
Convective vortices and dust devils at the MSL landing site

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Convective vortices and dust devils at the MSL landing site: Annual variability

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Abstract Two hundred fifty-two transient drops in atmospheric pressure, likely caused by passing convective vortices, were detected by the Rover Environmental Monitoring Station instrument during the first Martian year of the Mars Science Laboratory (MSL) landed mission. These events resembled the vortex signatures detected by the previous Mars landers Pathfinder and Phoenix; however, the MSL observations contained fewer pressure drops greater than 1.5 Pa and none greater than 3.0 Pa. Apparently, these vortices were generally not lifting dust as only one probable dust devil has been observed visually by MSL. The obvious explanation for this is the smaller number of strong vortices with large central pressure drops since according to Arvidson et al. [2014] ample dust seems to be present on the surface. The annual variation in the number of detected convective vortices followed approximately the variation in Dust Devil Activity (DDA) predicted by the MarsWRF numerical climate model. This result does not prove, however, that the amount of dust lifted by dust devils would depend linearly on DDA, as is assumed in several numerical models of the Martian atmosphere, since dust devils are only the most intense fraction of all convective vortices on Mars, and the amount of dust that can be lifted by a dust devil depends on its central pressure drop. Sol-to-sol variations in the number of vortices were usually small. However, on 1 Martian solar day a sudden increase in vortex activity, related to a dust storm front, was detected.

1. Introduction

1.1. Dust Devils and Their Importance for the Martian Climate

Even before the time of spacecraft exploration of Mars it was known that the Martian atmosphere is loaded with dust [Ryan, 1964; Sagan and Pollack, 1969]. Dust affects the dynamics of the atmosphere by absorbing incoming and outgoing radiation and thus warming the atmosphere and cooling the surface [Leovy and Zurek, 1979; Zurek and Leovy, 1981; Guzewich et al., 2016]. Therefore, understanding the processes that lift dust from the surface into the atmosphere is essential when modeling the Martian climate.

Dust devils are small-scale whirlwinds, driven by solar insolation, that lift loose dust from the ground. They are a common phenomenon on arid areas on Earth [Sinclair, 1966, 1969]. The role of dust devils as dust lifters on Mars was first suggested by Ryan [1964]. He postulated that dust devils played a central part in the formation and growth of dust storms. However, observations by the Viking probes [Pollack et al., 1979] and by the Mars Orbiter Camera on board Mars Global Surveyor (MGS) [Cantor et al., 2006] have shown that dust devils do not lead to nor create the conditions for dust storms. On the other hand, it is thought that dust devils maintain the background dust load of the Martian atmosphere. Numerical models of the Martian atmosphere fit observations better if year-round dust injection by dust devils is included in the model [Newman et al., 2002a, 2002b; Basu et al., 2004, 2006; Kahre et al., 2006; Mulholland et al., 2013; Newman and Richardson, 2015], and orbital imaging of dust devils and their tracks has shown that dust devils may lift enough dust in all seasons to do so [Cantor et al., 2006; Stanzel et al., 2008; Whelley and Greeley, 2008; Reiss et al., 2011]. Slow fallout of the dust lifted by dust storms seems a less likely explanation for the background haze, as outside the storm season the dust load is highly repeatable from year to year even if the size and duration of the storms varies strongly [Basu et al., 2004].
Dust devils form when solar heating of the surface leads to a superadiabatic lapse rate in the lower part of the boundary layer, causing an unstably stratified atmosphere and hence strong convection [Sinclair, 1969, 1973]. The convective cells are characterized by descent in the cool center and ascent at the warm edges [Gheynani and Taylor, 2010]. Vortices usually form at the edges of cells when a pressure depression is formed under a rising plume of warm air, attracting an inflow of replacement air near the surface [Sinclair, 1973; Rennó et al., 1998; Toigo et al., 2003; Gheynani and Taylor, 2010]. The updraft causes vertical stretching of initially horizontal velocity, leading to a spiraling flow around a funnel of rising air [Gheynani and Taylor, 2010; Ito et al., 2013]. Dust devils appear to get their energy directly from solar buoyancy, in contrast to tornadoes which are powered in part by the release of latent heat within the column [Balme and Greeley, 2006]. Hence, dust devils form most efficiently under clear skies. In addition to surface heating, dust devils may be boosted by solar heating of the dust load within a dust devil [Fuerstenau, 2006].

Not all such convective vortices lift dust, either because there is no loose dust available or because the vortex is not strong enough. Sometimes the term “dust devil-like vortex” is used as a general name for these phenomena. In this work the term “convective vortex” is used as a synonym of dust devil-like vortex, i.e., this category includes dust devils and other (dust-free) vortices formed by the same mechanism but excludes vortices formed by different mechanisms (e.g., tornados) and larger-scale vortices (e.g., mesoscale convective vortices).

The energy budget of dust devil-like vortices may be described by the “heat engine” model of Rennó et al. [1998, 2000]. In this model, the flux of energy available to drive dust devils depends on the product of two factors: the surface sensible heat flux $F_s$, and the thermodynamic efficiency of vortices $\eta$. This product is called the Dust Devil Activity (DDA)

$$\text{DDA} = \eta F_s.$$  

(1)

The surface sensible heat flux $F_s$ is approximately proportional to the temperature difference of the surface and the near-surface air. The thermodynamic efficiency of vortices $\eta$ is defined by equation (22) in Rennó et al. [1998] and related to the depth of the boundary layer of the atmosphere

$$\eta = 1 - \frac{\rho_s^{\chi+1} - \rho_{\text{top}}^{\chi+1}}{(\rho_s - \rho_{\text{top}})(\chi + 1)/\chi}.$$  

(2)

where $\rho_{\text{top}}$ is the pressure at the top of the planetary boundary layer, $\rho_s$ is the surface pressure, and $\chi$ is the specific gas constant divided by the specific heat capacity at constant pressure. Representative values of these parameters, for Earth and for Mars, are given in Table S1 in the supporting information.

1.2. Previous Research on Martian Dust Devils and Convective Vortices

Dust devils on Mars were first imaged by the Viking orbiters [Thomas and Gierasch, 1985]. The Viking landers were not able to image dust devils because their cameras were single-pixel raster-scan devices and were thus not suitable for imaging moving objects. The meteorological pressure sensors of the Viking landers were also not capable of detecting fluctuations caused by convective vortices as their quantization limit was only 8.8 Pa [Tillman et al., 1993]. However, signs of convective vortices were identified in the wind data measured by the Viking landers [Ryan and Lucich, 1983; Ringrose et al., 2003].

Mars Pathfinder was the first lander that succeeded in imaging dust devils on the surface of Mars [Metzger et al., 1999]. Fourteen dust devils were observed by Imager for Mars Pathfinder camera [Ferri et al., 2003]. Also, 79 sudden pressure drops accompanied by abrupt shifts in wind direction, interpreted as being caused by passing convective vortices, were identified in the meteorological data measured during the mission that lasted for 83 sols [Schofield et al., 1997; Murphy and Nelli, 2002].

Dust devils could be seen in images taken by the Mars Orbiter Camera on board the Mars Global Surveyor (MGS) spacecraft that orbited Mars from 1997 to 2006 [Malin and Edgett, 2001]. These images were used in several dust devil surveys [e.g., Cantor et al., 2002; Fisher et al., 2005], climaxing in the comprehensive survey by Cantor et al. [2006], where 11,456 dust devils were identified in images taken over more than 4 Martian years. Since MGS, Martian dust devils have been imaged by three orbiters. The Thermal Emission Imaging System on board Mars Odyssey has enabled the study of thermal properties of dust devils from orbit [Cushing et al., 2005; Towner, 2009], and the high-resolution cameras on board Mars Express and Mars Reconnaissance Orbiter...
have enabled studies on translation and rotation motions, structures, and lifetimes [Stanzel et al., 2006, 2008; Choi and Dudas, 2011, Reiss et al., 2011, 2014]. These studies focus on investigating certain features of individual dust devils, and the data sets used are rather small, from one to a few hundred dust devil observations.

Images taken by orbiters have also been used to study the dark tracks that Martian dust devils leave behind [Balme et al., 2003; Greeley et al., 2005; Drake et al., 2006; Whelley and Greeley, 2006, 2008; Verba et al., 2010]. These investigations have provided information on the spatial and temporal distribution of dust devil activity, directions of motion, and amounts of dust lifted.

Meanwhile on the surface, the Mars Exploration Rover (MER) Spirit imaged 761 dust devils in Gusev crater during 3 Martian years [Greeley et al., 2006, 2010], while its sister Opportunity roamed the plains of Meridiani for longer than this before detecting its first dust devil [Greeley et al., 2010]. As the MERs have no meteorological instrumentation, Phoenix became the second Mars lander after Pathfinder that could observe dust devils by both imaging and atmospheric measurements. Five hundred two vortices with a pressure drop larger than 0.3 Pa were identified in the atmospheric pressure data, and 37 dust devils were imaged during the 151 sol mission [Ellehoj et al., 2010]. One hundred ninety-seven of the pressure drops had a magnitude higher than the detection threshold used in the present study (0.5 Pa). As imaging sequences of Phoenix’s Telltale wind indicator covered only a few hours of a sol, and during these sequences wind data were acquired less frequently than once every 50 s [Holstein-Rathlou et al., 2010], only nine pressure events could be correlated with wind perturbations [Ellehoj et al., 2010].

1.3. Parameterizing Dust Devils in Numerical Models of the Martian Atmosphere

Dust devils are far smaller than the grid scale of global and mesoscale models of the Martian atmosphere, so they cannot be explicitly resolved. As the dust lifted by dust devils affects the dynamics of the atmosphere, schemes for parameterizing their effects have been developed. In the “threshold-independent scheme” defined by Newman et al. [2002a], the amount of dust lifted by dust devils is estimated by multiplying the Dust Devil Activity (DDA), derived from the heat engine model (section 1.1), by a constant. This scheme has been used to parameterize dust lifting by dust devils in several Mars models [e.g., Newman et al., 2002b; Basu et al., 2004, 2006; Kahre et al., 2006; Mulholland et al., 2013; Newman and Richardson, 2015]. An alternative approach is the “threshold-dependent scheme” defined by Newman et al. [2002a], where the maximum tangential wind speed in a vortex is calculated via the heat engine model, and dust lifting is assumed to happen only if this wind speed exceeds a threshold value determined semiempirically from laboratory vortex experiments [Greeley and Iversen, 1985].

Kahre et al. [2006] evaluated both schemes by comparing model-predicted dust lifting by dust devils to the dust devil observations by the MGS orbiter and the MER Spirit rover. Regions of high- and low-dust devil activities in the threshold-independent model corresponded to regions of high and low numbers of dust devils in the survey of MGS images by Fisher et al. [2005]. However, the predicted spatial variation in dust lifting was relatively smaller than the observed spatial variation in the number of dust devils, especially when comparing to the later surveys by Cantor et al. [2006] and Whelley and Greeley [2008]. The seasons of maximum vortex activity at the Spirit landing site and at the regions included in Fisher et al.’s survey were predicted correctly, but the simulated dust devil activity did not go to zero at any site, even if dust devils are completely absent from observations for long periods on most sites. By contrast, Newman et al. [2002a] noted that the threshold-dependent model had areas with zero dust lifting, varying with season. However, the predicted dust devil activity in the Northern Hemisphere (versus that in the south) was far too high compared with observations [Newman et al., 2002b]. Partly for this reason, and partly for its greater simplicity, the threshold-independent scheme has tended to be used for most atmospheric modeling studies.

1.4. Background and Scope of This Study

The Mars Science Laboratory (MSL) rover Curiosity landed in Gale crater on Mars (4.5°S latitude, 137.4°E longitude) on 6 August 2012 (UTC) [Grotzinger et al., 2012]. To date, MSL has operated on the surface for longer than 2 Martian years. The payload includes a suite of meteorological and environmental sensors called the Rover Environmental Monitoring Station (REMS) [Gómez-Elvira et al., 2012]. One of the REMS sensors is a pressure gauge with noise level < 0.2 Pa peak to peak, low enough for detecting pressure drops caused by convective vortices [Harri et al., 2014]. Previous Mars missions equipped with high-resolution pressure sensors,
Pathfinder and Phoenix, lasted for only a fraction of the Martian year. Thus, MSL is the first lander whose data can be used to study the annual variation in vortex activity using pressure measurements.

Before MSL landed the expectation was that dust devil activity inside Gale crater would be tenuous. Orbital imaging revealed no dust devil tracks (F. Calef, Jet Propulsion Laboratory/Caltech, personal communication, 2012), and models predicted that the daytime boundary layer at the bottom of the crater would be suppressed [Tyler and Barnes, 2013], which should suppress vortex activity according to the heat engine model [Rennó et al., 1998, 2000].

In this study, REMS data measured during MSL sols 1 to 681 (August 6, 2012 to July 7, 2014) were searched for signatures of dust devils and dustless convective vortices. This time interval covers one full Martian year plus 12 sols. However, as regular REMS observations were not started before sol 10, and no vortices were detected during sols 10 to 12, the time interval that we use in our analysis is the full Martian year from sol 13 to sol 681, i.e., solar longitude \( L_\odot \, 157.5^\circ \) on Mars Year (MY) 31 [Clancy et al., 2000] to \( L_\odot \, 157.5^\circ \) on MY 32. (The term “solar longitude” \( L_\odot \) is explained in Appendix A)

First, we introduce a method for identifying vortices in the data. Statistics are made of the detected events and compared to previous studies. The frequency of occurrence of vortices at different seasons is also compared to Dust Devil Activity predictions by the MarsWRF mesoscale climate model [Richardson et al., 2007]. The lessons learned from this comparison regarding modeling dust devils in climate models are discussed in section 4. In section 3.5 we pay special attention to a sudden increase in vortex activity, lasting for 1 sol, and show that this event was related to a dust storm front. Preliminary results of this study have been published in Kahanpää et al. [2013, 2014], Harri et al. [2014], Haberle et al. [2014], and Gómez-Elvira et al. [2014].

2. Methods

2.1. The REMS Data

The Rover Environmental Monitoring Station (REMS) instrument on board MSL measures atmospheric pressure, air and ground temperature, wind speed and direction, humidity, and intensity of ultraviolet (UV) radiation [Gómez-Elvira et al., 2012]. The REMS data are available on the NASA Planetary Data System [Gómez-Elvira, 2013a, 2013b]. Unfortunately, the REMS wind sensor was found to be partly damaged after MSL had landed [Gómez-Elvira et al., 2014]. This initiated an ongoing recalibration effort. The first calibrated wind measurements from MSL were published on 31 July 2015, but they include only median horizontal wind velocities binned every 5 Martian minutes, and are only available for hours of the day when the wind does not come from the rover rear direction (which puts the surviving wind sensor on the opposite side of MSL’s large remote sensing mast, perturbing the flow massively). Hence, the available calibrated wind data cannot be used in the study of phenomena with a timescale of seconds.

The measurement strategy of the REMS instrument is described by Gómez-Elvira et al. [2014]. All sensors are read with 1 s sampling interval when the instrument is used. The baseline is to perform measurements for 5 min at the start of every Martian hour. Added to this, a variable number of 1 h “extended blocks” are performed at different times of the sol. The timing of the extended blocks is rotated to cover the diurnal cycle completely over several sols. Since sol 97, one of the extended blocks has been located around local noon, starting at either 11:00 or 12:00 Local Mean Solar Time (LMST), whenever possible. (The terms “Local Mean Solar Time” and “Local True Solar Time” are explained in Appendix B.) This “noon block” was added after the first signs of convective vortices were identified in the REMS data set, one of its motivations being monitoring variation in vortex activity on a daily basis.

The operation of the REMS instrument has been suspended several times because of rover-level maintenance, hardware issues, and communication gaps. The longest data gaps during the first Martian year occurred during sols 201 to 214 and 216 to 221 and were related to a flash memory anomaly in the Rover Compute Element, an update of the Flight Software, and a software bug that caused the rover to enter safe mode. These events were independent and only by coincidence did they occur close to each other.

2.2. Modeling the Pressure Curve of a Passing Dust Devil

The method that we use to identify vortices in the REMS data is described in section 2.3. This method includes determining the pressure drop magnitudes and durations of the identified vortex candidates by fitting a
modeled pressure curve to each event. In this section we evaluate analytical vortex models with the aim of finding an appropriate function for this purpose.

The detected vortex events last typically ~10 s, and often less. Thus, with 1 Hz sampling rate, of the order 10 measurement points are recorded when a vortex passes by. This small amount of data per event forces us to model the pressure curve with a simple model, with as few free parameters as possible. The majority of the detected pressure drops are rather smooth and symmetrical, with one clear pressure minimum. Hence, we consider only one-core models. Various such models are described in the literature, e.g., the Rankine model [Rankine, 1882; Sinclair, 1973], the Burgers-Rott model [Burgers, 1948; Rott, 1958], and the Vatistas model [Vatistas et al., 1991]. These models are axially symmetric so that the tangential wind speed \( v_o \) depends only on the distance \( r \) from vortex center. The Burgers-Rott model is based on fluid dynamics and the Vatistas model on laboratory measurements, while the Rankine model is a commonly used approximation based on the assumption that the vortex core rotates as a rigid body. Field studies have shown that the visually observable radii of terrestrial dust devils, defined by the wall of the dust devil column, correspond with the distance from vortex center where the tangential wind velocity reaches its maximum [Ryan and Carroll, 1970; Fitzjarrald, 1973; Metzger et al., 2011]. The distance of maximum tangential velocity is thus often called the "core radius" \( R_c \) in vortex models. A common feature of the models mentioned above is that the function describing \( v_o \) as a function of \( r \) approaches asymptotically \( v_o \propto r^{-1} \) when \( r \gg R_c \). This property follows from the assumption that vorticity is zero far outside the vortex core. It can also be derived from the assumption that the angular momentum of all gas parcels in the outer part of the vortex is constant, which is reasonable as all gas in the vortex at a certain moment of time is sucked in from the same source region.

To a first approximation a dust devil-like vortex is in cyclostrophic balance, i.e., centrifugal forces are balanced by pressure gradient forces [Sinclair, 1973; Rennó et al., 2000]:

\[
\frac{v_o^2}{r} = \frac{1}{\rho} \frac{\partial p}{\partial r},
\]

where \( \rho \) is the density of the gas. This relation couples the wind and pressure fields inside dust devil-like vortices, as have been proven with satisfactory accuracy in field studies [Sinclair, 1973; Tratt et al., 2003; Lorenz, 2016]. A consequence of this coupling is that the pressure depression at distance \( R_c \) is 50% of the depression at the vortex center in the Rankine and Vatistas models, a result that roughly matches the results of the field measurements by Sinclair [1973]. The density can be assumed constant in equation (3) as the pressure depressions associated with dust devil-like vortices are small, less than a few percent of the atmospheric pressure on both Earth and Mars [Balme and Greeley, 2006]. Substituting the \( v_o \propto r^{-1} \) dependence into equation (3) produces the pressure field far outside the core:

\[
p = p_\infty - \alpha r^{-2}.
\]

where \( \alpha \) is an arbitrary constant and \( p_\infty \) is the background pressure.

Now consider a vortex that moves along a straight line with velocity \( U \) and passes by a stationary pressure sensor on moment \( t_0 \) at a miss distance \( r_0 \gg R_c \). The distance \( r \) between vortex center and sensor can be expressed as a function of time \( t \)

\[
r(t) = \sqrt{U^2(t-t_0)^2 + r_0^2}.
\]

Substituting equation (5) into equation (4) gives

\[
p(t) = p_\infty - \frac{\alpha U^2}{(t-t_0)^2 + (r_0/U)^2},
\]

i.e., the pressure curve measured by the sensor approaches a Lorentzian function when \( r_0 \gg R_c \).

Next consider the case that the vortex passes straight over the sensor. In this case \( r(t) = |U(t-t_0)| \), i.e., the detected pressure curve as a function of time has the same functional form as the radial pressure profile of the vortex. Figure 1 shows normalized radial pressure profiles of the three vortex models mentioned above as well as a Lorentzian function. The Lorentzian function approximates the physical Burgers-Rott and Vatistas models better than the commonly used Rankine model. This result is in accordance with that of the similar comparison of vortex models by Lorenz [2014].
The Lorentzian function is therefore a close approximation of the expected pressure curve caused by a symmetrical one-core vortex passing right over a stationary sensor, and when \( r_0 > R_c \), it provides exactly the expected curve. Ellehoj et al. [2010] also found that the Lorentzian function is a good fit to measured pressure profiles of Martian convective vortices. This all suggests using the Lorentzian function when determining pressure drop magnitudes and durations.

2.3. Vortex Identification

When a convective vortex passes by a fixed meteorological station, abrupt variations in several meteorological parameters are detected. The four main components of the "signature" of a convective vortex are changing wind speed, changing wind direction, a drop in pressure, and a rise in temperature [Ringrose et al., 2007].

Elevated temperatures are, however, only encountered if the sensor enters the vortex core, with little short-term temperature variations occurring outside this region [Ringrose et al., 2007]. Also, previous Mars landers have detected that there are temperature events of comparable size not associated with convective vortices [Ellehoj et al., 2010]. Variations in wind speed and direction [Ryan and Lucich, 1983; Ringrose et al., 2003] and pressure drops [Murphy and Nelli, 2002; Ellehoj et al., 2010] have been used as primary vortex identification methods in previous studies of Martian dust devils. In the case of MSL, calibrated wind data with adequate time resolution are not yet available. Thus, we identify vortices primarily by searching for transient drops in the pressure record measured by the REMS instrument.

The algorithm that we used to identify pressure events associated with vortices is a direct adaptation of that used by Ellehoj et al. [2010] on the Phoenix data. This algorithm searches for 20 s intervals that fulfill the following criteria: (1) minimum pressure > 0.1 Pa lower than mean of previous and next 20 s intervals, and (2) mean pressure > 0.3 Pa lower than mean of previous and next 20 s intervals.

Surprisingly, 65% of all pressure drops originally identified by the algorithm occurred before 7:00 or after 19:00 Local Mean Solar Time (LMST). There were especially high numbers of identifications in the late evening and early night, peaking between 21 and 22 LMST. This observation is in sharp contrast to the results of the earlier Mars landers: Pathfinder detected no nighttime sudden pressure drops [Murphy and Nelli, 2002] and Phoenix only a few between 21:00 and 01:00 LMST [Ellehoj et al., 2010]. A closer analysis of the late evening and nighttime events detected by MSL revealed that they were caused by a wave-like oscillation with approximately 5–18 min periods. Several studies have shown that this oscillation is probably caused by topographic winds or mountain waves [Zorzano et al., 2013; Haberle et al., 2014; Pla-Garcia et al., 2016]. These theories explain the difference to the results of the earlier Mars landers: as the landing sites of Pathfinder and Phoenix had gentler topography than that of Gale Crater, only far weaker topographic winds or mountain waves could have existed. Since these events were clearly not associated with passing vortices we decided to automatically remove all events that occurred before 7:00 or after 19:00 LMST. Nighttime pressure events are thus not analyzed in this study.

Preliminary values of the magnitudes \( \Delta p \) and half maximum durations \( \Gamma \) of the identified daytime pressure drops were then determined by fitting to the measured pressure data a linear combination of a Lorentzian function and a line

\[
p(t) = p_{\infty} + k(t - t_0) - \frac{\Delta p}{\left(\frac{t - t_0}{1.72}\right) + 1}.
\]

**Figure 1.** Normalized radial profiles of the pressure depressions described by the Rankine (blue), Vatistas (gray), Burgers-Rott (green), and Lorentzian (red) vortex models. The x axis shows the distance from vortex center \( r \) normalized by the core radius of the Rankine model, and the y axis shows the pressure depression at distance \( r \) from vortex center normalized by the central pressure drop. The parameters of the Rankine, Burgers-Rott, and Vatistas models have been set so that their pressure profiles asymptotically approach. The core radius of the Lorentzian model is set equal with that of the Burgers-Rott model.
The rationale for using the Lorentzian function is given in section 2.2. The acquired values of \( \Delta p \) and \( \Gamma \) depend somewhat on the time interval that is used when fitting the model to the data. The program calculates the preliminary values for the fit parameters by using a time interval that covers equal times before and after the pressure minimum. All intervals from ±15 s around the minimum to ±150 s are gone through with 5 s steps, and the interval for which \( \Delta p \) preliminary is maximized is chosen.

If the fit does not converge with any of the time intervals or the acquired \( \Delta p \) preliminary is less than 0.3 Pa, then the event candidate is discarded.

After this, the pressure data measured ±3 min before and after the pressure minima of all remaining vortex candidates were plotted and the events classified as "true," "potentially true," or "false," the subjective criteria being similar to those used by Lorenz and Lanagan [2014].

1. True (equivalent to Lorenz and Lanagan class A) is a clear, sharp pressure decline and recovery, well in excess of nearby pressure excursions.
2. Potentially true (equivalent to Lorenz and Lanagan classes B and C) is an apparent pressure drop, but only modestly larger than background variations and/or has a shape clearly not characteristic of a classical vortex passage. Also events that would have otherwise fulfilled the criteria of the “true” rank but were suspected to be instrument artifacts went to this rank, as discussed below.
3. False is an event identified by the algorithm but lacking completely an apparent, isolated pressure drop. False indications were caused, for example, by data gaps and high noise.

Final values for the pressure drop magnitudes \( \Delta p \) and half maximum durations \( \Gamma \) were then determined for all events classified as true by fitting a modeled pressure profile (equation (7)) to the pressure data as shown in Figure 2. Now the time interval used when fitting the model to the data was chosen by hand, individually for each event, the subjective criteria being that the pressure drop should be completely included in the interval and that the amount of surrounding data should be as small as possible, but still such that the modeled slope and level of the background pressure correspond to what can be estimated by eye. Unlike in the case of Phoenix [Ellehoj et al., 2010], there was no need to perform any response time correction for the acquired \( \Delta p \) and \( \Gamma \) values, as the response time of the REMS pressure sensor is faster than the 1 s sampling interval [Harri et al., 2014]. Some events had multiple, separate pressure minima; these “double events” are discussed in section 3.1. \( \Delta p \) was determined for the double events by fitting a linear combination of two Lorentzian functions and a line as shown in Figure 3. A model with only two Lorentzian functions worked well enough also for events that had three or more separate minima.

It becomes difficult to determine if a pressure drop with magnitude barely over the 0.2 Pa noise level has a shape characteristic of a vortex passage. Thus, only 48% of the pressure drops with magnitudes in the range 0.3 Pa, . . . , 0.5 Pa were classified as true while 28% were classified as potentially true. By contrast, of the > 0.5 Pa events, 88% were classified as true and only 6% as potentially true. Hence, using the events with magnitude 0.3 Pa, . . . , 0.5 Pa would have added a substantial subjective element to our analysis, so we decided to use only the events that were classified as true and had final \( \Delta p \) greater than 0.5 Pa. This 0.5 Pa detection threshold equals that used by Murphy and Nelli [2002] on the Pathfinder data. As the noise level of the Phoenix pressure sensor was lower, Ellehoj et al. [2010] were able to use a 0.3 Pa detection threshold.

Several of the identified pressure drops occurred within minutes of the REMS UV sensor passing into or coming out of the shadow of rover structures. The number of these cases seemed to be too high to be coincidental. Apparently, there is an obscure error mode in the REMS pressure sensor that causes these signals...
The root cause of this anomaly is as yet unknown. Because of this “shadow effect” the intensity data of the A, ABC, and E bands of the UV sensor [Gómez-Elvira et al., 2012] was plotted together with the pressure data when the vortex candidates were examined, and all events that occurred close to times when the UV sensor went into or came out of shadow were classified as potentially true or false. However, the majority of these discarded pressure drops were small, ~0.3 Pa. Only 10 events larger than 0.5 Pa were classified as potentially true instead of true because of this criterion. The shadow effect has thus only a small impact on the data that we use in the present study. The plotted UV intensity values were taken from the REMS “Environmental Magnitude”-level data files (ENVRDR) [Gómez-Elvira, 2013a] and not the higher level “Models Reduced Data Record” files (MODRDR) [Gómez-Elvira, 2013b], since the ENVRDR files contain all data measured by the UV sensor while sequences classified unreliable are missing from the MODRDR data.

Finally, variations in air temperature and wind occurring concurrently with the pressure events were checked for time intervals ±108 s before and after the pressure minima of the true pressure events with magnitude > 0.5 Pa. For the air temperature sensor the calibrated local air temperatures of both REMS booms [Gómez-Elvira et al., 2012] were plotted separately in the same graph. For the wind sensor no calibrated data with adequate time resolution were available, so we plotted the raw data of all boards of the undamaged sensor on boom 2 [Gómez-Elvira et al., 2012]. For the UV sensor a similar check was already performed during the classification phase, as described above.

All known uncertainty modes in the REMS pressure data are discussed by Harri et al. [2014]. Besides instrument noise and the shadow effect, the only uncertainty mode that could cause artificial variation with a time scale of seconds is the “warm-up effect” [Harri et al., 2014]. However, this effect does not affect the analysis here, as it uses the MODRDR-level pressure data [Gómez-Elvira, 2013b] that were measured by Barocap 2, the sensor head that is negligibly affected by the warm-up effect [Harri et al., 2014]. Since events with magnitudes comparable to the noise level and events that could have been caused by the shadow effect have been removed, the vortex data set should contain practically no instrument artifacts.

2.4. The Effect of the Vortex Identification Method on the Results

As the vortex identification algorithm used is practically the same as that used by Ellehoj et al. [2010], the MSL data set is directly comparable to the Phoenix vortex data set. The drawback of this algorithm is that it finds only the events with duration of the order 20 s. The reason for this is the criterion that the mean pressure of the 20 s interval around the pressure minimum must be more than 0.1 Pa lower than mean of the previous and next 20 s intervals. Figure 4 shows an estimate of the detection threshold caused by this criterion as a function of the event’s half maximum duration \( \Gamma \). The estimate has been calculated by assuming that the pressure drops have Lorentzian shapes and that the minimum pressure always coincides with one of the measurements, sampled with 1 s intervals. In this case, the criterion that the mean pressure of the 20 s interval around the pressure minimum must be at least 0.1 Pa lower than the mean of the previous and next 20 s intervals can be written as

\[
\frac{1}{19} \sum_{i=-9}^{9} \frac{\Delta p}{(t_i^2) + 1} - \frac{1}{20} \sum_{j=-10}^{10} \frac{\Delta p}{(j^2) + 1} > 0.1 \text{ Pa,}
\]
since 19 readings are read within ±10 s of the pressure minimum and the previous and next 20 s intervals
cover the time span from 10 s to 29 s before and after the minimum. The smallest
\( \Delta p \) that leads to a detection

\[
\Delta p_{\text{threshold}} = \frac{0.1 \text{ Pa}}{\frac{1}{19} \sum_{i=9}^{9} \left( \left( \frac{i}{11/2} \right)^2 + 1 \right)^{-1} - \frac{1}{29} \sum_{i=10}^{29} \left( \left( \frac{i}{11/2} \right)^2 + 1 \right)^{-1}}.
\]

Figure 4 shows that a pressure drop with duration shorter than about 3 s or longer than ~70 s must have a
magnitude above the 0.5 Pa detection threshold to be identified. An event with duration of 400 s would not
be detected unless it had a magnitude over 10 Pa. This means that large vortices, with diameters of hundreds
of meters, could be detected only if they passed right over the rover with fast velocity. Population studies of
dust devils on both Earth and Mars have shown that the number of large vortices falls with diameter,
approximately by a power law with exponent \( \frac{1}{2} \) [Lorenz, 2011], so a direct hit by a large vortex is extremely
improbable. Thus, large vortices are hard to detect by the methods used here, especially if they have weak
central pressure drops. This should be taken into account when comparing this data set to modeled
vortex populations.

As shown in section 2.2, in the outer part of a vortex the magnitude of the wind perturbation is inversely
proportional to the distance from the vortex center, while the magnitude of the pressure perturbation is
inversely proportional to the square of the distance. Large, distant vortices are hence easier to detect in sur-
veys based on wind measurements. This is shown in the results of the survey by Ringrose et al. [2003], based
on Viking lander 2 wind measurements from the first 60 sols, when meteorological data were logged with
8 s intervals, in contrast to 60 s used later. Ringrose et al. reported 38 possible vortices, of which 9 were
suspected to be false positives produced by wind disturbed by the lander body. Miss distances and half
maximum diameters were determined by fitting a Rankine vortex model to each event. The reported
diameters of the 29 probable vortices range from 22 m to 450 m, and all vortices with a diameter larger
than 150 m have a miss distance greater than 700 m. A full set of Rankine fit parameters, including
maximum tangential wind speed at the edge of the core, is given for eight probable vortices. We used
these fit parameters to calculate the magnitudes and half maximum durations of the pressure drops that
these vortices caused at the Viking lander’s site. The magnitudes ranged from 0.2 Pa to 1.2 Pa and durations
from 23 s to 1113 s. Five events had magnitude greater than 0.5 Pa, but the durations of all of these were
longer than 100 s, thus none of them would have been identified in the present survey. On the other hand,
short-duration events (which form the bulk of the observations of this survey) are rare in the Viking records,
due to the longer sampling interval. It is also interesting to note that the calculated pressure drop
magnitudes are below the quantization limit of the Viking pressure sensor, which explains why coincident
pressure anomalies were not detected by Ringrose et al.
3. Results and Discussion

3.1. Signs of Vortices in Pressure, Temperature, Wind, and UV Data

Two hundred fifty-two sudden pressure drops classified as “true vortices” with magnitude > 0.5 Pa were identified in the REMS data measured during MSL sols 1 to 681. These events are listed in Table S2 in the supporting information. In most cases the pressure curve was rather smooth with one clear minimum, and the Lorentzian function fitted the measured pressure values well, as shown in Figure 2. Thirteen percent of the events had multiple minima as shown in Figure 3. As suggested by Lorenz [2013], events like this are probably caused by multiple-core vortices, two-cell vortices wherein a central downdraft exists inside the core, or by vortices moving along cycloidal tracks and thus passing by the sensor several times. The percentage of double events in our survey is clearly higher than seen by Ellehoj et al. [2010] in the Phoenix data: they recorded only two such events among the 197 vortices that had a Δp larger than 0.5 Pa. On the other hand, in a survey of dust devil activity on Earth using three independent pressure loggers at El Dorado Playa, Nevada, Lorenz [2013] detected that 18–28% of the pressure drops caused by dust devils were double dipped, multidip, or otherwise complex. Measurements on more sites on both planets would be needed to determine whether any underlying differences exist between dust devil shapes and motions on Earth and Mars.

Interpretation of the air temperature data measured concurrently with the pressure events proved to be challenging, as the REMS air temperature sensors are affected by heat generated by the rover [Gómez-Elvira et al., 2014]. The air temperature sensors are mounted on the two REMS booms, attached to the rover’s Remote Sensing Mast and placed 50 mm apart vertically, and 120° apart in azimuth. Each air temperature sensor consists of three thermistors installed on a short rod, and the data from all three are used in the retrieval of ambient air temperature [Gómez-Elvira et al., 2012]. The result is two estimates of the ambient air temperature, one for each boom. The ambient air temperature retrieval method works relatively well under still conditions or when there is a constant flow. However, one or both air temperature sensors may be affected by the flow of heat from the rover’s Radioisotope Thermoelectric Generator (RTG) and/or rover body, depending in part upon wind direction. In addition, depending on time of day, one or both booms may be in direct sunlight or in shadow [Gómez-Elvira et al., 2014].

In 42% of the pressure events the warming or cooling rate of one of the two ambient air temperature readings, or both, suddenly changes concurrently with the pressure minimum. Typically, the retrieved air temperature is either more or less constant before the pressure drop but warms or cools strongly after the drop, or the temperature warms or cools strongly before the pressure drop but stays constant after it. In many cases the readings of the two air temperature sensors change in different directions, i.e., one warms when the other cools. We interpret these events as being possibly caused by the sudden change in wind direction and velocity as a vortex passes by. The warming could be caused by wind blowing air heated by the RTG or rover body over the sensor and the cooling by wind bringing fresh air from outside the rover’s thermal plume. As the two temperature sensors are located at different elevations and point in different directions, the change in wind direction and velocity affects them in different ways. There are also cases when semiconstant warming turns to semiconstant cooling at the time of the pressure event, forming a temperature maximum concurrently with the pressure minimum. These events are probably caused by the change in wind direction rather than by the hot core of the vortex. However, in 20% of all pressure drops the reading of either air temperature sensor is more or less constant both before and after the pressure event but there is a clear, larger than 1 K rise in temperature coincident with the pressure drop, with the duration of this temperature maximum very close to that of the pressure minimum. These events seem to be possible detections of hot vortex cores. In 32 of the 50 events with a temperature rise like this, the rise is detected only by the air temperature sensor whose reading is lower, i.e., is less affected by the thermal contamination from the rover. In 13 cases the rise is detected by both temperature sensors and in 5 cases only by the sensor whose reading is higher. In 25 events the warming or cooling rate of one air temperature sensor changes abruptly, while the other detects a short-duration temperature rise concurrently with the pressure drop. An example of this is shown in Figure 5.

For 48% of the pressure events any temperature signal was lacking which could possibly be associated with a passing vortex. This is not surprising taking into account that many of the vortices detected by Pathfinder and Phoenix were also missing concurrent temperature perturbations [Murphy and Nelli, 2002; Ellehoj et al., 2010], even if the air temperature sensors of these low-power landers were mounted on 1 m tall meteorological masts and were thus subjected to smaller thermal contamination [Schofield et al., 1997; Davy et al., 2010].
Figure 5. REMS measurements during a vortex event on MSL sol 86 at 11:02 Local Mean Solar Time. (top left) Pressure and air temperature. (top right) Ultraviolet radiation intensity. (bottom left) Wind sensor raw data in transversal direction. (bottom right) Wind sensor raw data in longitudinal direction. The wind sensor data show that before the pressure minimum the wind came from behind the rover and turned through the forward direction to the right during the pressure drop. Note that as the wind sensor is located on REMS boom 2, pointing in the driving direction of the rover, it is on the lee side of the mast when the wind comes from behind the rover. Thus, the wind might actually have been strong before the vortex encounter regardless of the near-zero values of all but one wind sensor raw readings. There are two downward pointing peaks in the transversal data of board 1, timed at the beginning and end of the pressure event. These are probably caused by upward flow, indicating that the lifting motion was strongest at the edges of the vortex core. Before the pressure drop the air temperature sensed by boom 2 was ~13 K higher than that sensed by the right-pointing boom 1. During the encounter the boom 2 temperature started to decrease, reaching 90 s later almost the same value as boom 1. The explanation for this might be that before the encounter boom 2 was affected by thermal contamination as it was on the lee side of the mast, but after the encounter boom 2 was cooled by wind coming from the right, i.e., from outside the rover’s thermal plume. Boom 1 that was in free flow both before and after the encounter recorded a small air temperature rise contemporary with the pressure minimum, perhaps caused by the hot core of the vortex. A faint, ~0.3% decrease in the UV intensity was detected contemporary with the pressure minimum in the A, B, E, and ABC bands. This decrease could not be detected in the C and D bands as the quantization steps of these narrow bands are higher than the magnitude of this intensity drop.

Possible reasons for the absence of clear temperature anomalies, besides the thermal contamination, are listed by Ellehoj et al. [2010], and they include turbulent temperature fluctuations masking the temperature perturbations of the vortices, passage of vortices not directly over the lander, the hot core missing the temperature sensor in the vertical direction, and vertical flow distortions due to lander structures.

Wind sensors are mounted on both REMS booms but unfortunately the sensor on boom 1 was damaged upon landing so only the sensor on boom 2, pointing in the driving direction of the rover, is producing meaningful data [Gómez-Elvira et al., 2014]. The structure of the wind sensor is shown in Figure 6. The Environmental Magnitude-level REMS data (ENVRDR) [Gómez-Elvira, 2013a] contains values of six raw data parameters of the wind sensor: differential thermal conductance in two directions measured by transducer boards (explained in the caption of Figure 6). In the absence of calibrated wind data with a time resolution of seconds, these raw data may be used to identify wind variations as explained in section 2.3. There were five pressure events for which reliable wind data were not available. In 87% of the remaining events, variations in the wind sensor raw readings clearly above background level were observed concurrently with the pressure...
tion events, but only ~20% of the events caused dimming greater than 2%. Thus, the obscuration caused by

part was associated with a clear, coincident drop in UV intensity. The UV light curves measured during this

If the vortices detected in the REMS pressure and wind data also lifted dust, they could obscure sunlight when

Figure 6. The REMS wind sensor. The sensor consists of three identical hot film anemometer transducer boards, each housing four “hot dices” in a square configuration and a separate “cold dice.” The dices are silicon chips with resistors printed on the upper side, used to heat the dice and measure its temperature. The heating power is controlled so that the temperature difference between the hot dices and the cold one is constant [Gómez-Elschner et al., 2012]. The raw data produced by the sensor contain two readings for each board: differential thermal conductance in longitudinal and transversal directions. These are dimensionless numbers proportional to the amount of heat conducted by convection from the two front hot dices to the two back and from the two left hot dices to two right, respectively [Dominguez et al., 2008]. Boards 1 and 3 are located on the left and right sides of the boom and board 2 on its underside. Thus, when looking from the base of the boom toward its tip, the transversal wind directions sensed by boards 1, 2, and 3 are from right/up, from left, and from right/down, respectively. The longitudinal direction is from the tip toward the base for all boards. (Credit: NASA/JPL-Caltech and CSIC-INTA).

raw readings prevented the detection of the potential effect of the vortex. Of the 22 events belonging to this
category, 11 occurred during MSL sol 664. As discussed in section 3.5, the atmosphere at the bottom of Gale

minimum. In most cases the readings changed back and forth on a timescale comparable to the duration of the pressure event, but in approximately one fourth of the events the change in the wind sensor raw readings was more or less permanent. Almost all of these “permanent changes” occurred in situations when the dominant wind direction given in the calibrated, 5 min wind data was from behind the rover. Under this wind direction the remaining wind sensor is on the lee side of the Remote Sensing Mast, which makes its readings unreliable [Gómez-Elschner et al., 2014]. Thus, most of the permanent changes could actually be caused by small differences in wind direction after the vortex encounter compared to that before. The high percentage of pressure drops accompanied by wind direction changes, providing further evidence of vortex passage, supports the validity of the vortex-detection method used here.

The 32 pressure events not accompanied by clear wind perturbations could be divided into three categories. First, there were events where high background variation in the wind sensor

perturbation difficult. The second category consists of eight events that had a long half maximum duration
(>20 s) and small pressure drop magnitude (<1.1 Pa), implying that they were probably caused by vortices
that passed far from the lander, as explained in section 3.2. Such far encounters might cause only a small var-

ation in wind direction depending on the geometry of the encounter and rotation direction of the vortex
[Ringrose et al., 2007]. Indeed, weak variations in the wind sensor raw readings were observed in these cases,
but as they lacked the abrupt nature of the perturbations associated with shorter duration events they could
not be distinguished with certainty from the background. Finally, there were two events lacking a clear expla-
nation for the missing wind signal, but these also had relatively long half maximum durations (9, . . . , 13 s) and
small pressure drop magnitudes (<1.0 Pa), and the background wind direction was from behind the rover in
both cases, so these might also be caused by far encounters with an unfavorable geometry. Given these likely
explanations for the missing wind signal, these 32 events were retained in the vortex event data set. This is
also consistent with the earlier studies by Murphy and Nelli [2002] and Ellehoj et al. [2010], in which vortex
events were identified using pressure data only.

If the vortices detected in the REMS pressure and wind data also lifted dust, they could obscure sunlight when they pass by and cause dips in the detected solar UV flux. However, only one of the pressure drops in the data set was associated with a clear, coincident drop in UV intensity. The UV light curves measured during this event, on sol 86, by four of the UV photodiodes of the REMS instrument are shown in Figure 5. The obscuration was very faint, only 0.3% of the mean intensity. This can be compared to the results of a dust devil survey by Lorenz and Jackson [2015] in Nevada, USA. They used four small stations that record pressure and solar flux and found that ~60% of the vortex events identified in the pressure data were accompanied by obscuration events, but only ~20% of the events caused dimming greater than 2%. Thus, the obscuration caused by
the sol 86 event was of the same order as those caused by faint terrestrial dust devils. As can be seen from Figure 5, the pressure drop of the sol 86 obscuration event had only ~ 1.0 Pa magnitude. This vortex encounter occurred just 20 Martian minutes before solar noon on an equatorial location, so the direction of insolation was almost directly from above. Therefore, the fact that an obscuration was detected implies a near overhead passage of the vortex. Also, the wind data show signs of updraft, suggesting that the vortex core was penetrated (Figure 5). The magnitude of the central pressure drop was thus probably not much more than twice the measured pressure drop, taking into account the relation between the pressure drop magnitude at the edge of the core and that at the vortex center (section 2.2). However, as dust devils evolve all the time, the vortex could have been stronger and thus able to lift dust before the encounter. The sol 86 obscuration event resembles the event on sol 62 of the Mars Pathfinder mission, when the passage of a vortex detected in the Atmospheric Structure Investigation/METeorology experiment (ASI/MET) pressure record was correlated with a reduction of about 1.5% in the power generated by the Pathfinder solar panels [Schofield et al., 1997].

The nondetections of UV dips in almost all events in the MSL data set do not prove that the sol 86 event was the only dust-lifting vortex, as the dust devil must pass between the sensor and the direction of the Sun to cause an obscuration. Also, in 21 cases simultaneous UV data were not measured or the UV sensor was obscured by rover structures. The observation that only a very small proportion of the vortices in our data set cause obscurations of the solar UV flux fits very well with the results of a campaign where Dust Devil Search movies were imaged using MSL’s navigation cameras, reported by Moores et al. [2015]. Based on the number of vortices detected in the present survey during MSL’s first 360 sols, Moores et al. estimated that about 100 dust devils should have been captured in the Dust Devil Search movies if all detected vortices lifted dust, but only one possible dust devil was observed.

3.2. Magnitude, Duration, and Diameter Distributions

The cumulative magnitude distribution of the true vortices detected during MSL sols 13 to 681 is shown in Figure 7. For comparison, the magnitude distributions of the transient pressure drops detected by Mars Pathfinder [Murphy and Nelli, 2002] and Mars Phoenix [Ellehoj et al., 2010] are shown in the same graph. The y axis shows the number of events with pressure drop larger than the $\Delta p$ shown on the x axis divided by the total number of events with $\Delta p > 0.5$ Pa found in the survey. Also shown in Figure 7 are power law fits to the cumulative magnitude distributions of the pressure drops detected by Pathfinder and MSL. Power law functions are used to model the distributions since Lorenz has demonstrated their feasibility for this purpose in several studies [Lorenz, 2012; Lorenz and Lanagan, 2014; Lorenz and Jackson, 2015; Lorenz et al., 2015]. Figure 7 shows that the magnitude distribution of the pressure drops detected by MSL decreases faster than the distributions detected by Pathfinder and Phoenix, and that events stronger than 3.0 Pa are completely absent. The latter could be a statistical coincidence: in the case of Phoenix only 0.5% of all transient pressure drops larger than 0.5 Pa had magnitudes above 3.0 Pa, and if this proportion holds also for the vortex population at the MSL site, then the probability of not detecting a pressure drop stronger than 3.0 Pa among 252 events would be 28%. However, the overall faster decline of the distribution is clearly statistically significant. A natural explanation for this is the suppressed daytime boundary layer at the MSL landing area, predicted by Tyler and Barnes [2013] and observed by Moores et al. [2015] and Moore et al. [2016].
The exponent of our power law fit to the cumulative Pathfinder pressure drop magnitude distribution is $-1.68$ (Figure 7). This value is close to that given by Lorenz [2012] for the differential magnitude distribution of the Pathfinder pressure drop observations: $-1.56 \pm 0.49$. These results seem to be in conflict since the exponent of the cumulative distribution should be that of the differential summed by 1 as the cumulative distribution is the integral of the differential. Both results are based on the same data, reported by Murphy and Nelli [2002]. The differential magnitude distribution exponent given by Lorenz [2012] was calculated by binning the vortex events into logarithmic bins based on the pressure drop magnitude $\Delta p$ and then performing a linear regression on the data points, defined as the logarithm of the number of events per bin versus the logarithm of the geometric mean of the bounds of each bin. However, the number of events per bin should have been divided by the bin widths to get the empirical differential distribution. This affected the determined slope of the distribution as the bins did not have equal width. We reperformed the analysis described by Lorenz [2012], using the same binning and weighting of the data, and ended up with the same exponent ($-1.56$) if the number of events per bin was not divided by the bin widths, but if this division was performed then the exponent was $-2.55$, in rough accordance with the exponent that we determined for the cumulative distribution.

The magnitudes $\Delta p$ of all single-minimum pressure events are plotted against their full width at half maximum (FWHM) durations $\Gamma$ in Figure 8. Events with multiple minima are not included in this graph. Comparing Figure 8 to the corresponding plot shown by Ellehoj et al. [2010] reveals that the vortex duration distributions at the Phoenix and MSL sites are very similar, taking into account that the quantity on the x axis of the Phoenix plot [Ellehoj et al., 2010, Figure 7] is actually full duration, i.e., two times FWHM, even if the caption says that the quantity was FWHM (H. P. Gunnlaugsson, Aarhus University, personal communication, 2015). Also the mean FWHM durations of the single-minimum events with $\Delta p > 0.5$ Pa detected by Phoenix and MSL (sols 13 to 681) are almost identical: 8.9 s and 9.2 s, respectively. Moores et al., 2015 claimed that the events detected by MSL had shorter durations, but they did not take into account the above mentioned typographical error in the caption of Figure 7 in the Ellehoj et al. [2010] paper. Ferri et al. [2003] reported clearly longer durations for the vortex events detected by Mars Pathfinder, but as they did not explain how the durations were defined we cannot know if the results are comparable to those found by MSL. The similarity of the pressure event durations detected by Phoenix and MSL shows that the diameter distributions of the vortices are similar at both sites, and also that the vortices move with similar speeds, indicating that the daytime wind velocities must be similar. Background median wind velocities measured by REMS during 92 pressure events are shown in Table S2 (in the supporting information), and they range from 4.8 m/s to 12.5 m/s, both the mean and median being 7.6 m/s. This indeed matches the range of daytime mean wind velocities detected by the Telltale wind indicator on board Phoenix, especially during the latter part of the mission when most vortices were detected [Holstein-Rathlou et al., 2010].
A relation between small pressure drop magnitudes $\Delta p$ and long FWHM durations $\Gamma$ can be seen in Figure 8. The explanation is the same as in the case of Phoenix [Ellehoj et al., 2010]: as the miss distance of a vortex increases its detected pressure drop magnitude decreases, but at the same time the detected half maximum duration increases as the shape of the detected pressure curve smoothens out. Far misses by relatively strong vortices are thus detected as events with small pressure drop magnitudes but long FWHM durations. As explained in section 2.4, the vortex identification algorithm affects the distributions of both the magnitude and duration of the detected pressure drops. The lack of events with FWHM duration longer than 55 s is hence not a property of the vortex population but a property of the method used. This holds for the Phoenix data too, as the vortex identification algorithm used by Ellehoj et al. [2010] was essentially identical to that used here.

The property that the full width at half maximum duration increases with miss distance makes it a bad estimator for the dimensions of the vortices. Therefore, we use for this purpose durations defined as the time when the pressure perturbation is stronger than 0.5 Pa. We denote this event duration as $t_{\Delta p > 0.5}$. We calculated $t_{\Delta p > 0.5}$ durations for all single-minimum events (Table S2 in the supporting information) using the fit parameters $\Delta p$ and $\Gamma$ and a relationship between these and $t_{\Delta p > 0.5}$, derived as follows.

From equation (7) we see that the magnitude of the pressure perturbation $d_p$ compared to the background pressure at time point $t$ is

$$d_p(t) = p_\infty + k(t - t_0) - p(t) = \frac{\Delta p}{\left(\frac{t - t_0}{\Gamma}\right)^2 + 1}. \quad (10)$$

The time $t$ when the magnitude of the perturbation is $d_p$ can be solved from this

$$t = t_0 \pm \frac{\Gamma}{2} \sqrt{\frac{\Delta p}{d_p(t)} - 1}. \quad (11)$$

By definition $t_{\Delta p > 0.5}$ is the time between the two instances when $d_p$ is 0.5 Pa. Therefore,

$$t_{\Delta p > 0.5} = \frac{\Gamma}{2} \sqrt{\frac{\Delta p}{0.5 \text{ Pa}} - 1}. \quad (12)$$

Figure 9 shows the magnitudes $\Delta p$ of all single-minimum pressure events plotted against their $t_{\Delta p > 0.5}$ durations. Events with large $\Delta p$ have now on average slightly longer durations but the correlation is weak, in agreement with studies on terrestrial dust devils [e.g., Lorenz and Lanagan, 2014]. The mean $t_{\Delta p > 0.5}$ duration of the single-minimum pressure events detected during MSL sols 13 to 681 is 5.5 s. For the first 360 sols the mean $t_{\Delta p > 0.5}$ duration was 6.3 s; this value was used by Moores et al. [2015] when estimating the number of dust devils that should have been seen in the Dust Devils Search Movies if all vortices detected by REMS lifted dust.

Next we estimate the diameter distribution of the pressure depressions associated to the detected vortices. For this purpose we define the "perturbation diameter" $D_{\Delta p > 0.5}$ of a vortex as the diameter of the area where the pressure depression of the vortex exceeds 0.5 Pa. Assuming that the vortices are circular and move along
straight trajectories, then the relation between the perturbation diameter $D_{Ap} > 0.5$ and the detected duration $t_{Ap} > 0.5$ of the pressure drop is

$$U_t = \frac{t_{Ap} - 0.5}{(D_{Ap} > 0.5)^2 - r_0^2}, \quad (13)$$

where $r_0$ is the miss distance between the vortex center and the pressure sensor and $U$ is the translation velocity of the vortex. Perturbation diameters $D_{Ap} > 0.5$ of individual vortices cannot be directly solved from equation (13) as we do not know their miss distances. However, a relation between the probability density $g(D_{Ap} > 0.5)$ of the perturbation diameter distribution and the probability density $w(l)$ of the “encounter length” $l = U_t \times t_{Ap} > 0.5$ distribution can be derived from equation (13) by assuming that the miss distance $r_0$ is an evenly distributed random variable [Kurgansky, 2014].

$$w(l) = \frac{l}{(D_{Ap} > 0.5)^2} \frac{g(D_{Ap} > 0.5)}{\sqrt{D_{Ap} > 0.5} - r^2} dD_{Ap} > 0.5 \quad (14)$$

where $(D_{Ap} > 0.5)$ is the expected value of the perturbation diameter distribution. We estimate the distribution of the pressure perturbation diameters $D_{Ap} > 0.5$ of the detected vortices by substituting a trial function $g_{trial}(D_{Ap} > 0.5)$ into equation (14) and then determining the values of the free parameters of this trial function by fitting the distribution $w(l)$ given by equation (14) to the distribution of detected encounter lengths $l$. To be able to do this, we first determine the empirical distribution of the encounter lengths of the detected vortex passes and then define a suitable trial function.

Translation speeds $U$ of the detected vortices are needed for converting the detected pressure drop durations $t_{Ap} > 0.5$ into encounter lengths $l = U_t \times t_{Ap} > 0.5$. It can be assumed that the vortex translation speed is a function of the background wind velocity $V$ as the vortices move with the wind. In the case of Martian dust devils the exact relation between the translation speed and the wind velocity is, however, not well known as no Mars lander has succeeded in imaging moving dust devils, determining their distance and measuring the wind vector at the same time. In the lack of such direct measurements, we have to rely on studies where observed dust devil speeds are compared to modeled wind velocities. In the latest and most complete such study, Reiss et al. [2014] derived horizontal speeds of 44 large Martian dust devils by comparing image data sets of two time-delayed camera systems on board Mars Reconnaissance Orbiter (MRO) and found out that the dust devils move with a velocity proportional to the modeled wind velocity at the dust devil top height, ~2 times faster than the modeled surface wind. However, because of the suppressed daytime boundary layer in Gale crater [Tyler and Barnes, 2013] we assume that the vortices at the MSL landing area are lower than those studied by Reiss et al. and that the wind speed at their top height is thus closer to the surface wind velocity. Hence, we calculate the encounter lengths of the 79 single-minimum pressure events detected during time intervals when REMS background wind data are available by multiplying the $t_{Ap} > 0.5$ durations by the wind velocities $V$ measured by REMS.

The thus determined encounter lengths range from 2.3 m to 755 m, and their cumulative and differential distributions are shown in Figure 10. The bin limits and data of the differential distribution are also given in Table S3 in the supporting information. In the differential distribution (Figure 10, bottom) the most common encounter lengths are in the range $8.37 \ldots 15.92$ m, and the number of longer encounters falls following approximately a power law with exponent $\approx -2$. Likewise, the cumulative distribution (Figure 10, top) follows a power law with exponent $\approx -1$ in the high end, as expected taking into account that the cumulative distribution is the integral of the differential distribution. The diameter distribution of dust devils detected visually by the MER Spirit rover during its first Martian year in Gusev crater [Greeley et al., 2006] is shown for comparison in Figure 10 and in Table S4 in the supporting information. This MER Spirit data have been taken from Figure 8a in Greeley et al. [2006], except diameters $> 90$ m that have been taken directly from values given in Figure 8b in Greeley et al. [2006]. When plotting the cumulative distribution (Figure 10, top), the six largest diameters (>130 m) reported in Greeley et al. [2006] have been used explicitly instead of the binned data, and in the differential distribution (Figure 10, bottom) the diameters $> 90$ m have been divided into bins that are wider than those used by Greeley et al. [2006, 2010] and Lorenz [2011] to ensure statistically significant numbers of observations for each bin (Table S4 in the supporting information).

To find a suitable trial function for modeling the distribution of the perturbation diameter $g(D_{Ap} > 0.5)$, we consider separately the low and high end of the distribution. It can be calculated from equation (14) that if the distribution of the perturbation diameter followed a power law with exponent $\approx -3$ in the high end,
i.e., \( g(D_{\Delta p} > 0.5) \sim D_{\Delta p}^{-3} \), then the distribution of the encounter length \( w(l) \) would be a power law with exponent \(-2\) in the high end, in accordance with the empirical distribution of encounter lengths shown in Figure 10. In the low end we try to model the distribution of perturbation diameters with a linear function as the distribution of dust devil diameters detected by MER Spirit, shown in Figure 10, and other similar statistics shown by Lorenz [2011] are approximately linearly rising in the range of diameters smaller than the most common diameter. However, we emphasize that using a linear function to model the distribution of vortex pressure perturbation diameters in the low end is only an ad hoc solution and needs to be critically evaluated in future studies. For these reasons, we use a trial perturbation diameter distribution \( g_{\text{trial}}(D_{\Delta p} > 0.5) \) with the form

\[
\begin{align*}
g_{\text{trial}}(D_{\Delta p} > 0.5) &= \frac{2}{3D_0} + \frac{\beta D_0}{3} + \frac{\beta}{3}(D_{\Delta p} > 0.5 - D_0) & \text{if } D_{\Delta p} > 0.5 < D_0 \\
g_{\text{trial}}(D_{\Delta p} > 0.5) &= \left( \frac{2}{3D_0} + \frac{\beta D_0}{3} \right) D_0^2 D_{\Delta p}^{-3} & \text{if } D_{\Delta p} \geq D_0
\end{align*}
\]

(15)
where \( D_0 \) is the most common perturbation diameter and \( \beta \) is the slope of the function for values \( D_{Ap} > 0.5 < D_M \). A trial model for the differential distribution of the encounter length \( w_{trial}(l) \) is gained by substituting this into equation (14). Further, trial models for the cumulative distributions of the perturbation diameter \( G_{trial}(D_{Ap} > 0.5) \) and the encounter length \( W_{trial}(l) \) can be calculated from the models of the differential distributions:

\[
G_{trial}(D_{Ap} > 0.5) = \int_{D_{Ap} > 0.5} g_{trial}(x) \, dx \tag{16}
\]

\[
W_{trial}(l) = \int w_{trial}(x) \, dx. \tag{17}
\]

We estimate the values of the parameters \( D_0 \) and \( \beta \) by fitting the modeled cumulative distribution of the encounter length \( W_{trial}(l) \) to the corresponding observed cumulative distribution (Figure 10, top). The differential and cumulative distributions of both \( D_{Ap} > 0.5 \) and \( l \), calculated with these best fit parameters, are shown in Figure 10. As can be seen, also the differential distribution of the encounter length \( w(l) \) fits well to the corresponding experimental distribution even if the values of the fit parameters are determined by using the cumulative distribution \( W(l) \). This adds confidence to the validity of the trial function. The expected value of the modeled distribution of the encounter length \( W(l) \) is 44 m when only the range where we have observations (from 2.3 m to 755 m) is taken into account. This expected value is close to the mean of observed encounter lengths (48 m), which also adds confidence to the model.

Statistical characteristics of the vortex pressure perturbation diameters can now be estimated by using the modeled diameter distribution \( g(D_{Ap} > 0.5) \). Considering again only the range where we have observations, from 2.3 m to 755 m, the median perturbation diameter is 16 m, the mean is 21 m, and the mean area of the pressure depressions of vortices is 890 m², corresponding to a diameter of 34 m. These values are properties of the sample of observations that we have, but they are probably poor estimators for the whole vortex population in Gale crater. First, our vortex identification method leads to undersampling of vortices with large diameters because of the selection bias discussed in section 2.4. In the derivation of equation (14) [Kurgansky, 2014, Appendix 3], it is implicitly assumed that all vortices that cause a pressure drop larger than the detection threshold at the site of the pressure sensor are detected. However, as mentioned in section 2.4, vortices with large diameters are identified by our method only if they pass more or less straight over the sensor with fast translation velocity and/or have a strong central pressure drop. Large, slow-moving vortices are hence missing from our data set as can be seen from Figure 11 where background wind velocities are plotted against the encounter lengths of the detected one-core vortices. Correcting equation (14) so that this selection bias was taken into account would require modeling the wind velocity and central pressure drop distributions and would thus make the analysis far more complex. Second, since our modeled distribution of pressure perturbation diameters \( g(D_{Ap} > 0.5) \), defined by equation (15), asymptotically follow a power law with exponent \(-3\), the mean pressure depression area of the whole population is not defined unless the distribution is truncated by setting a maximum value, and this maximum diameter affects strongly the mean area [Lorenz, 2011]. In reality, the distribution must start to fall faster than the power law at some point since the diameters of vortices must of course be limited. As large vortices are extremely rare, high numbers of observations would be needed for determining the point where this happens, so determining the mean area reliably would require a far bigger sample than we have available. According to a simulation by Lorenz [2011], of the order of one thousand observations would be needed on our own planet. And third, Martian dust devils may actually translate faster than the surface wind velocity, as discussed above. All three of these error sources lead to underestimating the characteristics of the pressure perturbation diameter distribution, so the statistical characteristics calculated above should be taken as minimums for the whole population.

The differential distribution of dust devil diameters observed by MER Spirit during its first Martian year [Greeley et al., 2006], shown in Figure 10, follows approximately a power law with exponent \(-2\) in the range from 10 m to 90 m, in agreement with the results of previous studies [Lorenz, 2011; Kurgansky, 2012]. However, in the range \( > 90 \) m the observed proportion of events falls faster than the \(-2\) power law. As a consequence, the distribution of dust devil diameters detected by Spirit resembles as a whole the modeled distribution \( g(D_{Ap} > 0.5) \) of vortex pressure perturbation diameters (dashed red line in Figure 10), even if \( g(D_{Ap} > 0.5) \) follows a \(-3\) power law in the high end. Taken directly, this result could be interpreted
as showing that the widths of the pressure depressions of Martian dust devils are proportional to the visually observable dust devil diameters. This would match the expectation based on the structure of terrestrial dust devils, whose visually observable column walls correspond radially with the maximum tangential wind velocity (section 2.2). As explained in section 2.2, it follows from the assumption of cyclostrophic balance that the pressure depression at the wall is ~ 50% of that at the vortex center, i.e., the full width at half maximum (FWHM) diameter of the pressure depression corresponds approximately the column diameter. However, the seeming similarity between the distributions of dust devil diameters detected by MER Spirit and diameters of vortex pressure perturbations inferred from the measurements by MSL might be partly coincidental. First, the perturbation diameters $D_{\Delta p > 0.5}$ derived from the MSL data are not defined as FWHM diameters, but instead as limits of areas where the pressure perturbation exceeds 0.5 Pa. The relation between these two diameters is analogous to the relation between the FWHM duration ($\Gamma$) and the $t_{\Delta p > 0.5}$ duration, given by equation (12), and this relation is not linear if the diameters of pressure depressions correlate with the central pressure drops. Second, these two data sets represent separate vortex populations at two sites ~ 2300 km apart. And third, both data sets are subject to selection biases. While the proportion of large diameters is apparently underestimated in the distribution of pressure perturbations deduced from the MSL data, for reasons mentioned above, the distribution of dust devils detected by MER Spirit is probably biased toward large diameters as larger dust devils are easier to detect visually [Lorenz, 2011]. Moreover, the dust-lifting vortices observed by MER Spirit must be on average stronger than the (almost) dustless vortices observed by MSL. Hence, the Spirit record should contain relatively more large vortices if there was a positive correlation between the diameters of convective vortices and their strengths (i.e., maximum tangential wind speeds or central pressure drops), as concluded by Ryan and Carroll [1970] based on their field measurements in Mojave Desert, California.

The size of the “low-pressure core” of Martian dust devils was a critical parameter in the analysis by Moores et al. [2015] (section 3.1), predicting that ~ 100 dust devils should have been seen in the Dust Devils Search Movies during MSL’s first 360 sols, if all vortices detected by REMS lifted dust. The low-pressure core was defined as the area where the pressure depression exceeds 0.5 Pa, in accordance with the definition of the perturbation diameter in the present study. The formula used to predict the number of dust devils that should have been observed [Moores et al., 2015, equation (6)] shows that the result is proportional to the ratio of the areas of the visually detectable core and the low-pressure core. By using the Rankine vortex model and assuming that a tangential wind speed of 25 m/s is needed for dust lifting, Moores et al. [2015] estimated that the “ratio of areas” was ~ 0.09, i.e., that the area of the low-pressure core was about 11 times larger than that of the visually detectable core. In contrast to this, the above calculated median (16 m) and mean (21 m) values of the pressure perturbation diameters detected by MSL are slightly smaller than the median (19 m) and mean (~30 m) values of the visual dust devil diameters detected by MER Spirit during its first Martian year [Greeley et al., 2010; Kurgansky, 2012]. Explicitly, the higher median and mean values of the dust devil diameters detected by Spirit result from the relatively higher proportion of observations in the range from 50 to 90 m as compared with the modeled distribution of the perturbation diameters of the vortices detected.

Figure 11. Median values of background wind velocity $V$ during vortex events plotted against the detected encounter lengths $l = V \times t_{\Delta p > 0.5}$ of the vortices. Events with multiple pressure minimums are not included. All vortices with encounter length longer than 50 m are detected during times when the wind velocity exceeds 6 m/s, probably because large, slow-moving vortices are not always identified by the used vortex detection algorithm.
The selection biases discussed above lead to underestimating the characteristics of the pressure perturbation diameters and overestimating the characteristics of the dust devil column diameters, but still, the elevenfold difference in areas assumed by Moores et al. [2015], corresponding to an approximately threefold difference in diameter, seems improbable. Hence, the ratio of areas used in the calculation by Moores et al. [2015] is probably underestimated. Taking this into account would lead to an even higher number of dust devils that should have been seen in the Dust Devils Search Movies if all vortices identified by REMS lifted dust, but still only one probable dust devil was detected. Our observations of the pressure perturbation diameters of the vortices detected by REMS thus strengthen the conclusion that almost all of them are dustless.

### 3.3. Diurnal Variation in Vortex Activity

All identified transient pressure drops that were classified as true vortex detections occurred between 9:02 and 15:56 Local True Solar Time (LTST). (The term Local True Solar Time is explained in Appendix B.) We calculated their mean frequency of occurrence during MSL sols 13 to 681, separately for each LTST hour, by dividing the number of identified events by the total duration of REMS measurements performed at that time of sol. The result is shown in Figure 12 and in Table S5 in the supporting information. As can be seen, the diurnal distribution in vortex activity is similar to that detected by Mars Pathfinder [Murphy and Nelli, 2002] with a clear peak in the noon hours between 11 and 13 LTST. The distribution is asymmetric so that there are more events in the afternoon hours than in the morning. Around 16:00 LTST the occurrence of vortices ends more or less abruptly which must be related to the collapse of the daytime boundary layer [Petrosyan et al., 2011; Fenton and Lorenz, 2015]. Mars Phoenix detected a smoother diurnal variation in the number of vortices with relatively more events in the afternoon hours [Ellehoj et al., 2010]. This is probably related to the landing site of Phoenix in the Arctic where the diurnal variation in solar heating is less prominent than at the equatorial and subtropical landing sites of MSL and Pathfinder. Figure 12 also shows the proportions of pressure drops with different magnitudes separately for each hour. Strong vortices are clearly more common in the afternoon and no pressure drops deeper than 1.5 Pa are detected in the morning hours before 11 LTST. Taking into account that only the strongest vortices lift dust, this result is in accordance with the statistic of dust devils imaged by MER Spirit [Greeley et al., 2006, 2010] and several terrestrial studies performed on sites with low cloudiness [e.g., Sinclair, 1969; Kurgansky et al., 2011; Lorenz and Lanagan, 2014] where the number of dust devils has been observed to peak between 13:00 and 16:00 in the afternoon. The reason why strong vortices are more common at the MSL landing site in the afternoon is apparently related to the boundary layer height. In the heat engine model the central pressure drop of a vortex is a function of the surface pressure, the temperature rise in the vortex core, the fraction of energy that is dissipated mechanically near the surface, and the vortex thermodynamic efficiency that depends on the thickness of the boundary layer [Rennó et al., 1998]. The Martian daytime boundary layer rises through the day and reaches maximum depth in the afternoon soon before it collapses [Spiga et al., 2010; Gheynani and Taylor, 2010]. On the other hand, the difference between the surface temperature and the near-surface air temperature, and thus also the surface sensible heat flux, is highest before noon [Martínez et al., 2014; Pla-Garcia et al., 2016]. This explains why the rate of vortex encounters peaks already before the boundary layer reaches maximum height.
The vortices identified in our survey did not occur with random intervals, instead there were many instances when two vortices were detected within minutes of each other. Also, the pressure events with magnitudes greater than 0.5 Pa that were included in our statistics were often accompanied by smaller pressure drops. These detections are in accordance with the observation that both terrestrial and Martian dust devils sometimes occur in groups [Flower, 1936; Ryan and Carroll, 1970; Sinclair, 1973; Hess and Spillane, 1990; Fenton and Lorenz, 2015], even if some of these detections might be caused by the same vortex passing by the sensor several times as vortices can move along cycloidal tracks [Lorenz, 2013].

As can be seen from Figure 12, the noontime occurrence frequency of transient pressure drops with magnitude greater than 0.5 Pa is ~ 0.27 events/h. This is less than what was detected by previous landers: Pathfinder detected ~ 0.6 events/h [Murphy and Nelli, 2002] and Phoenix ~ 0.4 events/h during the latter part of the mission (LS 111–148) [Ellehoj et al., 2010]. However, the MSL result is an annual average, while the measurements of Pathfinder and Phoenix were performed during Northern Hemisphere summer and early autumn. Figure 13 shows the noontime (11 to 13 LTST) vortex occurrence frequency detected by MSL as a function of solar longitude $L_S$. The data have been binned into eight “seasons” centered at $L_S$ 0°, 45°, 90°,…, 315°. This binning is convenient as one of the bin edges is at $L_S$ 157.5°, corresponding to MSL sol 13, just after regular REMS measurements had started but before the detection of the first vortex. This is precisely the reason why we chose to use data from the time interval between sols 13 and 681 in our study. Figure 13 reveals that during the period $L_S$ 112.5° to 247.5° the noontime occurrence frequency of pressure drops larger than 0.5 Pa was close to that detected by Phoenix between $L_S$ 111° and 148°. This period covers also the operation time of Pathfinder ($L_S$ 142° to 183°).

The occurrence frequency $f$ of pressure drops $> 0.5$ Pa can be converted into areal density $C$ of vortices, i.e., number of vortices per square kilometer, if the mean area $\bar{A}$ of the pressure depressions of the vortices is known, using equation (2) in Moores et al. [2015]

$$C = f \frac{\Delta p > 0.5}{\bar{A}}$$

where $\bar{t}_{\Delta p > 0.5}$ is the mean $t_{\Delta p > 0.5}$ duration of the vortices. Using the values calculated in section 3.2 ($\bar{A} = 890$ m$^2$ and $\bar{t}_{\Delta p > 0.5} = 5.5$ s), the annual mean noontime occurrence frequency (0.27 events/h) corresponds to 0.5 vortices with central pressure depressions $> 0.5$ Pa per square kilometer. This is ~ 10 times more than the diurnal maximum areal density of dust devils observed visually by MER Spirit [Greeley et al., 2010]. The Spirit record contains only strong, dust-lifting vortices, while the MSL record contains more abundant weak vortices that can be detected only by meteorological measurements. The order of magnitude higher areal density of the vortices detected by MSL is hence not surprising. However, as noted in section 3.2, the mean area is an ill-defined property of the distribution of vortex pressure depression diameters, so the above calculated areal density should be taken as a property of the sample of observation that we have rather than as a property of the whole vortex population in Gale crater.

### 3.4. Annual Variation in Vortex Activity

Next we compare the detected annual variation in the number of vortices to the annual variation of the Dust Devil Activity (DDA) in Gale crater, calculated via equations (1) and (2) using meteorological variables.

![Figure 13. Mean frequency of occurrence of vortex events with $\Delta p > 0.5$ Pa during the noon hours (11 to 13 LTST) as a function of solar longitude $L_S$. The error bars show $N^{0.5}$ counting errors for each bin.](image-url)
predicted by the MarsWRF mesoscale model [Richardson et al., 2007]. The MarsWRF simulation included spatially variable surface properties (topographic height, surface roughness, albedo, thermal inertia, and emissivity) derived from Mars Orbiter Laser Altimeter and Thermal Emission Spectrometer observations [Smith and Zuber, 1996; Garvin et al., 1999; Christensen et al., 2001; Putzig and Mellon, 2007] and used the wide band model radiative transfer scheme described in detail in Richardson et al. [2007]. The modeled data were generated by mesoscale runs, performed with settings otherwise identical to those mentioned in Bridges et al. [2014] except that the innermost nest had a resolution of ~1.4 km in Gale Crater, in contrast to ~4 km used by Bridges et al. [2014]. The opacities of atmospheric dust were based on Mars Global Surveyor Thermal Emission Spectrometer (TES) dust climatology (limb values averaged over ~3 Mars years) as described in Guzewich et al. [2014]. Figure 14 shows that the variation with season of this prescribed dust opacity is in good agreement with the variation of the column optical depth measured by the Mast Camera of MSL (note that the difference in actual magnitude is due to the different wavelengths here).

The model was run for seasons $L_s$ 0°, 30°, 60°, ..., 360°, for 12 sols per season, with only the final 8 sols used to avoid initialization effects. Variables needed to derive DDA (such as surface temperature, near-surface air temperature, and boundary layer depth) were output from the model every 3 h, providing three DDA values for each model sol during the hours when vortices are active. Figure 15 (and Table S6 in the supporting information) shows the mean values of these “daytime DDA readings” for each season. The mean daytime DDA values are shown for two model grid points: at 137.4438°E, 4.6049°S on the “hummocky plains” [Vasavada et al., 2014], close to the MSL landing site, and at a grid point representing the location of MSL at the corresponding time of year, chosen from the same geologic unit with the location of MSL. Also shown in Figure 15 (and in Table S7 in the supporting information) are estimates of the mean number of vortices with pressure drops $>0.5$ Pa that passed over MSL per sol. These estimates have been calculated by first assessing the mean number of vortices detected each hour, as in Figure 12, separately for each season bin, and then summing these hourly means. Mean values of the “daytime readings” of the two components of DDA, the surface sensible heat flux $F_s$ and the thermodynamic efficiency of vortices $\eta$, are plotted separately against $L_s$ in Figures 16 and 17. Figure 17 also presents daily maximum values of surface sensible heat flux readings calculated from the REMS air temperature and ground temperature measurements, and daily maximums of the model-derived $F_s$. Note that the values of $F_s$ determined by the MarsWRF model and the values calculated from the REMS measurements are in different arbitrary units, so they are not in scale in Figure 17. Figure 18 shows the diurnal maximum ground temperatures predicted by the MarsWRF model and measured by REMS as a function of $L_s$.

As can be seen from Figure 15, the model-predicted DDA follows approximately the detected number of vortex encounters, but there are also some deviations that exceed the error bars. These are discussed in the following paragraph. The ratio of the annual maximum and minimum is ~4 for both the number of vortices and for the DDA, and both reach their annual minimum around $L_s$ 90° (the start of local winter at Gale Crater). Figure 16 shows that the model-predicted thermodynamic efficiency $\eta$ varies smoothly with season. The error bars that show the range of variation during the 8 model sols per season are short, and the values calculated for the location of MSL and for the hummocky plains are close to each other, indicating that also the spatial variation between the grid points is small. The surface sensible heat flux $F_s$, shown in Figure 17, varies more than this both spatially and temporally, and there are also clear differences in the REMS measurements and the model-predicted values of $F_s$. Thus, the “small-scale” deviations between the DDA and the observed
Vortex encounter numbers are more probably related to $F_s$ than to $\eta$. The ratio of the annual maximum and minimum is 2.4 for the mean of $\eta$ and 2.0 for the mean of the model-derived $F_s$, indicating that both contribute significantly to the annual variation of DDA in the model, even if the impact of $\eta$ is more important.

There are two bins in the record shown in Figure 15 when the estimated number of vortices that passed over MSL differs clearly from the trend predicted by the DDA. During the bin between $L_s$ 112.5° and 157.5° relatively many vortices were observed compared to the DDA, but this is explained by the exceptional sol 664, discussed in the following section. The clearest difference between the model output and observations is the bin between $L_s$ 247.5° and 292.5° (MSL sols 162 to 231) when DDA peaks but there is a dip in the number of vortex observations. As can be seen from Figure 15, the longest data gaps during MSL’s first Martian year, discussed in section 2.1, occurred during this bin. However, the availability of data is accounted for in the averaging, so the data gaps affect only the error ranges. High dust loading of the atmosphere is known to reduce dust devil activity on Mars by decreasing the surface to air temperature difference [Cantor et al., 2006; Greeley et al., 2010; Lemmon et al., 2015], but also this cannot be the explanation for the observed dip since the skies were relatively clear between $L_s$ 247.5° and 292.5° and the modeled atmospheric opacity varies in accordance with observations, as can be seen from Figure 14. During this bin MSL was in the “Yellowknife Bay” region (YKB), an area belonging to a geologic unit with considerably higher thermal
inertia than on the hummocky plains and “rugged terrain” units where MSL spent most of its first Martian year [Vasavada et al., 2014; Martínez et al., 2014]. Between sols 119 and 122, when MSL entered the YKB region, the diurnal maximum ground temperatures measured by REMS abruptly dropped by ~ 12K, and between sols 312 and 324, when MSL climber out of YKB, the measured maximum ground temperatures increased by ~ 10 K (Figure 18). The diurnal minimum temperatures correspondingly increased when MSL entered YKB [Martínez et al., 2014].

The soil did not warm during the day as much as on the other units, but it kept warmer during the night due to the high thermal inertia. As can be seen from Figure 17, the consequence of this was that the surface sensible heat flux measured by REMS suddenly dropped by ~ 30% around sol 120.

MSL moved less than during any other bin. On sols 162 to 166 MSL moved a total of 17 m, and then it stayed at one site, called “John Klein,” for the rest of the bin [Vasavada et al., 2014]. A reference study on our own planet by Lorenz et al. [2015] has shown that the occurrence rate of convective vortices may vary by a factor of a few over only a few tens of meters. As MSL is a moving platform we can assume that it samples both more and less favorable sites during most seasons, but this was not the situation during the season from $L_S$ 247.5° to 292.5°. MSL remained in the YKB region throughout the entire next bin between $L_S$ 292.5° and 337.5° (sols 232 to 307), but on sol 272 it left John Klein. The number of vortex detections increased after this: 21 vortices were identified during the 36 sol interval between sols 272 and 307, while only 9 vortices were identified during the 40 sol interval between sols 232 and 271. Thus, an unfavorable microenvironment at John Klein, at least partially caused by the reduction of the surface sensible heat flux due to the high thermal inertia, is the apparent reason for the observed dip in the vortex encounter rate between $L_S$ 247.5° and 292.5°.

One can see from Figures 17 and 18 that the ground temperature ($T_g$)
and surface sensible heat flux \( (F_s) \) derived from the MarsWRF output for the location of MSL are clearly lower than those derived for the hummocky plains during the interval when MSL was in the YKB region (seasons \( \text{LS} \) 240°, 270°, 300°, and 330°). The differences between the \( T_g \) and \( F_s \) values predicted for the hummocky plains, and those predicted for the location of MSL are still relatively small compared to the reductions in the observed values of these quantities when MSL entered YKB. The explanation for this is that according to in situ measurements the contrast in thermal inertia between the hummocky plains and YKB is stronger than that between the model grid points we used to represent these locations. The model grid point chosen to represent the location of MSL during the interval when MSL was in the YKB region is 137.4438°E, 4.5556°S. This is not the closest grid point but it belongs to the same geologic unit as YKB. The thermal inertia of this model grid point is 385 \( \text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2} \) while the thermal inertias of the grid points on the hummocky plains and rugged terrain units along the traverse of MSL vary from 338 to 345 \( \text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2} \). These values can be compared to thermal inertias calculated by Martínez et al. [2014] using the REMS ground temperature data. Martínez et al. [2014] report thermal inertias from 295 to 306 \( \text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2} \) for two locations on the hummocky plains (“Rocknest” and “Point Lake”) and 452 \( \text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2} \) for YKB (location on sol 139). Thus, according to in situ measurements the thermal inertia of the location of MSL on sol 139 in YKB is ~ 50% higher than that of the hummocky plains while in the model the difference is only ~ 13%. The reduction of the \( F_s \) values predicted for the location of MSL during the interval when MSL was in YKB, compared to the values predicted for the hummocky plains, is also reflected in the Dust Devil Activity (DDA) values, as can be seen from Figure 15. This reduction of DDA is greatest at \( \text{LS} \) 270°, concurrently with the dip in the number of observed vortices that was discussed in the previous paragraph. However, there is still a peak at \( \text{LS} \) 270° in the DDA graph derived for the location of MSL, even if this peak is less pronounced than in the DDA graph derived for the hummocky plains. If the actual reduction of \( F_s \) was higher than in the model, as the analysis above implies, then the DDA at the location of MSL would probably fit even better to the observed annual variation in vortex activity.

Comparing Figure 18 to Figure 15 reveals that the detected number of vortices correlates with the measured ground temperature. This is in accordance with previous studies where correlations between annual variations in the number of dust devils detected in restricted areas on Mars and local surface temperatures have been found [Fisher et al., 2005; Greeley et al., 2006, 2010; Cantor et al., 2006]. However, we emphasize that correlations like this are local. Whelley and Greeley [2008] mapped dust devil track densities globally and found no spatial correlation with seasonal mean daytime surface temperature. The detected correlation between the number of vortices and surface temperature follows from the fact that all observations are made on a restricted area so that spatially variable factors are more or less constant and hence the time-dependent ground temperature dominates the annual variation in DDA.

As can be seen from Figures 15 and 16, the detected vortex activity is highest during Northern Hemisphere autumn and winter, i.e., local spring and summer in Gale Crater, which is in the Southern Hemisphere. This is in agreement with the results of orbital surveys of dust devil activity on Mars [Thomas and Gierasch, 1985; Balme et al., 2003; Fisher et al., 2005; Cantor et al., 2006; Stanzel et al., 2008; Whelley and Greeley, 2008; Verba et al., 2010; Reiss et al., 2014]. The most relevant comparison point, however, is the dust devil survey by the MER Spirit rover [Greeley et al., 2010] as Spirit’s landing site in Gusev crater is similarly in the Southern Hemisphere tropics, at latitude 14.6°S, while Gale Crater is at latitude 4.5°S. Spirit detected dust devils only during “dust devil seasons” starting soon after \( \text{LS} \) 170°. During Spirit’s first and third Martian year the dust devil season ended just before \( \text{LS} \) 355°, so the intervals when Spirit detected dust devils during those years coincide with the time of the Martian year when the frequency of vortices detected by MSL is highest. Spirit’s second Martian year was characterized by a dust storm that ended the dust devil season early, at \( \text{LS} \) 267° [Greeley et al., 2010]. The most significant difference between the results of the visual dust devil surveys, both orbital and lander based, and the meteorological vortex survey by MSL is that the occurrence of visually detected dust devils ceases completely during the quiet season, while MSL detected vortices all the year round during its first Martian year, even if their frequency of occurrence was considerably lower between \( \text{LS} \) 22.5° and 157.5° (except on sol 664).

The only previous study on the annual variation in vortex activity on Mars that is based on surface meteorological data is that by Ryan and Lucich [1983]. They also concluded that the occurrence frequency of vortices diminishes, but does not cease, during the quiet season. The mean number of vortices per sol identified in the Viking lander 2 wind data (latitude 48°N) during summer was ~ 8 times higher than during winter, and
during spring ~ 11 times higher. For Viking lander 1 (latitude 22.5°N) the ratio between summer and winter was ~ 4 and no data for spring were reported [Ryan and Lucich, 1983]. As the reported numbers of identified vortices per season were rather small some caution should be taken in interpreting these numbers. However, it is interesting to note that Viking lander 1 seems to have detected an annual variation in vortex activity of the same order as that detected by MSL during its first year, while Viking lander 2 farther north detected a 2 to 3 times stronger variation.

The pressure drop magnitudes $\Delta p$ of all true vortex events identified in the present study are presented as a function of solar longitude $L_S$ in Figure 19. As encounters with vortices causing large pressure drops are rare, sporadic events, caution should be taken in interpreting the variation of pressure drop magnitudes using this data set. However, it is interesting to note that the timing of the first vortex with $\Delta p > 1.5$ Pa coincides with the onset of the dust devil seasons detected by MER Spirit [Greeley et al., 2010]. Figure 19 also shows that the median magnitude of pressure drops barely changes with season.

### 3.5. The Sol 664 Vortex Burst

The number of vortices detected during a sol is affected by the variable timing of the REMS measurements (section 2.1). If several “extended blocks” are performed around noon, then more vortices are probably detected than if the extended blocks occurred during the night. Thus, the daily vortex count is a bad estimator for vortex activity. However, as explained in section 2.1, REMS has measured for 1 h covering approximately local noon, starting at 11 or 12 Local Mean Solar Time (LMST), on almost all sols since sol 97. As these measurement sessions are performed each sol at the time of day when vortices are most common (Figure 12), the number of vortices per hour detected during noontime (11 to 13 LMST) can be used as a proxy for daily vortex activity.

On all but 1 sol during our study period (sols 13 to 681), fewer than seven vortex candidates were identified in the noon block and fewer than three of these were classified as “true.” The noon block on sol 664 ($L_S$ 148°), timed between 11 and 12 LMST, was a clear exception. Our vortex identification algorithm detected 28 vortex candidates whereof 17 were classified as true in this measurement session. Taken directly, these numbers would mean that the noontime vortex activity on sol 664 was 4 to 5 times stronger than on any other sol and ~ 60 times higher than the annual mean. However, determining the exact number of true vortices in this particular measurement session was challenging. Figure 20 shows the REMS pressure data of this noon block. The pressure is fluctuating all the time and downward pointing “spikes,” interpreted as vortex signatures, occur so often that it is hard to determine where one event ends and another starts. As a consequence of this, 8 of the 17 true vortices in the sol 664 noon block were classified as double events (section 2.3). Also the wind sensor raw readings fluctuated somewhat more than usual, making it hard to determine which pressure events were associated with wind perturbations, the criteria being that the variation in wind sensor raw readings should be concurrent with a given pressure minimum and stronger than the background fluctuation (section 3.1). Only six of the pressure events fulfill these criteria and can thus be interpreted as obvious vortex detections, but even this number is more than double compared to the number of true vortex detections in the noon block of any other sol, and ~ 20 times higher than the annual mean. The fact that fluctuations stronger than usual were detected both in the REMS pressure data and in the wind data practically excludes the possibility of an instrument anomaly. Besides, the pressure sensor has no error mode that could cause this amount of artificial fluctuations on this timescale [Harri et al., 2014]. MSL was in good health on sol 664 and nothing exceptional occurred in MSL operations.

![Figure 19. Magnitudes $\Delta p$ of the transient pressure drops detected during the first Martian year of MSL as a function of solar longitude $L_S$ (blue crosses). Median values of the magnitudes for each season bin are shown as a bar graph. The gray vertical bars show sols when no REMS measurements were performed.](image-url)
An inspection of the REMS readings and column optical depth measurements by MSL’s cameras [Moore et al., 2016] around sol 664 (Ls 148°) reveals that this sol was exceptional also in other ways. First, the annual pressure minimum of MY 32 at MSL’s landing site occurred on this particular sol (Figure 21). This is in accordance with the results of previous landers: Viking landers 1 and 2 detected an annual pressure minimum at Ls 148° and 149°, respectively [Tillman et al., 1993], and Mars Pathfinder around Ls 153° [Schofield et al., 1997]. The minimum was, however, sharper than that detected by the Viking landers and Pathfinder, indicating that a local pressure minimum, probably related to a regional-scale weather phenomenon, may have occurred concurrently with the global minimum. Second, the first dust event of MY 32 detected in the MSL Mast Camera (MastCam) optical depth record peaked around sol 664 (Figures 14 and 20). On sol 647, the MastCam optical depth was close to the annual minimum (~0.37). After that the opacity started to rise quickly, reaching ~0.82 on sol 665, and then fell back to 0.70 over the next 3 sols. Unfortunately, no optical depth measurements were performed on sol 664. This dust event led the dusty season of Mars Year 32 [Guzewich et al., 2016]. Third, there was also a local minimum in the range of diurnal pressure variation on sol 664 (Figure 22). It is well known that the diurnal range of pressure variation on Mars, caused for most parts by the thermal tide, is positively correlated with atmospheric opacity [e.g., Zurek and Leovy, 1981; Harri et al., 2014; Guzewich et al., 2016]. Hence, it is surprising that the local opacity maximum around sol 664 was accompanied with a local minimum in the pressure range rather than a maximum. And fourth, the convective boundary layer depth estimated using REMS air temperature and wind measurements by Moore et al. [2016] shows sudden increments from typical values, between 1 and 4 km, to depths as high as 8–10 km during the season when the “sol 664 vortex burst” was detected. The first of these increments was detected around sol 669. However, the derivation of the boundary layer depth depends on the REMS acquisition sequence. On sols 668 and 669, extended REMS observations were performed within the main hours of convection in the afternoon. This was the situation also on sol 665 but not on sol 664. Hence, it may be that the abrupt increments in the boundary layer depth actually started a few sols earlier than could be resolved with the method used by Moore et al.

Figure 20. REMS pressure data (left) during the sol 664 noon block and (right) during a similar measurement session on a typical sol (sol 658).

Figure 21. Frequency of occurrence of vortex events during the noon hours (11 to 13 LMST) and diurnal mean surface pressure measured by REMS around sol 664. The light grey bar graph shows the frequency of all vortex candidates detected by our vortex identification algorithm. The dark grey bar graph shows the frequency of events classified true with Δp > 0.5 Pa. The mean pressures have been calculated by first taking the mean values of each 5 min REMS measurement session performed on the hour and then averaging these hourly means.
the sol 664 event on Phoenix sol 95 ($L_s$ 120°) [Ellehoj et al., 2010]. A survey of images taken by the Mars Color Imager (MARCI) [Malin et al., 2008] on board the Mars Reconnaissance Orbiter (MRO) revealed that this vortex activity was triggered by a cold front with associated water ice clouds, related to a passing low-pressure baroclinic system [Ellehoj et al., 2010]. We performed a similar survey of MARCI images of the area surrounding Gale crater around MSL sol 664 (Figure 23). These image mosaics reveal a dust storm that is advancing northward toward the

Figure 22. Atmospheric opacity and the range of diurnal pressure variation around sol 664. Black line = column optical depth measured by MSL’s Mast Camera (880 nm filter) [Moore et al., 2016]. Blue line = difference between the maximum and minimum of the mean pressures of the 5 min REMS measurement sessions performed on the hour.

Figure 23. MARCI image mosaics of the area surrounding Gale crater on 17–20 June 2014 (MSL sols 663 to 666). The maps cover the area 50°S–30°N, 80–180°E; north is up and east is to the right. The resolution is 8 pixels per degree (~7.5 km/pixel). The oval shaped black areas are regions were data are missing due to planned spacecraft maneuvers. Gale crater is marked by a white circle. White features are water ice clouds. Dust storms, marked with arrows, are transient features that are brownish in color. Elysium Mons, surrounded by water ice clouds, can be seen toward the upper right corner and north-east Hellas Basin in the bottom left corner. The condensate clouds across the middle of the figure are part of the aphelion cloud belt that is observed during this season. The condensate ice clouds at the bottom of the figure are associated with the south polar hood. Note that the solar longitudes ($L_s$) have been rounded down to the closest half degree. The 18 June (top right image) corresponds to MSL sol 664. The raw MARCI images used to generate these mosaics are available freely in the MARCI Experiment Data Record (EDR) Archive on the NASA Planetary Data System [Malin, 2007]. Image credit: NASA/JPL-Caltech/Malin Space Science Systems.
equator from north of the polar hood edge on 17 June 2014 (sol 663), reaching the equatorial region on the 18 (sol 664) west of Gale crater. Two additional storms are observed on sol 664 south of Gale, in line with the crater. Unfortunately, MRO passed relatively far from Gale crater on 18–20 June, and the crater is hence close to a seam between individual images in the mosaics of these sols. Because of the unfavorable viewing geometry the dustiness right over Gale crater is hard to assess during these sols. However, the passage of the front associated with the storms mentioned above on sol 664 correlates well with the spike in the number of vortices detected in the REMS data and the peak in atmospheric opacity detected by MastCam.

In their comprehensive survey of dust devil activity using Mars Orbiter Camera observations, Cantor et al. [2006] observed that “there are also times when an advancing storm front or the haze from a regional storm may create conditions in which dust devils form for 1 sol during a period of relative quiescence in terms of dust devil activity.” The sol 664 event is apparently an observation of this phenomenon. There was nothing atypical about the ground temperature measured by REMS around sol 664, so apparently the increase in vortex activity was not related to thermal forcing. However, besides a source of energy, the formation of vortices requires a source of vorticity [Ryan and Carroll, 1970; Toigo et al., 2003; Ito et al., 2013]. High-resolution numerical modeling of the Martian atmosphere [Takahashi et al., 2006; Takahashi and Hayashi, 2014] has revealed that vorticity increases at weather fronts, but the grid scale of these models is still too large for resolving dust devil scale vortices. On the other hand, the increments in boundary layer depth reported by Moore et al. [2016] should increase the thermal efficiency of vortices. If these increments were related to dust storm fronts, then they could be the mechanism that triggers vortex formation at these fronts. More research is still needed to find the cause of these increments in boundary layer depth and their effect on vortex activity.

4. Conclusions

Five spacecraft equipped with meteorological instruments have so far operated on the surface of Mars: Two Viking landers, Mars Pathfinder, Mars Phoenix, and MSL. All of these have observed convective vortices. Pathfinder and Phoenix operated for only a small fraction of the Martian year, but MSL and the Viking landers [Ryan and Lucich, 1983] have seen that convective vortices occur in all seasons, even if their frequency of occurrence varies. The landing sites of these five spacecraft are rather different, spanning latitudes from 4.5°S to 68.2°N. A common feature is that all of the landing sites have a low elevation: from −3637 (Viking 1) to −4495 m (Viking 2) relative to the Mars Orbiter Laser Altimeter (MOLA) 2000 areoid. On the other hand, orbital imaging has revealed that dust devils occur on all elevations on Mars: from the top of Arisia Mons to the bottom of Hellas basin [Balme et al., 2003; Cushing et al., 2005; Cantor et al., 2006; Whelley and Greeley, 2008]. Thus, it seems that convective vortices form almost everywhere on Mars, in all seasons. This is in accordance with the results of numerical climate models using the threshold-independent scheme, giving nonzero Dust Devil Activity (DDA) values the year round at almost all locations during the daytime hours [Newman et al., 2002a; Basu et al., 2004, Kahre et al., 2006]. However, both orbital and lander-based imaging of Martian dust devils have revealed stronger spatial and temporal variation, with large areas completely void of dust devils depending on season [Cantor et al., 2006; Whelley and Greeley, 2008; Greeley et al., 2010].

Before MSL landed it was predicted based on the heat engine theory [Rennó et al., 1998] that the Dust Devil Activity in Gale crater would be low because of the suppressed daytime boundary layer [Tyler and Barnes, 2013]. However, it was not clear how this prediction would manifest itself: would there be any vortices, and if there was, would their number density be smaller and/or would they be weaker compared to the Phoenix and Pathfinder landing sites? The results show clearly that, above all, the boundary layer depth affected the pressure drop distribution of the vortices: there were less pressure drops deeper than 1.5 Pa and none greater than 3.0 Pa. On the other hand, the noontime occurrence frequency of convective vortices causing pressure drops greater than 0.5 Pa was surprisingly high: during the most favorable season practically the same as that observed by Phoenix [Ellehøj et al., 2010] and about two thirds of that detected by Pathfinder [Murphy and Nelli, 2002].

Only two signs of dust-lifting vortices were observed during MSL’s first year on the Martian surface: a possible, faint dust devil imaged by the Navigation Camera [Moores et al., 2015] and a faint obscuration of UV flux observed concurrently with a pressure minimum detected by REMS (Figure 5). Hence, it seems that dust devils do occur in Gale crater, but they are extremely rare and very weak and lift thus practically no dust. The obvious explanation for the lack of dust devils is the pressure drop distribution of the convective vortices:
even if there are almost as many vortices stronger than 0.5 Pa as on the Pathfinder and Phoenix landing sites, practically none of them are strong enough to lift dust. This suggests that a Martian dust devil must have a central pressure drop greater than the magnitudes of the transient pressure drops detected by MSL. Hence, it seems that 3.0 Pa is a lower limit for the dust-lifting threshold of Martian dust devils. On the other hand, also in the cases of Pathfinder and Phoenix only a small fraction of the detected transient pressure drops had magnitudes above 3.0 Pa and still these landers imaged numerous dust devils [Metzger et al., 1999; Ferri et al., 2003; Ellehoj et al., 2010]. Moores et al. [2015] calculated that the number of dust devils imaged by Pathfinder matched the number of transient pressure drops larger than 2.0 Pa detected by Pathfinder’s ASI/MET experiment. However, Moores et al. assumed that the mean area where a vortex causes a pressure depression deeper than 0.5 Pa is 11 times larger than the mean surface area of visually detectable dust devils. This is an overestimation based on our comparison of pressure depression diameters of vortices detected by MSL and dust devil diameters detected by MER Spirit [Greeley et al., 2006, 2010] (Figure 10). Reducing the “ratio of diameters” increases the number of dust devils that should be visible in images, so the assumption that all pressure drops larger than 2.0 were caused by dust-lifting vortices would lead to a predicted dust devil number higher than what was actually detected by Pathfinder. Apparently, the dust devils imaged by Pathfinder and Phoenix were caused by vortices at least as strong as the strongest detected in the pressure records, too rare to be encountered in abundance during the short missions.

The occurrence frequency of convective vortices detected by MSL varied with season following approximately variations of the DDA calculated by the MarsWRF mesoscale model [Richardson et al., 2007]. The prediction of the amount of dust lifted by dust devils in Gale crater would still not be correct if the threshold-independent scheme was used in a numerical climate model. In Gale crater the DDA differs from zero during daytime every sol, during all seasons, so multiplying DDA with a constant would lead to nonzero dust lifting. But according to the observations mentioned above, the vortices in Gale crater actually lift almost no dust.

The theory stating that the number of dust devils should be linearly proportional to DDA is based on Rennó’s observation that the diurnal variation in the number of dust devils detected by Sinclair [1966] in Avra Valley, Arizona, follows DDA [Rennó et al., 1998]. In places like Avra Valley, where strong dust devils are frequently observed, the maximum pressure drop of the dust devil population is orders of magnitude higher than the dust-lifting threshold [Lorenz and Jackson, 2015]. In such populations most of the energy available to drive convective vortices goes to the dust-lifting vortices; and hence, the number of dust devils is linearly proportional to the energy available. The situation is apparently different on Mars. In places like the Pathfinder and Phoenix landing sites, dust devils form only the “tip of the iceberg” of the whole vortex population. In such populations most of the energy available to drive convective vortices goes to those that do not lift dust. Hence, solar forcing affects the number of dust devils on Mars in two ways: by modulating the number of all vortices and by modulating the proportion of vortices stronger than the dust-lifting threshold. As a consequence, the number of dust devils should increase faster than linearly with the amount of energy available. This matches the result of the analysis by Lemmon et al. [2015], showing that the dust devil number density detected by MER Spirit [Greeley et al., 2006, 2010] seems to increase exponentially with the flux of solar insolation reaching the surface.

The modulation of the vortex pressure drop distribution explains why the number of dust devils imaged by Mars orbiters and landers varies both spatially and seasonally more than the DDA. Even if convective vortices form almost everywhere on Mars, in all seasons, no visually detectable dust devils form if all vortices are too weak to lift dust. This is the situation in places like Gale crater all the year round, and apparently also almost everywhere else during the “quiet season.” Predicting the number of dust devils in a given area and in a given season would thus require a theory where the energy available to drive vortex activity and the pressure drop distribution of the vortices were modeled separately. When parametrizing the amount of dust lifted by the devils, the effect of the pressure drop distribution becomes even more important as strong vortices lift more dust. Laboratory tests by Neukrasc and Greeley [2010] showed that the sediment flux lifted by a vortex in Mars analog conditions was proportional to $(\Delta p)^{3.4}$, where $\Delta p$ is the central pressure drop. Tests under Earth ambient conditions yielded similar results. Terrestrial field studies have shown a less strong dependence between $\Delta p$ and the sediment flux, at least partly because in nature the amount of dust lifted depends also on the amount of dust available, but still the maximum dust load that a dust devil can carry has been detected to depend linearly on the central pressure drop [Mason et al., 2014; Lorenz and Jackson, 2015].
The classical threshold-dependent scheme introduced by Newman et al. [2002a] is an attempt to take the strength of the vortices into account. However, in that parametrization it is implicitly assumed that all vortices inside a grid area have the same tangential wind velocity, so all vortices become suddenly dust lifting when the modeled tangential wind velocity exceeds the threshold value. This makes the model highly sensitive to the value of the threshold wind velocity. The threshold wind velocity used by Newman et al. [2002a, 2002b] was based on the work reported by Greeley and Iversen [1985], but later studies have shown that it was probably overestimated [Greeley et al., 2003; Neakrase and Greeley, 2010; Choi and Dundas, 2011]. As a consequence, the threshold-dependent model predicted dust lifting only under extreme conditions [Newman et al., 2002a]. The development of a more realistic dust-lifting parametrization, where the pressure drop distribution was taken into account, goes far beyond the scope of this study. We only note here that this parametrization would not necessarily be much more complicated than the classical threshold-dependent scheme. According to the work by Lorenz [2012], the pressure drop distributions of all studied vortex populations on Earth and Mars can be modeled by power laws. Hence, only two parameters are needed for characterizing the pressure drop distribution: the exponent of the power law and the maximum pressure drop or the "knee point" where the distribution starts to fall faster than the power law. These two parameters might of course be linked, in which case the population could be characterized by just one variable.

Sol-to-sol variations in vortex activity were minimal during MSL’s first Martian year, with one exception. On MSL sol 664 (Ls 148°) we detected an increase in vortex activity apparently caused by a dust storm front. The noontime occurrence frequency of vortices was at least 20 times higher than the annual mean on this sol. Increases in dust devil numbers associated with advancing dust storm fronts have previously been detected by orbital imaging [Cantor et al., 2006], and a similar increase in vortex activity, triggered by a cold front, was detected in the meteorological data of the Phoenix lander [Ellehoj et al., 2010]. Dust devil activity related to weather fronts is not taken into account in current climate models, but probably its impact is insignificant as these events form only a small fraction of all dust devils on Mars [Cantor et al., 2006].

Appendix A: List of Symbols
All symbols used in the present article are listed below in alphabetical order.

\[\begin{align*}
\alpha & \quad \text{Arbitrary constant (equation (4))} \\
\beta & \quad \text{Slope of the function } f_{\text{trial}} \text{ for values } D_{\Delta p > 0.5} < D_0 \text{ (fit parameter)} \\
\Gamma & \quad \text{Full width at half maximum duration of pressure drop} \\
\Delta p & \quad \text{Magnitude of detected pressure drop} \\
\Delta p_{\text{preliminary}} & \quad \text{Preliminary magnitude of pressure drop (fit parameter)} \\
\Delta p_{\text{threshold}} & \quad \text{Detection threshold, i.e., the smallest detectable pressure drop} \\
\eta & \quad \text{Thermodynamic efficiency of vortices} \\
\rho & \quad \text{Density} \\
\chi & \quad \text{The specific gas constant divided by the specific heat capacity at constant pressure} \\
\bar{A} & \quad \text{Mean area of the pressure depressions of vortices} \\
C & \quad \text{Areal density of vortices = number of vortices per square kilometer} \\
D_{\Delta p > 0.5} & \quad \text{Perturbation diameter of a vortex = the diameter of the area where the pressure} \\
& \quad \text{depression of the vortex exceeds 0.5 Pa} \\
D_0 & \quad \text{Most common perturbation diameter (fit parameter in } f_{\text{trial}}) \\
\text{DDA} & \quad \text{Dust Devil Activity} \\
\Delta p & \quad \text{Momentary pressure perturbation, compared to the background pressure} \\
f & \quad \text{Occurrence frequency of pressure drops with } \Delta p > 0.5 \text{ Pa = number of events/h} \\
F_s & \quad \text{Surface sensible heat flux} \\
g(D_{\Delta p > 0.5}) & \quad \text{Probability density of the distribution of perturbation diameters} \\
G(D_{\Delta p > 0.5}) & \quad \text{Cumulative distribution of perturbation diameters} \\
g_{\text{trial}}(D_{\Delta p > 0.5}) & \quad \text{Trial model for the probability density of the distribution of perturbation diameters} \\
G_{\text{trial}}(D_{\Delta p > 0.5}) & \quad \text{Trial model of the cumulative distribution of perturbation diameters} \\
k & \quad \text{Rate of background pressure variation (unit Pa/s)} \\
l & \quad \text{Encounter length = pressure drop duration } t_{\Delta p > 0.5} \text{ multiplied by the translation velocity} \\
& \quad \text{U of the vortex}
\end{align*}\]
Solar longitude = orbital position of Mars. $L_S$ goes from $0^\circ$ to $360^\circ$ during 1 Martian year and $L_S = 0^\circ$ is the Northern Hemisphere spring equinox.

$N$ Number of observations

$p$ Pressure

$p_\infty$ Background pressure = pressure outside the vortex (at moment $t_0$)

$p_s$ Surface pressure

$p_{top}$ Pressure at the top of the planetary boundary layer

$r$ Distance from vortex center

$r_0$ Miss distance = distance between the vortex center and a stationary pressure sensor at the moment of closest encounter

$R_c$ Radius of the vortex core = radius where the tangential wind velocity reaches its maximum in a vortex model

$t$ Time

$t_0$ The moment of closest encounter when a vortex passes by a stationary pressure sensor

$t_{\Delta p > 0.5}$ Duration of the interval when the pressure perturbation of a passing vortex is stronger than 0.5 Pa

$T_g$ Ground temperature

$U$ Translation velocity of a vortex

$V$ Background wind velocity = median horizontal wind velocity over 5 Martian minutes

$v_{\phi}$ Tangential wind velocity

$w(l)$ Probability density of the distribution of encounter lengths

$W(l)$ Cumulative distribution of encounter lengths

$w_{\text{trial}}(l)$ Trial model for the probability density of the distribution of encounter lengths

$W_{\text{trial}}(l)$ Trial model of the cumulative distribution of encounter lengths

### Appendix B: List of Acronyms

All acronyms used in the present article are listed below in alphabetical order.

ASI/MET Mars Pathfinder Atmospheric Structure Investigation/METeorology experiment

DDA Dust Devil Activity

ENVRDR ENVironmental magnitude Reduced Data Record

FWHM Full width at half maximum

IMP Imager for Mars Pathfinder

LMST Local Mean Solar Time. The length of 24 LMST hours is exactly one mean Martian solar day (sol) = 88,775.24409 s. As the actual length of the sol changes with season, 12:00 LMST is either before or after solar noon (= the instant when the Sun is highest in the sky), depending on the time of year. MSL operations use LMST at the landing location.

LTST Local True Solar Time. LTST is the time that a sundial would show on Mars. Solar noon (= the instant when the Sun is highest in the sky) is always 12:00 LTST irrespective of the time of year. As the length of the sol (= solar day) changes with season, so does also the length of LTST hours.

MARCI MARs Color Imager

MarsWRF Mars Weather Research and Forecasting model

MastCam Mars Science Laboratory Mast Camera

MER Mars Exploration Rover

MGS Mars Global Surveyor

MODRDR MODels Reduced Data Record

MOLA Mars Orbiter Laser Altimeter

MRO Mars Reconnaissance Orbiter

MSL Mars Science Laboratory

MY Mars Year (see explanation in Clancy et al. [2000])

REMS Rover Environmental Monitoring Station
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