We thank the reviewers for the constructive comments and suggestions. We have modified the manuscript and believe that these modifications have substantially improved the manuscript. The following text contains the reviewers' comments (in black), our responses (in blue). All modifications in the revised manuscript associated with the reviewers' comments are highlighted in blue.

Anonymous Referee #3:

accepted as is

Response: We thank the reviewer for her/his positive appreciation of our work.

Anonymous Referee #4:

The author's responses of the review are long and in detailed. However, there are still some problems remaining:

1. According to the revised manuscript and the response of the review, the author expected the 3D electric field is produced by the very large turbulence structure, based on the idea of the volcanic eruption experiment of Cimarelli (2013). However, the size of particles in Cimarelli's experiment is binary distribution, and move in the vertical direction, while in the simulation of this paper, the size distribution of sand is continuous distribution based on field observation, and move horizontal, is the pattern of movement still the same as that of Cimarelli's experiments? In my opinion, the large particles are more likely to distribute near the ground due to gravity, and small particles disperse in the air, so that the vertical electric field should be much larger than horizontal electric field.

Response: We thank the reviewer for this important comment. Yes, we ensure that the pattern of particles' movement in our study is still the same as that of Cimarelli's experiments. The reasons are based on the following two facts. First, triboelectric charging in granular systems is generally size-dependent; that is, larger particles tend to charge positively while smaller particles tend to charge positively (please see Lacks, D. J., and Sankaran, R. M., J. Phys. D-Appl. Phys., 44, 453001, 2011 for the details). For example, Forward et al. have experimentally demonstrated that for a continuous distribution sand sample (see Fig. R1b), triboelectric charging still leads to the charge separation; that is, larger particles charge positively and the smaller particles charge negatively (see Fig. R1a). Second, the preferential concentration of discrete particles is a common occurrence in particle-laden turbulent flows (such as sand saltations and dust storms). In such cases, the small particles are affected by local turbulence and tend to accumulate in the interstitial regions between vortices, while the positively charged larger particles are unresponsive to turbulent fluctuations and are more uniformly distributed than the smaller. Notably, preferential concentration is dependent on the particle's Stokes number rather than the gravity (please see Eaton, J. K., and

Fessler, J. R., International Journal of Multiphase Flow, 20, 169-209, 1994 for the details). In summary, we can reasonably infer that during dust storms, the negatively charged finer dust particles (<10 μm) accumulate in specific regions, while the positively charged coarser sand particles (>100 μm) are more uniformly distributed due to its large inertia. In addition to Cimarelli et al. (2013), this charge separation phenomenon has also been demonstrated in various conditions (for example, Renzo and Urzay, 2018; Lu et al. physical review letters, 104(18), 184505, 2010).

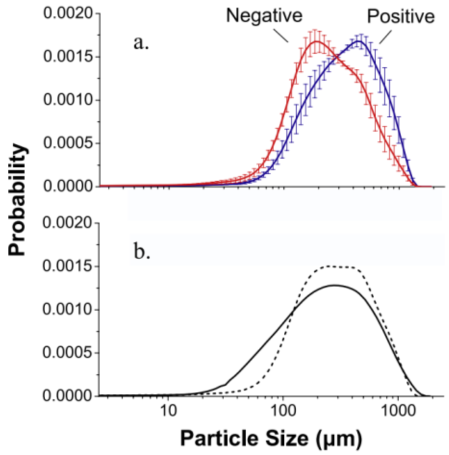

Figure R1 (adapted from Forward et al. 2009, Geophys. Res. Lett., 36, L13201). Particle size distribution of JSC-1 Mars simulant. (a) Negatively charged (red) and positively charged (blue) particles. (b) Original sample (solid) and average of collected samples (dashed).

2. The author explained that large-scale and super large-scale turbulent structures are the reasons for formation of the horizontal electric field. While the size of large-scale or the super large-scale structures should be several ten meters or hundred meters, which is much larger than the scale of the experiment (below 1m) in the manuscript.

Response: We thank the reviewer for this comment. Yes, our field measurements were performed within the layer below 1 m height because we focused on the sand saltation during dust storms (the mean saltation height is less than 0.2 m, see Kok et al., Rep. Prog. Phys., 75, 106901, 2012 for the details). However, in addition to sand saltation, there exists a huge number of suspended dust particles (i.e., suspension movement) during dust storms. The actual dust storms occurred in a very large area over hundreds of square kilometers and could reach up to thousands of meters of height (please see Shao, 2008).

3. The author declared it is a 3D simulation, but the width of the domain in the manuscript is only 0.1 meters, which is much smaller than vertical scale, which should be considered as a 2D model.

Response: We thank the reviewer for this comment. We believe that our simulation is 3D. Although the vertical size of the computational domain is set to be 1 m, the effective vertical size is less than about 0.2 m because a great amount of saltating particles is moving below 0.2 m (please see Figs. 4a and 10a). Therefore, the ratio of effective streamwise size: spanwise size: vertical size = 0.5:0.1:0.2 = 5:1:2, suggesting that streamwise, spanwise and vertical sizes are comparable. On the other hand, the ratio of the width of the domain to the mean particle diameter is 0.1/0.0001 = 1000, which is much larger than the 3D simulation in other DEM simulations (for example, 3D domain $700D_{mean}*50D_{mean}*7.5D_{mean}$ used in Carneiro et al., 2013).

4. The author indicated the mean mass-charge ratio is independent with the particle size distribution. However, the author calculated the charge based on the charge separation model, in which the amount charge transferred is calculated by the different contact surfaces. So, the mass charge ratio should be affected by the particle size distribution.

Response: We thank the reviewer for this comment. We agree with the reviewer that particle size distribution has a significant implication on the mean charge-to-mass ratio. However, in this manuscript, we did not discuss the influences of particle size distribution on the mean charge-to-mass ratio, because the particle size distribution was set the same as the field measurements and we are mainly concerned with the effects 3D E-field on saltation. According to the reviewer's suggestion, we plan to investigate the effects of particle size distribution on particle charging in future work.

5. The number of Eq. 28 (line 18 in page 19) is wrong, which should be 29.

Response: We thank the reviewer for noting this error. We have corrected it as suggested.

6. The author was wrong in response of question 10): below 0.01m, we can see from the Fig .10, mean velocity <up>, case 1<case 2≈case 3, not case 3 ≤case 2≤case 1, so we cannot conclude the value of mas flux: case2< case 1<case3, it should be case 1<case 2 < case 3.

Response: We thank the reviewer for this comment. The reviewer may confuse the x- and y-axis of Fig. 10b. In Fig. 10b, the x-axis represents the mean particle velocity $\langle u_p \rangle$ and the y-axis represents the height z. Below 0.01 m, for example at 7×10^{-4} m height (the inset of Fig. 10b), $\langle u_p \rangle$ =1.3 m/s for case 1, $\langle u_p \rangle$ =1.25 m/s for case 2, and $\langle u_p \rangle$ =1.225 m/s for case 3, as depicted by the dashed lines in the following figure. This suggests that for mean particle velocity $\langle u_p \rangle$ we have case 3 $\lesssim$ case 2 $\lesssim$ case 1 because these differences are less than 5 %, i.e., (case 1-case 2)/case 2 = (1.3-1.25)/1.25 =4 %. This indicates that mean particle velocities $\langle u_p \rangle$ are almost the same for the three cases. Since for mass concentration m_c we have case 2 < case 1 < case 3, we can reasonably conclude that case 2 < case 1 < case 3 for mass flux. Please see Fig. 10 for the details.

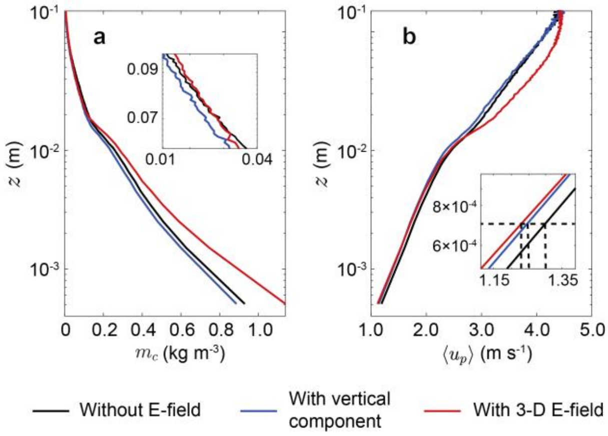

Figure 10. Vertical profiles of the particle mass concentration m_c and mean particle horizontal speed $\langle u_p \rangle$ for different cases, where $\langle u_p \rangle$ is calculated as the arithmetic mean of particle horizontal speed located in the range of $[z, z+\Delta z]$. Insets show the same data and emphasize the local information. In these cases u_*=0.37 m s^{-1}, d_m=200 μm, σ_p=exp(0.42), ρ_h^0=6×10^{15} m^{-2}, and e_n=0.7.

7. In section of 3.5, the author made a wrong cite, which there is no definition of mean charge to mass ratio in the papers of Carneiro et al., 2013 and Dupont et al., 2013. Actually, the unit of mean charge to mass ratio should be C/kg, while in the formula(28d), the author considered it as m*C/s, which is not suitable in basic physic meaning.

Response: We thank the reviewer for this important comment. Indeed, Carneiro et al. and Dupont et al. did not define the mean charge-to-mass ratio, but the mass flux was explicitly defined in their papers. Therefore, when calculating mass flux (i.e., Eqs. 28a and 28b) we cited these two papers. In this study, we defined the mean charge-to-mass ratio $\langle \zeta_p \rangle$ as the ratio of charge flux and mass flux in the range of $[z, z+\Delta z]$,

$$\langle \zeta_p \rangle = \frac{\sum \zeta_{p,i} m_{p,i} u_{p,i}}{\sum m_{p,i} u_{p,i}}$$

Clearly, the units of $\langle \zeta_p \rangle$ in the manuscript is

$$\frac{\text{C/kg*kg*m/s}}{\text{kg*m/s}} = \text{C/kg}$$

which is C/kg, not m*C/s. According to the reviewer's comment, we have cited these papers (i.e., Carneiro et al., 2013 and Dupont et al., 2013) at a suitable position. Please see lines 3-4 in page 18 for the details.

8. In the supplement file, the PSD of particles was plotted in Figure S1, in which the mean particle size is around 100um. The author chose 100uC/kg as the mean charge to mass ratio, as well as considered the mean charge of one particle with 1.64×10^{-12},

which are contradictory. The mean charge of one particle should be calculated as Q=charge mass to ratio*Mass of particle = 100uC/kg*4/3π*$(10^{-4})^3$ ≈ $(10)^{-16}$, which is not agree well with the value of charge to mass in the paper of Merrison (2013).

Response: The reviewer has omitted the mass density of sand particles (i.e., 2650 kg/m^3) when calculating the "mass of particle". The correct Q is estimated as: Q = 100μC/kg*4/3π*(10^{-4} m)^3*2650 kg/m^3 ≈ 1.11*10^{-12} C, consistent with Merrison (2012).

9. In page 23, the author wrote the charge density effects the magnitude of transferred charges a lot when the charge density is low, which is easily to make a misunderstand. First, the author needs to clarify the reason why different particles have different capacity on unit surface. Actually, this character ρ_0 should not be called the charge density of particles. The author used it as the maximum capacity of charge on each unit surface on particles. The charge density should be calculated by the total charge divided by the particle surface. ρ_0 should be a constant value, which should be only decide by the material of the particles. The reason why when ρ_0 is over 10^{18}, the mean charge to mass ratio getting stable is the product of $\rho_i S_i - \rho_j S_j$ is getting same value. ρ_0 is not the main decision role anymore in the calculating this formula.

Response: We thank the reviewer for this comment. In this study, the charge transfers between two contacting particles are determined based on the most commonly used asymmetric contact model (We refer the reviewer to the papers: Kok, J. F., and Lacks, D. J., Phys. Rev. E, 2009; Lacks, D. J., and Sankaran, R. M., J. Phys. D-Appl. Phys., 44, 453001, 2011). First, in this model, ρ_0 is the initial density of the electrons trapped in the high energy states on the surface of particle rather than the maximum capacity of charge on each unit surface on particles, because the instantaneous density ρ_h^i on particle i changes in every collision and can be larger than the initial density ρ_0. Second, the instantaneous density ρ_h^i is indeed determined by the total trapped electrons divided by the particle surface (i.e., Eq. 26). Third, under certain condition, ρ_0 is a constant, but it varies with environmental conditions such as ambient temperature and relative humidity (please see also Lacks, D. J., and Sankaran, R. M., J. Phys. D-Appl. Phys., 44, 453001, 2011). Therefore, the typical ρ_0 ranges from ~10^{14}-10^{20} states/m^2 (please see Kok, J. F., and Lacks, D. J., Phys. Rev. E, 2009). Finally, we agree with the reviewer that the reason for getting a stable value of mean charge-to-mass ratio when ρ_0 exceeds 10^{18} is due to the same values of $\rho_i S_i - \rho_j S_j$. In the revised manuscript, we have modified the statements as "However, for larger ρ_h^0, Δq_{ij} is no longer proportional to ρ_h^0 because in this case the difference of the number of trapped electrons between two colliding particles (i.e. $\rho_h^j S_j - \rho_h^i S_i$) has the same value and ρ_h^0 is not the key parameter for determining the mean charge-to-mass ratio (Kok and Lacks, 2009)." in order to more clearly illustrate the effects of larger ρ_0. Please see lines 6-10 in page 23 for more details.

10. In Figure 5, the author showed the details about the electric field value varies with time. There is an interesting phenomenon that the magnitude of spanwise electric field and streamwise electric field are almost the same, and the vertical electric field oppositely varies in trend comparing to them. The author didn't explain the reason of

this phenomenon. If the author considers the spanwise and horizontal electric field are caused by the structure of turbulence, why does the magnitude and variation of spanwise electric field and streamwise electric field are almost the same? In fact, the turbulence structures in spanwise and streamwise should be different.

Response: We thank the reviewer for this important comment. We are sorry that this issue is not clear enough in the previous version of the manuscript. In the previous manuscript, we only showed the electric field time series at 0.7 m height, which made a misunderstanding that the magnitudes of the streamwise and spanwise electric fields were larger than that of the vertical electric field. In fact, the relative magnitudes of the horizontal (i.e., streamwise and spanwise) and vertical electric fields vary from height to height. According to the reviewer's comment, we have added all measured electric field data from 0.05 to 0.7 m heights in Fig.5 of the revised manuscript (please see lines 3-6 in page 20 and Fig. 5 in page 44). For example, Fig. 5 shows that the magnitude of E_3 (vertical electric field) is larger than that of E_1 (streamwise electric field) and E_2 (spanwise electric field) 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). As we previously explained, this complex electric field pattern is due to the charge separation by turbulence. Also, the streamwise and spanwise electric fields are distinctly different, even though at 0.7 m height the time-varying means of these two electric field components are very similar.

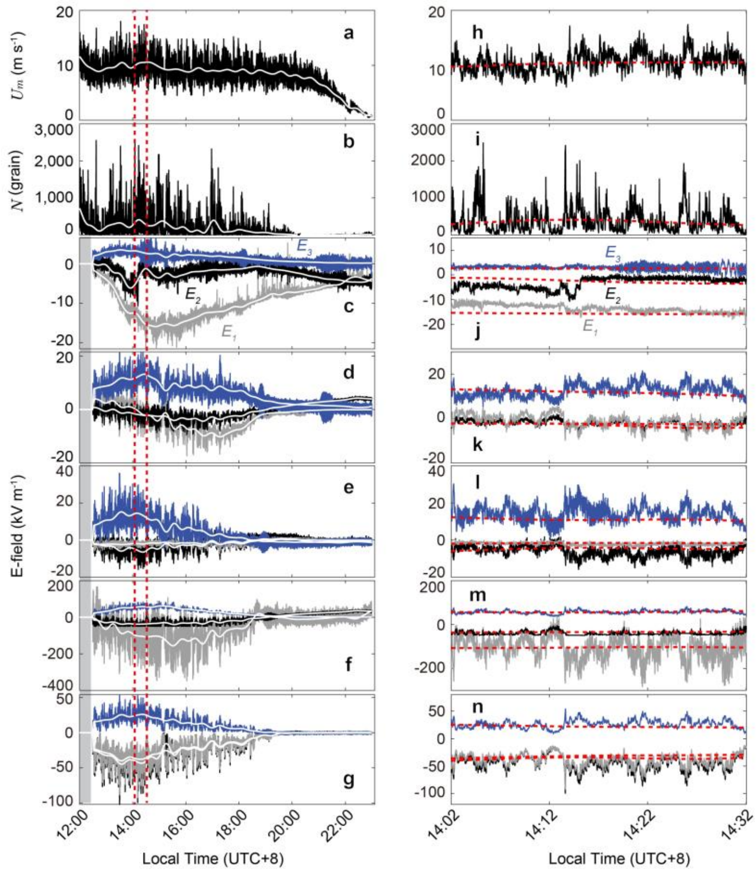

Figure 5. Measured data during a dust storm occurring on May 6, 2014, at the QLOA site. Panels (a)-(b) show the measured time series of the streamwise wind speed, u_m

at 0.7 m and the number of saltating particle N at 0.15 m. Panels (c)-(g) correspond to the streamwise E-field E_1 (grey lines), spanwise E-field E_2 (black lines), and vertical E-field E_3 (blue lines) at 0.05, 0.15, 0.3, 0.5, and 0.7 m height, respectively. Unfortunately, owing to the interruption of power supply, the 3-D E-field data have not been recorded before ~12:30, as represented by a shaded area in the last five panels (c)-(g). The dashed box denotes the relatively stationary period of the observed dust storm because during this period the time-varying means of all quantities (such as χ_{10} depicted by the solid white lines in panels a-g and dashed red lines in panels h-n) do not vary notably as time varies (Bendat and Piersol, 2011), as shown in (h)-(n).

11. In the manuscript, the results show that the horizontal electric field is much stronger than the vertical electric field, which indicate particles will have strong spanwise motions, which seem not consistent with the real situation. The author could compare the magnitudes of the horizontal electric force and drag force.

Response: We thank the reviewer for this comment. We disagree with the reviewer that the large horizontal electric field suggests a strong spanwise motion. The large horizontal electric field only suggests that space charge distribution in the horizontal plane is nonuniform, which can be caused by the unsteady incoming flow (e.g., Zhang et al., 2014) and turbulent fluctuations (e.g., Cimarelli et al. 2013; Renzo and Urzay, 2018). Since in actual conditions there are no significant spanwise motions, the comparison of the magnitudes of the horizontal electric force and drag force in the revised manuscript is not needed.