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Key Points:
- The tight interrelation between the dust-lifting process and atmospheric electric field is shown
- The role of the relative humidity is demonstrated
- Electric forces contribute to the entrainment of dust in the atmosphere

Supporting Information:
- Supporting Information S1

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The role of the atmospheric electric field in the dust-lifting process

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Abstract Mineral dust particles represent the most abundant component of atmospheric aerosol in terms of dry mass. They play a key role in climate and climate change, so the study of their emission processes is of utmost importance. Measurements of dust emission into the atmosphere are scarce, so that the dust load is generally estimated using models. It is known that the emission process can generate strong atmospheric electric fields. Starting from the data we acquired in the Sahara desert, here, we show for the first time that depending on the relative humidity conditions, electric fields contribute to increase up to a factor of 10 the amount of particles emitted into the atmosphere. This means that electrical forces and humidity are critical quantities in the dust emission process and should be taken into account in climate and circulation models to obtain more realistic estimations of the dust load in the atmosphere.

1. Introduction

Airborne dust and other aerosol particles affect the climate by absorbing and scattering thermal and solar radiation and acting as condensation nuclei for the formation of clouds. Thus, they strongly influence the atmospheric thermal structure, balance, and circulation [*James et al.*, 1992; *Jakosky and Haberle*, 1992; *Kahn et al.*, 1992; *Ryan and Henry*, 1979; *Forget et al.*, 2006; *Martin and Kieffer*, 1979; *Martin*, 1981; *Jakosky and Martin*, 1987; *Spiga and Lewis*, 2010]. The wind-driven blowing of sand and dust is also responsible for shaping planetary surfaces through the formation of sand dunes and ripples, the erosion of rocks, and the creation and transport of soil grains. These processes occur not only on Earth but also on Mars, Titan, and Venus [*Greeley and Iversen*, 1985].

It is clear that knowledge of the atmospheric dust properties and of the mechanisms of dust settling and rising into the atmosphere is a key to understanding the planetary climate and the interaction between the atmosphere and surface.

During the Climate Change Conference in 2014, it was highlighted that aerosols contribute the largest uncertainty to the total climate forcing estimate for the Earth [*Intergovernmental Panel on Climate Change*, 2014]. The dust tridimensional distribution and number size distribution are among the most uncertain and critical parameters that need to be estimated. Current models are still inadequate in predicting these values correctly, in particular the abundance and size distribution of the dust emitted into the atmosphere [*Cakmur et al.*, 2006]. Estimates of emissions obtained by recent models span over a factor larger than 2 [*Zender et al.*, 2004]. This translates into great uncertainties in the estimation of the dust impact on the climate (radiative forcing) [*Dubovik et al.*, 2002; *Durant et al.*, 2009; *McGowan and Soderholm*, 2012] and in understanding past and predicting future climate changes [*Forster et al.*, 2007; *Jickells et al.*, 2005; *Mahowald et al.*, 2006; *Jansen et al.*, 2007]. On Earth, dust is lifted into the atmosphere mainly through wind drag, in a process named *saltation* [*Bagnold*, 1941]. When the wind friction velocity u_* exceeds a certain threshold, soil particles with size ~100 μm are the first to be mobilized. They move over the soil in ballistic trajectories, where they hit and mobilize other particles. Dust grains (<63 μm in size) are very tightly bound to the soil due to strong interparticle forces and need very strong winds to be mobilized. They are generally brought into suspension through the impact of particles in saltation, which transfer sufficient momentum to break the interparticle forces in dust aggregates (*sandblasting*) [*Alfaro et al.*, 1997; *Shao*, 2008]. During impacts among grains, the particles exchange electric charges and become charged. It has been hypothesized that the transferred charge depends on the particle sizes involved in the impact, with smaller grains generally acquiring negative charge [*Freier*, 1960; *Inculet et al.*, 2006; *Duff and Lacks*, 2008]. Smaller (negatively charged) grains go then into suspension and are transported higher into the atmosphere by local turbulence, leaving the more massive sand particles, that can be positively or negatively charged, close to the surface. The consequence of this process is a net charge separation and the generation of strong, upward directed atmospheric electric fields. Several authors reported electric field measurements up to 150 kV/m [*Schmidt et al.*, 1998] at a few centimeters from the surface during saltation or a few tens of kV/m outside the saltation layer [*Rudge*, 1913; *Demon et al.*, 1953; *Williams et al.*, 2009; *Bo and Zheng*, 2013; *Zheng*, 2013]. As a feedback, some field observations and theoretical models [*Kok and Renno*, 2006, 2008a, 2008b; *Zheng et al.*, 2013] suggested that these electric forces can influence the motion of the saltating grains and thus the saltation process itself. However, the effect of the electric forces on the dust emission process has never been investigated in the field.

In the next sections, we describe the experiments we performed in the western part of the Sahara desert to study the complex relationship between the dust-lifting process and particle electrification and the role played by the ambient humidity. The obtained results will help to better constrain dust-lifting models and consequently improve the dust emission estimation.

2. Field Campaigns in the Sahara Desert

We performed two field campaigns in the West Sahara desert in the SE Tafilalt region (Morocco) in the periods of July–September 2013 and June–August 2014, when the peak dust activity usually occurs (as testified by the observed peak in the dust aerosol column optical depth at 550 nm, as measured by the Moderate Resolution Imaging Spectroradiometer instrument on board the Terra satellite). The geographical coordinates are 4.113° W, 31.161°N for the 2013 site and 4.110°W, 31.193°N for the 2014 site. The study area is characterized by a semiarid continental climate with a rate of precipitation that rarely exceeds 100 mm/yr [*Benalla et al.*, 2003]. Vast fields of dunes develop close to the campaign sites [*Benalla et al.*, 2003; *Kabiri*, 2003], which are best described as Quaternary sediment flats derived by either water or wind deposition from the Paleozoic and Mesozoic sedimentary bedrock (geologic map Tafilalt region [*Service*, *g. d. M. and s. r. l. S.E.L.C.A*, 1987]).

In the 2013 campaign, we deployed the following instrumentation: three 2-D sonic anemometers (Gill WindSonic) placed at 0.5, 1.41, and 4 m; two thermometers (Campbell Sci. (CS) thermistor + Vaisala HMP155) placed at 2.5 and 4.5 m; sensors for the measurement of pressure (Vaisala Barocap) (at 2 m), relative humidity (Vaisala Probe HMP155) (at 2.5 m), solar irradiance (LI-COR LI-200 Pyranometer) (at 4 m), atmospheric electric fields (CS110) (at 2 m and facing down), soil temperature (CS thermistor) and moisture (CS616-C), size-resolved airborne dust concentration in the range 0.265–34 μm (31 channels) versus time (Grimm EDM 164-E) (at 1.5 m); two impact sensors (Sensit, Inc.) for the detection of the sand grains saltation rate; and three "sand catchers" (BSNE) for the daily collection of sand saltating at different heights (12, 25, and 40 cm). Measurements were performed 24 h /d at a sampling rate of 1 Hz (except EDM 164-E, which was operated at 0.2 Hz) for approximately 3 months. In 2014, we also added a 3-D sonic anemometer (CSAT3), placed at 4.5 m and operated at 20 Hz; two additional 2D sonic anemometers (at 7 and 10 m); and a camera collecting images every 15 min (Figure 1). A solar panel system powered the station.

The CS110 field mill was set up to measure the atmospheric electric field at 2 m. The electrical connection of the reciprocating shutter to the ground potential is assured by a flexible stainless-steel strap, but it was reinforced by connecting the metallic support mast to a 1.5 m copper bar deeply buried in the ground.

3. Results and Discussion

3.1. Soil Composition

Our soil analysis shows that the soil in the study area has a complex composition, in testimony to the various processes involved in its production (mainly detrital comminution, detrital grain weathering, and evaporitic crystallization) (Table S1 in the supporting information). Because the relative humidity (RH) has a direct influence on the electric charge of the suspended dust grains (see section 3.2.2), we focus on the description of the mineral phases influenced by the RH.

The sites analyzed in the 2013 and 2104 campaigns have similar compositions but different amounts of evaporite minerals (22% and 3%, respectively, after normalizing for water loss, assuming the stable hydration state at the measured temperature conditions). This composition points to the presence of mineral species

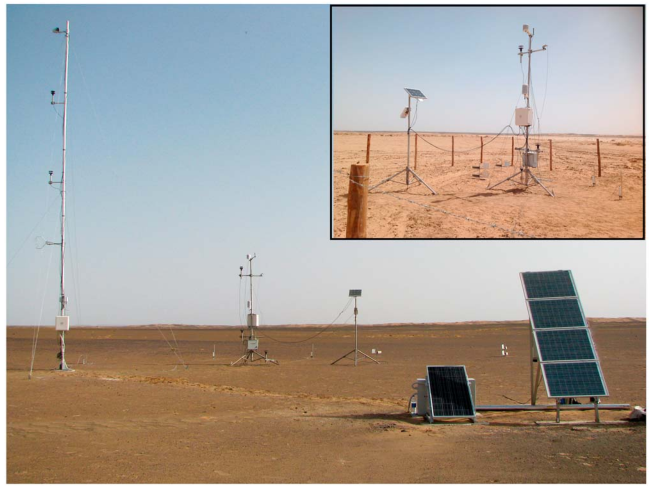

Figure 1. Instrument stations deployed during 2014 field test campaign in Merzouga desert, Morocco. The high mast on the left was deployed only in 2014, whereas all the other instruments were also present in the 2013 field campaign. The inset on the right shows the 2013 installation.

with the following order of appearance (for major phases): halite-mirabilite-bischofite-carnallite-tachyhydrite/antarcticite (see Table S2). Taken individually, the Mg and Ca chlorides have relative humidity equilibrium constants between salt and brine at approximately 30% RH, heavily dependent on the temperature [*Vergès-Belmin*, 2013]. It is likely that the absorbed water produces deliquescence, forming local brine pockets/films that influence the overall physical properties of the dust (e.g., electrical conductivity and electrical charge/discharge).

3.2. Data Analysis and Discussion

Measurements were performed during the peak of the dust storm season in Morocco. We encountered several dust storms and dust devils in both campaigns. During all of these dust events, we observed an enhancement of the atmospheric electric field, in line with what was reported by several other observers (see section 1).

3.2.1. Sign of the Observed Electric Field

The observed E-field was generally downward pointing, i.e., directed the same as the fair weather one, with occasional and short inversions in the sign (Figure 2). By using the same instrument in the same configuration, *Yair et al.* [2015] observed positive E-fields during a dust storm in Mitzpe Ramon (Israel) in February 2015. Nevertheless, negative E-fields have also been reported by other authors [*Demon et al.*, 1953; *Kamra*, 1972; *Williams et al.*, 2009]. Our observation is in contrast with the idea that the transfer of electric charge between particles during collisions (saltation, sandblasting, etc.) is exclusively a size-dependent process. This could evidence that the grain composition plays a key role in the charge transfer, too, as was also suggested by other authors. As an example, *Kamra* [1972] reported E-fields with different signs for different major constituent minerals in the observed dust storm (generally, a positive E-field for clay minerals and both polarities for what the authors generically refer to as "silica"). How the mineralogy involved in the dust storm is reflected in the observed E-field is a matter that needs to be further investigated.

3.2.2. Strong Relationship Between Sand Saltation, Dust Emission, and E-field and Role of Atmospheric Relative Humidity

Figure 2 also clearly shows how quickly (on the order of seconds or less) the electric properties of the atmosphere change in response to sand saltation and dust emission. To the best of our knowledge, these are the first published data showing simultaneous measurements of the dust concentration and E-field variation, acquired in the same location and at the same surface layer level.

To identify a possible trend between the dust concentration and E-field intensity, we performed a statistical analysis for all the data acquired during dusty events. These events have been identified by selecting time interval data where the Sensit sensors detect saltation impacts. As we observed that the relative humidity (RH) has a significant impact on the E-field intensity, we classified dusty events into four *humidity classes*:

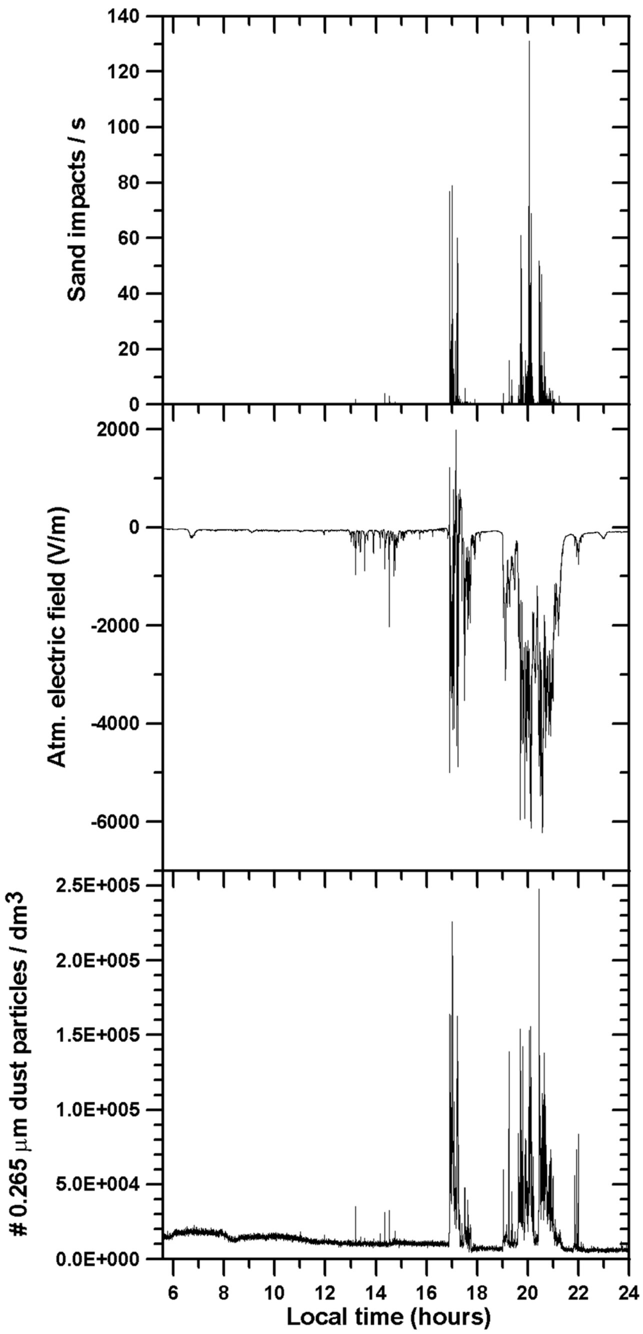

Figure 2. Time series acquired on 16 July 2013: saltating sand impact rate as detected by one of the (top) Sensit sensors, (middle) atmospheric E-field, and (bottom) concentration of suspended dust particles with size <265 nm.

RH < 10%, 10%–20%, 20%–30%, and >30%. Within each of these classes, we performed a binning of the E-field data in steps of 200 V/m and then averaged the data included in each bin in terms of the total dust concentration (total number of particles per liter, as acquired by the EDM 164-E device, in the whole size range). The results of this analysis are shown in Figure 3.

It is evident that there is a linear trend between the dust concentration and E-field intensity. The absolute value of its slope increases with the RH. This means that at a given dust concentration, the E-field decreases with the increasing RH. For the 2013 data set, such a decrease occurs for lower RH values (RH ~ 10% in 2013 versus ~ 30% in 2014), which is likely related to the higher moisture content in the 2013 soil with respect to 2014: 0.49 ± 0.03 versus 0.067 ± 0.010 H_2O vol/soil vol. The moisture content was obtained by averaging the data acquired by the CS616-C probe during the whole campaign. Despite the differences in soil composition, the slope obtained in dry conditions is the same at both sites: −240 ± 10 (dm^{-3}·$(V/m)^{-1}$) (coefficient of determination $R^2 = 0.90$). In wet conditions, the absolute slope value seems to initially increase and then decreases again at higher E-field intensities. This can be due to the high wind velocity [*Xie and Han*, 2012] and/or to some particular meteorological conditions related to those data (probably microburst events).

A dependence of E-field behavior on the RH was also observed during wind tunnel experiments by *Xie and Han* [2012]. The authors measured the E-field in a chamber (with a sand bed covered bottom) using a field mill (KDY-IV) and under different RH, wind, and temperature conditions. They observed that the E-field linearly increased with the RH up to a critical value and then exponentially decreased. This critical RH value was observed to increase upon increasing the wind speed. They reported values of approximately 20% for a wind speed of 12 m/s and ~40% at 14 m/s.

Even if the above experiment cannot be fully compared with the conducted Moroccan campaign due to the different conditions, the obtained results are in good agreement.

In our experiments, we clearly observed a critical RH value. Upon exceeding this threshold (placed somewhere in the range of 20%–30%), the E-field intensity decreases.

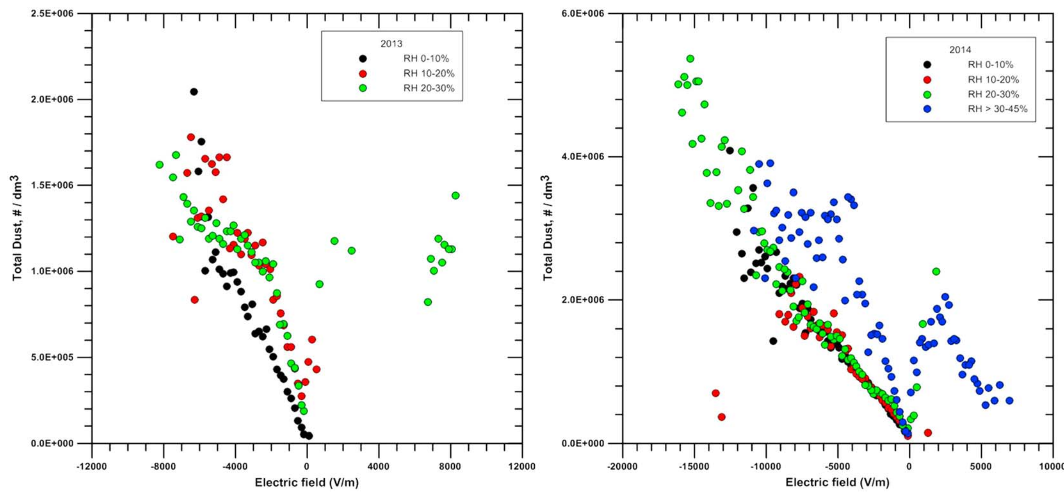

Figure 3. Relation between suspended dust concentration and E-field intensity for the (left) 2013 and (right) 2014 campaigns.

These observations provide strong evidence of the RH being a critical parameter in Aeolian processes, affecting the charging mechanism of dust and sand grains. A likely explanation of this phenomenon is the evaporite deliquescence. The hydrated evaporites (Mg and Ca chlorides) present in both the 2013 and 2014 soils (with different abundance) are affected by deliquescence at low RH values (see section 3.1) (critical RH, CRH = 28.7% for $CaCl_2 \cdot 2H_2O$ and 32.78% for $MgCl_2 \cdot 6H_2O$). When the atmospheric RH exceeds the local composition CRH value, the hydrated salts dissolve in the absorbed water and create a liquid film around the sand and dust grains, increasing their electrical conductivity and impacting the charging process.

A direct relation between the humidity and dust lifting could also exist and, consequently, influence the E-field. In field experiments, *Halleaux and Renno* [2014] found that the dust lifting increases with the soil humidity. They proposed that this could be due to either an increase in the amount of dust aggregates able to initiate saltation as the humidity increases or an increase in dust lifting due to the formation and breakup of crusts favored by the increase in humidity.

A summary of the observations is given below:

1. Saltation and dust emission processes produce an enhancement in the atmospheric electric field (due to the exchange of electric charge among grains and successive charge separation by local turbulence).
2. The concentration of emitted dust and the E-field intensity is linearly related at fixed RH (Figure 3).
3. Humidity affects the conductivity of the surface; evaporite deliquescence could play a key role in this.
4. The soil and air humidity affect the slope of the linear relation between the dust concentration and E-field: at a given value of the dust concentration, the E-field decreases when the humidity exceeds a threshold [*Xie and Han*, 2012] (Figure 3).
5. An increase in the soil humidity can favor dust lifting by the formation of dust aggregates and/or the formation and breakup of soil crusts [*Halleaux and Renno*, 2014].

It is difficult at this stage to discriminate between causes and effects in the phenomena observed in the field. It is evident that the concentration of lifted dust, E-field, and humidity are very strongly related in the way described in Figure 3.

3.2.3. Enhancement of Dust Emission Upon Exceeding an E-field Threshold

In the previous sections, we have shown evidence that the saltation and dust-lifting processes cause particles to become electrically charged and generate an atmospheric electric field, which is also affected by the ambient relative humidity and soil moisture. Here we present evidence that as a feedback, the generated E-field influences the saltation process itself. *Kok and Renno* [2006, 2008a, 2008b] and *Holstein-Rathlou et al.* [2012] predicted that when the E-field intensity exceeds a certain threshold, it produces a significant reduction of the static threshold friction velocity necessary for the saltation process to occur. This, in turn, causes a sudden increase in the concentration of saltating particles at a given wind speed (Figure 4) [*Kok and Renno*, 2008b] and a nonlinear increase of the E-field around this electric lifting threshold (Figure 4)

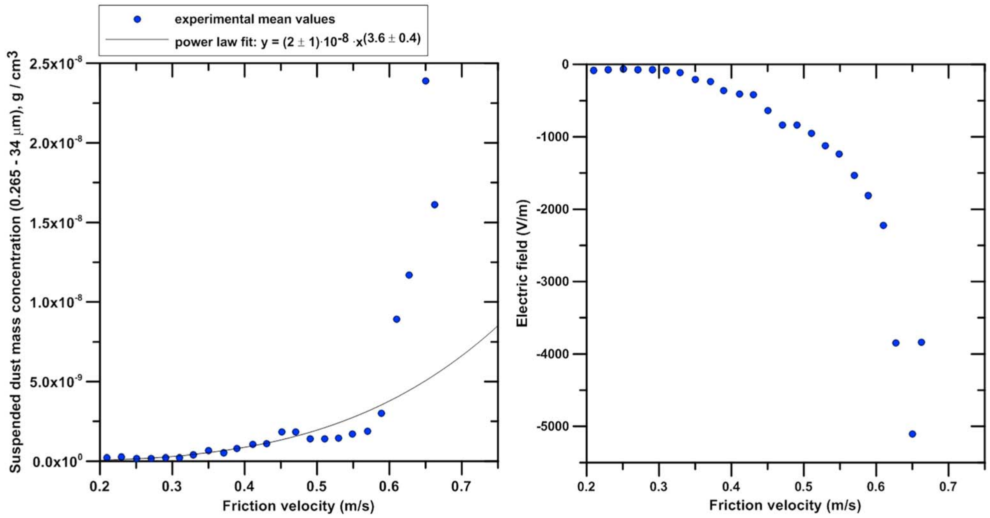

Figure 4. (left) Suspended dust mass concentration and (right) atmospheric E-field as a function of the wind friction velocity (Figure 4, left) for dust storm events with RH in the range 10–30%.

[*Kok and Renno*, 2008a]. The authors also predicted that by increasing the concentration of saltating grains, electric forces can lead to a reduction of the particle speeds. The effect of these two concurrent effects on the ejection of dust aerosol has never been investigated in the field. Our data, including simultaneous measurements of the wind, dust abundance, and electric field, has been used to explore this issue.

We derived the friction velocity u_* directly from the three orthogonal components of the wind, u, v, and w, as measured from the CSAT3 3-D anemometer at 4.5 m: $u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$. Considering that the vertical variation of u_* with height can be assumed to be negligible in the surface layer [*Haugen et al.*, 1971], we use this measured u_* value as the friction velocity value at the surface (more details are presented in the supporting information).

As in the simulations performed by Kok and Renno a conductive soil (due to the absorption of conducting films of water) is assumed, we considered only storms in a "wet" environment (RH > 10%). We also excluded from this analysis events with an RH higher than 30%, as they are peculiar events (probably microbursts). We averaged the total mass concentration of dust grains (obtained from the total number of grains, considering a typical bulk density of 2.7 g/cm^3) in bins of u_* with a step of 0.02 m/s. The results are shown in Figure 4.

The dust mass concentration increases with u_* with a power law $Q \propto u_*^{(3.6 \pm 0.4)}$ in line with the theoretical predictions [*Kok et al.*, 2012; *Merrison*, 2012] up to a threshold of approximately 0.57 m/s, where it experiences an abrupt increase that can be observed correspondingly in the E-field behavior. Note that the saltation threshold for the studied events has an average of 0.22 ± 0.07 m/s (see supporting information).

Kok and Renno showed that this sudden increase in the particle load is not predicted by lifting models that do not include electric forces in their formulation. By exceeding the threshold, our data show an increase of approximately an order of magnitude in the mass concentration of the lifted dust.

Note that *Kok and Renno* [2006, 2008a, 2008b] and other authors [i.e., *Rasmussen et al.*, 2009] found that to significantly affect the particle lifting, the E-field should exceed 150 kV/m. This high field intensity was measured at a very short distance from the sand bed (few centimeters) and thus cannot be compared with our measurements performed at 2 m from the ground (where E-field was found to be <20 kV/m).

Even if other interpretations could be found, our results provide strong evidence that electric forces play a key role in the dust-lifting process. It suggests the utmost importance of including their contribution in dust entrainment models to improve dust load predictions due to their effect on the atmospheric thermal structure and in general on the climate of the planet.

4. Conclusions

We performed field campaigns in the Sahara desert during the dust storm season in 2013 and 2014. The acquired data are unique in the literature and help to elucidate the complex relation between the saltation and lifting processes and the electric properties and the environmental parameters of the atmosphere. We found that (a) the particle emission process causes particles to be electrically charged and produces strong atmospheric electric fields (up to 20 kV/m as measured at 2 m from ground); (b) in contrast with models that predict upwardly directed E-fields, we generally observe downward fields (same sign as fair weather E-field). This may suggest that the charging process does not depend only on the grain size but also on the grain composition; (c) there is a very strong and fast feedback between sand / dust emission and electric field enhancement; (d) there is a linear relation between the concentration of lifted dust and the generated electric field, with the slope increasing upon exceeding a critical RH and soil moisture; and (e) we propose the existence of a threshold in the E-field intensity that, if exceeded, leads to a positive and abrupt effect in the emission of dust, with the mass concentration increasing by a factor of 10.

All these results highlight the key roles of electrification and humidity in the dust emission process. As a consequence, it is important to include these components in the models to adequately estimate the concentration of emitted dust and its strong effect on the climate.

Understanding the physical processes acting during dusty events on the Earth is an important step to shedding light on similar phenomena on Mars. In March 2016, the ExoMars space mission was launched, and it will deliver a lander (EDM *Schiaparelli*) to the surface of Mars in October of the same year. Schiaparelli includes, as the only payload operating at the surface, the meteorological station DREAMS [*Esposito et al.*, 2014, 2015; *Bettanini et al.*, 2014], which hosts six sensors for the measurement of the wind, temperature, pressure, RH, solar irradiance, and electric field. The station is expected to land in the Terra Meridiani region during the dust storm season. DREAMS will have the unique chance to study dusty events on Mars and their relationship with the atmospheric electric field.

Acknowledgments
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