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Enhancement of the emission of mineral dust aerosols by electric forces

Jasper F. Kok[1] and Nilton O. Renno[2]

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[1] Climate forcing by mineral dust aerosols is one of the most uncertain processes in our current understanding of climate change. The main natural sources of dust aerosols are blowing dust, dust devils, and dust storms. Electric fields larger than 100 kV/m have been measured in these phenomena. Theoretical calculations and laboratory experiments show that these electric fields produce electric forces that can reduce the critical wind speed necessary to initiate dust lifting and can even directly lift mineral particles from the surface. Thus, we conclude that electric forces enhance the natural lifting of mineral dust aerosols. **Citation:** Kok, J. F., and N. O. Renno (2006), Enhancement of the emission of mineral dust aerosols by electric forces, *Geophys. Res. Lett.*, *33*, L19S10, doi:10.1029/2006GL026284.

1. Introduction

[2] Mineral dust aerosols influence the Earth's climate by absorbing and scattering radiation [*Myhre and Stordal*, 2001], and by serving as cloud condensation and ice nuclei [*Twomey*, 1974; *DeMott et al.*, 2003]. Climate forcing by mineral dust aerosols is one of the most uncertain processes in our understanding of past and future climate change [*Intergovernmental Panel on Climate Change*, 2001].

[3] Because of their small size [*Tegen and Lacis*, 1996], mineral dust aerosols are subject to relatively large interparticle forces when compared to their weight or typical wind stress forces [*Greeley and Iversen*, 1985]. This generally prevents dust aerosols from being directly lifted by surface winds [*Gillette et al.*, 1974]. Instead, dust aerosols are normally lifted by a process called ''saltation'' [*Bagnold*, 1941; *Greeley and Iversen*, 1985]. In this process, larger sand particles are moved by the wind and bounce on the surface, ejecting smaller dust particles into the air. Convective motions and turbulent eddies then transport the dust aerosols to high altitudes, where they proceed to influence weather and climate [*Cakmur et al.*, 2004]. Saltation occurs in all main forms of natural dust lifting, such as blowing dust, dust devils, and dust storms. Blowing dust is defined as clouds of dust and sand particles lifted by wind [*Glickman*, 2000], while dust storms are blowing dust events in which visibility is reduced to less than 1 km [*Goudie*, 1983].

[4] Large electric fields have been measured in all natural dust lifting phenomena. In blowing dust, electric fields can reach up to ~160 kV/m [*Schmidt et al.*, 1998], while electric fields ranging from 10 to 100 kV/m have been measured in dust devils [*Stow*, 1969; *Renno et al.*, 2004]. Electric fields larger than 200 kV/m have been measured in dust storms [*Stow*, 1969; *Qu et al.*, 2004; *Zhang et al.*, 2004].

[5] The electric fields measured in the dusty phenomena mentioned above are thought to be caused by charge transfer during collisions of sand and dust particles [*Renno et al.*, 2003]. During these collisions, the larger sand particles become positively charged with respect to the smaller dust particles, although the exact mechanism by which this occurs is still under debate [e.g., *Lowell and Truscott*, 1986; *Desch and Cuzzi*, 2000]. The gravitational and aerodynamic forces then separate the heavier, positively charged particles from the lighter, negatively charged particles [*Schmidt et al.*, 1998; *Freier*, 1960]. The resulting charge separation produces the observed electric fields.

[6] The electric forces on saltating particles can be on the order of the gravitational force [*Schmidt et al.*, 1998], and can therefore affect their trajectories [*Zheng et al.*, 2003]. In this article, the effect of electric forces on the lifting of dust and sand particles is investigated for the first time. We show that electric fields at the surface induce charges in soil particles. The sign of the induced charge depends on whether the electric field at the surface is upward-pointing (positive charge) or downward-pointing (negative charge). Since the charged soil particles are in the electric field that induced them, they always experience an upward-pointing electric force (see Figure 1) [*Jackson*, 1999]. We found that these electric forces facilitate the aerodynamic lifting of particles from the surface and can even directly lift them. Therefore, electric fields in dust phenomena increase the number of saltating particles and thus enhance the emission of dust aerosols.

2. Theory of Dust Lifting by Electric Forces

[7] The charge separation in dust phenomena produces an electric field $E_0(z)$, where z is the vertical distance from the surface. The Earth's surface is generally a good conductor because soil particles are usually covered by a thin, conducting film of water [*Kanagy and Mann*, 1994]. Therefore, the electric field E_0 induces charges at the surface [*Wahlin*, 1986]. A conservative estimate of the induced surface charge density is obtained by approximating the Earth's surface to a flat plane, for which

$$\sigma_{\text{ind}} = 2E_0(0)\varepsilon_0, \tag{1}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1} is the electric permittivity of air. The induced surface charges produce a second electric field, $E_{\text{ind}}(z)$. The total field $E_{\text{tot}}(z)$ is then the sum of the ''original'' field $E_0(z)$ and the induced field $E_{\text{ind}}(z)$. Close to the surface, the electric field $E_{\text{ind}}(z)$ is approximately that of a charged infinite plane, with charge density

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[1] Applied Physics Program, University of Michigan, Ann Arbor, Michigan, USA.

[2] Department of Atmospheric, Oceanic, and Space Science, University of Michigan, Ann Arbor, Michigan, USA.

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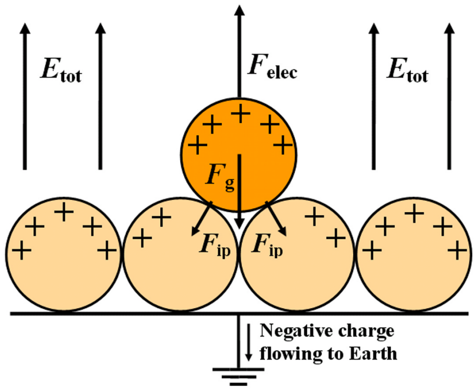

Figure 1. Force balance for a particle protruding from the surface. An upward (downward) pointing surface electric field (E_{tot}) can directly lift surface particles by inducing positive (negative) charges. These charged surface particles experience an upward-pointing electric force (F_{elec}). When the electric force exceeds the sum of the downward gravitational (F_g) and interparticle (F_{ip}) forces, particles are lifted from the surface. Particles protruding from the surface experience the largest electric forces, and are preferentially lifted.

given by equation (1), and it doubles the "original" electric field E_0

$$E_{tot}(z) = E_0(z) + E_{ind}(z) \approx E_0(z) + \frac{\sigma_{ind}}{2\varepsilon_0} = E_0(z) + E_0(0). \quad (2)$$

[8] The electric force on soil particles protruding from the surface (Figure 1) can be estimated using an idealized model of a spherical, conducting particle, placed on a conducting plane. In this case, the electric force is [*Lebedev and Skalskaya*, 1962]

$$F_{elec} = \frac{1.37\pi\varepsilon_0}{c_s} E_{tot}^2(0) d^2, \quad (3)$$

where d is the particle's diameter and c_s is a scaling constant introduced to account for the non-sphericity of soil particles. Since the electric force increases with the particle's surface area, non-spherical particles are subject to larger electric forces than spherical particles of the same mass. Therefore, $c_s = 1$ for soils composed of perfectly spherical particles, and $0 < c_s < 1$ for real soils composed of non-spherical particles.

[9] The upward-pointing electric force is opposed by the gravitational force (F_g)

$$F_g = \frac{\pi}{6} d^3 \rho_{part} g \quad (4)$$

and the vertical component of the interparticle force (F_{ip}), which is shown by *Shao and Lu* [2000] to be

$$F_{ip} = \beta d, \quad (5)$$

where $\rho_{part} \approx 2600$ kg/m^3 is the density of typical soil particles; $g = 9.8$ m/s^2 is the gravitational acceleration; and β is an empirical constant that scales the interparticle force and is on the order of 10^{-5}–10^{-3} kg/s^2 [*Corn*, 1961; *Zimon*, 1982; *Shao and Lu*, 2000].

[10] Soil particles are lifted when the upward electric force (equation (3)) exceeds the sum of the downward gravitational (equation (4)) and interparticle forces (equation (5)). The theoretical threshold electric field necessary to lift a particle of diameter d is then

$$E_{thr}(d) = \sqrt{c_s\left(\frac{\beta}{1.37\pi\varepsilon_0 d} + \frac{\rho_{part} d g}{8.22\varepsilon_0}\right)}. \quad (6)$$

3. Experimental Procedure

[11] We studied the lifting of soil particles by electric fields in the laboratory. Soil samples were collected from a field in the Sonoran desert in Arizona where dust devils and dust storms frequently occur [*Renno et al.*, 2004]. Lighter organic particles were removed from the soil samples. Fourteen samples of monodisperse (i.e., particles of similar size) mineral particles of diameters ranging from 20 to 300 μm were then wet sieved from the soil. Electron microscope images, available as auxiliary material[1], were taken to verify that each sample contained only monodisperse mineral particles. Measurements were made with both mixed (i.e., containing particles of all sizes) soil samples and monodisperse samples.

[12] Sample soil particles were loosely deposited onto a metallic disc, with 3.5 cm of diameter, using a sieve. The soil sample was placed at the center of a parallel-plate capacitor (PPC), with dimensions of 0.4 by 0.3 m. An upward-pointing electric field E_{PPC} was generated at the center of the PPC by applying a voltage difference ΔV between the two plates

$$E_{PPC} \approx \frac{\Delta V}{d}, \quad (7)$$

where the distance between the parallel plates was fixed at $d = 5$ cm. The effect of the soil sample on E_{PPC} is neglected because the sample was small compared to the dimensions of the PPC.

[13] We chose E_{PPC} to be upward-pointing since *Schmidt et al.* [1998] found upward-pointing electric fields near the surface during saltation. However, a downward-pointing electric field would similarly result in an upward force with value described by equation (3).

[14] The E_{PPC} was increased in steps ranging from 10 to 50 kV/m until nearly all sample particles were lifted or the electric field reached 600 kV/m. The electric field was held at each value for 60 s. Sensitivity tests showed that increases in the exposure time period above 60 s does not significantly affect the results.

[15] The amount of soil lifted by E_{PPC} was determined by weighing the soil samples before and after each incremental

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL026284.

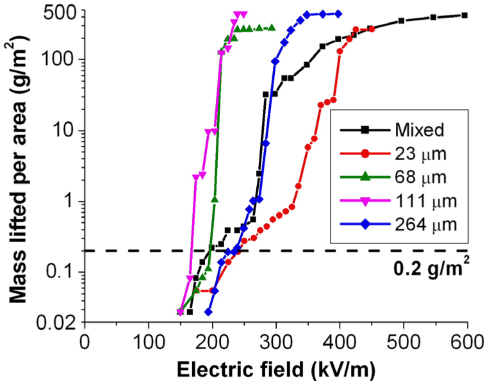

Figure 2. Soil mass lifted per area as a function of the applied electric field (E_{PPC}) for both mixed (solid black line) and representative monodisperse (solid colored lines) samples. The dashed black line represents the "threshold" value of 0.2 g/m^2, which we used to produce Figure 3. Values above ~100 g/m^2 need to be interpreted with caution, because parts of the sample were depleted of soil material. Error bars are not shown to avoid cluttering of the figure. Above the measurement noise (~0.1 g/m^2), the relative errors based on the standard deviation of the mean range between 1 and 60%.

increase in the value of E_{PPC}, and taking the difference between the two values. The initial mass of both mixed and monodisperse samples with particles larger than 90 μm was 0.400 ± 0.003 g. Because for a fixed mass the number of particles rapidly increases with decreases in the particles' size, and because samples of small particles are difficult to handle, we used an initial mass of 0.250 ± 0.003 g for samples of monodisperse particles smaller than 90 μm. All measurements were made at a temperature of 21 ± 1°C and relative humidity of 47 ± 5%.

4. Experimental Results and Analysis

[16] Our measurements show that both monodisperse and mixed soil particles are lifted by electric fields of ~150–175 kV/m (Figure 2). Electric fields of this value have been measured in most dust lifting phenomena [*Stow*, 1969; *Schmidt et al.*, 1998; *Zhang et al.*, 2004]. Measurements conducted with three different desert soil samples (not shown) yielded qualitatively similar results.

[17] A sharp increase in the mass of lifted soil particles occurs when the electric field exceeds that necessary to initiate lifting. This sudden increase is partially due to particles bouncing on the top plate, colliding with the soil sample on the bottom plate, and ejecting other particles. The ejected particles then undergo a similar process, ejecting still more particles from the surface.

[18] Since both the "cascading" effect and saltation involve grains impacting the surface and ejecting other grains, the cascade effect might illustrate potentially important effects of electric fields on saltation. Indeed, strong electric forces in saltation will facilitate the ejection of surface particles by saltating particles, resulting in more particle ejections per saltation impact. Animations of experiments showing the cascade effect are also available as dynamic content.

[19] Note that our results are quantitatively valid only for the relative humidity range of 47 ± 5%. This value is reasonable for blowing dust and dust storms because they frequently occur when the relative humidity is between 10 and 40% [e.g., *Jauregui*, 1989]. The dependence of electric lifting on humidity will be reported in a future publication.

[20] We define a threshold electric field (E_{thr}) as the field at which electric lifting first occurs. The threshold electric field is analogous to the concept of threshold friction velocity [*Bagnold*, 1941; *Greeley and Iversen*, 1985], which denotes the minimum surface shear stress needed for wind to move particles of a certain size. As such, the threshold friction velocity indicates the onset of saltation.

[21] We define the threshold electric field as that which lifts 0.2 g/m^2 of monodisperse soil particles (Figure 3). The value 0.2 g/m^2 was chosen because it lies sufficiently above our measurement uncertainty of ~0.1 g/m^2 to ascertain that electric lifting has occurred. By adjusting the parameter c_s of the theoretical threshold (equation (6)) to our experimental results (Figure 3), we obtain a semi-empirical expression for the threshold electric field

$$E_{\text{thr}}(d) = 0.69\sqrt{\frac{\beta}{1.37\pi\varepsilon_0 d} + \frac{\rho_{\text{part}} d g}{8.22\varepsilon_0}}, \tag{8}$$

where $\sqrt{c_s}$ = 0.69 ± 0.02 is obtained using a least-squares fitting.

[22] Figure 3 suggests that particles smaller than ~30 μm are poorly described by the physics underlying equation (6). This is probably because the interparticle forces of such small particles are insufficiently understood and might thus be poorly described by equation (5) [*Zimon*, 1982; *Shao and*

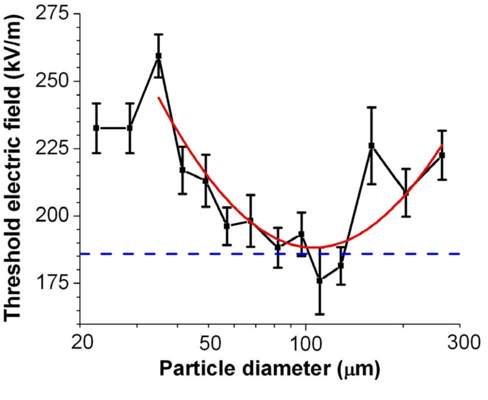

Figure 3. Threshold electric field at which 0.2 g/m^2 is lifted for monodisperse samples of particles of various diameters (black solid line). The error bars denote the uncertainty in determining the value of the threshold electric field and the standard deviation of the mean of four measurements for each sample. The red curve represents the least-squares fit of equation (6) to the experimental threshold electric field, corresponding to $\sqrt{c_s}$ = 0.69 ± 0.02. The blue dashed line represents the value of the electric field at which 0.2 g/m^2 of mixed sample is lifted, and has an uncertainty of ±7.5 kV/m. The parameter β was set to 1.5 × 10^{-4} kg/s^2 [*Shao and Lu*, 2000].

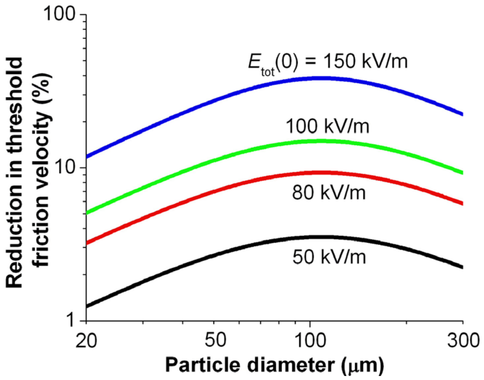

Figure 4. Percent reduction in the threshold friction velocity (see equation (9)), as a function of particle size and surface electric field. The geometric factor G was set to 1; β was set to 1.5×10^{-4} kg/s^2 [*Shao and Lu*, 2000].

Lu, 2000]. A more detailed discussion is available as auxiliary material. For the purpose of describing E_{thr} for the most easily lifted particles of diameters between ~50 and 200 μm, the data points for particles with diameters below 30 μm were omitted in the least-squares fitting of c_{s}.

[23] Although unable to directly lift particles, electric fields below E_{thr} (see equation (8)) can reduce the threshold friction velocity by providing an additional upward force. We derived an equation for the threshold friction velocity that includes the effect of electric forces following the ideas proposed by *Shao and Lu* [2000], finding

$$v_{\mathrm{thr}} = \sqrt{\frac{A_{\mathrm{n}}}{\rho_{\mathrm{air}}}\left(\rho_{\mathrm{part}}gd + \frac{6\beta G}{\pi d} - \frac{8.22\varepsilon_0 E_{\mathrm{tot}}^2(0)}{c_{\mathrm{s}}}\right)}, \qquad (9)$$

where $A_{\mathrm{n}} \approx 0.0123$ is a dimensionless parameter that scales the aerodynamic forces; G is a geometric parameter that depends on the bed stacking and is of order 1 [*Shao and Lu*, 2000]. This equation shows that electric fields above ~80 kV/m reduce the threshold friction velocity by over 10 % (Figure 4).

[24] In saltation, momentum is transferred from the air to saltating particles, thereby reducing the wind stress at the surface [*Bagnold*, 1941]. In steady-state saltation, the concentration of saltating particles is determined by the condition that the shear stress at the surface be just sufficient for surface grains to remain mobile [*Owen*, 1964]. Electric forces thus allow surface grains to remain mobile at a lower wind stress than in its absence. Therefore, electric forces allow saltation to equilibrate at a higher concentration of saltating particles.

5. Conclusions

[25] We show that electric fields exceeding ~150 kV/m can directly lift surface particles (Figure 2). Additionally, we show that electric fields above ~80 kV/m considerably reduce the threshold friction velocity necessary to lift particles by wind action (Figure 4). Both these effects peak for particles with diameters ranging from ~50 to 200 μm. These are the particles that first undergo saltation [*Bagnold*, 1941; *Greeley and Iversen*, 1985]. Therefore, rather than directly lifting dust aerosols, electric fields above ~80 kV/m intensify the saltation process that lifts mineral dust aerosols. Because electric fields in natural dust lifting phenomena can exceed 100–200 kV/m [*Schmidt et al.*, 1998; *Stow*, 1969; *Zhang et al.*, 2004], we conclude that electric forces play a potentially important role in the emission of terrestrial dust aerosols.

[26] Electric forces might also play an important role in the lifting of dust on Mars. However, electrical break-down of the thin Martian atmosphere occurs at ~20 kV/m [*Renno et al.*, 2003], limiting bulk electric fields.

[27] Additional studies are needed to further quantify the role of electric forces in the emission of dust aerosols. In particular, extensive measurements are necessary to assess whether strong near-surface electric fields are ubiquitous in dust lifting phenomena. If so, the incorporation of electric forces in dust lifting models would be essential.

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J. F. Kok, Applied Physics Program, University of Michigan, Ann Arbor, MI 48109, USA. (jfkok@umich.edu)

N. O. Renno, Department of Atmospheric, Oceanic, and Space Science, University of Michigan, Ann Arbor, MI 48109, USA.