



Publication Year	2018
Acceptance in OA @INAF	2021-02-25T14:57:00Z
Title	Electric properties of dust devils
Authors	Franzese, Gabriele; ESPOSITO, Francesca; Lorenz, Ralph; Silvestro, Simone; POPA, IONUT CIPRIAN; et al.
DOI	10.1016/j.epsl.2018.04.023
Handle	http://hdl.handle.net/20.500.12386/30616
Journal	EARTH AND PLANETARY SCIENCE LETTERS
Number	493

1 **Electric properties of dust devils**

2

3 Gabriele Franzese^{1,2}, Francesca Esposito¹, Ralph Lorenz³, Simone Silvestro¹, Ciprian Ionut Popa¹,

4 Roberto Molinaro¹, Fabio Cozzolino¹, Cesare Molfese¹, Laurent Marty¹, Natalia Deniskina¹

5

6 ¹Osservatorio Astronomico di Capodimonte, Istituto Nazionale di Astrofisica, Napoli, Italy;

7 ²Department of Physics “E. Pancini”, University of Naples “Federico II”, Napoli, Italy; ³John

8 Hopkins University Applied Physical Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723,

9 USA

10

11

12 **Keywords:**

13 Dust devils

14 Dust lifting process

15 Atmospheric Electricity

16 Earth

17 Mars

18 Meteorology

19

20

21 **Abstract**

22

23 Dust devils are one of the most effective phenomena able to inject dust grains into the atmosphere.

24 On Mars, they play an important role to maintain the haze and can significantly affect the global

25 dust loading, especially outside the dust storm season. Despite dust devils having been studied for a

26 century and a half, many open questions regarding their physics still exist. In particular, the nature

27 of the dust lifting mechanisms inside the vortices, the development of the induced electric field and
28 the exact contribution to the global atmospheric dust budget are still debated topics. In this paper,
29 we analyze the dust devil activity observed in the Moroccan Sahara desert during a 2014 field
30 campaign. We have acquired the most comprehensive field data set presently available for the dust
31 devils: including meteorological, atmospheric electric field and lifted dust concentration
32 measurements. We focus our attention on the electric field induced by vortices, using this as the
33 principal detection parameter. We present, for the first time, the statistical distribution of dust devil
34 electric field and its relationships with the pressure drop, the horizontal and vertical vortex velocity
35 and the total dust mass lifted. We also compare the pressure drop distribution of our sample with the
36 ones observed on the martian surface showing the similarity of the dust devils samples and the
37 usefulness of this study for the next martian surface missions.

38

39 **1 Introduction**

40

41 Dust devils are convective vortices, stable vertical air columns in rotary motion around a low pressure
42 core, able to entrain material from the surface. On Earth, the vortices affect the atmospheric dust
43 concentration of desert areas, but their contribution to the global dust budget is only a few percent
44 (Jemmett-Smith et al., 2015). On Mars, the full impact of dust devils on global dust circulation is not
45 yet fully understood, but is generally considered to be more substantial compared to the Earth (Fenton
46 et al., 2016). By analyzing the dust storms activity on Mars, Guzewich et al. (2015) concluded that
47 they can only explain $\sim 50\%$ of the total atmospheric lifted dust. Small scale dust lifting phenomena,
48 in particular dust devils, seem to contribute to the global martian dust budget between 25% and 75%,
49 sustaining the global haze and the concentration of fine aerosol into the atmosphere (Neubauer, 1966;
50 Thomas and Gierasch, 1985; Fedorova et al., 2014).

51 The first evidence of their existence on Mars was given by the Viking missions (Ryan and Lucich,
52 1983; Thomas and Gierasch, 1985). In the following years, the presence of dust devils on the planet
53 was largely confirmed and the NASA Mars Global Surveyor and the ESA Mars Express missions
54 allowed the observation from the orbit of dozen dust columns and dust devils tracks (Malin and
55 Edgett, 2001; Greeley et al., 2004; Stanzel et al., 2008). The nearly global Mars coverage of these
56 images showed that dust devils are common and widespread in both hemispheres in every season,
57 almost at every latitudes and elevation. The NASA Pathfinder, Phoenix and Curiosity missions have
58 acquired the meteorological signatures for hundreds of convective vortices (Schofield et al., 1997;
59 Murphy and Nelli, 2002; Ellehoj et al., 2010; Steakley and Murphy, 2016). This was performed by
60 using the atmospheric pressure as principal detection parameter and performing a “phase picker”
61 analysis in order to recognize the drops due to the passage of the vortices low pressure core (“phase
62 picker” is the term used in seismology for event detection – in dust devil analyses it is typically
63 implemented as the detection of a significant negative excursion of a short-period average pressure
64 signal from a long-period average).

65 However, the pressure is not the only parameter that can easily indicate the passage of dusty
66 vortices. On Earth, sand and dust lifting phenomena are associated with the formation of an induced
67 electric field (E-field). Indeed, during lifting, the individual grains tend to acquire an electric charge
68 by collisions even if the whole dust cloud remains neutral (Kunkel, 1950). On Mars, due to the lack
69 of an adequate in situ instrumentation, the presence of an atmospheric E-field has not yet been
70 confirmed. However, the abundance of entrained dust, the generally favorable condition for lifted
71 grains to acquire and hold charge and laboratory experiments performed in martian like condition,
72 suggest the existence of an atmospheric electric field, widespread across the planet and highly
73 variable in relation to the dust lifting activity (Eden and Vonnegut, 1973; Forward et al., 2009;
74 Barth et al., 2016). The electric field induced by lifted dust may significantly affect the composition
75 of the martian atmosphere and the habitability of the planet, locally enhancing by up to 200 times
76 the chemical formation of oxidants able to scavenge organic material from the surface (Atreya et

77 al., 2006). Due to the low martian atmospheric electric breakdown field strength (~ 20 kV/m)
78 (Melnik and Parrot, 1998), the concentration of suspended charges can also lead to the formation of
79 electric discharges that can interfere and cause damage to landed instrumentation, representing an
80 issue for human exploration.

81 The exact mechanism that leads to grain electrification is still debated and not completely
82 understood (see Harrison et al., 2016 for a review on the topic). For a heterogeneous system the
83 charge acquired during the impacts depends primarily on the composition of colliders (McCarty and
84 Whitesides, 2008), while in a homogenous dust cloud the process seems to be size-dependent:
85 smaller grains tend to charge negatively while larger ones positively (Forward et al. 2009; Lacks
86 and Levandovsky, 2007; Duff and Lacks, 2008; Desch and Cuzzi, 2000; Melnik and Parrot, 1998).

87 Atmospheric convective activity transports grains of different weight to different heights, producing
88 a vertical mass stratification which leads to the charges separation and to the formation of the
89 observed electric field.

90 The presence of suspended dust negatively charged over a cloud of sand of opposite sign (upward
91 directed E-field) is consistent with the majority of field and laboratory measurements reported in
92 literature (Bo and Zheng, 2013; Frier, 1960; Croizer, 1964 and 1970; Farrell et al., 2004, Jackson et
93 al., 2006). However, there are cases where this electric configuration is not reproduced (Trigwell et
94 al., 2003; Sowinski et al., 2010; Kunkel, 1950) and there are also reported cases where the electric
95 field is downward directed (Demon et al., 1953; Kamra, 1972; Esposito et al., 2016). These works
96 indicate that we are still far from a comprehensive understanding of the E-field development during
97 dust lifting events, motivating the execution of more detailed surveys. Furthermore, few
98 measurements (less than a tenth) of dust devil electric fields have been reported so far (Frier, 1960;
99 Croizer, 1964 and 1970; Farrell et al., 2004; Jackson and Farrell, 2006). These studies present the
100 analysis of isolated events where the E-field is not studied in combination with the meteorological
101 parameters and lifted dust concentration.

102 In this work we present the analysis of the dust devils activity observed in a field campaign
103 performed in the Moroccan Sahara desert during the 2014 dust storm season. The campaign was
104 carried out in the frame of the DREAMS project, the meteorological station on board of the
105 Schiaparelli lander of the ExoMars 2016 space mission (Esposito et al., 2017). In order to study on
106 Earth the physical processes to be likely encountered on Mars by DREAMS, we deployed a fully
107 equipped meteorological station able also to monitor atmospheric electric field and concentration of
108 lifted sand and dust, acquiring in this way a data set unique in literature. Here, we focus our
109 attention on the electric field induced by the vortices passage, identifying the events using it as
110 principal detection parameter. For the first time, we show the cumulative distribution of the dust
111 induced E-field and we present the relationship between the E-field and the other parameters of the
112 vortices, such as their pressure drop, horizontal and vertical wind speeds and the numeric and mass
113 concentration of lifted dust.
114 Moreover, we compare the distribution of our sample to the martian dust devils survey showing that
115 the present terrestrial dataset could be useful for studying the dust induced E-field on Mars.

116

117 **2 Methods**

118

119 **2.1 Equipment**

120

121 In this work we have analyzed the data acquired during our 2014 field campaign performed in
122 North-Western Sahara Desert of the Tafilalt region (Morocco, 4.110° W, 31.193° N). The site is on
123 the edge of a Quaternary lake sediment bed that is the main source of the measured atmospheric
124 suspended dust. The composition of the sediment (sand, silt, and clay fractions) is the result of the
125 erosion of the regional bedrock of late Paleozoic sedimentary rocks outcropping in the area and is

126 chiefly constituted of detrital shale, quartz, and carbonates grains (see Esposito et al., 2016 for more
127 details).

128 We have monitored a total of 83 days from June 15th to September 5th, using a meteorological
129 station equipped with soil temperature (CS thermistor) and moisture (CS616-C) sensors, three 2D
130 sonic anemometers (Gill WindSonic) placed at 0.5, 1.41, and 4m heights above the ground, one
131 thermometer and humidity sensor (Vaisala HMP155) at 4.5 m and one thermometer (Campbell Sci.
132 (CS)) placed at 2.5 m, one pressure sensor (Vaisala Barocap PTB110) at 2 m, a solar irradiance
133 sensor (LI-COR LI-200 Pyranometer) at 4 m and an atmospheric electric field sensor (CS110) faced
134 down at 2 m. In addition, we have monitored the saltation activity with two sand impact sensors
135 (Sensit Inc.) and three sand catchers (BSNE) placed at different heights (12, 25 and 40 cm) and the
136 atmospheric dust concentration with a sensor (Grimm EDM 164-E) placed at 1.5 m that analyses
137 the dust in 31 channels in the diameter range 0.265- 34 μm . From July 14th we have also added two
138 2D sonic anemometers (Gill WindSonic) placed at 7 and 10 m and one 3D sonic anemometer
139 (Cambell CSAT3) placed at 4.5 m.

140 The station operated 24 hours/day at a sampling rate of 1 Hz, only the 3D sonic anemometer has
141 acquired measures at 20 Hz.

142

143 **2.2 Dust devil structure and identification**

144

145 Fig. 1 shows a dust devil photographed near the measurement site. The diameter of the dust column
146 can remain roughly constant or increase with the height, the column can be perpendicular to the
147 surface or slightly tilted in the direction of motion (Fig. 1).



148

149 *Fig. 1.*

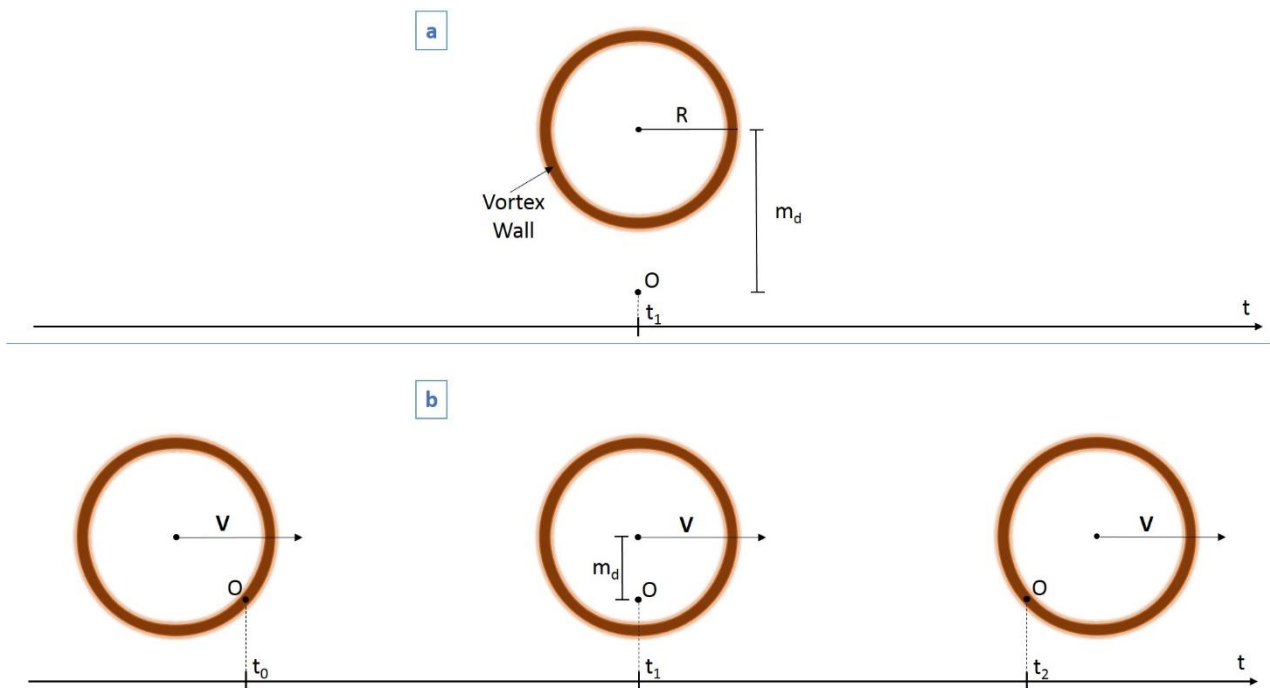
150 *A dust devil observed a few kilometers from the measurement site.*

151 At the center of the column there must be a low pressure core, related to the vertical convection,
152 that induces a horizontal rotary motion of the air flow. The rotational speed is approximately in
153 cyclostrophic balance with the magnitude of the pressure drop ΔP and it can be reasonably
154 described using the Rankine vortex model: the speed linearly increases with the radial distance r
155 from the center of the vortex up to its wall, where it reaches its maximum, then decreases as the
156 reciprocal of r . The pressure has its minimum value in the center of the vortex and the magnitude of
157 the drop decreases with the distance following a Lorentzian curve (Ellehoj et al., 2010). Inside the
158 wall of the column the lifted grains follow an upward helical pattern, forming a debris-laden

159 annulus, while the central region of the vortex is relatively dust free. The vertical wind speed
160 rapidly decreases outside the vertical column, and the dust devil is surrounded by a region
161 characterized by a downward directed motion, where the lifted grains relapse toward the surface.
162 The electrification by collision of the lifted grains and their separation in height induce a dipole
163 configuration of the charges inside the vortex column leading to the generation of an atmospheric
164 electric field (see Murphy et al., 2016 for a review on the subject). Depending on the closest
165 approach distance of the dust devil from the fixed meteorological station (impact parameter) we are
166 able to measure some or all of the characteristics just described. Indeed, we are able to monitor the
167 variation in atmospheric pressure due to ΔP , the peaks in horizontal and vertical wind speed due to
168 the vortex motion, the change in wind direction due to the rotation, the increase in the dust
169 concentration and saltation activity due to the lifted grains, the increase of atmospheric temperature
170 related to the lifting of the near ground air layers and the variation in atmospheric electric field due
171 to charged grains. Moreover, we are able to measure the decrease in solar radiation if the shadow
172 due to the dust column covers the station.

173 The evaluation of the impact parameter from the data acquired by a fixed meteorological station is
174 not a straightforward procedure. Recently, Lorenz (2016) has proposed a model to estimate this
175 parameter, however, the process entails some ambiguities and we have decided to not attempt this
176 kind of analysis in the present work. Nonetheless, we can easily recognize if an event passes over
177 the meteorological station by the peculiar features of the signal. Let us define the impact parameter
178 as the closest approach distance between the center of the vortex and our instruments. Fig. 2
179 schematically shows the passage of two dust devils: the first one does not intercept the
180 meteorological station (Fig. 2a), the second crosses the instruments (Fig. 2b). In the case depicted in
181 Fig. 2a we measure a single maximum in the variation of all the monitored parameters in the instant
182 t_1 , corresponding to the maximum approach of the vortex to the station. Instead, when the impact
183 parameter is smaller than the radius of the dust devil, the vortex wall passes two times over the
184 station (time instants t_0 and t_2 of Fig. 2b). In these instants the instruments measure the maximum

185 values of horizontal and vertical wind speed, lifted sand and dust concentration and hence E-field
 186 variation. Between t_0 and t_2 the dust-free inner part of the vortex crosses the station resulting in a
 187 decreasing of the magnitude of the wind speed and grains concentration, that reach the local
 188 minimum in the instant t_0 . For the pressure signal, taking into account that the magnitude of the
 189 pressure drop ΔP is maximum in the center of the vortex and not on the wall, we measure a single
 190 maximum of ΔP in the instant t_1 in both cases of Fig. 2a and Fig. 2b. We are then able to distinguish
 191 between the case of Fig. 2a and Fig. 2b by looking for a single or a double peak trend in the
 192 measured data of wind speed, grains concentration and E-field. The double peak feature is usually
 193 particularly marked in the horizontal wind speed data, becoming clearer also in the other affected
 194 parameters when the impact parameter approaches zero.
 195 We report the magnitude of the monitored parameters inside the dust devils as the values assumed:
 196 in t_1 for the Fig. 2a case, and in the higher of the two maxima for parameters affected by the double
 197 peak trend for the Fig. 2b case.



198
 199 *Fig. 2.*
 200 (a) A dust devil of radius R that passes out of the meteorological station placed at the point O . t_0 represents the instant of maximum
 201 approach m_d to the station. (b) A dust devil that intercepts the meteorological station seen in three different instants. The vector V
 202 represents the translational velocity of the vortex. t_0 represents the instant when the vortex wall passes over the station the first

203 *time, t_1 represents the instant when the vortex center reaches its maximum approach to the station and t_2 represents the instant*
204 *when the dust devil moves away crossing for the second time the station with its wall.*

205

206 **2.3 Dust devils detection algorithm**

207

208 The signatures related to the dust devil passage last from few seconds to a couple of minutes. The
209 vortices encounters are usually identified by performing a “phase picker” analysis on the recorded
210 pressure time series (Murphy and Nelli, 2002; Ellehoj et al., 2010; Steakley and Murphy, 2016;
211 Lorenz and Lanagan, 2014). The phase picker compares a long term estimator of the pressure with a
212 short term one to recognize the fast variation of the signal. In order to identify even the shortest
213 encounters, we have chosen to compare the twelve minutes median of the signal with the 1 Hz rate
214 measurements. Unlike the previous literature works, we have chosen to use the electric field instead
215 of the pressure as the principal detection parameter. Indeed, the vortex pressure drop ranges from few
216 tenths of mbar to a couple of mbar, while the standard deviation along the twelve minutes’ pressure
217 median is ~ 0.1 mbar. Instead, the vortex induced E-field ranges from few hundreds of V/m up to
218 twenty thousand V/m, while the deviation around the twelve minutes’ median is only few V/m. For
219 this reason, the E-field variation is the most easily recognizable feature associated with the dust devil
220 passage.

221 Our algorithm splits the whole day in time intervals of 12 minutes each and selects as “Class D”
222 events the ones for which: $|E - E_m| \geq E_l$, where E_m is the median E-field, E is the 1 Hz
223 measurement and E_l is the chosen threshold. The detection of a single dust devil feature, e.g. only
224 the E-field variation, is not enough to unambiguously recognize the event. This is because we need
225 the synchronous detection of other vortex distinctive characteristics in order to proper distinguish
226 between a dust devil and other kind of dust lifting phenomena. As an example, a gust could exhibit
227 a similar E-field variation but not the same trend of pressure drop and change in wind direction.
228 Hence, the next step of the algorithm analyses the wind direction and the pressure time series of

229 each Class D event. For the pressure we have chosen to perform an 11 seconds running average in
230 order to reduce the rather high noise of our sensor. When the pressure drop (ΔP) and wind direction
231 variation (ΔWd) overcome the chosen thresholds P_1 and Wd_1 respectively, the events are categorized
232 as “Class C”.

233 We used the following thresholds: $E_1=250V/m$, $P_1=0.18$ hPa, $Wd_1=25^\circ$. The threshold values have
234 been chosen analyzing a subset of the whole dust devils sample, studying the typical magnitude of
235 the induced variation and the noise level. In order to eliminate the false-positive detections (mainly
236 gusts and pieces of dust storms), the Class C events have been cross-checked using the other
237 measured parameters as the horizontal and vertical wind speed, lifted sand and dust concentration,
238 solar radiance and atmospheric temperature. We categorized as Class B events the ones with a clear
239 dust devil signature in all the parameters, except the pressure drop, whose magnitude could remain
240 partially hidden by the noise. When also the pressure shows a clear vortex trend the event is
241 categorized as Class A.

242 The Class A detections represent roughly a quarter of the Class C and one half of the Class B events
243 and they are the only ones considered and analyzed in the present work.

244

245 **2.4 Evaluation of the vortex wind speed and the concentration of the lifted mass**

246

247 Let us call vortex wind speed (v_w) the relative horizontal speed of the dust devil in the rest frame of
248 the background wind (b). We directly measure the total wind speed $v_t = v_w + b$. The point of
249 minimum distance of the dust devil from the meteorological station corresponds to the maximum
250 measured velocity. In order to estimate v_w in this point we can consider the relation: $v_w = v_M - b$,
251 where v_M is the maximum of v_t measured during the dust devil encounter, while b is the median
252 background wind speed on a time interval of twelve minutes around the events. We have evaluated
253 all the quantities using the data acquired by the anemometer placed at 4 m.

254

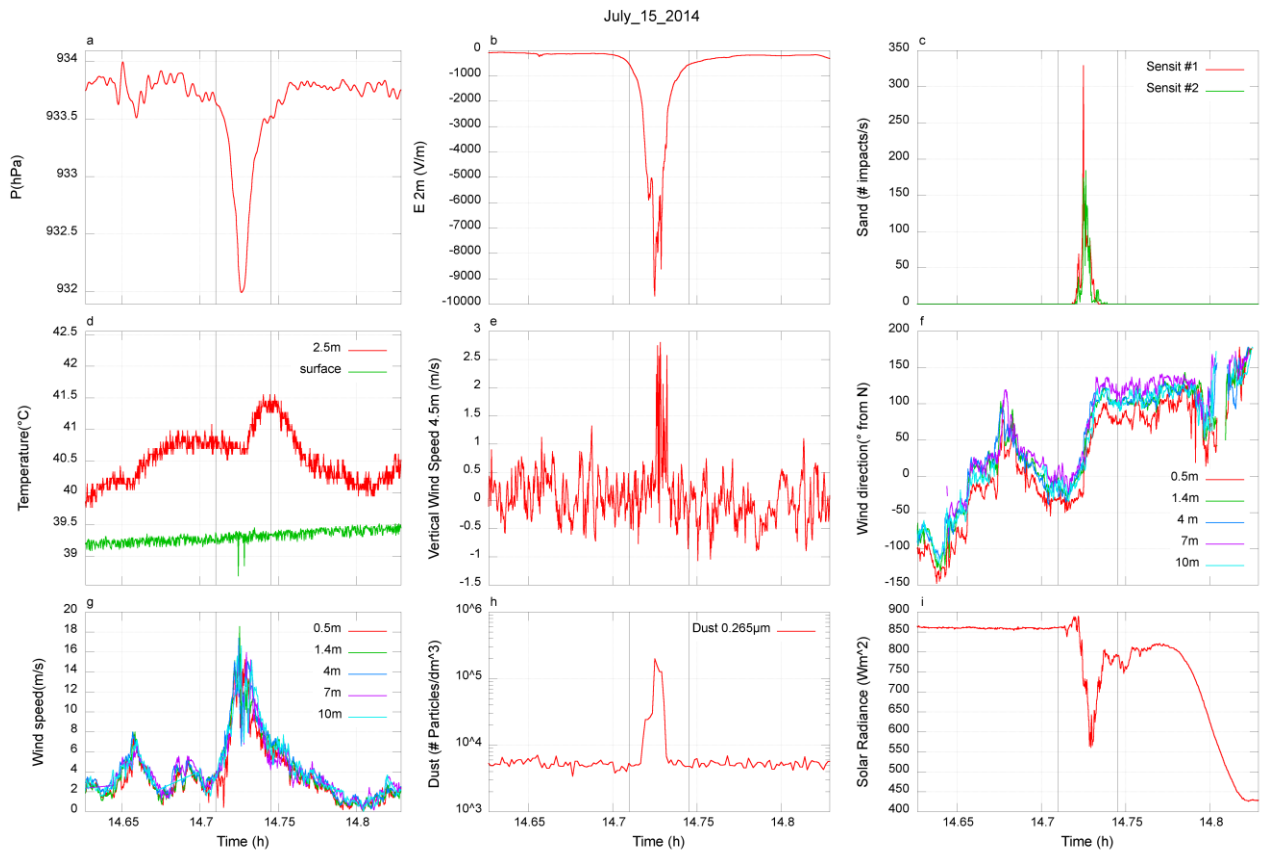
255 The dust size fraction of the soil in the site of measurements is composed mainly of quartz ($\rho=2.66$
256 g/cm^3) and muscovite ($\rho=2.82 \text{ g/cm}^3$), with a minor part of calcite ($\rho=2.71 \text{ g/cm}^3$) and illite ($\rho=2.79$
257 g/cm^3) (Esposito et al., 2016). Its density can be roughly estimated as $\rho_t=2.7 \text{ g/cm}^3$. We have
258 evaluated the total lifted mass density of dust (with diameter $\leq 34 \mu\text{m}$) using the direct measurement
259 of the dust grains numeric concentration and size distribution and assuming ρ_t as the mean density.
260

261 **3 Results**

262

263 We observed a total of 556 Class A dust devil's passages during 83 days of measurements. For 338
264 of these we also collected their vertical wind speed (only 54 days are comprehensive of the 3D
265 anemometer measurements). The values of the measured parameters for all the Class A events are
266 presented in Supplementary Table 1.

267 Fig. 3 shows an example of sensors' response to one of the events. In this instance, all the dust devil
268 features previously described are clearly recognizable. In Fig. 3a we can see the drop due to the
269 vortex low pressure core, Fig. 3b shows the E-field peak due to the passage of the charged grains,
270 Fig. 3c shows the increase in saltation activity measured by the Sensit and Fig. 3d the increase in
271 temperature related to the convection lifting of the warm air layer near the ground. In Fig. 3e we
272 show the peak in vertical wind speed connected with the upward motion inside the vortex column
273 (negative values indicate a downward directed velocity). The rotational motion of the vortex it is
274 added to the motion of the wind background. Hence, during the passage of the dust devil the
275 measured wind speed will increase proportionally to the magnitude of the rotational speed (Fig. 3f)
276 and the direction of the wind will change accordingly to the rotation (Fig. 3g). Finally, Fig. 3h and
277 Fig. 3i show the peak in the lifted dust concentration and the decrease in the measured solar
278 radiance due to the passage of the dust column and its shadow.



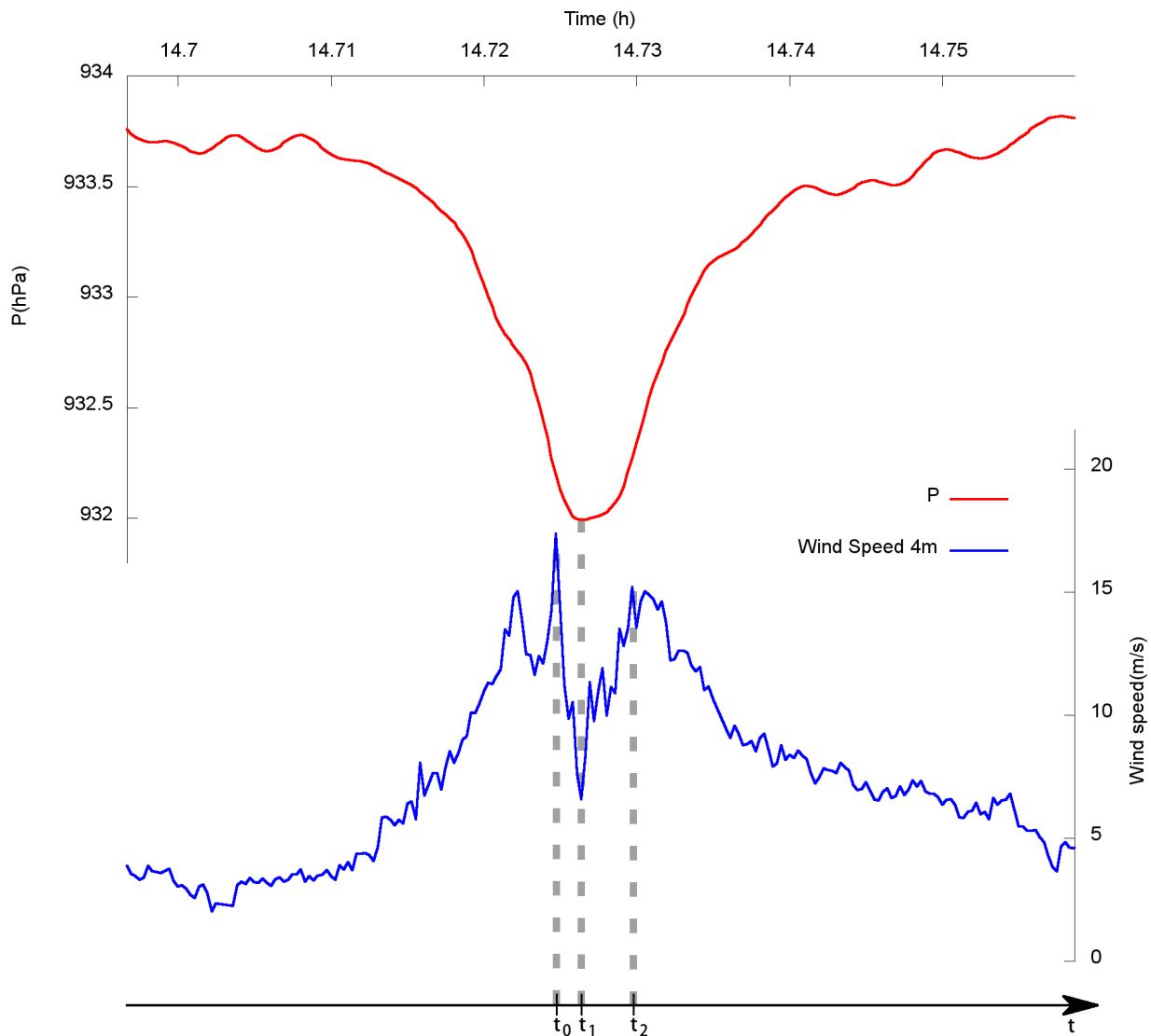
279

280 *Fig. 3.*

281 *A dust devil (Class A) encounter as detected by our measurement station. The plots show the time series of the different monitored*
 282 *parameters. In order from left to right and from top to bottom there are: (a) atmospheric pressure, (b) E-field, (c) counts of near*
 283 *surface saltating grains, (d) temperature, (e) vertical wind speed, (f) horizontal wind direction, (g) horizontal wind speed, (h) lifted*
 284 *dust concentration and (i) solar radiance.*

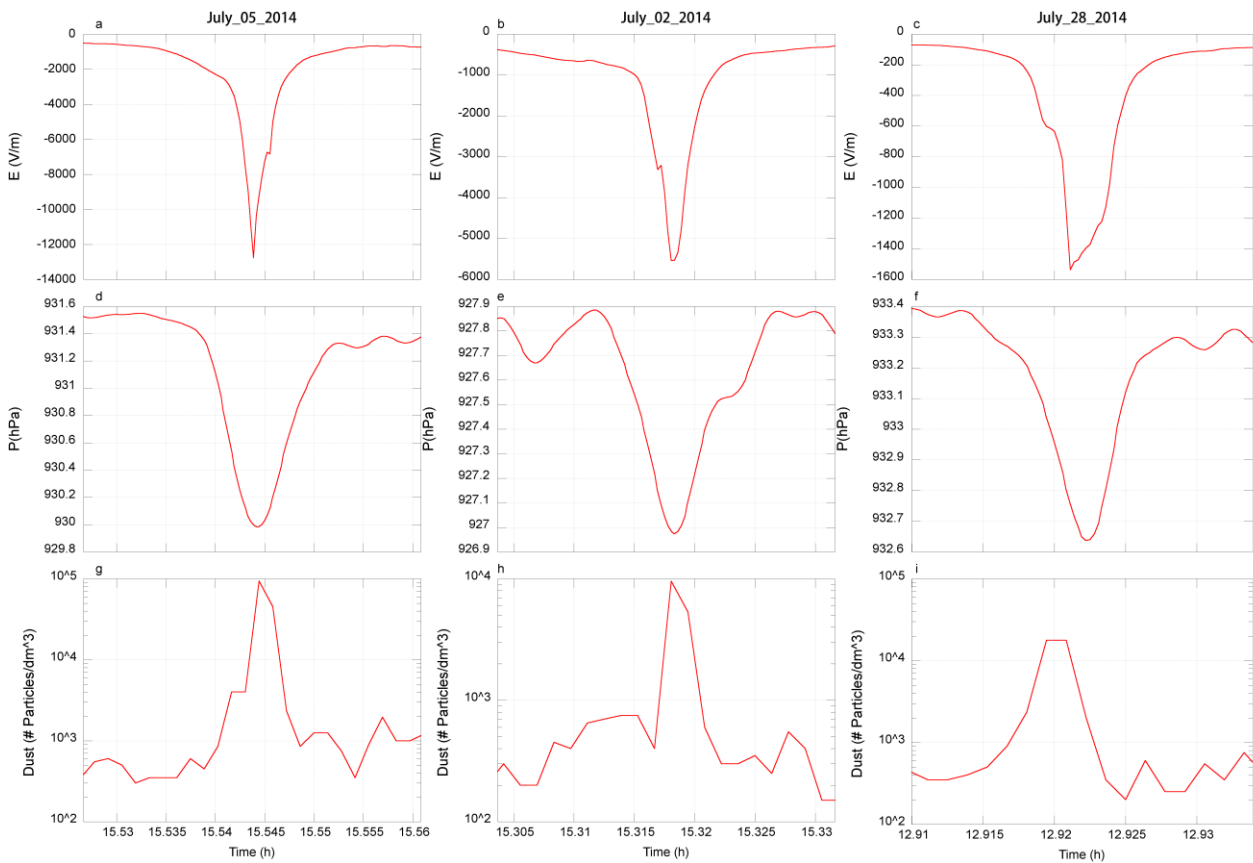
285 Fig. 4 shows a zoom of the same event where, in order to make the figure as clear as possible, we
 286 have plotted only the time series of the wind speed measured at 4 m and of the pressure. It is
 287 possible to recognize how the wind speed shows a double peak trend. The two maxima are located
 288 at the time instant t_0 and t_2 , they precede and follow the maximum pressure drop located at t_1 , which
 289 is synchronized with a local minimum in the wind speed. This particular trend reflects the case
 290 described in Fig. 2b, indicating the passage of the vortex directly over our meteorological station.
 291 The individuation of the exact position of the instants t_0 , t_1 and t_2 can result tricky, because it
 292 depends on the wall thickness of vortex, its motion and fluctuation speed level. For example, in the
 293 specific case of Fig. 4, t_0 and t_2 are not evenly spaced from t_1 and we observe two different

294 maximum values. This is probably due to a small deviation of the vortex from the uniform linear
 295 motion, suggested also by the slight asymmetry of the pressure drop. Anyway, we are not interested
 296 in the evaluation of the peculiar position of these instants, but just to the individuation of the two
 297 peaks signal trends to obtain information on the vortices that crossed or not our instruments.



298
 299 *Fig. 4.*
 300 *Time series of the atmospheric pressure and horizontal wind speed of the events of Fig. 3. The single peak trend of the pressure and*
 301 *the double peak trend of the wind speed are clearly recognizable indicating the direct passage of the dust devil over the station. The*
 302 *time instant t_0 and t_2 represent the first and the second crossing of the vortex wall, while t_1 is the maximum approach point, as*
 303 *described in Fig. 2b.*

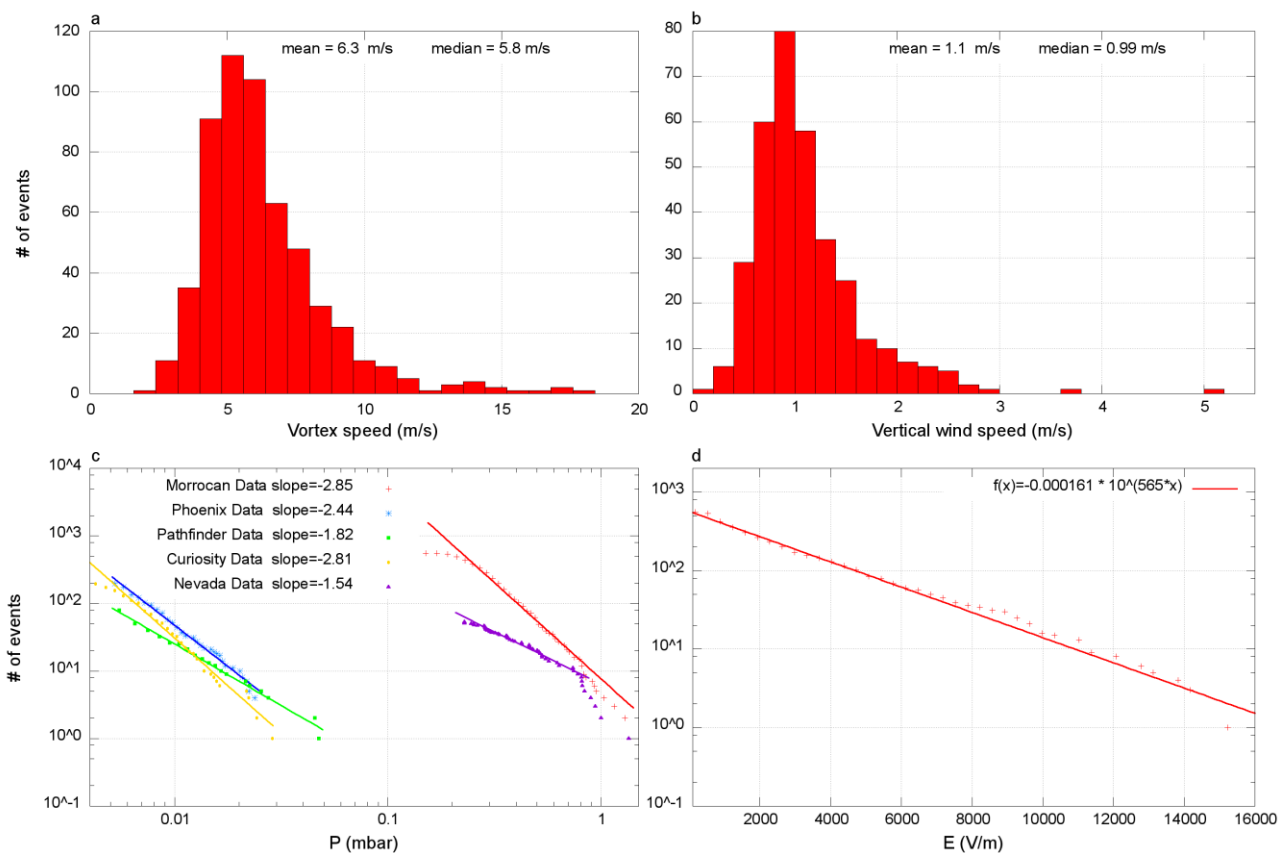
304 In Fig. 5 we take a close look to the recorded vertical E-field, pressure drop and lifted dust for three
 305 different events with a strong, medium and tiny atmospheric E-field variation, respectively. This
 306 signatures are always well visible and distinct from the background and the pressure signature
 307 appears to last for a longer time than the corresponding E-field variation. The E-field signature is
 308 usually roughly symmetric, however strongly asymmetric events as the one depicted in Fig. 5c are
 309 not totally uncommon. In particular, during the passages over the station, we observed both single
 310 and double peaks shape as well as irregular and highly noise signals. We do not to speculate on the
 311 meaning of these trends, because of the high number of possibilities coupled with low statistics for
 312 each case.



313
 314 *Fig. 5. The vertical E-field time series for three Class A events of strong (a), medium (b) and tiny (c) magnitude, respectively. For the*
 315 *same events there are also reported the pressure drops (d, e, f) and the dust concentration in the bin-size 1.45 μ m (g, h, i).*

316 Most of the dust devil events described in this study are coupled with moderate wind speeds (~ 6
 317 m/s) from the SW, which is the typical wind regime observed during the campaign. Fig. 6 shows
 318 the distributions of the vortex wind speed, vertical upward wind speed, pressure drop, and absolute

319 E-field observed during the dust devils encounters. The vortex wind speed ranges from 2.3 m/s to ~
 320 17.5 m/s, with a mean value of ~ 6 m/s (Fig. 6a). The vertical wind speed ranges from 0.1 m/s to 5
 321 m/s, with a mean value of ~ 1 m/s (Fig. 6b). Even when the vortices pass exactly over our station
 322 the maximum vertical wind speed remains ~ 1.5 m/s and only during two events it overcomes 3
 323 m/s. We observed that the dust devil passage leaves a signal clearly recognizable in horizontal wind
 324 speed and direction, pressure and E-field time series, with a full duration half maximum of various
 325 seconds. Compared to these ones, the trace left in the vertical wind speed is usually more similar to
 326 a delta function or a series of deltas, without a clear trend of growth and decrease in time (see for
 327 example the Fig. 3e). The reduced duration of the vertical flow signal coupled with its tiny
 328 magnitude makes the vertical wind speed peak less clear to recognize and study than the other dust
 329 devils features. This led us to the conclusion that the upward and downward vortex air flows have to
 330 decay much faster with the distance than the other monitored parameters.



331
 332 Fig. 6.
 333 (a) Histogram of the vortex wind speed; (b) Histogram of the maximum vertical wind speed;

334 (c) Cumulative distribution of the pressure drop for our data set (red) and for comparison a survey taken in Nevada (Category 1
335 events in the P28 dataset of Lorenz and Lanagan, 2014 – violet), the dust devils seen by the Phoenix (blue), the Pathfinder (green)
336 and the Curiosity (yellow) missions. The straight lines are the respective best fit functions.

337 (d) Cumulative distribution of the maximum electric field (red) in a semi-log plot with the best fit line (solid line).

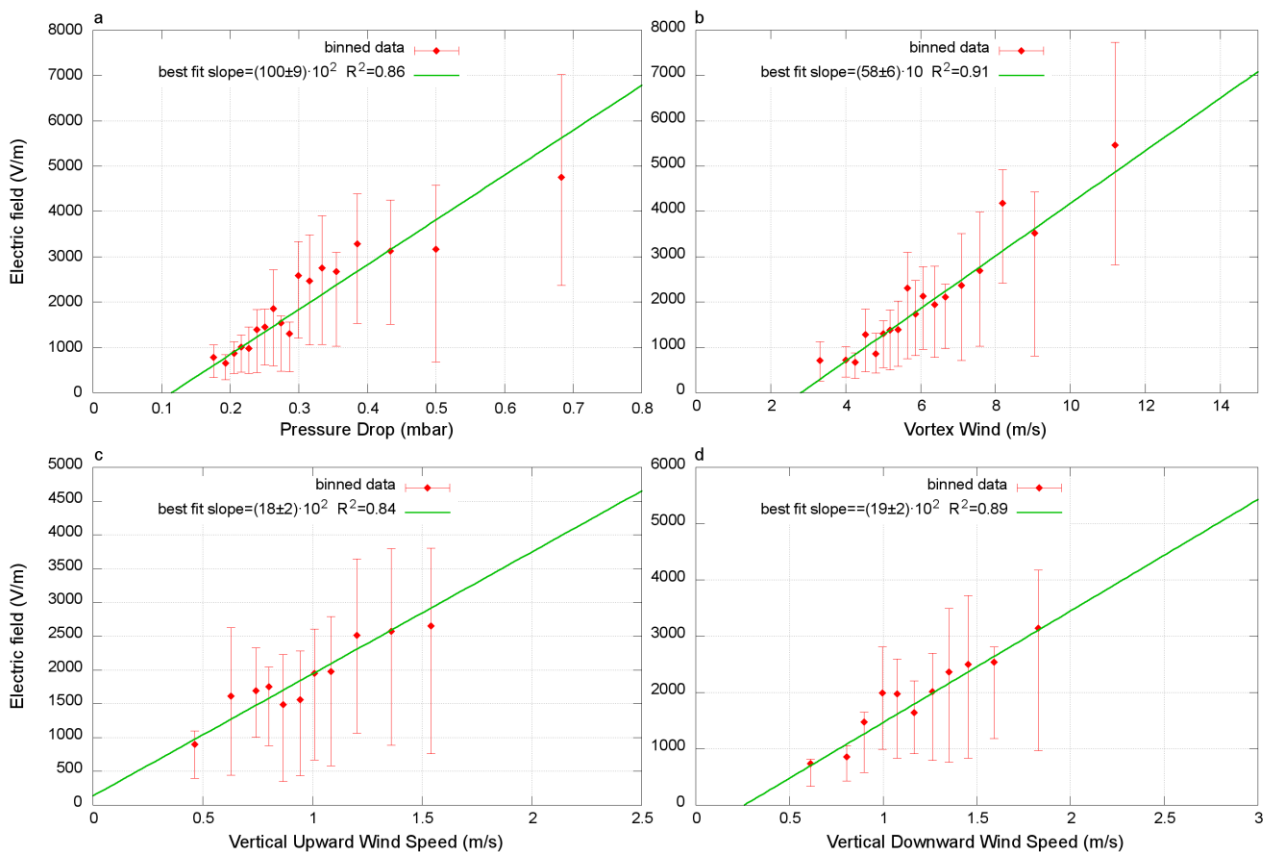
338 The measured pressure drops (ΔP) range from 0.18 (the chosen threshold) to 1.3 hPa (in red in Fig.
339 6c). Most of the detected vortices lie in the range 0.2-0.8 hPa and in this interval the ΔP cumulative
340 distribution is well described by a power law ($y = a x^b$ with an exponent $b = -2.85 \pm 0.05$). For the
341 largest and smallest ΔP values an appreciable drop off from the power law is apparent, as also seen
342 in other terrestrial data (e.g. in Fig. 6c we shown a dataset from Lorenz and Lanagan, 2014).

343 However, we observed that in the same range 0.2-0.8 hPa the ΔP cumulative distribution can be
344 also described by an exponential function with a coefficient of determination comparable to the one
345 of the power law fit ($y = a 10^{bx}$ with an exponent $b = -3.32 \pm 0.05$). Although there is not a
346 compelling reason to prefer one representation to another, throughout this paper we will continue to
347 use the results of the fit power law in order to allow an easier comparison with the literature.

348 Fig. 6c also shows a comparison of our data with the martian convective vortices survey obtained
349 by the Pathfinder and Phoenix landers and by the Curiosity rover, where a similar power law
350 cumulative distribution is observed (Murphy and Nelli, 2002; Ellehoj et al., 2010; Steakley and
351 Murphy, 2016). The exponent of the power law (-2.81 ± 0.07) that describes the vortex pressure
352 drops observed by Curiosity is compatible with the one obtained for our Moroccan data ($-2.85 \pm$
353 0.05).

354 Fig. 6d shows in a semi-log plot the cumulative distribution of the absolute E-field values measured
355 during the dust devils encounters. The vertical induced E-field is always downward directed and it
356 usually differs from the fair weather value (~ 50 V/m) of few thousands V/m, reaching values up to
357 16000 V/m. The cumulative distribution is well described in the whole variation range by an
358 exponential law, $y = a 10^{bx}$ with exponent of $(-161 \pm 4) \cdot 10^{-6} (\text{V/m})^{-1}$.

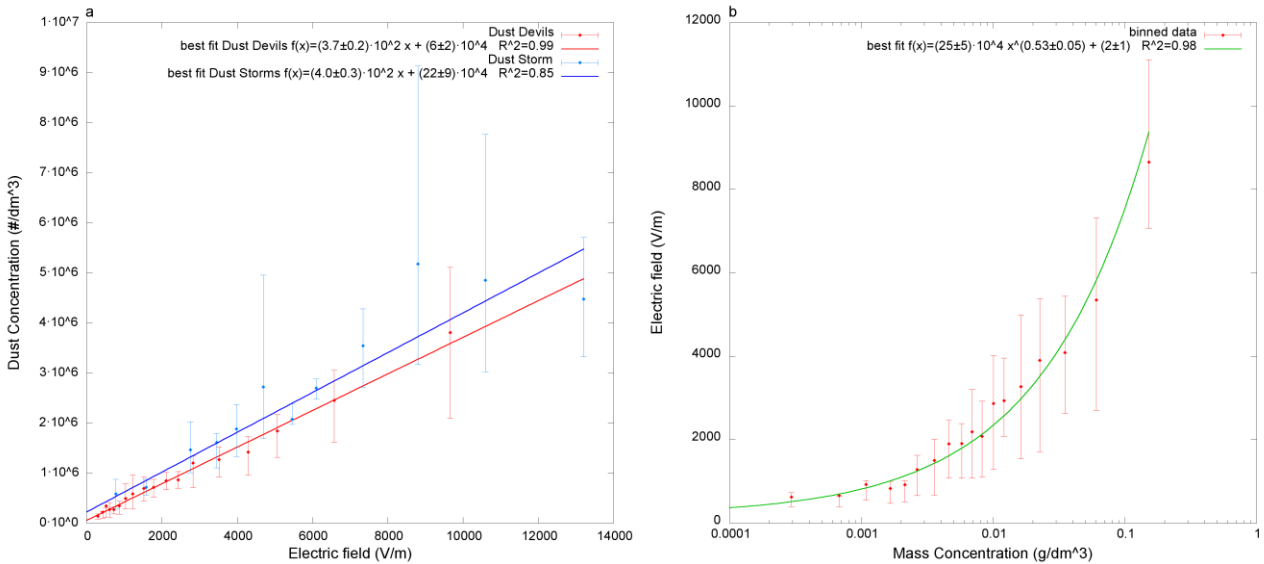
359 Fig. 7 shows the relations between the dust devils E-field and the other meteorological parameters.
 360 The E-field variations show an approximately linear relation with the pressure drop (Fig. 7a), the
 361 vortex wind speed (Fig. 7b), and with both the upward and the downward directed vertical wind
 362 speed (Fig. 7c and Fig. 7d).
 363 Fig. 8 shows the relation between the E-field and the amount of lifted dust. In Fig. 8a we plotted the
 364 lifted dust grains concentration against the corresponding E-field absolute value. In red are shown
 365 the data related to the dust devils and for comparison in blue there are data related to the dust storms
 366 observed during the same field campaign. We found that the dust concentration and the induced E-
 367 field are related by a linear function for both the dust devils and the dust storms and the slopes are
 368 compatible (dust devils slope = $(3.7 \pm 0.2) \cdot 10^2 \text{ dm}^{-3}(\text{V/m})^{-1}$, dust storms slope = $(4.0 \pm 0.3) \cdot 10^2$
 369 $\text{dm}^{-3}(\text{V/m})^{-1}$). Finally, Fig. 8b shows in a semi-log plot that the relation between the E-field
 370 magnitude and the lifted mass concentration can be described by a power law (exponent = $0.53 \pm$
 371 0.05).



373 Fig. 7.

374 Relation between the dust devils E-field and:

375 (a) the pressure drop, best fit slope= $(100 \pm 9) \cdot 10^2 \text{ (Pa)}^{-1} \text{ V/m}$ $R^2 = 0.86$; (b) the vortex wind speed, best fit slope= $(58 \pm 6) \cdot 10 \text{ (m/s)}^{-1}$
376 V/m $R^2 = 0.91$; (c) the upward vertical wind speed, best fit slope= $(18 \pm 2) \cdot 10^2 \text{ (m/s)}^{-1} \text{ V/m}$ $R^2 = 0.84$; (d) the downward vertical wind
377 speed, best fit slope= $(19 \pm 2) \cdot 10^2 \text{ (m/s)}^{-1} \text{ V/m}$ $R^2 = 0.89$. Each point in a) and b) represents a bin of 30 dust devils, in c) and d) due to
378 the lower statistic we used a bin of 28 dust devils; the error bars represent the 25th and 75th percentile.



379

380 Fig. 8.

381 a) the total dust grain concentration is shown as a function of the induced E-field for the dust devils (in red) and the dust storm (in
382 blue) events observed during the field campaign. (b) Semi-log plot that shows the relation between the induced E-field and the total
383 dust mass concentration during the dust devils events. Each point represents a bin of 30 events for the dust devils and of 7 events for
384 the dust storms; the error bars represent the 25th and 75th percentile.

385 4 Discussion

386

387 4.1 Wind speed distribution

388

389 Reporting the results of the field campaigns he performed in Arizona, Sinclair (1973) observed how
390 the vertical wind speed of the vortices measured approximatively at 2.1 m and 9.4 m usually
391 reaches 10 m/s inside the dust column, rapidly decreasing outside it. The vertical speeds we
392 measured at 4.5 m are far slower than the ones observed by Sinclair, even for the vortices that pass
393 exactly over our station (Fig. 6b). We also noted that the measured vortex horizontal wind speeds

394 usually overcome the vertical speeds. This result is in agreement with the observations made by
395 Ryan and Carroll (1970), which reported vertical wind speeds measured at 2 m from ground
396 between 0.2 m/s and 2.2 m/s, approximately one order of magnitude lower than the horizontal wind
397 speed. Hence, taking into account the typical values of vertical and horizontal wind regime
398 observed during our events, we can estimate that even for dust-size grains the contribution to the
399 lifting due to the horizontal wind stress is not negligible compared with the force due to the vertical
400 flow.

401

402 **4.2 Relation between the E-field and the pressure drop**

403

404 Greeley et al. (2003) observed how the dust devils can entrain dust with wind speed up to 80%
405 lower than the ones required by the simple boundary layer winds. This feature may derive from the
406 presence of the pressure gradient force due to the vortex low pressure core, that acts like an
407 additional lifting force (Neakrase et al., 2016). The magnitude of the pressure drop is therefore
408 related to the amount of the lifted dust that generate the E-field. Lorenz et al. (2016) present some
409 indications of a correlation between the vortex ΔP and the induced vertical electric current. Our data
410 show for the first time that the induced E-field and the vortex ΔP are actually connected, and that
411 the relation is approximatively describable by a linear function (Fig. 7a). A possible explanation for
412 the large error bars shown in Fig. 7a is the different dependence of plotted quantities on the distance
413 between the vortex and the station (impact parameter) and the impossibility to unambiguously infer
414 this parameter from the measurements acquired by a fixed meteorological station.

415 Indeed, the ΔP magnitude decreases like the square of the impact parameter (Ellehoj et al., 2010),
416 while the E-field decreases like the third power of the distance (assuming a dipole configuration).
417 This different dependence is noticeable also in our data. Indeed, we observed how the full width
418 half maximum of signal induced by the vortex passage is around 50% longer in the pressure time
419 series than in the E-field one, see for example Fig. 5 for a comparison of the two signal duration.

420 Moreover, we have to consider that also the vortex diameter could not be directly inferred from our
421 data. Currently it is not known how the magnitude of the induced E-field depends on the vortex
422 size, hence, a different dependence on the diameter of the two quantities plotted in Fig. 7a could not
423 be excluded and could lead to a further increase of the uncertain. These last considerations can also
424 be extended the other reported comparisons between the vortex parameters, and we believe that the
425 indetermination on impact parameter and vortex size represents the main source of error for each
426 relation shown in Fig. 7 and Fig. 8. A new field campaign with synchronous measurements of the
427 electric, meteorological and morphological vortex parameters has already been planned by the
428 authors in order to resolve the degeneration that currently affect the data and further investigate this
429 subject.

430

431 **4.3 E-field orientation and its relation with the wind speed**

432

433 Farrell et al. (2006) modelled the electric field generated by a dust devil system composed by grains
434 of two sizes stratified by gravity, assuming that the small and the large ones tend to acquire a
435 negative and a positive charge respectively (E-field upward directed). Moreover, they assumed the
436 horizontal wind contribution to the lifting process to be negligible compared to the vertical one. In
437 Fig. 7 of their paper, the authors showed how the modelled vertical E-field is linearly related to the
438 upward vertical wind speed. Nonetheless, they pointed out that this relation has to be applied with
439 caution to the case of vertical speed whose magnitude is small enough to be compared with the
440 horizontal one, because this possibility is not contemplated in their model.

441 Actually, according to our data, the E-field and the vertical wind speed seems to be linearly related
442 and the relation subsists also for the low upward vertical wind speed (Fig. 7c). Differently to the
443 assumption of Farrell et al. (2006), we see that the contribution of the horizontal wind is not
444 negligible, indeed, a relation between and the E-field and v_w exists (Fig. 7b).

445 Moreover, we have observed that the induced E-field seems to be also related to the downward
446 directed wind component (Fig. 7d). This downward motion is usually predominant right outside the
447 dust column, where the grains start to sediment by convective flow motion and gravity. This
448 suggests that the electric current related to the descending motion of the grains could play an
449 important role on the behavior of the E field, while, currently the dust devils E-field models don't
450 take into account this contribution (Farrell et al., 2006, Barth, 2016).

451 An important difference between our results and those commonly reported in the dust devil's
452 literature is represented by the orientation of the vertical E-field. The charges configuration inside
453 the dust column is usually described as an electric dipole with the positive charges below and the
454 negative ones above, leading to an upward directed vertical E-field (Farrell et al., 2006; Barth et al.,
455 2016). This assumption is in agreement with the previous field measurements of dust devils E-field
456 (Freier, 1960; Crozier, 1964; Farrell et al., 2004; Jackson et al., 2006). As far as we know, our data
457 set is the first example of a dust devils sample entirely characterized by a downward directed E-
458 field. This could be a first evidence that the orientation of the E-field induced by dust devil is not a
459 universal property but is a variable that may depend on local atmospheric conditions and soil
460 composition, as observed e.g. by Kamra 1972 for the dust storms.

461 The comprehension of this subject require further investigation, in particular laboratory analysis on
462 the composition and size distribution of the soil that sustain the whirlwinds.

463

464 **4.4 The E-field in other dust lifting processes**

465

466 Esposito et al. (2016) showed that during the dust storms the vertical E-field is linearly related to
467 the lifted grains concentration.

468 Here, in the place of the instant by instant values considered by Esposito et al. (2016), we have
469 analyzed the maximum of grains concentration vs maximum induced E-field intensity for both dust
470 devils and dust storms events (Fig. 8). We have observed that the E-field (E) and the grains numeric

471 concentration (η) are linearly related also during the dust devil events, and even that the slope of the
472 relation is compatible with the dust storms one. This correspondence indicates that the linear
473 relation E-field/grain concentration is probably a general law common for the dust lifting
474 phenomena.

475 Assuming a dipole model with the charges uniformly distributed inside the walls of a cave cylinder,
476 starting from the E/ η relation we can suppose on a first approximation a direct linear relation
477 between space charge density ρ and η . We have applied this simple model to the vortices passing
478 over the station, roughly estimating their size from the passage duration and travelling speed. With
479 these parameters, we can estimate the average charge per grain (q) and the charge density ρ for
480 these events. We have found a value of q ranging between $8 \cdot 10^{-18}$ and $5 \cdot 10^{-17}$ C, in agreement with
481 what reported by Kunkel 1950, and a value of ρ between $3 \cdot 10^{-9}$ and $4 \cdot 10^{-8}$ C/m³.

482 Using these values of q and scaling the other parameters to the ones expected during dust devils on
483 Mars: an η around hundreds of grains for cm³ and a vortex diameter between 2 and 276 m (Greeley
484 et al. 2010); we obtain a value of E ranging from few hundreds of V/m up to over 35 kV/m. Hence,
485 supposing a similar value of charge per grains on Earth and Mars, there is the possibility to
486 overcome the value expected for the martian electric breakdown, as firstly supposed using
487 laboratory measurements by Eden and Vonnegut 1973 and recently repurposed by the work of
488 Farrell et al. 2017.

489

490 **4.5 Comparison with martian data**

491

492 Previous convective vortex studies have observed how, for both terrestrial and martian surveys, the
493 ΔP cumulative distribution appears to be well described by a power law function. In some cases, the
494 distribution of the smallest and largest ΔP does not follow the main trend (Steakley and Murphy,
495 2016; Lorenz and Lanagan, 2014). This deviation could be attributable to the inefficient detection of
496 the smallest vortices and to the under sampling of the largest ones due to the finite sample size

497 (Jackson and Lorenz, 2015). However, a reason of physical nature cannot be excluded. Our results
498 are generally in agreement with the literature, but the value of our power law exponent (-2.85)
499 differs from the ones previously reported in other dust devil terrestrial surveys (\sim -1.5). Our power
500 law exponent approaches the one observed on Mars during the Phoenix (-2.44) and Curiosity (-
501 2.81) missions, resulting compatible with this last one (Fig. 6c). The exact exponent value and
502 uncertain evaluated through the regression process are strictly related to the chosen ΔP range and
503 binning procedure (see e.g. Lorenz and Jackson, 2016), thus a precise comparison of the different
504 surveys is not possible. However, it is clear that the terrestrial and the martian convective vortices
505 distribution show many similarities, allowing to speculate that our results on the induced E-field
506 could be representative also of the martian dust devils.

507

508 **5 Summary and conclusions**

509

510 In preparation to the ExoMars 2016 Schiaparelli mission, we have performed a field test campaign
511 in the Moroccan Sahara Desert. We deployed a fully equipped meteorological station, also able to
512 measure the vertical atmospheric electric field and the lifted dust concentration. We monitored three
513 months of dust devils activity and we observed how the variation in atmospheric electric field
514 induced by the dust devil passages represents the clearest and easiest feature to recognize. On this
515 basis, we used the vertical E-field as the principal probe parameter to detect the dust devils'
516 passage. We identified 556 events, acquiring a data set unique in literature with synchronous
517 measurements of the meteorological parameters, atmospheric electric field and dust concentration.
518 These data represent up to now the most comprehensive survey available for the convective vortices
519 and they allow the first statistical study of the dust devils induced electric field. The data set is
520 entirely characterized by a downward directed E-field, whose cumulative distribution is well
521 described by an exponential law. The E-field orientation is opposite to that reported in literature for

522 previous dust devils measurements suggesting a charge distribution in the dust column not
523 contemplated in the current dust devil E-field model (Barth et al., 2016).

524 We observed how the induced E-field appears to be related to the other vortex parameters: it is
525 linearly related to the vortices pressure drop and horizontal wind speed, to both the upward and
526 downward maximum vertical wind speed observed during the events and to the numeric
527 concentration of dust lifted grains. In addition, the E-field is related by a power law to the lifted dust
528 mass concentration. In particular, we observed that the dust storms and the dust devils present the
529 same correlation between the induced E-field and the amount of lifted grains, suggesting the
530 existence of a general law common to different kinds of dust lifting events.

531 We compared our vortex pressure drop distribution with the one obtained for the martian surveys.
532 In analogy to Mars the ΔP cumulative distribution follows a power law function with an exponent
533 compatible with the one observed by NASA Curiosity mission (Steakley and Murphy, 2016). The
534 similarity between the dust devils distribution in the two planets emphasizes the usefulness of our
535 work for the understanding of the martian dust lifting phenomena. The study of the martian
536 atmospheric electromagnetic field in dusty environment is one of the objectives of the ExoMars
537 2020 mission. The surface platform of the mission has on board the “Dust suite”, a package of
538 sensors able to monitor the lifted dust size distribution, concentration and atmospheric electric field,
539 that will acquire data similar to the ones collected in Morocco. The present study on the dust
540 induced E-field on Earth is a fundamental preparation to the analysis of the martian measurements,
541 providing also the best comparative data available at moment.

542

543 **Acknowledgments**

544

545 This work has been supported by the Italian Space Agency through the agreement I/018/12/0:
546 “DREAMS EDM Payload—ExoMars 2016”, and, in part by the Istituto Nazionale di Astrofisica
547 (INAF). The development of DREAMS instrument is funded and coordinated by ASI under the
548 leadership of INAF-Naples, Italy.

549

550 **References**

- 551 1. Atreya, S. K., Wong, A. S., Renno, N. O., Farrell, W. M., Delory, G. T., Sentman, D. D., ... &
552 Catling, D. C. (2006). Oxidant enhancement in martian dust devils and storms: implications for life
553 and habitability. *Astrobiology*, 6(3), 439-450.
- 554
- 555 2. Barth, E. L., Farrell, W. M., & Rafkin, S. C. (2016). Electric field generation in Martian dust devils.
556 *Icarus*, 268, 253-265.
- 557
- 558 3. Bo, T. L., & Zheng, X. J. (2013). A field observational study of electrification within a dust storm in
559 Minqin, China. *Aeolian Research*, 8, 39-47.
- 560
- 561 4. Crozier, W.D. (1964), The electric field of a New Mexico dust devil, *J. Geophys. Res* 69, 5427,
562 1964. doi: 10.1029/JZ069i024p05427.
- 563
- 564 5. Crozier, W. D. (1970), Dust devil properties, *J. Geophys. Res.*, 75, 4583–4585.
- 565
- 566 6. Demon, L., DeFelice, P., Gondet, H., Kast, Y., & Pontier, L. (1953). Premiers résultats obtenus au
567 cours du printemps 1953. *J. Rech. Cent. Natl Rech. Sci*, 24, 126-137.
- 568
- 569 7. Desch, S. J., & Cuzzi, J. N. (2000). The generation of lightning in the solar nebula. *Icarus*, 143(1),
570 87-105.
- 571

- 572 8. Duff, N., & Lacks, D. J. (2008). Particle dynamics simulations of triboelectric charging in granular
573 insulator systems. *Journal of Electrostatics*, 66(1), 51-57.
574
- 575 9. Eden, H. F., & Vonnegut, B. (1973). Electrical breakdown caused by dust motion in low-pressure
576 atmospheres: Considerations for Mars. *Science*, 180(4089), 962-963.
577
- 578 10. Ellehoj, M. D., Gunnlaugsson, H. P., Taylor, P. A., Kahanpää, H., Bean, K. M., Cantor, B. A., ... &
579 Holstein-Rathlou, C. (2010). Convective vortices and dust devils at the Phoenix Mars mission
580 landing site. *Journal of Geophysical Research: Planets*, 115(E4).
581
- 582 11. Esposito, F., Molinaro, R., Popa, C. I., Molfese, C., Cozzolino, F., Marty, L., ... & Ori, G. G. (2016).
583 The role of the atmospheric electric field in the dust-lifting process. *Geophysical Research Letters*,
584 43(10), 5501-5508.
585
- 586 12. Esposito et al. 2017 The DREAMS experiment onboard the Schiaparelli Module of the ExoMars
587 2016 mission: design, performances and expected results, *Space Science Reviews*, under review
588
- 589 13. Farrell, W. M., Smith, P. H., Delory, G. T., Hillard, G. B., Marshall, J. R., Catling, D., ... &
590 Cummer, S. A. (2004). Electric and magnetic signatures of dust devils from the 2000–2001
591 MATADOR desert tests. *Journal of Geophysical Research: Planets*, 109(E3).
592
- 593 14. Farrell, W. M., Renno, N., Delory, G. T., Cummer, S. A., & Marshall, J. R. (2006). Integration of
594 electrostatic and fluid dynamics within a dust devil. *Journal of Geophysical Research: Planets*,
595 111(E1).
596
- 597 15. Farrell, W. M., McLain, J. L., Collier, M. R., & Keller, J. W. (2017). The Martian dust devil electron
598 avalanche: Laboratory measurements of the E-field fortifying effects of dust-electron absorption.
599 *Icarus*, 297, 90-96.

600

601 16. Fedorova, A. A., Montmessin, F., Rodin, A. V., Korablev, O. I., Määttänen, A., Maltagliati, L., &
602 Bertaux, J. L. (2014). Evidence for a bimodal size distribution for the suspended aerosol particles on
603 Mars. *Icarus*, 231, 239-260.

604

605 17. Fenton, L., Reiss, D., Lemmon, M., Marticorena, B., Lewis, S., & Cantor, B. (2016). Orbital
606 observations of dust lofted by daytime convective turbulence. *Space Science Reviews*, 203(1-4), 89-
607 142.

608

609 18. Forward, K. M., Lacks, D. J., & Sankaran, R. M. (2009). Particle-size dependent bipolar charging of
610 Martian regolith simulant. *Geophysical Research Letters*, 36(13).

611

612 19. Freier, G. D. (1960), The electric field of a large dust devil, *J. Geophys. Res.*, 65(10), 3504,
613 doi:10.1029/JZ065i010p03504

614

615 20. Greeley, R., Balme, M. R., Iversen, J. D., Metzger, S., Mickelson, R., Phoreman, J., & White, B.
616 (2003). Martian dust devils: Laboratory simulations of particle threshold. *Journal of Geophysical*
617 *Research: Planets*, 108(E5).

618

619 21. Greeley, R., Whelley, P. L., & Neakrase, L. D. (2004). Martian dust devils: Directions of movement
620 inferred from their tracks. *Geophysical research letters*, 31(24).

621

622 22. Greeley, R., Waller, D. A., Cabrol, N. A., Landis, G. A., Lemmon, M. T., Neakrase, L. D., ... &
623 Whelley, P. L. (2010). Gusev Crater, Mars: Observations of three dust devil seasons. *Journal of*
624 *Geophysical Research: Planets*, 115(E7).

625

- 626 23. Guzewich, S. D., Toigo, A. D., Kulowski, L., & Wang, H. (2015). Mars Orbiter Camera climatology
627 of textured dust storms. *Icarus*, 258, 1-13.
- 628
- 629 24. Harrison, R. G., Barth, E., Esposito, F., Merrison, J., Montmessin, F., Aplin, K. L., ... & Houghton, I.
630 M. P. (2016). Applications of electrified dust and dust devil electrostatics to Martian atmospheric
631 electricity. *Space Science Reviews*, 1-47.
- 632
- 633 25. Jackson, T. L., & Farrell, W. M. (2006). Electrostatic fields in dust devils: an analog to Mars. *IEEE*
634 *Transactions on Geoscience and remote sensing*, 44(10), 2942-2949.
- 635
- 636 26. Jackson, B., & Lorenz, R. (2015). A multiyear dust devil vortex survey using an automated search of
637 pressure time series. *Journal of Geophysical Research: Planets*, 120(3), 401-412.
- 638
- 639 27. Jemmett-Smith, B. C., Marsham, J. H., Knippertz, P., & Gilkeson, C. A. (2015). Quantifying global
640 dust devil occurrence from meteorological analyses. *Geophysical research letters*, 42(4), 1275-1282.
- 641
- 642 28. Kamra, A. K. (1972). Measurements of the electrical properties of dust storms. *Journal of*
643 *Geophysical Research*, 77(30), 5856-5869
- 644
- 645 29. Kunkel, W. B. (1950). The static electrification of dust particles on dispersion into a cloud. *Journal*
646 *of Applied Physics*, 21(8), 820-832.
- 647
- 648 30. Lacks, D. J., & Levandovsky, A. (2007). Effect of particle size distribution on the polarity of
649 triboelectric charging in granular insulator systems. *Journal of Electrostatics*, 65(2), 107-112.
- 650
- 651 31. Lorenz, R. D., & Lanagan, P. D. (2014). A barometric survey of dust-devil vortices on a desert
652 playa. *Boundary-Layer Meteorology*, 153(3), 555-568.

653

654 32. Lorenz, R. D., and B. K. Jackson, 2016. Dust Devil Populations and Statistics, *Space Science*
655 *Reviews*, 10.1007/s11214-016-0277-9

656

657 33. Lorenz, R. D., 2016. Heuristic Estimation of Dust Devil Vortex Parameters and Trajectories from
658 Single-Station Meteorological Data: Application to InSight at Mars, *Icarus*, 271, 326-337

659

660 34. Lorenz, R. D., Neakrase, L. D., Anderson, J. P., Harrison, R. G., & Nicoll, K. A. (2016). Point
661 discharge current measurements beneath dust devils. *Journal of Atmospheric and Solar-Terrestrial*
662 *Physics*, 150, 55-60.

663

664 35. Malin, M. C., & Edgett, K. S. (2001). Mars global surveyor Mars orbiter camera: interplanetary
665 cruise through primary mission. *Journal of Geophysical Research: Planets*, 106(E10), 23429-23570.

666

667 36. Melnik, O., & Parrot, M. (1998). Electrostatic discharge in Martian dust storms. *Journal of*
668 *Geophysical Research: Space Physics*, 103(A12), 29107-29117.

669

670 37. McCarty, L. S., & Whitesides, G. M. (2008). Electrostatic charging due to separation of ions at
671 interfaces: contact electrification of ionic electrets. *Angewandte Chemie International Edition*,
672 47(12), 2188-2207.

673

674 38. Melnik, O., & Parrot, M. (1998). Electrostatic discharge in Martian dust storms. *Journal of*
675 *Geophysical Research: Space Physics*, 103(A12), 29107-29117.

676

677 39. Montabone, L., Marsh, K., Lewis, S. R., Read, P. L., Smith, M. D., Holmes, J., ... & Pamment, A.
678 (2014). The Mars analysis correction data assimilation (MACDA) dataset V1. 0. *Geoscience Data*
679 *Journal*, 1(2), 129-139.

680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706

40. Murphy, J. R., & Nelli, S. (2002). Mars Pathfinder convective vortices: Frequency of occurrence. *Geophysical research letters*, 29(23).
41. Murphy, J., Steakley, K., Balme, M., Deprez, G., Esposito, F., Kahanpää, H., ... & Patel, M. (2016). Field measurements of terrestrial and martian dust devils. *Space Science Reviews*, 203(1-4), 39-87.
42. Neakrase, L. D. V., Balme, M. R., Esposito, F., Kelling, T., Klose, M., Kok, J. F., ... & Wurm, G. (2016). Particle lifting processes in dust devils. *Space Science Reviews*, 203(1-4), 347-376.
43. Neubauer, F. M. (1966). Thermal convection in the Martian atmosphere. *Journal of Geophysical Research*, 71(10), 2419-2426.
44. Ryan, J. A., & Lucich, R. D. (1983). Possible dust devils, vortices on Mars. *Journal of Geophysical Research: Oceans*, 88(C15), 11005-11011.
45. Schofield, J. T., Barnes, J. R., Crisp, D., Haberle, R. M., Larsen, S., Magalhaes, J. A., ... & Wilson, G. (1997). The Mars Pathfinder atmospheric structure investigation/meteorology (ASI/MET) experiment. *Science*, 278(5344), 1752-1758.
46. Sowinski, A., Miller, L., & Mehrani, P. (2010). Investigation of electrostatic charge distribution in gas–solid fluidized beds. *Chemical engineering science*, 65(9), 2771-2781.
47. Stanzel, C., Pätzold, M., Williams, D. A., Whelley, P. L., Greeley, R., Neukum, G., & HRSC Co-Investigator Team. (2008). Dust devil speeds, directions of motion and general characteristics observed by the Mars Express High Resolution Stereo Camera. *Icarus*, 197(1), 39-51.

- 707 48. Steakley, K., & Murphy, J. (2016). A year of convective vortex activity at Gale crater. *Icarus*, 278,
708 180-193.
- 709
- 710 49. Thomas, P., & Gierasch, P. J. (1985). Dust devils on Mars. *Science*, 230(4722), 175-177.
- 711
- 712 50. Trigwell, S., Grable, N., Yurteri, C. U., Sharma, R., & Mazumder, M. K. (2003). Effects of surface
713 properties on the tribocharging characteristics of polymer powder as applied to industrial processes.
714 *IEEE Transactions on Industry Applications*, 39(1), 79-86.