust cycle plays an integral role in the continued exploration of Mars: dust constantly settles out of the atmosphere onto spacecraft sent to Mars to explore the surface, affecting surface mobility and solar-powered power generation (Greeley et al., 2006, 2010). It is possible that the electrostatic properties of fine grains can wreak havoc with moving parts (e.g., Wagner, 2004). However, the enhanced ability of dust devils to lift fine grains can also be beneficial by sometimes removing dust from spacecraft solar panels as the dust devils pass over them (Greeley et al., 2006, 2010; Lorenz and Reiss, 2015).

Dust devils, although localized, small-scale meteorological phenomena, seem to be more significant sources of atmospheric aerosols on Mars than on Earth (e.g., Metzger et al., 1999; Balme and Greeley, 2006; Greeley et al., 2010; Allen et al., 2015; Jemmett-Smith et al., 2015, see also Klose et al. *this*

issue). The presence of dust devils on Mars has led to many dust devil laboratory and field studies aimed at investigating their ability to lift fine particles, which explore the idea that dust devils might be the cause of pervasive background dust concentration required to maintain the ongoing dustiness of the martian atmosphere (Montabone et al., 2015). Exactly how dust devils lift fine-grained sand and dust is not well understood, being a complex set of interactions within a transient, micrometeorological process. However, significant work has been performed to investigate the conditions responsible for the enhanced lifting capabilities of dust devils compared to simple boundary layer flow.

On Earth, dust devils share many attributes of their martian counterparts, but are smaller in size, perhaps due to Earth's shallower planetary boundary layer (Fenton and Lorenz, 2015). Dust devils occur frequently in arid and semi-arid regions of the Earth, where sensible heat fluxes are large, and loose sediment is available (e.g. Sinclair, 1969; Snow and McClelland, 1990; Hess and Spillane, 1990; Oke et al., 2007; Kurgansky et al., 2011; Lorenz et al., 2015). They rarely form in other regions, where aeolian sediment transport is severely hampered by the presence of soil moisture and vegetation, which prevents the lifting of soil particles and reduces sensible heat fluxes (and thus reduces the likelihood of dust devil formation). Dust devils tend to be most active during the middle of the day starting in the mid-morning and tapering off in the late afternoon, and have a seasonal dependence ('dust devil season') with minimum activity in winter and maximum activity in summer. Due to their localized extent, less attention has been paid to the impact of dust devils in dust modeling than to the impact of regional or continental-scale dust storms (Klose et al., *this issue*). In addition, turbulence in the atmospheric boundary layer (ABL) is highly stochastic and, although bulk properties of the ABL are relatively well understood (e.g., Kaimal and Finnigan, 1994; Smits et al., 2011), microscale meteorological phenomena such as dust devils remain difficult to represent in atmospheric circulation models.

In this paper we review our current understanding of the processes involved in dust devil sediment lifting, including a discussion of possible contributing factors to the " ΔP -effect". After reviewing the general physics of aeolian particle lifting (Section 2), we discuss insights into particle lifting specifically by dust devils with respect to: (i) results from Mars and Earth field observations (Section 3.1), (ii) laboratory experiments (Section 3.2), and (iii) analytical modeling (Section 3.3). Examining all three methodologies together provides a more complete picture of the underlying physics of dust lifting within dust devils, including exploring why not all vertical thermal convective vortices are necessarily capable of lifting dust, and what the dust lifting potential on Earth and Mars implies for the global and regional dust budgets of both planets.

2.0 Physics of Particle Lifting

There is a long history of the study of aeolian particle movement dating back to the early 20th century, including wind tunnel experiments and observations pertaining to the movement of sand in dunes and ripples (Bagnold, 1941; Chepil, 1945). Observations showed that aeolian sediment transport is initiated if the wind stress τ at the surface exceeds a threshold value τ_t . Since $\tau = \rho u_*^2$, where u_* is the friction velocity, this threshold stress is usually expressed in terms of the threshold friction velocity, u_{*t} . For a given pressure, u_{*t} is a property of the surface, describing its resistance to wind erosion (Shao and Lu, 2000). Theoretical considerations on the balance of forces acting on a particle at rest lead to estimates on u_{*t} . By accounting for aerodynamic drag and gravity forces, Bagnold (1941) obtained

$$u_{*t} = A_B (Re_{*t}) (\sigma_p g d)^{1/2} \quad (1)$$

where σ_p is the ratio of particle to air density, g is the gravitational acceleration, d is the particle diameter, and A_B is a coefficient that depends on the particle friction Reynolds number, Re_{*t} . According to Equation (1), u_{*t} increases monotonically with particle diameter. However, observations have shown that there exists a minimum of u_{*t} for particles with diameters of $\sim 100 \mu\text{m}$, with u_{*t} increasing with decreasing particle size below that value (e.g. Iversen et al., 1976) (Figure 1a). By further including aerodynamic lift and interparticle cohesion in addition to drag and gravity, u_{*t} including this minimum can be predicted (Iversen and White, 1982; Greeley and Iversen, 1985) using

$$u_{*t} = A_1 F(Re_{*t}) G(d) \quad (2)$$

where A_1 is an empirical constant and F and G are relatively complex empirical functions. Shao and Lu (2000) found that these functions can be replaced by a simple theory-based expression if interparticle cohesion is treated explicitly, and if the Reynolds number dependence of aerodynamic forces is neglected. They obtained:

$$u_{*t} = A_N(\sigma_d g d + \gamma / \rho d)^{1/2} \quad (3)$$

where A_N is a dimensionless coefficient, and γ [N/m] scales the interparticle force.

Figure 1: (a) Theoretical relations for the threshold friction velocity from Bagnold (1941), Greeley and Iversen (1985) and Shao and Lu (2000) (colored lines), with experimental measurements using sand and dust (filled symbols) and other materials (open symbols). After Kok et al. (2012). (b) Relative importance of forces relevant for dust emission (from Klose (2014), modified from Shao (2008)). The aerodynamic force is shown for $u_* = 0.4 \text{ m s}^{-1}$. Error bars indicate the standard deviation of the cohesive force as given in Klose et al. (2014, Eq.8). The stochastic nature of the cohesive force may lead to particle uplift at a lower threshold.

If roughness elements on the soil surface are present or if the soil is moist, the shear stress required to mobilize particles is larger than predicted based on u_{*t} for idealized (smooth and dry) surfaces. Drag partition is used to describe the influence of roughness elements on the surface momentum flux. In drag partition, the total drag is decomposed into a pressure-drag on the roughness elements, a skin-drag on the roughness element surface, and a skin-drag on the ground surface (e.g. Schlichting, 1936; Arya, 1975; Raupach, 1992; Raupach et al., 1993; Marticorena and Bergametti, 1995; Shao and Yang, 2008). The latter is what drives dust emission. The ratio of surface to total drag is used to correct either u_{*t} (Marticorena and Bergametti, 1995; Marticorena et al., 1997; Shao, 2008), or u_* (Kok et al. 2014b) depending on the theoretical approach used for parameterization of the effect in models. For Earth, the moisture cohesion must be additionally accounted for in parameterizations of u_{*t} . Such parameterizations have been developed by McKenna-Neuman and Nickling (1989), Fecan et al. (1999), McKenna-Neuman et al. (2003), and Cornelis et al. (2004a, 2004b).

Due to the minimum in u_{*t} , sand particles or particle aggregates with diameters $\sim 100 \mu\text{m}$ are most readily entrained (Figure 1a). Corresponding to their large sizes, such grains are often too heavy to remain suspended. Rather, they hop along the surface horizontally in a process called saltation. During saltation, dust can be emitted either by the impacts of saltating particles overcoming the energetic interparticle bonds between soil particles, which is called saltation bombardment or sandblasting (Gillette, 1974; Shao et al., 1993), or by the physical break-up of saltating dust aggregates (Shao, 2001; Kok et al., 2014b) (Section 2.3).

Dust particles generally need stronger aerodynamic forces for direct aerodynamic entrainment than sand-sized particles, due to the larger entrainment thresholds at smaller diameters (Figure 1). Since particle weight scales with d^3 , whereas most cohesion forces are thought to scale with d (Hamaker, 1937; Johnson et al., 1971), the interparticle cohesive force f_i is the dominant retarding force acting on small particles. Interparticle cohesive forces include Van der Waals forces, electrodynamic forces, and chemical forces (e.g., Castellanos, 2005). These are governed in turn by a variety of factors such as particle shape, particle surface roughness, and chemical composition. Although theory suggests that f_i is, on average, proportional to d (Hamaker, 1937; Johnson et al., 1971), the influencing factors suggest a stochastic behavior as has been observed by Zimon (1982). This stochastic behavior due to the various controls on f_i is more relevant for dust-sized particles than for sand-sized particles,

because gravity dominates over interparticle cohesion for larger particles (Figure 1b). This means that in the dust-size range, cohesion can be well below average and the lifting of dust-sized particles is thus also possible through direct aerodynamic entrainment and without saltation as an intermediate process (e.g. Loosmore and Hunt, 2000; Roney and White, 2004; Macpherson et al., 2008; Chkhetiani et al., 2012; Klose et al., 2014). The assumption of a stochastic behavior of interparticle cohesion suggests that the entrainment threshold friction velocity for the fraction of dust particles with smaller-than-average cohesion may be as small as that for particles in the saltation size range. The entrainment of this fraction is most likely strongly supply limited (Shao and Klose, 2016).

Although the flux of directly entrained dust is typically smaller (for most natural surface types) than the dust amount lifted by the much more efficient saltation-bombardment mechanism, it can become a dominant mechanism in the absence of saltation. For example, while mean wind shear stresses may be below entrainment threshold during a calm summer day, organized atmospheric turbulence can produce shear stresses strong enough to lift sand-sized particles, leading to intermittent saltation and associated dust emission (Stout and Zobeck, 1997; Dupont et al., 2013) and to aerodynamically entrain dust particles directly (Klose and Shao, 2013). This is especially relevant for dust devils due to intense shear stresses associated with their rotation (e.g. Balme et al., 2003).

3. Dust devil sediment entrainment

Dust devils contain complicated wind fields that include significant rotational components, near-surface inflows, and vertical updrafts and downdrafts within the core. In addition, many dust devils vary rapidly in intensity, and even when the dust devil as a whole is in a steady state, the wind field can change significantly at the small scale as the vortex traverses the surface. Nevertheless, by using a combination of approaches, there has been significant progress in understanding how, and how much, material is lifted by dust devils.

Dust devils may contain a variety of structural and morphological features including all or some of the following depending on the ambient conditions, as well as on the internal pressure structure. Visualization of each of these conditions is dependent on the availability of sediment to trace the dust devil's helical flow. The most dramatic feature of a fully developed dust devil is the dust column (Fig. 2, number 1), which comprises dust lofted from the surface wrapped up around a central thermal updraft. Individual dust grains and/or aggregates of dust are lifted into the helical flow by a combination of the shear stress from air inflow at the base of the dust devil and other, poorly understood mechanisms, such as low-pressure core effects (Sinclair, 1966; Balme and Greeley, 2006; Balme and Hagermann, 2006). The column may extend beyond the top of the visible dust devil, which is highly dependent on the ambient conditions and the strength of the vortex itself. In many weak cases, dust devils may only produce a partially visible column due to inadequate flow velocities, small core pressure gradients, or sediment availability.

Another common feature in many dust devils is a saltation skirt. Saltation skirts (Fig.2, number 2) can be seen around the base of a dust devil, demarking sediment load that was initially lofted by the dust devil but was comprised of particles too large or heavy to be suspended in the column. The presence of this saltation skirt is highly dependent on the particle size distribution at the surface and the strength of each individual dust devil (Balme and Greeley, 2006). In some cases the larger grains can be thrown out of the skirt producing a cycloidal deposition track. This is often seen on Mars but is less common on Earth (Greeley et al., 2004; Neakrase, 2009; Reiss et al, 2010; Neakrase et al., 2012; Reiss et al., *this issue*).

In many of the strongest dust devils, a clear central core may be observed (Fig.2, number 3). This feature requires a strong pressure gradient within the dust devil allowing a central, dust-free, downdraft to form (Sinclair, 1966; Balme and Greeley, 2006). Cooler air in this downdraft is brought into the structure from outside the dust devil at the top: warm, dust-laden air is rising and rotating upwards around the downdraft.

Figure 2. Schematic diagram showing various parts of a dust devil. (Left) Unprocessed, unannotated image of the dust devil to clearly see structure (Center) Annotated, 1 indicates the main column of the dust devil, 2 the “saltation skirt” where larger and heavier particles fall out of the column, and 3 the dust-free core downdraft that sometimes occurs. (Right) The individual velocity components of dust devil vortical flow where u_θ , u_z , and u_r are respectively the tangential, vertical and radial velocity components. U_∞ represents the background boundary layer wind field that increases with height, z , causing dust devils to tilt by a proportional angle, α . [Photo credit: S.P. Idso, Arizona, c. 1975]

Once a stable dust devil has formed, it can behave as a single structure. The column can be pushed by the ambient winds, with the ambient wind speed controlling the lateral motion of the dust devil (Balme et al., 2012). Because the ambient boundary layer winds increase with height above the surface, often dust devils will tilt in the direction of motion (Sinclair, 1966; Kaimal and Businger, 1970; Balme and Greeley, 2006). The flow within a dust devil, resulting in a variety of dust devil morphologies, is controlled by complex interactions between all these processes. Figure 3 shows an idealized two-dimensional view of the dust devil flow structure. Stagnation points where flow reverses within the dust devil can occur near the surface, where the strength of the updraft can allow a region of no flow near the center. If the dust devil is strong enough to have a clear core, another stagnation point can form at the interface of where the downdraft meets the rising, warm, dust-laden air.

Figure 3. Sketch showing vertical flow within an idealized dust devil. Stagnation points indicate where possible flow reversal occurs in some dust devils. The upper stagnation point can be due to the presence of a core downdraft, as observed in some dust devils, and could progress all the way to the surface within the core depending on the strength of the vortex. When an elevated stagnation point is not present, flow within the dust devil is dominated by only vertical flow. (After Balme and Greeley, 2006, and Neakrase, 2009).

3.1 Field Observations

Earth

Various field investigations of dust devils have been made in arid environments on Earth, but only a few have attempted to measure the flux of dust emitted from the surface beneath a dust devil. Renno et al. (2004) used LIDAR to remotely estimate a terrestrial dust devil column peak loading of 100 mg m^{-3} in a dust devil with a peak vertical velocity of 10 m s^{-1} to estimate a dust flux of $1000 \text{ mg m}^{-2} \text{ s}^{-1}$. The largest data set, though, comes from several field campaigns made between 1996 and 2005 at the El Dorado Playa, Nevada, and near Eloy, Arizona, both USA (Metzger et al., 2011). Metzger et al. (2011) made measurements using two types of commercial sensors, PM10 (particulate matter with diameter $< 10 \mu\text{m}$) dust sensors, and TSP (Total Suspended Particle Load) aerosol monitors, as well as piezoelectric saltation-impact detectors being tested for the Beagle2 Mars mission (Towner et al., 2004). In many cases, these dust concentration data were acquired at high sample rates allowing particle-load profiles through the dust devil to be made. By combining these data with simultaneously acquired vertical wind speed profile data, they estimated the integrated upwards flux of dust or particulates. Metzger et al. (2014) found that the TSP concentrations in the dust devils they sampled ranged from 6 to 875 mg m^{-3} , whereas the PM10 concentration varied from 1.3 to 162 mg m^{-3} . From this they extrapolated TSP fluxes of between about 600 to $4375 \text{ mg m}^{-2} \text{ s}^{-1}$ and PM10 fluxes of between 1.3 and $162 \text{ mg m}^{-2} \text{ s}^{-1}$. The Metzger et al. (2011) flux estimates are about an order of magnitude lower than those obtained by Renno et al. (2004) using LIDAR remote sensing. This probably reflects the fact that the Metzger et al. (2011) data are integrated over profiles of dust load and wind speed, whereas the Renno et al. (2004) flux is calculated from peak vertical wind speed multiplied by peak dust concentration. Metzger et al. (2011) also found that the PM10 concentration was around 10% of the TSP value thus about 90% of sediments entrained by dust devils in their field areas were larger than $10 \mu\text{m}$ and unlikely to be carried into suspension but instead form the 'sand-skirt' seen in many dust devils. The presence of a sand-skirt (saltation-skirt) indicates that wind speeds have exceeded threshold conditions to entrain larger particles in the dust devil and is dependent on the sediment distribution for each field area. Skirtless dust devils could indicate either dust devil

conditions allow only dust lifting and the largest grains are not sufficiently lofted to form the skirt, or the sediment fraction contains fewer coarse grains available for lofting.

While these data can inform about the amount of dust contained in a dust devil, and how rapidly it is lifted, they do not inform about the processes by which the dust is entrained. While the ΔP effect could play a role, Balme et al. (2003) showed that the intense winds contained in dust devils generate shear stresses sufficient to lift most natural materials on their own, so it seems likely that, on Earth, shear stress dominates any other effect within dust devils. However, as outlined by Balme and Hagermann (2006), the suction effect created by the low-pressure core of a dust devil passing over a particulate surface is likely to be more effective when particle size is small, and when the dust devil is itself small and travelling quickly across the surface (i.e., when the pressure change occurs suddenly). Hence there might be occasions, even on Earth, when dust devils can suck material up rather than or in addition to blowing it into motion.

Even on Earth, quantitatively measuring dust vertical lifting is a difficult task and dust emission flux data sets are not numerous. A large part of this difficulty comes from the fact that it is difficult to properly sample the large size-range of mineral dust, especially with a high temporal frequency. Dust emission fluxes are usually estimated using the so-called "gradient method" (e.g., Gillette, 1977; Nickling, 1983; Nickling and Gillies, 1993; Nickling et al., 1999; Gomes et al., 2003; Rajot et al., 2003). This method is based on the assumption that particles with aerodynamic diameters smaller than 20 μm are light enough to follow air movements perfectly and that the dust flux is constant with height (Gillette et al., 1972). In such conditions the causal relationship of air momentum and particle mass exchanges allows the upward vertical flux of particles to be expressed as a function of the wind friction velocity (u_*) and of the difference of dust concentration measured at two vertical levels (Gillette, 1972). As noted by Shao et al. (2011), however, even in emission conditions the diffusive flux is not constant with height due to gravitational settling and a correction may be applied to the computed flux as a function of particle size. For particles in the range of 2 - 3.5 μm , this correction is estimated as being negligible (2%), but it is 15% for particle sizes from 6 to 8 μm , and should be higher for larger particle sizes (Shao et al., 2011).

From field measurements, the computation of u_* is usually performed over durations of at least 15 min, in order to integrate over the major time scales of turbulence occurring in the atmospheric boundary layer (Wieringa, 1993). In addition, if dust concentration is measured with filter-based instruments a minimum integration time is required to get measurable dust loads. For measurements within dust devils, exposure times may be too short to obtain meaningful results depending on the method of instrument deployment (stationary versus mobile platforms). Dust sampling also involves the use of inlets with a specified size range. The most commonly used is the PM_{10} inlet that allows an efficient collection of particles up to 10 μm . More recently, the gradient method was applied to size-resolved dust measurements performed in Australia (Shao et al., 2011a) during the Japanese Australian Dust Experiment (JADE, Ishizuka et al., 2008) and in Niger (Sow et al., 2009), as part of the AMMA (African Monsoon Multidisciplinary Analysis) international project. In both cases, significant, large, vertical dust fluxes were measured only during periods where saltation occurred, confirming the efficiency of the sand-blasting process to release fine dust particles.

Mars

Both in situ meteorological measurements (landers/rovers) and remote sensing estimations (landers/rovers/orbiters) have provided a consistent picture of dust devils for different regions on Mars. Of particular interest to examine the processes of particle entrainment in dust devils are exact measurements and estimations of the surface conditions. However, observations of the surface conditions and their variation throughout the year have been limited by instrument availability on landers/rovers/orbiters. The most active dust devil period, or "dust devil season", on Mars is roughly defined as local spring and summer - i.e., for solar longitudes, L_s , of 0 to 180° in the northern hemisphere and 180 to 360° in the southern hemisphere. It varies for individual locations predominantly due to surface geometry with respect to solar illumination. Therefore, the dust devil season is typically defined as the time of the year where dust devil activity is at its maximum for a given area, which usually coincides with maximum insolation of the surface. Dust devil activity ceases almost completely in autumn, partly due to seasonal variability in regional to global dust storm activity reducing solar irradiation through increased atmospheric dust load, and partly due to the change in solar radiance associated with the transition from summer to winter. (Greeley et al., 2006; 2010)

Dust devils were never imaged by the *Viking* landers in the late 1970s (see also Murphy et al., this issue). However, the detection of short isolated pressure drops in the meteorological data (Ryan and Lucich, 1983; Ringrose et al. 2003) suggest that convective vortices did pass over or close to the lander, though it is not possible to tell whether they were dust loaded or not. Further information from

these early surface vortex detections was limited due to the low resolution and sampling rate, and the sheltered position of the pressure sensors on the *Viking* landers. Diurnal and seasonal relationships can be seen as similar to terrestrial cases with peak activity occurring near midday and more detections occurring during the summertime (Ringrose et al., 2003).

Visual surface observations of dust devils began with *Mars Pathfinder* (MPF), in 1997, with the first images of dust devils from a lander in Ares Vallis. Metzger et al. (1999) discovered dust devils around the lander after employing a filter subtraction method to make the dust devils visible in the enhanced images. They reported the first estimates of dust devil properties on Mars, including sizes, speeds, and dust concentrations made with assumptions based on terrestrial field studies. Assuming vertical velocities of $\sim 7 \text{ m s}^{-1}$ and measured dust concentrations of $\sim 70 \text{ mg m}^{-3}$, from MPF dust opacity studies, Metzger et al. (1999) estimated the average dust devil dust flux to be $\sim 500 \text{ mg m}^{-2} \text{ s}^{-1}$. They also estimated a range in dust devil diameter of 14-79 m and estimated heights of 46-350 m. Dust devil traverse speeds were estimated at $\sim 0.5\text{-}4.6 \text{ m s}^{-1}$. Ferri et al. (2003) performed a reanalysis of the MPF dust devil data substituting vertical velocities of up to 20 m s^{-1} (based on martian thermal convection studies), and making more detailed estimates of the distances to the dust devils and hence the dust devil diameters. The largest dust devils were determined to be around 100-200 m in diameter with a dust loading of ~ 700 times the background dust concentration. Average dust devil dust fluxes were determined to be $\sim 70 \text{ mg m}^{-2} \text{ s}^{-1}$ for a 200 m diameter dust devil. Local activity at MPF was observed at $L_s = \sim 143\text{-}188$, toward the end of northern summer, suggesting that *Pathfinder* potentially observed only the end of the dust devil season in Ares Vallis.

Further visual observations during the course of the *Mars Exploration Rover, Spirit* campaign in Gusev Crater (2004-2010) suggested that, as is the case for Earth, dust devil activity and dust lifting capability is highly variable from region to region and from year to year (Greeley et al., 2006; 2010). Three dust devil seasons were visually observed from *Spirit* in Gusev Crater, where over 700 individual dust devils were cataloged corresponding to local southern hemisphere spring to autumn (for Gusev $L_s = \sim 173\text{-}340$). Due to a favorable viewing geometry, namely the location of the rover on the Columbia Hills for each of the dust devil seasons, a more accurate estimate of the distances from the rover to the dust devils was possible. Gusev Crater contained relatively few large dust devils – their sizes ranged from a few meters up to $\sim 276 \text{ m}$ – but over the three seasons about six dust devils out of 761 were calculated as being larger than 160 m in diameter. Dust fluxes of between 0.004 and $460 \text{ mg m}^{-2} \text{ s}^{-1}$ were estimated, suggesting lower values than the estimates from Ares Vallis, but the frequency of dust devils was higher during the three dust devil seasons observed in Gusev Crater than in Ares Vallis (Greeley et al., 2006; 2010). The use of higher resolution cameras in conjunction with the better viewing angles is likely the reason so many more smaller dust devils were observed (as many as 51 dust devils per sol (martian day)) at Gusev compared to Ares Vallis. The other improvements used in this mission included “movie” sequences taken by *Spirit*, in which rapidly acquired sequences of images were used to capture dust devil movement. The same dust devil could be captured in many frames in a time sequence. The benefits of these sequences included being able to monitor how dust devils changed with time as they traversed the floor of Gusev Crater and the ability to estimate their translation speeds and hence, indirectly, the instantaneous near-surface wind speeds in the study area. Estimations of vertical velocities were also made within some of the dust devils. Traverse speeds were consistent with $1\text{-}3 \text{ m s}^{-1}$ ambient winds, and where clumps of sediment could be identified in subsequent frames, vertical velocities were estimated as being between $1\text{-}2 \text{ m s}^{-1}$ (Greeley et al., 2006; 2010). Other observations from the Mars Exploration Rovers suggest that dust devil induced removal of dust from solar panels occurred, and that this coincided with the peak diurnal dust devil activity when boundary layer winds alone probably would not have been as effective an agent (Greeley et al., 2006; 2010; Lorenz and Reiss, 2015).

During the course of the 2008 Mars Phoenix Lander (PHX) mission several dust devils were detected at high northern latitudes. The meteorological package recorded ~ 502 pressure drops $> 0.3 \text{ Pa}$ and lasting at least 20 s, presumably associated with the nearby passage of dust devil-like vortices (Ellehoj et al., 2010). Using a method similar to that used by Murphy and Nelli (2002) to estimate vortex populations at MPF from the meteorological instruments, Ellehoj et al. (2010) examined the frequency of convective vortices at the PHX landing site (68.2°N , 234.3°E). Their results showed that convective vortices at high latitudes on Mars might have complicated initiation mechanisms, including sources of vorticity such as local weather systems and topographic controls. For example, a few vortex signatures were detected at night, when there is no solar input. These nighttime vortices are hypothesized to be due to vortex shedding from surrounding topographic features. Vortex detections at the PHX site peaked with the typical midday activity for dust devil populations, albeit having a slightly earlier peak than previously measured on Mars, but the seasonal activity was different due to

the high latitude and interactions with weak frontal systems and topographic controls (Ellehoj et al., 2010). Measured ambient winds during the PHX mission were on average $4\text{--}5\text{ m s}^{-1}$ in the NE-SE direction with estimated vortex wind speeds of $5\text{--}10\text{ m s}^{-1}$ (Ellehoj et al., 2010; Holstein-Rathlou et al., 2010), well below the boundary layer wind tunnel estimates of $\sim 30\text{ m s}^{-1}$ necessary for dust entrainment (e.g., Greeley and Iversen, 1985) but similar to values estimated from other landing sites.

Surface observations of martian dust devils have all suffered from the same issues that hinder good correlative studies: firstly, visual detections of dust devils (e.g., Greeley et al., 2010) are generally not available with correlated meteorological information (i.e., pressure, temperature, wind speed, etc.). Secondly, meteorological detections of convective vortices, as in the *Viking*, *Pathfinder*, and *Phoenix* cases, generally lack simultaneous images. This dichotomy illustrates the difficulties in documenting such a transient natural phenomenon, compounded by remote sensing limitations of exploring a planet other than Earth.

3.2 Laboratory Investigations of Particle Lifting

3.2.1 Wind stress entrainment

Numerous terrestrial boundary layer wind tunnel studies of sediment lifting have been performed under varying planetary conditions, such as using different ambient temperatures and pressures, and particle sizes and densities to mimic the effects of lower gravity (e.g., Bagnold, 1941; White et al., 1983/84; reviewed in Greeley and Iversen, 1985, etc.) These experiments all suggest that threshold wind speed curves for wind stress lifting are likely to be similar but shifted when extrapolated to other planetary bodies; specifically, that a minimum in the u_{τ} curve should occur at a particular particle diameter (see Section 2.0), with that diameter and minimum u_{τ} varying from planet to planet.

One possible explanation for easier entrainment of dust-sized particles presented and discussed in the 1970s (e.g., reviewed in Greeley and Iversen 1985), was that aggregated dust could be removed as 'low density sand particles'. Such aggregates would have the lower cohesion forces of large particles yet be lighter than solid particles of the same diameter. In support of this claim dust aggregates are seen to be ubiquitous on Mars (e.g., Sullivan et al. 2008). Experiments in wind tunnels have also recently demonstrated that the threshold wind speed falls significantly for increased deposited dust depth (i.e., greater than 1 mono layer), due to the formation of low-density dust particle aggregates (Rondeau 2015, Merrison et al. 2007, Merrison 2012). The detailed micro-scale dynamics of aggregate removal/breakup has yet to be studied in detail; however, the experimental techniques necessary for such studies (e.g., the use of high-speed cameras or laser-based velocimetry) are now readily available.

It is widely accepted that the simple boundary layer model typically used in sand/dust entrainment is incomplete and that in most cases turbulence plays a significant role in aeolian mobilization (Ibrahim et al. 2008, Reeks and Hall 2001, Ziskind et al. 1995, Dupont et al., 2013, Klose et al., 2014, Carneiro et al., 2015). The role of turbulence has been widely discussed in experiments and modeling of dust (and sand) entrainment, though there has been limited success in implementing a quantitative model to reproduce observed dust re-suspension (e.g., Rondeau et al. 2015).

It is typical in wind tunnel studies of sand transport that mobilization (detachment) occurs at significantly lower wind speeds (shear stress) than entrainment (lift). This type of transport, thought to result from rolling detachment, is a pre-cursor to entrainment. It has been shown that rolling detachment can have a qualitatively different behavior than the conventional aerodynamic model (e.g., De Vet et al. 2014, Reeks and Hall 2001), and could lead to particles on Mars being transported by winds at speeds below the usually considered aerodynamic threshold.

3.2.2 Thermo-luminescent lifting

Atmospheric pressure has a significant influence on the particle entrainment threshold. Small particles such as fine sand and dust are more difficult to lift by aerodynamic forces because of stronger interparticle forces acting on small particles. At lower atmospheric pressures, changes in the flow regime near the surface can have significant influence on particle entrainment. Cohesion and electrical effects are generally described as retarding forces. In typical wind tunnel experiments, particle entrainment is explained through fluid (wind) shear stress providing a lift component to the

particles that will induce motion through rolling, saltation, secondary impacting, and eventually some amount of suspension. Vortex studies (see Section 3.2.4) demonstrated that dust devil passage overcomes retarding forces more efficiently than typical boundary layer winds. However, wind shear stress may only be one piece of the total effect. Another potential lifting effect involves exchange of gas flows between sub-soil overpressures and the near-surface boundary layer flow resulting from temperature gradients within the soil.

Gas exchange in this context is a function of the ratio between the mean free path of the gas molecules (λ) and the dust or pore diameter (d) within the soil which defines the Knudsen number ($Kn = \lambda / d$). If Kn increases or approaches 1, the gas can no longer be considered an ideal gas and the relationship between pressure, temperature, and gas density can no longer be applied. If the connection between the soil and the atmosphere is smaller than the mean free path ($Kn \gg 1$), the pressure is not equal across the interface. In this case, gas – somewhat counterintuitively – flows from the cold to warm side until the flow balances if $n_1 v_1 = n_2 v_2$, where n is the particle number density and v the thermal velocity. This corresponds to $P_1/P_2 = (T_2/T_1)^{1/2}$. This type of gas flow along a surface (here the walls of the connecting capillary) is known as thermal creep.

At martian conditions the mean free path is on the order of 10 μm , within the range where low pressure physics ($Kn \geq 1$) becomes important for dust and sand-sized structures. Therefore, if temperature gradients are present within the martian soil, thermal creep gas flow, as above, dictates flow from cold to warm. Under these conditions, the martian soil could act as a natural pump. Drop tower experiments used by de Beule et al. (2015) demonstrated gas flow within soils. Their experiments were not buoyancy driven as thermal convection does not exist in microgravity. Using tracer particles for visualization, the gas flow was found to be into cool areas and out of warm areas. For comparison, the mean free path for air on Earth at 1 bar is only 67 nm. (Because typical pore-diameters for sand and soil are much larger than this, thermal creep is not important in natural terrestrial settings.)

The question is if and how this process can lead to dust or sand lifting. Thermal creep gas flow does not directly provide lift within the pumping soil because it requires a temperature gradient to exist. The top layer of the soil does not show a strong temperature variation because of insolation, which can cool by thermal radiation. The thickness of this insulated layer depends on the duration of illumination. De Beule et al. (2015) found thicknesses of 100 to 200 μm in laboratory settings for seconds of observation. More extended illumination times over a day on the surface of Mars, might lead to mm-thick layers of constant temperature. Gas flow in the layers below this constant temperature cap would be subject to thermal creep. Continuity requires that the gas pumped from below passes through the top layer. In the absence of thermal creep, gas flow can only be produced by a pressure-driven gas flow. Therefore, a sub-surface overpressure is established, with a mass flow rate described by Muntz et al. (2002). Two flow types contribute to mass flow: thermal creep flow characterized by the non-dimensional gas flow, and the pressure difference driven flow. The pressure difference (ΔP) driven flow provides a lift for particles on an illuminated surface on Mars, which is set by the temperature difference along capillaries or pores, ΔT .

This thermal-creep lifting force can be strong, but as outlined above is generally limited to low, millibar-pressure for soils. Wurm and Krauss (2006) found that particle lifting can easily overcome gravity and interparticle forces if essentially any light-absorbing dust sample was illuminated with a strong laser beam. Wurm et al. (2008) studied the gravity dependence and applied the results to Mars. An example of the gravity dependence is shown in Fig. 4 taken from de Beule et al. (2013). The light flux used in the experiments (12 kW/m^2) is an order of magnitude larger than natural insolation at the martian surface.

Figure 4. Examples of particle ejections due to illumination at different g-levels (de Beule et al. 2013).

On Earth typically at least a few kW m^{-2} are needed to lift dust in a millibar-pressure environment. In this case no other lifting force is needed, but if the light flux is lower, thermal creep and the pressure gradient are less intense though still present. At lower light fluxes, below 1 kW m^{-2} , the flow is not strong enough to lift particles against gravity (terrestrial or martian) or interparticle forces. De Beule et al. (2015) conducted experiments where a short vibration removed cohesive forces between the particles. As a result, the topmost layers were lifted by the pressure gradient created by thermal pumping. De Beule et al. (2015) called this an insolation-activated layer. This shows that the pressure support is still present at low light flux.

Estimates for martian conditions imply that insolation activation could reduce the threshold velocity for gas drag to lift dust (de Beule et al., 2015). This is consistent with current wind tunnel experiments by Kuepper and Wurm (2015) where the threshold friction velocity was dependent on the insolation for Mars-analog pressures. Figure 6 shows the results of their laboratory measurements of threshold friction velocities depending on the insulating flux.

Figure 5. Threshold friction velocities at given light flux and for different pressures (Kuepper and Wurm, 2015).

Scaled to Mars, Kuepper and Wurm (2015) found that illumination can reduce the threshold velocity by between 5 - 18%. Applied to dust devils this means that threshold velocities for translational or rotational motion of the vortex could also be smaller, making them more capable of lifting dust. Kelling et al. (2011) and Kocifaj et al. (2010) also demonstrated that up to 100 times more particles could be released counterintuitively after the light source was shut off. The implication is that as a dust devil

traverses and blocks the sunlight from the surface, the shadowed dust could be more easily lifted as a result of similarly forcing a change in the soil temperature gradient producing outgassing.

3.2.3 The role of electrodynamics in natural particle lifting

Electrification of particles is another candidate for enhanced lifting in martian dust devils. Although not specific to dust devils, grains moving via saltation favor particle electrification. In ballistic trajectories, particles bounce along the surface colliding with other grains and exchanging electric charge (Harper, 1967; Renno et al., 2004; Kok and Renno, 2008). The exact mechanism governing this charge exchange is not yet completely understood, but some theoretical models and some experiments suggest this is a size dependent process (Freier, 1960; Schmidt et al., 1998; Inculet et al., 2006; Duff and Lacks, 2008). During dust events, as local turbulence transports the finest particles higher into the atmosphere leaving the more massive grains closer to the surface, the atmosphere experiences a charge separation that produces an enhancement of its electric field. Moreover, some theoretical models and laboratory experiments suggest that the electric forces produced this way can be of the same order as gravitational forces. Thus, electric forces could be able to influence the trajectories of charged particles (Schmidt et al., 1998; Zheng et al., 2003) and also to reduce the threshold friction velocity u_{*t} necessary to initiate saltation and dust lifting. Electrical forces could thus play a major role in enhancing the particle lifting process especially in phenomena such as dust devils that are efficient at segregating particle sizes (Kok and Renno, 2006).

Recent field experiments (Esposito et al., 2015) monitored the atmospheric electric field during dust events, including saltation, dust storms and dust devils. The experiments were conducted during an intense field campaign in the West Sahara. Esposito et al. performed simultaneous measurements of atmospheric parameters (pressure, wind, relative humidity, temperature, solar irradiance, electric field), soil parameters (temperature, moisture), and sand and dust parameters (dust size distribution and abundance, sand saltation rate and flux) during the dust storm seasons in 2013 and 2014 in the desert region of Merzouga in Morocco. They observed a very strong correlation between saltation rate and dust emission, and between these two parameters and the intensity of the atmospheric electric field. This demonstrated both the role of saltation in the dust emission and the particle electrification processes acting during these phenomena (Figure 6).

Figure 6: Typical dust storm observed in the Moroccan desert (Esposito et al., 2015): sand saltation rate, atmospheric dust concentration and electric field at 2 m from the ground versus time.

Esposito et al. (2015) observed E-fields up to 15 kV/m during the strongest dust events as measured by a field mill mounted two meters above the ground, similar to what has been reported by other observers (Rudge, 1913; Demon et al., 1953; Stow, 1969; Kamra, 1972; Williams et al., 2009). E-fields were generally directed in the downward direction, the same as the fair-weather field. A linear trend was observed between dust abundance and the E-field shown in Figure 7.

Figure 7: Atmospheric dust concentration as a function of the electric field. Data acquired in two different sites in the desert region of Merzouga (Morocco) respectively in 2013 and 2014 (Esposito et al., 2015) in dry conditions (relative humidity below 10%).

The observed trend was almost the same in both the 2013 and 2014 campaigns even if the two measurement sites were different in terms of soil moisture content and composition. This demonstrates the effect of the electrification of fresh lifted dust on the electric properties of the atmosphere. A similar trend was observed in dust devils (see Murphy et al., *this issue*) suggesting that the electrification process is similar and pertinent to particle entrainment in dust devils. Although it is thought that electrification of dust is typical during mobilization and that it can be instrumental in the formation of dust aggregates (see Harrison et al., *this issue*) it has yet to be implemented into a predictive model.

3.2.4 The “ ΔP -Effect”

Laboratory studies of the mechanical properties of dust devils were conducted via a series of experiments using the Arizona State University Vortex Generator (ASUVG) (Greeley et al., 2003; Greeley et al., 2005; Neakrase et al., 2006; Neakrase and Greeley, 2010a; 2010b). These experiments explored dust devil particle entrainment threshold, sediment flux and basic interactions with surface roughness. Initial threshold studies (Greeley et al., 2003) demonstrated that vortices were very efficient at lifting small particles (Figure 8). This suggested that a rotationally induced pressure drop in the vortex core provided an additional lift component that was substantial enough to overcome the interparticle forces acting on the small grains allowing them to be more easily entrained in the vortex flow.

Figure 8. Plot of the threshold parameter (left), Φ , versus threshold friction speed, u_{*t} , showing differences in laboratory data comparing boundary layer versus vortex induced particle thresholds, where ρ_p is particle density, g is gravity, D_p is particle diameter, ρ is atmospheric density. Image of the ASUVG with CO_2 sublimate for flow visualization (right). (After Greeley et al., 2003, and Neakrase and Greeley 2010a)

Further laboratory characterization of this “ ΔP -effect” examined sediment flux for vortex flow on both aerodynamically smooth and rough surfaces (Neakrase et al., 2006; Neakrase and Greeley, 2010a; 2010b). Expanding on the threshold experiments of Greeley et al. (2003), sediment flux was examined for a variety of materials at a range of tangential velocities ($1\text{--}45\text{ m s}^{-1}$), which were above the measured threshold for both terrestrial ambient and martian analog conditions. The parameterized sediment flux was demonstrated to be a function of the strength of the vortex, described by the “lifting parameter”, $\Delta P/u_\phi$. The use of this parameter allowed comparison of sediment lifting in Earth and Mars

environments, and accommodated the non-coupled nature of the core pressure differential and the tangential velocity. In other words, the tangential velocity is not determined solely by the size of the vortex, meaning that for the same sized vortex, there could exist multiple configurations of ΔP and tangential velocity (Neakrase et al., 2006; Neakrase and Greeley, 2010a). The empirical results of their work showed that dust devil sediment flux is proportional to the lifting parameter to the fourth power.

Balme and Hagermann (2006) sought to examine the nature of the “ ΔP -effect” and explain the wind-stress-entrainment laboratory results by using two different simple numerical models to explore how vertical pressure gradients (caused by, for example, the passage of the low-pressure core of a dust devil over a surface) might lift loose particles. The two potential mechanisms described by Balme and Hagermann (2006) included 1) an impermeable bed of particles with lifting by vertical pressure gradients only, and 2) a bed in which lifting is controlled by the drag forces on particles as gas is sucked out from the interparticle pore spaces. Their conclusion was that the vertical pressure-gradient process alone was the more efficient and effective process and that equilibration of pore space pressures with the transient passage of the localized low-pressure system led to a decrease in the lifting potential of the vortex. Hence, for a permeable bed, the lifting potential would be largest when the pressure gradient is applied suddenly, and when the particle sizes of the sediment are small, such that ‘degassing’ from the interparticle pore-spaces happens slowly compared to the application of the pressure gradient. As a consequence, the ΔP effect would be most effective in small, fast-moving (across the surface) dust devils with intense low-pressure cores. This might explain why the ΔP effect was seen so clearly in the small, laboratory-scale vortices, but is yet to be seen in the natural dust devil size regime. It is also possible that this effect is negligible in real dust devils (Shao and Klose, 2016) or currently too difficult to assess in the natural case.

Figure 9. Simplified force diagram showing idealized forces acting on a particle as it is lifted in boundary layer flow (gray) and vortex flow with ΔP -effect (red). F_g represents gravity, F_σ interparticle forces, M , the Magnus rotational force, F_τ , the lift component from boundary layer shear stress, and F_p , lift component from the change in pressure possibly resulting from pore space pressure equalization creating a pressure differential across the particle. (After Greeley et al. (2003), Neakrase and Greeley (2010a), and Balme and Hagermann (2009)).

As has been shown through the laboratory studies throughout this section, this added lift component from vortex action, the “ ΔP -effect”, is most likely a complex interaction of several factors resultant from the passage of the dust devil over the surface. As such, it is perhaps better to designate this combined

lifting effect the “enhanced vortex entrainment effect” (EVE-effect). Any or all of the contributing factors could be active in any given dust devil, contributing to rates of change for each process. Pressure-excursion effects such as those proposed by Greeley et al. (2003) could be explained in part by Balme and Hagermann (2006) as mechanical pressure equalization, where the ‘trapped’ pockets of gas beneath a low pressure zone within a dust devil lifts particles into the flow. Furthermore, vortex-induced particle lifting could occur by some combination of those mechanical processes with varying contributions from thermo-luminescent (e.g., Küpper and Wurm, 2015) or electrodynamical processes (e.g., Esposito et al., 2015). The EVE-effect is thus not only a function of the vortex properties, but also in part, the surface materials and the ambient atmospheric conditions. Availability of sediment, pore space within the sediment, surface roughness, and sediment intrinsic properties (e.g., particle size and density distributions, moisture content, electrical properties, etc.) all influence how the surface responds to the passage of a convective vortex and whether or not that vortex becomes a dust devil by entraining sand and dust. Background ambient atmospheric conditions add to this effect by externally controlling the formation of the convective vortex. All of these factors are important to consider for designing new multi-tiered, co-registered observations in the field and laboratory to separate individual factors better for consideration within analytical models.

In summary, although wind tunnel and vortex generator studies demonstrated that small vortices are particularly efficient at lifting particles of all sizes under both terrestrial and martian conditions, they have not been able to explain the process by which this occurs specifically. As wind tunnel studies progress, there has been new recognition of the effects of saltation triggering, rolling, and turbulence on the lifting of dust and sand. All of these mechanisms are probably important for dust devils on Mars, but, as shown above, other, perhaps less intuitive, effects might also play a role.

3.3 Analytical parameterizations of dust emission

As outlined in Section 2, aerodynamic entrainment, saltation bombardment, and aggregate disintegration processes can contribute to dust emission in dust devils. On Earth, saltation bombardment and aggregate disintegration are the most effective dust emission mechanisms (Gillette et al., 1974; Shao et al., 1993) and have thus been the main focus of research. Both require saltation as an intermediate process. Parameterizations of saltation commonly used for dust emission modeling (e.g. Owen, 1964; Kawamura, 1964; White, 1979) assume that the downward flux of horizontal fluid momentum, which sustains saltation against dissipation due to friction with the bed, remains approximately constant over a time period of a few to a few tens of minutes, and that saltation is in equilibrium with the atmospheric forcing (Barchyn et al., 2014). This assumption may be especially inappropriate in the case of dust devils due to their short duration and small spatial extent. However, although the indiscriminate application of existing parameterizations of saltation bombardment and aggregate disintegration to dust entrainment by dust devils is problematic, both processes likely contribute to dust emission in dust devils. Their parameterizations are thus useful starting points for understanding dust entrainment in dust devils, and are discussed in the following.

On Mars, the mechanics of dust lifting are quite different from those on Earth. In particular, because of Mars’ low atmospheric density, formidable wind speeds of the order of $u_{t1} \approx 2$ m/s are needed to initiate saltation (Iversen and White, 1982). However, theory and numerical modeling indicate that, once initiated, saltation (and thus dust emission) can be sustained by wind speeds that are an order of magnitude less intense (Claudin and Andreotti, 2006; Almeida et al., 2008; Kok, 2010a, b; Pahtz et al., 2012). This occurs because the lower gravity and vertical drag on Mars makes saltating particles travel higher and longer trajectories, causing them to be accelerated by wind for a much longer duration during a single hop than on Earth. Furthermore, since wind speed increases away from the surface, the higher particle trajectories increase the acceleration on the particles (Kok, 2010a). These two factors compensate for the lower atmospheric density on Mars, causing Martian saltators to relatively easily pick up large speeds. Upon impact, these particles then eject (‘splash’) surface particles into the air stream, thereby sustaining saltation at relatively low wind speeds. Consequently, the ‘impact threshold’ shear velocity down to which saltation can be sustained by splashing is predicted to be well below the ‘fluid threshold’ required to initiate saltation. The theoretical and numerical prediction that the Martian impact threshold is well below the Martian fluid threshold is supported by the Earth-like size of ripples encountered by Mars rovers (e.g., Sullivan et al., 2005), which are consistent with a low Martian impact threshold (Yizhaq et al., 2014). Nonetheless, the extent of the role that saltation plays in dust lifting in martian dust devils and dust storms remains unclear (Kok, 2012). Indeed, observations by Sullivan et al. (2008) indicate that dust emission regularly occurs without saltation, namely by the

aerodynamic entrainment of low-density sand-sized aggregates of dust that has settled from the sky (also see Merrison et al., 2007).

Below, we discuss parameterizations of dust emission through either saltation bombardment and aggregate fragmentation (3.3.1) or direct aerodynamic entrainment (3.3.2). These parameterizations have been developed for Earth, where observations are available to test them. Some of these process-based parameterizations were applied to estimate the dust emission by a "typical" dust devil (Wang et al., 2016) or by a dust devil population (Klose et al., 2016). Because of the dearth of experimental constraints, dust devil parameterizations for Mars are generally less based on the microphysics of dust emission, and instead aim to quantify dust devil emission from thermodynamics-based estimates of dust devil activity (Newman et al., 2002; Basu et al., 2004; Kahre et al., 2006; Newman and Richardson, 2015). The parameterization of dust lifting by dust devils in martian atmospheric circulation models is thus generally more simplistic, in part because of the lack of observations, and in part because of the aforementioned remaining fundamental questions regarding the mechanics of martian dust lifting (Sullivan et al., 2008; Kok, 2010b; Mulholland et al., 2015).

3.3.1 Parameterizations of dust emission due to saltation bombardment and aggregate disintegration

Due to their hopping motion, the effective movement of saltating grains is in the horizontal wind direction and is expressed as a horizontal saltation flux, Q . For smaller dust devils, saltating particles might be expelled from the bottom of the vortex quite rapidly, but in larger ones, wind speeds are intense enough to make sand grains follow broad curving paths within the dust devil. In parameterization schemes, saltation is typically described as a uniform equilibrium process based on the momentum balance in the saltation layer, a layer close to the surface covering the height of most saltation trajectories (Owen, 1964), though the accuracy of this simplifying assumption has been questioned by recent studies (e.g., Barchyn et al., 2014). Most studies, starting with Bagnold (1941), have suggested that Q is proportional to the cube of the friction velocity (u_*) (Kawamura, 1951; Owen, 1964; Lettau and Lettau, 1978; Raupach and Lu, 2004). However, more recent theoretical, numerical, and experimental studies have suggested that the linear scaling of particle speed with wind speed assumed in these models is incorrect (Ungar and Haff, 1987; Rasmussen and Sorensen, 2008; Cressels et al., 2009; Kok, 2010a, b; Ho et al., 2011; Martin and Kok, 2016). Models that do not assume that particle speed scales with wind speed instead conclude that sand flux scales with the square of u_* (Duran et al., 2011; Kok et al., 2012; Pathz et al., 2012; Rasmussen et al., 2015). A recent comprehensive set of field campaigns directly supports the scaling of sand flux with the square, not the cube, of u_* (Martin and Kok, 2016).

The vertical dust emission flux, F , generated by saltation bombardment (also known as abrasion) or aggregate disintegration (auto-abrasion) is dependent on the horizontal saltation flux, Q , as the energy transferred to the surface by saltating grains at impact determines the energy available for dust lifting (e.g., Shao et al., 1993; Marticorena and Bergametti, 1995). Thus, F is often expressed as

$$F(d_i, d_s) = \alpha(d_i, d_s)Q(d_s) \quad (5)$$

where d_i denotes the diameter of dust particles, and d_s that of saltating grains (Shao, 2004). The determination of α is the major challenge addressed in saltation-based dust emission parameterizations.

Figure 10. Illustration of (a) dust emission by aerodynamic lift, (b) by saltation bombardment, and (c) through aggregate disintegration. Modified from Shao (2008).

Marticorena and Bergametti (1995) proposed a semi-empirical dust emission parameterization. The authors suggest that the magnitude of F depends on dust particle abundance at the surface and relate α to soil clay content. Other studies propose physically-explicit parameterizations. For example, Shao et al. (1993, 1996) and Alfaro and Gomes (2001) relate α to the binding energy, ψ , of the particles at the surface, $\alpha = \beta / \psi$, where β is a parameter.

Shao (2001, 2004) explicitly consider both saltation bombardment and aggregate disintegration. The bombardment process is described in terms of the volume removal at the soil surface through impacting grains based on the work of Lu and Shao (1999) (Figure 15a). Whether dust is emitted through abrasion or aggregate disintegration is determined by the mass fraction of free/aggregated dust available. The size of the volume that can be removed depends on the resistance the saltating grain experiences at impact. As a consequence, α is based on soil texture and soil plastic pressure in the scheme of Shao (2001, 2004).

More recently, Kok (2011b) proposed that most dust aerosol emission results from the fragmentation of aggregates of dust particles, which can occur either from impacts of saltators onto these aggregates, or from the saltation of the aggregates themselves (Figure 15b). This analogy with the well-studied phenomenon of brittle material fragmentation (Astrom, 2006) allowed the derivation of a simple analytical expression for the size distribution of emitted dust aerosols that eliminates some of the complexities of previous schemes, while being in good agreement with available measurements (also see Mahowald et al., 2014). Kok et al. (2014b) then built on this hypothesis that most dust emission results from aggregate fragmentation to propose a new theoretical model for how the dust flux emitted by an eroding soil depends on wind and soil properties. In this model, the efficiency with which the horizontal saltation flux produces a vertical dust flux depends primarily on soil clay content, which determines the dust mass available for disaggregation, and on the soil binding energy, which determines the resistance of the soil to fragmentation. This new dust emission model improves the representation of the global dust cycle in the Community Earth System Model (Kok et al., 2014a).

Figure 11. (a) Illustration of dust emission via soil volume removal by impacting saltating grains during saltation bombardment as described by Shao (2001, 2004) (from Shao, 2001); (b) Illustration of dust emission through soil or saltation aggregate disintegration in analogy with brittle fragmentation as described by Kok (2011b) and Kok et al. (2014b).

All schemes have been proven valuable for the modeling of regional and/or global-scale dust patterns, such as dust storms (e.g. Cavazos et al., 2009; Shao et al., 2010; Kok et al., 2014b), although differences between model predictions and observations of the dust cycle remain substantial (Huneeus et al., 2011; Evan et al., 2014). These differences can be due to a number of problems, including sub-gridscale variability and errors in wind speeds (Ridley et al. 2014), uncertainties in soil properties and moisture, sub-gridscale variability in the threshold wind speed due to spatial heterogeneity in soil properties and moisture, and deficiencies in parameterizations of the effects of differences in soil properties on the dust flux (Kok et al., 2014b).

Some of these problems are mitigated when applying the parameterizations on local scales for which soil properties can be defined with greater accuracy. However, all these parameterizations are formulated in terms of the friction velocity, which is by its nature a time-averaged property of the turbulent wind. Applying these parameterizations on smaller time scales, such as necessary for dust devils, can thus produce errors (Martin et al., 2013; Barchyn et al., 2014). Nonetheless, dust emission parameterizations such as the above are still a viable option for describing saltation-induced dust fluxes in dust devils. This can for instance be done by simulating (using high-resolution modeling frameworks such as large-eddy simulation; see Spiga et al., this issue) or measuring the spatial distribution of the instantaneous wind stress on the soil surface, and using the above parameterizations to estimate the dust emission flux. This ignores the fundamental problem in applying friction velocity-based parameterizations on short time scales (Barchyn et al., 2014), but the sensitivity study of Namikas et al. (2003) suggests that the effect of this discrepancy on predicted fluxes might be limited. Further work is needed to better resolve this issue.

3.3.2 Parameterizations of dust emission due to aerodynamic entrainment

When the averaged wind stress is below the threshold stress, i.e. in the situation of $u_* < u_{*t}$, the above-mentioned dust emission schemes do not predict any dust emission. However, wind gusts can cause the instantaneous wind stress on the surface to exceed the threshold required to initiate saltation, causing dust emission to occur intermittently even though u_* is on average smaller than u_{*t} (Stout and Zobeck, 1997; Cameiro et al., 2014). Furthermore, dust can also be aerodynamically entrained when $u_* < u_{*t}$ (Loosmore and Hunt, 2000; Macpherson et al., 2008).

Intermittently large momentum fluxes that can cause aerodynamic dust entrainment are due to atmospheric turbulence, which is most coherent in the case of unstable atmospheric stratification or in the presence of roughness elements (Stull, 1988; Raupach et al., 1996). Klose and Shao (2012) and Klose et al. (2014) developed a parameterization for the direct aerodynamic entrainment of dust with a focus on convective turbulent conditions. Dust emission is described as a stochastic process by representing both interparticle cohesive forces and aerodynamic lifting forces, i.e. momentum fluxes due to atmospheric turbulence, as probability distributions. Dust emission fluxes produced by the scheme are mostly two to three orders of magnitude smaller than fluxes typically obtained for saltation-generated dust emission. However, under favorable conditions such as in dust devils, fluxes can be of similar magnitude and have been found to be close to those observed in the field (Klose and Shao, 2016). Turbulent gusts also entrain sand-sized particles. This intermittent saltation is not yet included in the scheme and would further increase modeled turbulent dust emission. Klose and Shao (2016) applied the scheme in the framework of large-eddy simulation (LES) to investigate the dust entrainment associated with dust devils. They found that fluxes due to aerodynamic entrainment can be as large as $\sim 1000 \mu\text{g m}^{-2} \text{s}^{-1}$ in dust devils and thus can explain large parts of dust fluxes measured in dust devils. Based on LES experiments for a wide range of atmospheric conditions, Klose and Shao (2016) related dust devil dust emission to Richardson number and suggested a simple parameterization for use in regional and global models. See Klose et al. *this issue* for more detail.

Wang (2016) compared the friction and horizontal pressure forces acting in a dust devil and found that friction forces are strong enough to lift dust particles while pressure forces are not. Wang concluded that dust entrainment in dust devils is likely caused by friction rather than pressure forces. The author derived a theoretical expression for the direct aerodynamic entrainment of dust in dust devils based on the Navier-Stokes equations for a rotating flow and obtained larger emissions for direct aerodynamic entrainment than for dust emission generated by saltation bombardment. However, interparticle

cohesion has been neglected in the approach of Wang (2016), so his estimate of aerodynamic dust emission is likely an overestimation.

4. Conclusions & Future Work

Particle lifting and entrainment within dust devils are complicated processes that result from the internal balancing of multiple subsidiary processes, all of which may or may not be active in any given dust devil. The complex nature of these interactions means they are difficult to separate and study in the context of dust devils on Earth and Mars. Nevertheless, interactions between the various dust devil communities has led to advances that incorporate field observations on both planets, laboratory experiments (at terrestrial ambient and Mars analog conditions), and analytical modeling, clarifying many of the component processes for sediment transport within dust devils. The so-called ΔP -effect, describing the 'suction' of a low-pressure core within a dust devil, is perhaps better described as the EVE-effect (enhanced vortex entrainment), as it is actually a combination of many processes resulting from the conditions associated with the passage of a dust devil over the surface. Initial laboratory work characterized the wind shear component of the lift, without consideration of other processes tied to the material properties of the soil and how airflow in and around the grains affects their entrainment. Dust devil entrainment is intimately tied to the rate of change in each of the processes interacting with the surface, which leads to varying amounts of sediment lifting depending on the strength and translation speed of the dust devil. For example, electrification processes could affect the amount of dust lifted, but is dependent on the strength and speed of the dust devil to allow enough interaction time to be effective. So, dust lifting within dust devils is resultant from both the combined effects of the ambient conditions necessary for producing the vorticity and pressure structure within the dust devil. Furthermore, the instantaneous interactions between the lifting potential of the flow and the heterogeneous characteristics of sediment on the surface also strongly control the amount of dust seen lofted from the surface. The dust load within the dust devil, and even the orientation of the dust devil with respect to the sun, might have an additional effect, as the thermo-luminescent effect might be enhanced by sudden shadowing of the surface as the dust devil passes. The dominant form of lifting within a single dust devil could therefore be dominated by pore-space pressure equalization or thermo-luminescent enhanced lifting or mechanical wind shear, but it is likely the feedback of each of these within the dust devil which helps fuel many of the other processes ongoing within the vortex, and ultimately leading to dust lifting and the production of the 'classical' dust devil column.

Dust devils have been demonstrated to be intrinsically different lifting phenomena (Lorenz et al., *this issue*) compared to boundary layer winds. Through experiments and observations dust devils have been identified as effective lifters of dust given the proper conditions on Earth and Mars, and have been shown to be capable of removing dust on spacecraft solar panels. One of the more difficult remaining questions for dust devil studies involves discerning the individual roles of each of the component processes acting at any given time in dust devils. The difficulty arises in the ability to simultaneously collect bulk data on both the internal properties via in situ sensor suites (e.g., how pressure, wind velocities and particle counts are changing with time) and external measurements of how the dust composition, size distributions, and flux are changing over the lifetime of a dust devil. Future field observations will need to make better use of combined networks of sensors and camera systems to better characterize dust devil populations by attempting to get both types of data simultaneously. Laboratory studies can aid in development of instrumentation for these types of networks. Laboratory studies can also continue to refine our knowledge about the individual component processes by further isolation of specific variables including mechanical versus thermal versus electrodynamical dust lifting mechanisms. Analytical parameterizations and numerical dust lifting simulations that predict dust emission fluxes can continue to evolve with better computational ability and improved inputs from both observations and laboratory experiments. Such theoretical and modeling work serves the important role of connecting what we know about the specific processes to the larger regional and global systems and helps to define how dust devils result from and are tied to the bigger picture.

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