Thanks are extended to the Editor, Ulrich Pöschl, and the anonymous Reviewer, for their kind work and very constructive comments and suggestions. Following these comments, we have modified the manuscript and believe that these modifications have substantially improved the manuscript. The following text contains the reviewer's comments (in black) and our responses (in blue). The related references are listed at the end of this file. All modifications in the revised manuscript are highlighted in blue.

Anonymous Referee #4:

1. There are some basic scientific questions that conflicted in the manuscript, and the author's responses to the last review are not clearly and cannot be fully accepted.

Reply: We are sorry that the previous responses are not clear enough for some important questions. In this response letter, we try our best to answer these questions accurately and convincingly. We hope that the following responses can be accepted by the reviewer.

2. The first response from author is not carefully expressed, and not enough investigation for the research background. The viewpoint that the triboelectric charging in a granular system is generally size-dependent is right, although different researchers have different views. Some researchers claimed that large particles tend to charge positively while smaller particles tend to charge negatively (the author make a mistake writing in the response), and other researchers claimed that small particles tend to charge positively while larger particles tend to charge positively (Mehrani and Grace, 2005; Sowinski et al., 2010) .

Reply: We thank the reviewer for noting this mistake writing in the previous version of our response. Indeed, as the reviewer noted that, for granular systems, many studies showed that larger and smaller particles tended to charge positively and negatively, respectively (for simplicity, hereafter referred to as normal-size-dependent charging), but a few studies reported the opposite polarity (hereafter referred to as abnormal-size-dependent charging), such as Mehrani et al. (2005) and Sowinski et al. (2010). Lacks and Sankaran (2011) inferred that such a difference is probably caused by the different materials used or different experimental protocols that weight various contributions differently, for example, particle-particle interactions versus particle-wall interactions. It is clear that there are only particle-particle interactions in dust events, but there exist both particle-particle and particle-wall interactions in fluidized beds. This implies that particle charging in dust events (i.e. this study) is quite different from that in fluidized beds (e.g. Mehrani et al., 2005; Sowinski et al., 2010). To verify the inference mentioned above, Forward et al. (2009) developed an experimental apparatus to quantify particle charging due only to the particle-particle interactions, and the results showed that particles exhibited a normal-size-dependent charging (please see Fig. R1 for the details). Besides, such normal charging phenomena was directly verified by the measurements of wind-blown sand flows (Zheng et al., 2003). As shown in Table R1, particles smaller than 250 μm tend to charge negatively while particles larger than 500 μm tend to charge positively. Following the reviewer's suggestion, we have added the comments, "Note that numerous studies found that larger and smaller particles tended to charge positively and negatively, respectively (e.g. Zheng et al., 2003; Forward et al., 2009; Kok and Lacks, 2009), but a few studies reported the opposite polarity when containing particle-wall interactions (e.g. Mehrani et al., 2005; Sowinski et al., 2010).", on the abnormal-size-dependent charging in section 5.2. Please see lines 20-24 on page 25 in the revised manuscript for the details.

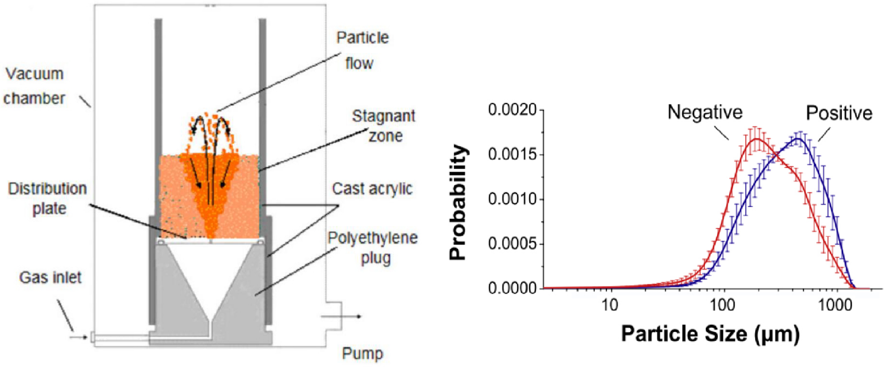
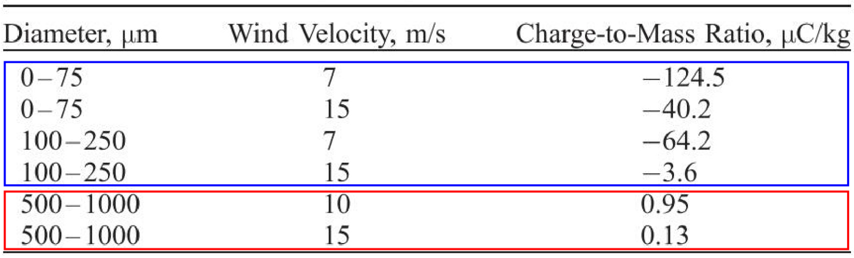


Figure R1. Left panel: single-hole particle flow apparatus used to study particle electrification. The single hole ensures that only particle-particle interactions occur (no contact with the container wall). Right panel: Particle-size distributions of JSC-1 Mars simulant after particle flow. Negatively charged (red) and positively charged (blue) particles. Clearly, particle charging without particle-wall interactions exhibited a normal-size-dependent charging. Adapted from Forward et al. 2009, Geophys. Res. Lett., 36, L13201.

Table R1. Measurement data of average charge-to-mass ratio for "uniform" sands at height region of 2–22 cm in the saltation layer. The blue box represents the negatively charged small particles, while the red box represents the positively charged larger particles in wind-blown sand. Adapted from Zheng et al. 2003, J. Geophys. Res., 108(D10), 4322.



Diameter, μm	Wind Velocity, m/s	Charge-to-Mass Ratio, μC/kg
0–75	7	−124.5
0–75	15	−40.2
100–250	7	−64.2
100–250	15	−3.6
500–1000	10	0.95
500–1000	15	0.13

3. The author claimed that the horizontal electric field is caused by the un-uniformly distributed fine particles, and the fine particles are more sensitive to the turbulent structure. But in this study, the author cannot explain from the simulation that the turbulent has effect on the small particle distribution, for the wind field in the simulation

is a horizontally uniformed one. And due to the un-uniformed distribution of fine particles, the electric field in vertical or the horizontal from the large scale is much stronger cannot clearly shown yet.

Reply: We thank the reviewer for this important question. In this study, we indeed cannot account for the effects of turbulent fluctuations on the finer dust particles, because we only consider the first-order statistics (i.e. mean values) in the steady-state model. As shown in Fig. 5 in the manuscript, in the relatively stationary period of the observed dust storms, all physical quantities, such as wind speed and 3D electric field, are statistically one-dimensional and stationary averaged over the ~10 min timescale. In such cases, the governing equation of the mean wind flow u_m is reduced to (e.g. Kok and Renno, 2009; Kok et al., 2012; Pähtz et al., 2015)

$$\frac{du_m(z)}{dz} = \frac{u_*}{\kappa z}\sqrt{1 - \frac{\tau_p(z)}{\rho_a u_*^2}} \tag{1}$$

where u_* is the friction velocity, κ is the von Kármán constant, ρ_a is the air density, and $\tau_p(z)$ is the particle momentum flux. In pure sand saltation, there only exists the vertical component of the 3D electric field (e.g. Zheng et al., 2003; Kok and Renno, 2008). However, as we found that the electric field in dust storms is distinctly three-dimensional, where the three components (i.e. streamwise, spanwise, and vertical) are comparable in magnitude. This suggests that the horizontal components (i.e. streamwise and spanwise components) may have a potential effect on sand transport. The main contribution of this study is that we characterize the profiles of the 3D electric field within the saltation layer and quantity these effects on sand transport during dust storms for the first time.

A clear physical explanation of the 3D electric field during dust storms is beyond the scope of this paper, which focuses on the effects of the 3D electric field on sand saltation. However, in our recently published work (Zhang and Zhou, 2020, Nature Commun.), the generating mechanism of the 3D electric field in dust storms is clearly shown. A brief introduction is given as follows. In dust storms, in addition to saltating sand particles there exist a huge amount of suspended dust particles in the air (see Figure R2). More recently, we proposed an inversion method, which is based on inverting the 3D electric field data collected in an atmospheric surface layer observation array, to reconstruct the electrical structures of dust storms (Zhang and Zhou, 2020). The results show that the space-charge density of dust storms exhibited a universal mosaic pattern of oppositely charged regions (see left panel of Figure R3). Meanwhile, the electric field in dust storms is distinctly three-dimensional, where the three components of the electric field are comparable in magnitude (see right panel of Figure R3). Such a 3D electric field is produced by the mosaic charge pattern of dust storms, which is closely related to the turbulence-driven separation of oppositely charged larger and smaller particles. Following the reviewer's comment, we have added the description, "More recently, using the 3-D E-field data collected in an atmospheric surface layer observation array, Zhang and Zhou (2020) established an inversion method based on Tikhonov regularization to reconstruct the electrical structures of dust storms, and the results demonstrated the turbulence-driven charge segregation and 3-D E-field pattern of dust storms.", in section 5.2 in the revised manuscript. Please see lines 25-29 on page 25 in the revised manuscript for the details.

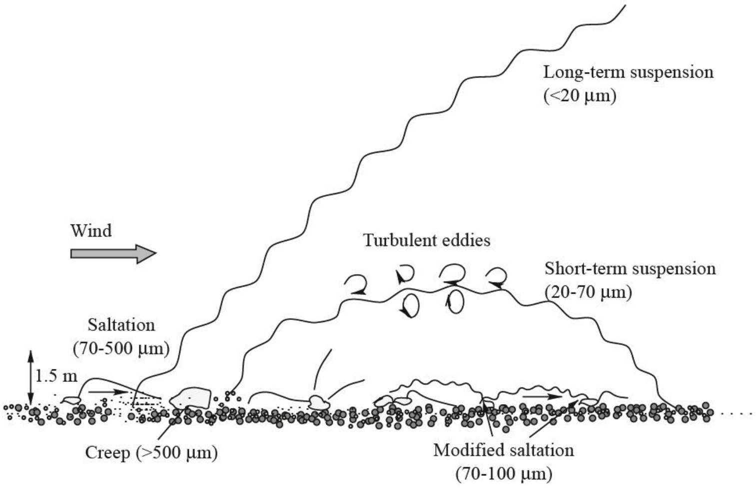


Figure R2. Schematic of creep, saltation, and suspension of soil particles during an erosion event. Saltation is further classified into pure and modified saltation and suspension is further divided into short-term and long-term suspension. Adapted from Shao (2008).

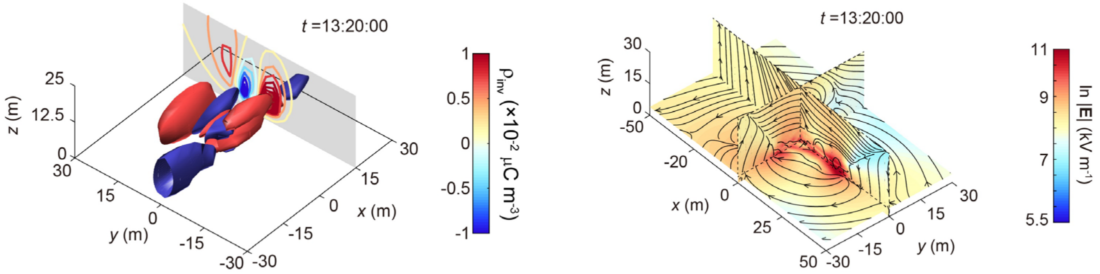


Figure R3. Left panel: 3D structure of the space-charge densities in an observed dust storm. Here, ρ_{inv} denote the reconstructed space-charge densities; x, y, and z denote the streamwise, spanwise, and wall-normal (i.e. vertical) directions, respectively. The isosurfaces are shown at a space-charge density magnitude of 0.02 μC m^{-3}; the positive surfaces are colored in red, while the negative surfaces are colored in blue. Times t are shown as the local time on April 16, 2017 (UTC+8). Contourslices at x = 15 m are colored based on the space-charge densities. Right panel: 3D structure of the E-fields in an observed dust storm. The 3D electric field was predicted from the reconstructed space-charge densities. Slices at x = 0 m, y = 0 m, z = 4 m are colored based on the log-magnitude of the 3D electric field, ln |**E**|. Times t are shown as the local time on April 16, 2017 (UTC+8). Lines represent the electric field lines. Adapted from Zhang and Zhou (2020).

4. The author didn't reply directly to the second review question. The author said the large-scale and super large-scale turbulent structures are the reasons for formation of the horizontal electric field, but actually the field measurement was below 1m height.

So why does the horizontal electric field is still produced under such a small-scale field?

Reply: We thank the reviewer for this comment. In dust storms, the electric field is produced by all charged particles, including saltating sand particles and suspended dust particles. Although the field measurement was performed below 1 m height (within the saltation layer), the electric field produced by the suspended dust particles (Figure R2) still exists in the saltation layer. In other words, the horizontal electric field is partly produced by the highly charged suspended dust particles. As shown in Figure R3, the large-scale charge pattern indeed produces an intense horizontal electric field in the saltation layer.

5. I know what the author mean for the 3D, but I think it is better to point out that the simulation is a 3D-DEM model rather than a 3D model, since it is a horizontal uniformed case.

Reply: We thank the reviewer for pointing out this question. In the revised manuscript, we have added the description, "In steady-state saltation, the mean streamwise wind speed is statistically stationary and statistically 1-D, so that the mean wind flow can be modeled as a 1-D field. In other words, in this study the numerical simulation is a 3-D DEM model for particle motion but a 1-D model for wind field.", in section 3 in the revised manuscript. Please see lines 6-10 on page 10 for the details.

6. In the response, the author considered if the difference between two velocity value is less than 5%, then the values are almost the same. But for the mass concentration of case 2 and case1, the difference is also less than 5%, and the author didn't consider it.

Reply: We thank the reviewer for pointing out this important question. We can explain this question by the actual values of the mass concentration m_c and mean particle horizontal speed $\langle u_p \rangle$ for different cases. As an example, at the 0.0008 m height, m_{c1}=0.841 kgm^{-3} and $\langle u_{p1} \rangle$=1.31 ms^{-1} for case 1 (i.e. without E-field), m_{c2}=0.8029 kgm^{-3} and $\langle u_{p2} \rangle$=1.2547 ms^{-1} for case 2 (i.e. with vertical component), and m_{c3}=1.0248 kgm^{-3} and $\langle u_{p3} \rangle$=1.2406 ms^{-1} for case 3 (i.e. with 3-D E-field). Hence, the mass fluxes for cases 1-3 are approximately 1.1017, 1.0074, and 1.2714 kgm^{-2}s^{-1}, respectively. It is clear that for mass fluxes we have case 2 < case 1 < case 3.

7. The updated fig. 5 shows the electric fields in different height. However, the horizontal E-fields are not always much larger than the vertical ones. It is height dependent. Thus, the author should point out it in his manuscript.

Reply: We thank the reviewer for this constructive suggestion. In the revised manuscript, we have added the description, "From Fig. 5, it can be seen that, the relative magnitudes of E_1, E_2, and E_3 vary with height. For example, the magnitude of E_3 is larger than that of E_1 and E_2 at 0.15 m height (Fig. 5k) but is smaller than that of E_1 and E_2 at 0.7 m height (Fig. 5n).", in section 4.1 in the revised manuscript. please see lines 5-8 on page 20 for the details.

8. The author added that “ the man-made 1-D E-field may enhance sand transport in pure saltation”. However, the 3D E-field introduced in this simulation work is also man-made, not self-produced by the charged particles. Thus, the difference between previous works and this work is just the direction of the E-field, which is easy to know the effects on the transport rate. Addition, I think the horizontal electric force do have significant impact on the trajectory since the transport rate is affected mainly by vertical electric field, and the horizontal electric field is even larger than the vertical one.

Reply: We thank the reviewer for this comment. We agree with the reviewer that the difference between previous works and this work is just the direction of the E-field. Accordingly, the sentence “It is worth noting that, unlike the natural 1-D E-field produced by the charged sand particles, the man-made 1-D E-field may enhance sand transport in pure saltation when it is oriented opposite to the natural 1-D E-field.” has been added in the manuscript. Please see lines 22-25 on page 27 for the details. Besides, the horizontal electric field indeed affects the transport rate significantly, because the mean particle horizontal speed is dependent on the horizontal electric field.

9. In the description of Fig. 7 (line 14-15, page 46), better as “ are estimated from Zheng et al (2003)”.

Reply: We thank the reviewer for this constructive suggestion. We have changed the description as suggested. Please see lines 14-15 on page 47 for the details.

10. In all, this manuscript is not suggested to publish before the revise.

Reply: We thank the reviewer again for the constructive comments. We hope that our new replies can be accepted by the reviewer.

References

Forward, K. M., Lacks, D. J., and Sankaran, R. M.: Particle-size dependent bipolar charging of Martian regolith simulant, Geophys. Res. Lett., 36, L13201, doi:10.1029/2009GL038589, 2009.

Kok, J. F., and Renno, N. O.: Electrostatics in wind-blown sand, Phys. Rev. Lett., 100, 014501, doi:10.1103/PhysRevLett.100.014501, 2008.

Kok, J. F., and Renno, N. O.: A comprehensive numerical model of steady state saltation (COMSALT), J. Geophys. Res.-Atmos., 114, doi:10.1029/2009JD011702, 2009.

Kok, J. F., and Lacks, D. J.: Electrification of granular systems of identical insulators, Phys. Rev. E, 79, 051304, doi:10.1103/PhysRevE.79.051304, 2009.

Kok, J. F., Parteli, E. J., Michaels, T. I., and Karam, D. B.: The physics of wind-blown sand and dust, Rep. Prog. Phys., 75, 106901, doi:10.1088/0034-4885/75/10/106901, 2012.

Lacks, D. J., and Sankaran, R. M.: Contact electrification of insulating materials, J. Phys. D-Appl. Phys., 44, 453001, doi:10.1088/0022-3727/44/45/453001, 2011.

Mehrani, P., Bi, H. T., and Grace, J. R.: Electrostatic charge generation in gas–solid fluidized beds. J. Electrostat., 63, 165-173, doi: 10.1016/j.elstat.2004.10.003, 2005.

Pähtz, T., Omeradžić, A., Carneiro, M. V., Araújo, N. A., and Herrmann, H. J.: Discrete Element Method simulations of the saturation of aeolian sand transport, Geophys. Res. Lett., 42, 2063–2070, doi:10.1002/2014GL062945, 2015.

Shao, Y. P.: Physics and Modelling of Wind Erosion, Springer Science & Business Media, Heidelberg, 2008.

Sowinski, A., Miller, L., and Mehrani, P.: Investigation of electrostatic charge distribution in gas–solid fluidized beds, Chem. Eng. Sci., 65, 2771-2781, doi: 10.1016/j.ces.2010.01.008, 2010.

Zhang, H., and Zhou, Y. H.: Reconstructing the electrical structure of dust storms from locally observed electric field data, Nat. Commun., in press, doi: 10.1038/s41467-020-18759-0, 2020.

Zheng, X. J., Huang, N., and Zhou, Y. H.: Laboratory measurement of electrification of wind-blown sands and simulation of its effect on sand saltation movement, J. Geophys. Res.-Atmos., 108, doi:10.1029/2002JD002572, 2003.