The effects of electric forces on dust lifting: Preliminary studies with a numerical model

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Abstract. Atmospheric dust aerosols affect the Earth's climate by scattering and absorbing radiation and by modifying cloud properties. Recent experiments have indicated that electric fields produced in dusty phenomena such as dust storms and dust devils could enhance the emission of dust aerosols. However, the generation of electric fields in dusty phenomena is poorly understood. To address this problem, we present results from the first physically-based numerical model of electric fields in dust lifting. Our model calculates the motion and collisions of air-borne particles, as well as the charge transfer during these collisions. This allows us to simulate the formation of electric fields as a function of physical parameters, such as wind stress and soil properties. Preliminary model results show that electric fields can indeed enhance the lifting of soil particles. Moreover, they suggest that strong electric fields could trigger a positive feedback because increases in the concentration of charged particles strengthen the original electric field, which in turn lifts additional surface particles. We plan to further test and calibrate our model with experimental data.

1. Introduction

Mineral dust aerosols affect climate by scattering and absorbing radiation [1] and by modifying cloud properties such as lifetime and reflectance [2]. The uncertainty of these effects is considerable, which hinders both our understanding of past climate changes and our ability to predict future changes [3]. Understanding the sources of mineral dust aerosols and the processes that lift them from the surface is therefore essential for improving climate change predictions.

Dust aerosols generally have diameters smaller than a few microns [1] and thus experience large interparticle forces that prevent them from being directly lifted by wind [4]. Instead, dust aerosols are lifted from the surface by saltation (figure 1), the process by which larger sand particles bounce on the surface and eject smaller dust aerosols into the air [5]. Some of these mineral dust aerosols are then transported to high altitudes by convection and turbulent eddies, where they proceed to affect weather and climate.

Large electric fields have been measured in saltation on Earth [6] and are predicted on Mars [7]. The resulting electric forces are thought to affect both the particle mass flux [8] and trajectories [6]. In addition, Kok and Renno [9] recently showed that electric fields measured in saltation can directly lift sand and dust particles from the surface.

The electric fields in saltation are generated by collisions of particles with each other and with the surface. These collisions produce a charge transfer that generally leaves saltating particles negatively charged and the surface positively charged [10-13]. This charge separation can produce large electric fields [6].

In this article, we describe a physically based saltation model that includes the generation of electric fields. The model explicitly simulates the motion, concentration, and charge transfer between saltating particles and the surface. The predictions of the model are compared with measurements of electric fields during saltation, in the absence of suspended dust particles [6]. Our model includes the effect of suspended dust on the electric field, but we are currently unable to test this portion of the model, because experimental data is not yet available. Thus, current simulations do not include dust.

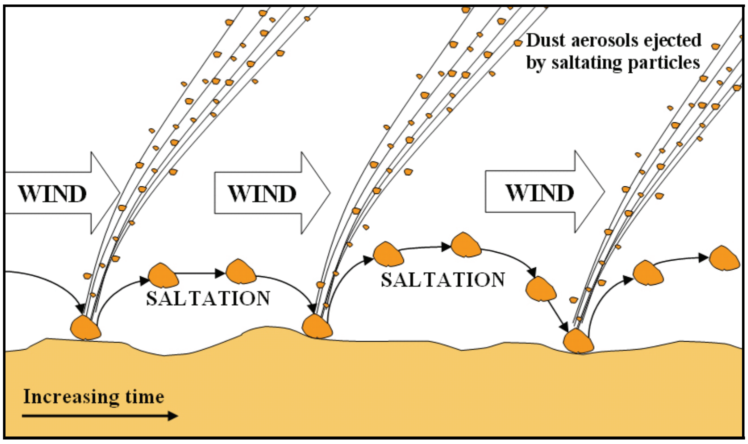

Figure 1. In saltation, larger sand particles (~200 μm in diameter) are dragged by the wind and eject the smaller dust aerosols (~1 μm) when they bounce on the surface.

2. Model description

We propose a new model containing the essential physics of saltation, including sand/dust electrification (see figure 2). Particle motion is modelled in two dimensions and all particles are assumed to be spherical. For simplicity, the effects of turbulence and collisions on the trajectories of saltating particles are not included because there is evidence that their effect is small compared to uncertainties in other modelled processes [14, 15].

Above the surface, the wind shear stress τ is given by

$$\tau = \rho\left(\kappa z \frac{\partial u}{\partial z}\right)^2, \tag{1}$$

where ρ is the air density, κ = 0.4 is the von Karman constant, z is the vertical distance from the surface, and u is the horizontal wind speed [4]. The saltation layer is defined as the region in which particles saltate, usually from the surface up to ~0.1-1 m above it. In this layer the fluid shear stress (τ_{fl}) and the shear stress due to saltating particles (τ_{p}) sum to the fluid shear stress outside the saltation layer (τ), that is, $\tau = \tau_{\mathrm{fl}} + \tau_{\mathrm{p}}$, when steady-state is reached.

In steady-state saltation, the fluid shear stress at the surface is assumed to be at the threshold value (τ_{t}) necessary to initiate the motion of surface particles [16]. Since the shear stress exerted by a single saltating particle is known from its trajectory, the concentration of saltating particles is determined from the condition that the particle shear stress (τ_{p}) at the surface equals the shear stress at the top of the saltation layer (τ) minus the critical fluid shear stress (τ_{t}). This follows directly from the balance of momentum fluxes in the saltation layer. The size distribution of saltating particles is assumed to be similar to that of the soil, in agreement with data from field experiments [17].

The wind profile is initially assumed to follow a logarithmic profile known as the "law of the wall" [4]. This wind profile is used to calculate the initial trajectories of the saltating particles. After the shear stress exerted by saltating particles is obtained from their trajectories, the wind profile in the saltation layer is obtained directly from equation (1) and from the condition that $\tau_{\mathrm{fl}} = \tau - \tau_{\mathrm{p}}$, that is

$$\frac{\partial u_{\mathrm{sl}}}{\partial z} = \left(\frac{\tau - \tau_{\mathrm{p}}}{\rho \kappa^2 z^2} \right)^{1/2}, \tag{2}$$

where u_{sl} is the horizontal wind speed in the saltation layer. The saltation mass flux that arises from the above procedure is in good agreement with empirical relations derived from measurements [5].

After the wind profile and the saltation trajectories are calculated, the collision frequencies among saltating particles and between saltating particles and the surface are determined. We use a new parameterization of the charge transfer induced by these collisions to determine the charge acquired by saltating particles and the surface. The resulting charge density is then used to calculate the electric field.

Both the wind profile and the electric field depend on the saltating particles' motion and concentration, which in turn are affected by the wind profile and the electric field. Therefore, the particle concentration, wind profile, and the electric field are modified iteratively until steady state is reached (figure 2).

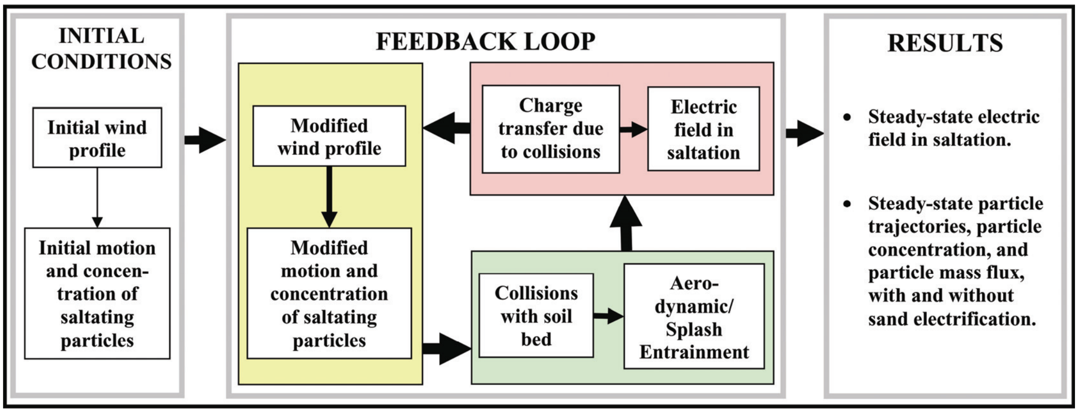

Figure 2. Schematic diagram of our physically based saltation model. It includes sand/dust electrification and the effects of electric fields on saltation. The steps indicated in the feedback loop are repeated until the changes in the saltation trajectories, the wind profile, and the electric field are smaller than a specified value in successive iterations.

2.1. The motion of saltating particles

Usually, the trajectories of saltating particles are determined primarily by fluid drag and gravitational forces [14]. However, we also include electric forces because they reach values comparable to that of gravity [6] and significantly affect the trajectories of saltating particles [18]. The mechanics of the collision of saltating particles with the surface (figure 1) is modelled based on results from numerical and laboratory studies [14, 15, 19].

2.2. Particle charging

The exchange of charges during collisions of particles with each other and the surface is due to tribo-electric charging [19], caused by differences in the contact potential of the colliding particles [11]. Field and laboratory measurements indicate that, during collisions, small particles preferentially acquire negative charges with respect to larger particles of similar composition [13].

The detailed physics of the tribo-electric charging of colliding dust and sand particles is not well understood. Nonetheless, Desch and Cuzzi [11] developed a model in which the charge transferred during collisions depends on the pre-existing charge, the particle radii, and the difference in contact potential between them. They propose that

$$q_S^{'} = \frac{c_{21} + c_{22}}{c_{11} + c_{12} + c_{21} + c_{22}} \left(q_S + q_L \right) - \frac{c_{12} c_{21} - c_{11} c_{22}}{c_{11} + c_{12} + c_{21} + c_{22}} \Delta\Phi_{cp}$$
$$q_L^{'} = \frac{c_{11} + c_{12}}{c_{11} + c_{12} + c_{21} + c_{22}} \left(q_S + q_L \right) + \frac{c_{12} c_{21} - c_{11} c_{22}}{c_{11} + c_{12} + c_{21} + c_{22}} \Delta\Phi_{cp} \tag{3}$$

where q_S and q_L are respectively the charges of the smaller and larger particles before the collision, and q'_S and q'_L are the charges after the collision; $\Delta\Phi_{cp}$ is the difference in contact potential between the two particles; and c_{11}, c_{12}, c_{21}, and c_{22} are the mutual capacitances of the two particles, which depends on their radii according to equations (7)-(10) of Desch and Cuzzi [11].

For particles of similar composition ($\Delta\Phi_{cp} = 0$), such as typical soil particles, equation (3) suggests that no charge transfer occurs when the colliding particles are not initially charged. However, this contradicts experiments which show that neutral particles of different sizes get charged when they collide with each other [13]. Since the physical reason for this charging is poorly understood [21], we propose an effective potential difference $\Delta\Phi_{cp}^{eff}$ between particle pairs of similar composition. That is

$$\Delta\Phi_{cp}^{eff} = S\left(\frac{r_L / r_S - 1}{r_L / r_S + 1} \right), \tag{4}$$

where S is a physical parameter with units of Volts, and r_S and r_L are the radii of the smaller and larger particles. This simple model has the functional form expected from physical arguments; the smaller particles acquire negative charges during collisions with larger particles, and the charge transfer decreases as the difference between the particle sizes is reduced. Since the charge transfer parameterization is the most uncertain portion of our model, we take S to be a tunable parameter. We use measurements of the electric fields in saltation [6] to find the value of S. For collisions of saltating particles with the surface, we set $r_L = \infty$ in equation (4), and get $\Delta\Phi_{cp}^{eff} = S$.

2.3. Electric fields in saltation

Using the model described above, the charges on the surface and on each particle population are calculated as a function of time. Saltation generally occurs over areas much wider than the depth of the saltation layer. Therefore, the saltation layer can be approximated by infinite sheets of charge [10]. The electric field is then obtained from the charge density ρ_c and the surface charge density σ, that is

$$E(z) = \frac{1}{2\varepsilon_0} \left(\sigma + \int_0^z \rho_c(z') dz' - \int_z^\infty \rho_c(z') dz' \right), \tag{5}$$

where ε_0 is the electric permittivity of air.

3. Preliminary results

The most detailed and reliable measurements of electric fields in saltation were made by Schmidt *et al.* [6]. We use their measurements to calibrate the parameter S in equation (4), which scales the collisional charge transfer, and find that $S \approx 3$V. The uncertainty in S is considerable, due to the limited experimental data available to determine its value. The results reported here are therefore preliminary (finalized and more detailed results are reported in [22]).

The surface electric field is of prime interest, because recent experiments show that electric fields larger than ~175 kV/m can directly lift surface particles [9]. Moreover, electric fields larger than ~80 kV/m can substantially reduce the critical shear stress (τ_t) necessary to lift surface particles. This means that particles can be lifted at a lower surface fluid shear stress, leading to an increased concentration of saltating particles [9, 16]. This increased charged particle concentration strengthens the original electric field, which our results indicate results in a positive feedback that leads to a non-linear increase in the electric field. This effect is clearly seen in figure 4, which shows the surface electric field as a function of the friction velocity, $u^* = (\tau/\rho)^{1/2}$.

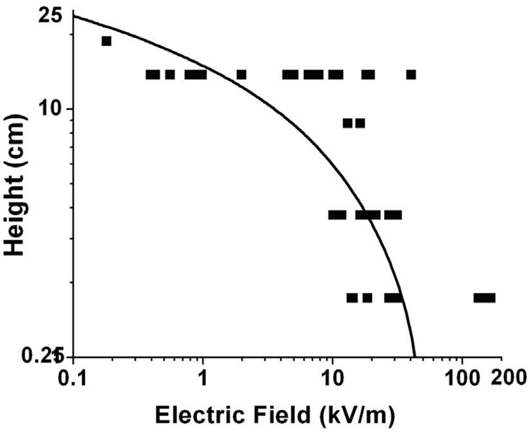

Figure 3. Comparison of the simulated electric field (solid line) with the measurements (squares) of Schmidt *et al.* [6] for similar conditions.

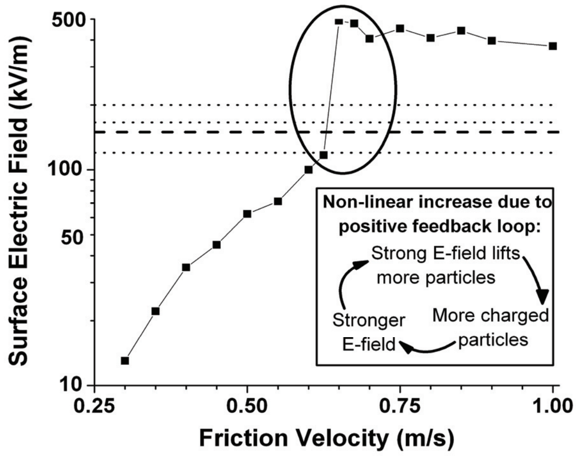

Figure 4. Modeled surface electric field as a function of friction velocity $u^* = (\tau/\rho)^{1/2}$. When the surface electric field approaches the electric lifting threshold (dashed line) measured by [9], a strong positive feedback occurs and causes a non-linear increase in the electric field. Dashed lines represent upper values of electric fields measured in dusty phenomena [6, 23, 24]

4. Conclusion

Saltation is the primary mechanism of aeolian sand transport and is therefore important to many geological and atmospheric processes [4, 5]. Recent field measurements, laboratory experiments, and theoretical studies have suggested that electric forces play an important role in saltation [6, 8, 9, 18]. We developed the first physically-based numerical model of saltation that includes the electrification of saltating particles. Since little experimental data is currently available to test and calibrate the model, our results are preliminary. However, agreement between the functional form of the simulated and measured electric fields suggests our model is capturing the essential physical processes.

Our preliminary results suggest that when the surface electric field approaches the electric lifting threshold [9], a positive feedback occurs. This happens because strong surface electric fields cause additional particles to saltate, leading to enhanced charge density and thus a strengthening of the original electric field, which further increases the concentration of saltating particles. This positive feedback might play a role in dust lifting by dust storms and dust devils. The effect of electric forces on the motion and concentration of saltating particles is described in a future publication [22].

We are currently developing a miniature sensor designed to make accurate near-surface electric field measurements in dusty phenomena [25]. Additional measurements of electric fields in saltation will serve to both reduce the uncertainties in our model, and answer the question of whether large electric fields, such as those measured by Schmidt et al. [6] and predicted by our model, are indeed ubiquitous in dusty phenomena.

Acknowledgments
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