Dear Editor Ulrich Pöschl and reviewers,

Thank you very much for reviewing our work and for providing the insightful and helpful comments. The following text contains the Referees' comments (black), our replies (blue) and the changes made to the manuscript (dark green). Due to the new analyses, several figures have been renumbered. We believe that the revised manuscript comprehensively addresses all concerns raised.

Anonymous Referee #1
accepted as is

We would like to thank Anonymous Referee #1 for her/his positive appreciation of our work.

Anonymous Referee #2

accepted subject to minor revisions

1. The authors stated in the introduction that the E-field effects on lifting and transport have been studied, which is followed by saying the effects on saltation remain obscure. Saltation is also a transport process. Please revise the statement to clarify what aspects of transport have been studied.

Thank you very much for this very insightful comment. We have now revised the statement as suggested.

Changes made: The significant influences of E-field on pure saltation (that is, in the absence of suspended dust/aerosol particles) have been verified, both numerically (e.g. Kok and Renno, 2008; Zhang et al., 2014) and experimentally (e.g. Esposito et al., 2016; Rasmussen et al., 2009). The effects of E-field on saltation during dust storms, however, remain obscure.
Please see lines 12-16 in page 3.

2. In the revised MS, both discrete wavelet transform (DWT) and the ensemble empirical mode decomposition (EEMD) are used to estimate the time-varying mean E-field. The authors used the 10th order approximation component of DWT that reflects an average timescale of 2e10 s and the last four EEMD components with a maximum mean frequency of 5.78e-2 Hz to reach the conclusion that both methods can capture the time-varying mean over a timescale of 17 minutes. However, 5.78e-2 Hz equals to ~ 17.3 seconds. Therefore the two methods should have captured different features but interestingly results seemed to agree. Does it mean that the dust storm actually was more stationary than expected at least in the timescale range of 17 s - 17 min?

We are sorry that the relationship between DWT and EEMD was not clear enough in the previous version of the manuscript. In fact, DWT and EEMD capture a very similar time-varying mean almost over the same timescale, because EEMD is conceptually very similar to the DWT and EEMD behaves as a “wavelet-like” filter bank. A detailed description of the similarities between DWT and EEMD can be found in Flandrin (2004). In the revised manuscript, a clear and concise statement is added to section 2.2, following the discussion of fig. 3.

Flandrin, P., Rilling, G., and Goncalves, P.: Empirical mode decomposition as a filter bank, IEEE Signal Process. Lett., 11, 112–114, doi: 10.1109/LSP.2003.821662, 2004.

Changes made: It can be seen that DWT and EEMD can properly capture a similar time-varying mean (Fig. 2a). This is because the EEMD is conceptually very similar to the DWT and thus behaves as a “wavelet-like” filter bank (Flandrin, 2004). As shown in Fig. 3, the frequencies contained in the DWT and EEMD components become progressively lower, where the mean frequencies of ψ_{10} and ξ_9 are 7.69×10^{-4} and 7.24×10^{-4} Hz, respectively. The time-varying means (defined as the summation of the components below the dashed line in Fig. 3) χ_{10} and $\sum_{i=10}^{13}\xi_i+\eta_{13}$ show very close mean frequencies of 7.71×10^{-6} and 7.85×10^{-6} Hz,

respectively. We thus conclude that such definitions in Eq. (3) and (5) can extract the time-varying mean over a certain scale of about 7.47×10^{-4} Hz (below the dashed line in Fig. 3).
Please see lines 13-22 in page 8.

Added figure:

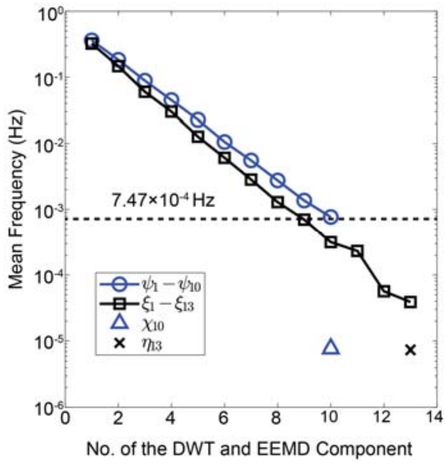

Figure 3. The Mean frequencies of DWT and EEMD components of E_3 at 0.5 m height. The dashed line around the components ψ_{10} and ξ_9 corresponds to the frequency of 7.47×10^{-4} Hz.

Additionally, we cannot conclude that dust storm was more stationary than expected in the timescale range of 17 s - 17 min, because the stationarity is measured by the statistics (such as mean and autocorrection function) of a time series rather than its DWT and EEMD components.

3. The authors used >= 0.5 for the restitution coefficient in the analysis. Would you please provide reasoning for excluding the <0.5 range? Is there a known range of en for sand particles?

Thank you for pointing this out. As in previous studies, we used $e_n \geq 0.5$ because e_n has been determined to lie in the range of ~0.5-0.6 for sand particles. Please see Haff and Anderson (1993) and Kok et al. (2012) for more details.

Added text: As in previous studies (e.g. Haff and Anderson, 1993; Carneiro et al., 2013), the selected e_n is larger than 0.5 since the e_n of quartz sand particles has been expected to lie in the range of ~0.5-0.6 (Haff and Anderson, 1993; Kok et al., 2012).
Please see lines 17-19 in page 21.

4. In the revised MS, the dimensionless variables are denoted with a superscripted '+'. This can cause confusion, especially when talking about E-field. I would suggest to follow the usual custom by using '*' instead.

Corrected as suggested.

5. How is the steady period of the observed dust storm defined? Also please be consistent with either 'steady' or 'stationary' period when referring to the shaded area in Fig. 4.

Thank you for this very insightful suggestion. As suggested, in the revised manuscript we use 'stationary' rather than 'steady' when referring to the shaded area in fig.4. A period is said to be relatively stationary if time-varying means of all quantities (including wind speed, number of saltating particle, and 3-D electric field) do not vary notably with time (Bendat and Piersol, 2011). By contrast, 'steady' generally indicates that a quantity (not its statistics) does not vary with time. Therefore, in the revised manuscript, fig. 4 (i.e. fig.5 in the revised manuscript) and its caption have been changed as follows.

Bendat, J. S., and Piersol, A. G.: Random data: analysis and measurement procedures, John Wiley & Sons, Hoboken, 2011.

Changes made:

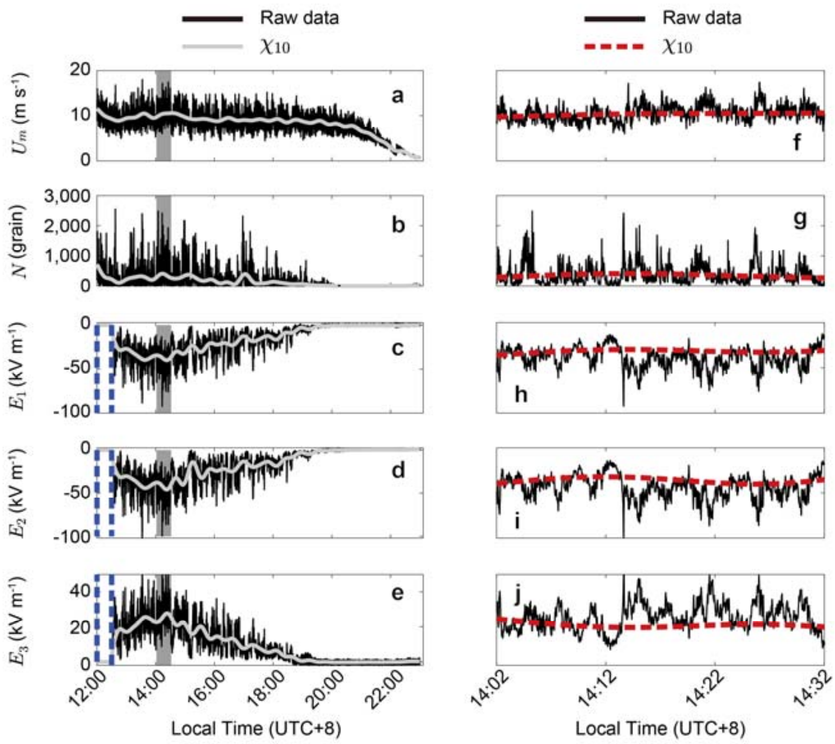

Figure 5. Measured results during a dust storm occurring on May 6, 2014, at the QLOA site. (a)-(e): the measured time series of the streamwise wind speed, u_m at 0.7 m; the number of saltating particle N at 0.15 m; streamwise E-field E_1, spanwise E-field E_2, and vertical E-field E_3 at 0.7 m. Unfortunately, owing to the interruption of power supply, the 3-D E-field data have not been recorded before ~12:30, as represented by a dashed box in the last three panels (from top to bottom). The shaded area denotes the relatively stationary period of the observed dust storm, because during this period the time-varying means of all quantities (i.e. χ_{10}) do not vary notably as time varies (Bendat and Piersol, 2011), as shown in (f)-(j).

6. Some editing and grammatical suggestions (incomplete): P2: line22, remove 'truly'; line24, remove 'will'; line29, an ubiquitous. P3: line4, its direction reversed. P11: line1, is altered. P20line1 & P21line 24 dependent on...P24: line9, is effective to...

We have corrected all the noted grammatical suggestions, and thank you for catching them.

Anonymous Referee #3
Rejected

I think there are some major problems in the paper, which suggest that the main ideas and conclusions may be incorrect. Furthermore, I don't think the reviewer responses really addressed the previous reviewer comments -- the responses were so long and strayed from the point, rather than clearly and effectively focusing on the concern.

Thank you very much for reviewing our work and many very insightful comments. As you suggested, this new response letter is clear, concise and well-documented. We believe that all problems you concerned have been addressed.

1. The authors continually say throughout the paper that previous 1d electric fields found reduction in saltation mass. This is not true. Kok Renno 2008, as well as other papers, predicted/found enhancement of saltation with 1d electric fields. This is a major problem.

Thanks for your comments. In fact, the saltation mass flux is indeed inhibited by the vertical electric field (1D electric field) in pure saltation (Zheng et al. 2003; Kok and Renno, 2008). This is because the electrostatic forces exerted by the natural electric field on the saltating particles are downward-pointing, as illustrated in Fig. R1a.

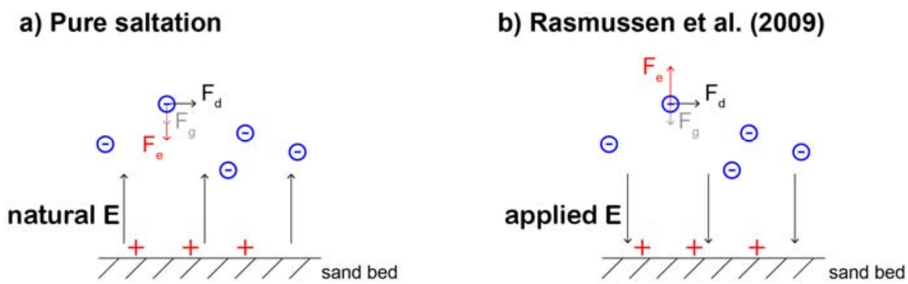

Figure R1. Schematic of the forces acting on the negatively charged (on average) saltating particles. Here, F_d, F_g, and F_e denote the drag force, gravitational force, and electrostatic force. (a) The downward-pointing F_e exerted by the natural electric field produced by the charged sand particles. (b) The upward-pointing F_e exerted by the man-made electric field.

For example, the results of Kok and Renno (2008) found that 1D (vertical) electric field inhibited saltation mass flux in the case of pure saltation. As shown in Fig. R2, with vertical electric fields (red lines), mass flux is decreased compared to without vertical electric fields (black lines), especially for high shear velocity. This conclusion is also demonstrated by other studies conducted in pure saltation when saltating particles is negatively charged, such as Zheng et al. (2003).

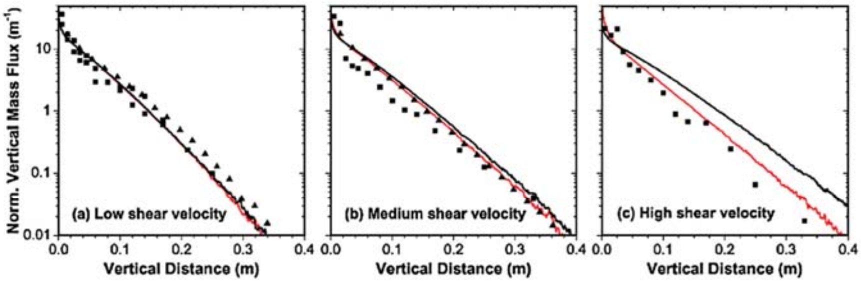

FIG. 3 (color). Vertical profiles of saltation mass flux measured in field experiments (squares [13] and triangles [14]), and compared to model results with and without electric forces (solid red lines and solid black lines, respectively). Both measured and modeled mass flux profiles are normalized by their total mass flux to simplify comparison. Results are shown for (a) low shear velocity ($u^* = 0.32$ m/s), (b) medium shear velocity ($u^* = 0.47$ m/s), and (c) high shear velocity ($u^* = 0.63$ m/s). Model results were obtained for the size distribution reported in Ref. [13].

Figure R2. (adapted from Kok and Renno, 2008) Effects of vertical electric field on saltation mass flux.

As you pointed out that, on the other hand, the saltation mass flux is enhanced by a man-made (produced by two parallel-plate electrodes) intense inverted electric field, as illustrated in Fig. R1b. Rasmussen et al. (2009) found an increase of mass flux with 1D electric fields, but this case is quite different form our simulated true saltation during dust storms. Rasmussen et al. (2009) used two parallel-plate electrodes to generate a downward-pointing electric field up to 270 kV/m in a wind tunnel (please see Fig. R3), where the applied electric field is opposite to and two orders of magnitude larger than the natural electric field produced by the charged sand particles in wind tunnel (see Fig. R4, Zheng et al., 2003). Such intense electric field applies a large upward-pointing electrostatic force on sand particles, leading to a significant enhancement in saltation mass flux.

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

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.

Rasmussen, K. R., Kok, J. F., and Merrison, J. P.: Enhancement in wind-driven sand transport by electric fields, Planet Space Sci., 57, 804–808, doi:10.1016/j.pss.2009.03.001, 2009.

In order to make this issue clearer, we have added additional discussion of man-made electric field.

Added text: 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. For example, Rasmussen et al. (2009) found that sand mass flux in pure saltation is significantly enhanced when a downward-pointing external E-field (opposite to the direction of actual vertical E-field) with magnitude of 270 kV m^{-1} is applied. Please see lines 13-18 in page 27.

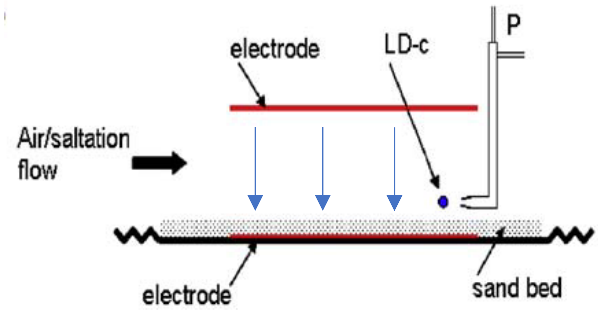

Figure R3. (adapted from Rasmussen et al., 2009) Two parallel-plate electrodes are used to generate the external electric field.

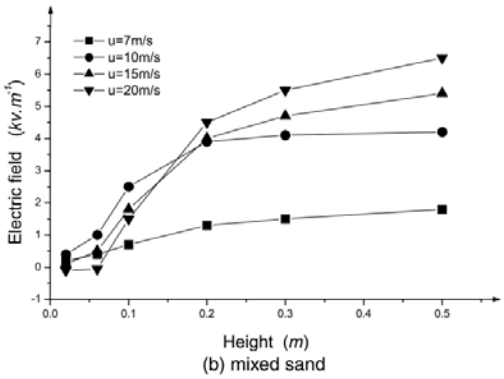

Figure R4. (adapted from Zheng et al., 2003) Measurement of magnitude of electric field strength versus height in wind-blown sand cloud with mixed sand in a wind tunnel.

2. A previous reviewer brought up a very important point, and the authors do not give a convincing answer. The reviewer says "However, the manuscript does not explain why streamwise E-field and spanwise E-field happens, and why are they an order of magnitude larger than the vertical electric field?" - the answer the authors give is vague hand waving, and does not convince me. There is a physical justification for electric field in the vertical direction -- charge depending on particle size, and height of particles depending on particle size -- thus charge depends on height giving an electric field. But there is no physical justification for systematic streamwise or spanwise fields (that I'm aware of), other than random fluctuations - in my opinion, this finding suggests that perhaps the results are simply incorrect and unreliable, and that the paper should not be published as it would be very misleading. It is incumbent on the reviewers to demonstrate that their results are correct, both in terms of the measurement and the physically reasonable basis.

Thanks for your very important comments. We apologize for the lack of clarity here. In the revised manuscript, the generating mechanisms of the intense streamwise and spanwise electric fields are discussed in detail in section 5.2.

We infer that the generation of streamwise and spanwise electric fields is related to the charge segregation of oppositely charged particles by turbulence. The reasons are as follows. In fact, the aerodynamic generation of 3-D electric fields in particle-laden turbulent flows has been previously documented by both numerical simulations (Renzo and Urzay, 2018) and laboratory experiments (Cimarelli et al., 2013). That is, the negatively charged 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. For example, as shown in Figs. R5C and R5E, due to different responses to turbulence, charge separation is produced according to grain size (please see Cimarelli et al., 2013 for more details). In dust storms, the particle size is widely distributed from several micrometers to a few millimeters, indicating that charge separation is ubiquitous. In addition, since there exist large or very large turbulent structures in atmospheric surface layer flows, we thus expect that the very strong streamwise and spanwise electric fields are related to the large or very large turbulent structures. Please see section 5.2 in the revised manuscript for more details.

Cimarelli, C., Alatorre-Ibargüengoitia, M. A., Kueppers, U., Scheu, B., and Dingwell, D. B.: Experimental generation of volcanic lightning, Geology, 42, 79 – 82, doi: 10.1130/G34802.1, 2014.

Di Renzo, M., and Urzay, J.: Aerodynamic generation of electric fields in turbulence laden with charged inertial particles, Nat. Commun., 9, 1–11, doi: 10.1038/s41467-018-03958-7, 2018.

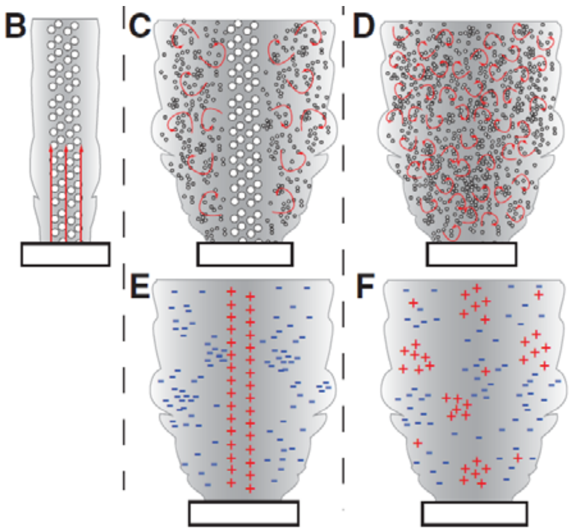

Figure R5. (adapted from Cimarelli et al., 2003) B: Monodisperse coarse beads form collimated flow and no lightning occurs. C: In bimodal blends, coarse beads are at core of flow and fines form turbulent shell. D: Monodisperse fine beads move according to local flow turbulence. E: For bimodal blends, coarser particles tend to have relative positive charge with respect to Earth, whereas smaller particles tend to charge negatively. Their different responses to fluid dynamics provide mechanism for charging and charge separation according to grain size. F: For monodisperse fine particles, transient clustering with different relative charge density provides necessary gradient for discharges (in E and F, positive and negative symbols represent relative charge density, not necessarily different polarity).

Added text: In contrast to the vertical component which is closely related to the total mass loading (Esposito et al., 2016; Williams et al., 2009), the intense streamwise and spanwise components of the E-field may be aerodynamically created by the unsteady wind flows (Zhang et al., 2014) and turbulent fluctuations (Cimarelli et al., 2013; Renzo and Urzay, 2018). It is well-known that dust storm is a polydisperse (having dust particles with diameters from <10 μm to ~500 μm) particle-laden turbulent flow at very high-Reynolds-number (up to ~108). The wind flow in dust storms is certainly unsteady and random. Numerical simulation by Zhang et al. (2014) showed that the unsteady incoming flow could lead to the nonuniform transport of charged particles in the streamwise direction and thus resulted in fluctuating streamwise and vertical E-fields. In addition to unsteadiness, recent direct numerical simulation (Renzo and Urzay, 2018) and laboratory experiment (Cimarelli et al., 2013) of particle-laden turbulent flows demonstrated that the generation of 3-D E-field could be caused by turbulent fluctuations. That is, the negatively charged 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 (Cimarelli et al., 2013; Renzo and Urzay, 2018). We thus reasonably expect that 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. Doubtless, such charge segregation could produce 3-D E-field (e.g. Renzo and Urzay, 2018). To sum up, the generating mechanisms responsible for the streamwise and spanwise E-fields in dust storms are probably the charge segregation caused by unsteady wind flows and turbulent fluctuations.

Additionally, one possible explanation for the intense streamwise and spanwise E-fields is that there exists large- and very-large-scale motions in atmospheric surface flows, leading to a large extent charge segregation in the streamwise and spanwise directions. In atmospheric surface layer flows, the largest vortices or coherent motions of the wind flows are found to be compared to the boundary layer thickness (~60-200 m) (Kunkel and Marusic, 2006; Hutchins et al., 2012). This may lead to a phenomenon that the charged particles are more nonuniformly distributed (over a larger spatial scale) in the streamwise and spanwise directions than in the vertical direction. Accordingly, the intensity of the streamwise and spanwise E-fields is probably larger than that of the vertical E-field.

Please see pages 24-26.

3. The authors argue that the effects of mid-air particle-particle collisions are significant. I'm surprised by this, since the density of particles in the air is low, but perhaps they might be right. The authors should justify this claim is reasonable with a simple and easy-to-follow analysis, where they find the mean free path between collisions of the particles, which can be easily done in the same way its done for gases in physical chemistry textbooks. How does the mean-free path compare with the distance traveled during a saltation hop, and how many collisions would be expected per hop?

Thanks for your comments. Many studies reported that midair collisions played important roles in sand saltation, because the volume fraction of saltating particles was too high near the sand bed, for example

Carneiro, M. V., Araújo, N. A., Pähtz, T., and Herrmann, H. J.: Midair collisions enhance saltation, Phys. Rev. Lett., 115, 058001, doi:10.1103/PhysRevLett.111.058001, 2013.
Huang, N., Zhang, Y., and D'Adamo, R.: A model of the trajectories and midair collision probabilities of sand particles in a steady state saltation cloud, J. Geophys. Res.-Atmos., 112, doi: 10.1029/2006JD007480, 2007.
Sørensen, M., and McEwan, I.: On the effect of mid-air collisions on aeolian saltation, Sedimentology, 43, 65-76, doi: 10.1111/j.1365-3091.1996.tb01460.x, 1996.

Previous studies found that midair collisions enhanced saltation mass flux substantially (Carneiro et al., 2013) and the probability of midair collisions increased linearly with wind speed (Huang et al., 2007). We thus consider midair collisions in our numerical model. The collisions frequency p of a particle during time interval dt can be readily estimated as follows (see Sørensen and McEwan, 1996; Huang et al., 2007 for the detailed derivation):

$$p = c\pi d^2 u dt \qquad (R1)$$

where c is particle number concentration, d is particle diameter, and u is particle velocity. As shown in Fig. R6, for typical wind shear velocity of 0.49 m/s, sand concentration c is about 10^{10} grains/m^3. If we set d=200 μm, u=5 m/s and dt=0.001 s, then p is estimated to be

$$p = 10^{10} \times \pi \times (2 \times 10^{-4})^2 \times 5 \times 0.001 \approx 6 \qquad (R2)$$

This estimation indicates that midair collisions is significant at lower height. In the revised manuscript we have added a related description.

Added text: Under moderate conditions, saltation is a dilute flow in which the particle-particle collisions are negligible. However, as wind velocity increases, midair collisions become increasingly pronounced, especially in the near-surface region (Sørensen and McEwan, 1996). Previous studies found that the probability of midair collisions of saltating particles almost increased linearly with wind speed (Huang et al., 2007) and such collisions indeed enhanced the total mass flux substantially (Carneiro et al., 2013).
Please see lines 23-28 in page 13.

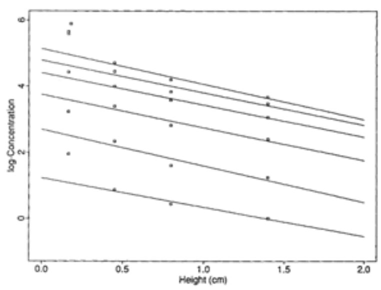

Figure R6. (adapted from Sørensen and McEwan, 1996). Concentration profiles (grains/cm^3) calculated by the McEwan-Willetts model (squares) and the fitted curves of the type given by Eq. (5) (full drawn lines). The grain concentration increases with shear velocity (U*=28, 35, 49, 66, 79, 90 cm/s).

Anonymous Referee #4

accepted subject to minor revisions

This manuscript discovered an interesting phenomenon in wind blown sand field, which is 3D-electric field. This topic in frontier and has innovation. There are some questions according to the manuscript.

Thank you for your positive and constructive comments.

1) The electric field caused by the wind blown sand is due to the charged particles, and the 3D E-field is correlated with the particle concentration on 3 direction. It is suspicious that the magnitude of streamwise E-field is ten times larger than the vertical E-field. For the streamwise and spanwise particle concentration is much more even than the vertical E-field. Why there would be a stronger E-field in streamwise and spanwise? Does the value of wind pressure related with the measured E value? Please explain more in details about the sensor you use and the measure method.

Thanks for your important suggestions. We are sorry that this was not clear in the previous version of the manuscript.

In the revised manuscript, we infer that the possible generating mechanisms of the streamwise and spanwise electric fields include the charge segregations by turbulent fluctuations (Cimarelli et al., 2013; Renzo and Urzay, 2018). In fact, the aerodynamic generation of 3-D electric fields in particle-laden turbulent flows has been previously documented by both numerical simulations (Renzo and Urzay, 2018) and laboratory experiments (Cimarelli et al., 2013). For example, as shown in Figs. R1C and R1E, due to different responses to turbulence, charge separation is produced according to grain size (please see Cimarelli et al., 2013 for more details). We can reasonably expect that, in dust storms, the negatively charged fine dust particles tend to accumulate in the interstitial regions between vortices (with largest size of compared to boundary layer thickness, ~60-200 m), while the positively charged coarser sand particles are more uniformly distributed due to its large inertia. Such charge segregations by turbulence can produce 3-D electric field.

Cimarelli, C., Alatorre-Ibargüengoitia, M. A., Kueppers, U., Scheu, B., and Dingwell, D. B.: Experimental generation of volcanic lightning, Geology, 42, 79 – 82, doi: 10.1130/G34802.1, 2014.

Di Renzo, M., and Urzay, J.: Aerodynamic generation of electric fields in turbulence laden with charged inertial particles, Nat. Commun., 9, 1–11, doi: 10.1038/s41467-018-03958-7, 2018.

In addition, since there exist large or very large turbulent structures in atmospheric surface layer flows, we thus expect that the very strong streamwise and spanwise electric fields are related to the large or very large turbulent structures.

As suggested, a detailed discussion of the possible generating mechanisms of the streamwise and spanwise electric fields have been added in section 5.2 in the revised manuscript.

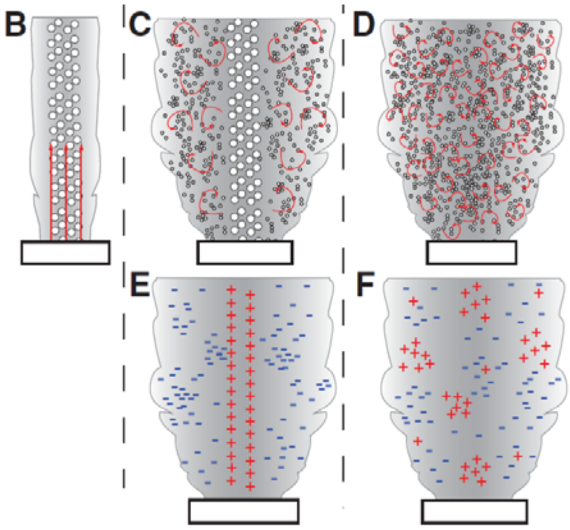

Figure R1. (adapted from Cimarelli et al., 2003) B: Monodisperse coarse beads form collimated flow and no lightning occurs. C: In bimodal blends, coarse beads are at core of flow and fines form turbulent shell. D: Monodisperse fine beads move according to local flow turbulence. E: For bimodal blends, coarser particles tend to have relative positive charge with respect to Earth, whereas smaller particles tend to charge negatively. Their different responses to fluid dynamics provide mechanism for charging and charge separation according to grain size. F: For monodisperse fine particles, transient clustering with different relative charge density provides necessary gradient for discharges (in E and F, positive and negative symbols represent relative charge density, not necessarily different polarity).

For VREFM, the measured electric field is independent of wind pressure because the working principle of VREFM is based on measuring the induced electric current on the vibrating electrode (dynamic capacity technique). As suggested, we have added an introduction of VREFM sensor in section 2.1 in the revised manuscript.

Added text1: In contrast to the vertical component which is closely related to the total mass loading (Esposito et al., 2016; Williams et al., 2009), the intense streamwise and spanwise components of the E-field may be aerodynamically created by the unsteady wind flows (Zhang et al., 2014) and turbulent fluctuations (Cimarelli et al., 2013; Renzo and Urzay, 2018). It is well-known that dust storm is a polydisperse (having dust particles with diameters from <10 μm to ~500 μm) particle-laden turbulent flow at very high-Reynolds-number (up to ~108). The wind flow in dust storms is certainly unsteady and random. Numerical simulation by Zhang et al. (2014) showed that the unsteady incoming flow could lead to the nonuniform transport of charged particles in the streamwise direction and thus resulted in fluctuating streamwise and vertical E-fields. In addition to unsteadiness, recent direct numerical simulation (Renzo and Urzay, 2018) and laboratory experiment (Cimarelli et al., 2013) of particle-laden turbulent flows demonstrated that the generation of 3-D E-field could be caused by turbulent fluctuations. That is, the negatively charged 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 (Cimarelli et al., 2013; Renzo and Urzay, 2018). We thus reasonably expect that 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. Doubtless, such charge segregation could produce 3-D E-field (e.g. Renzo and Urzay, 2018). To sum up, the generating mechanisms responsible for the streamwise and spanwise E-fields in dust storms are probably the charge segregation caused by unsteady wind flows and turbulent fluctuations.

Additionally, one possible explanation for the intense streamwise and spanwise E-fields is that there exists large- and very-large-scale motions in atmospheric surface flows, leading to a large extent charge segregation in the streamwise and spanwise directions. In atmospheric surface layer flows, the largest vortices or coherent motions of the wind flows are found to be compared to the boundary layer thickness (~60-200 m) (Kunkel and Marusic, 2006; Hutchins et al., 2012). This may lead to a phenomenon that the charged particles are more nonuniformly distributed (over a larger spatial scale) in the streamwise and spanwise directions than in the vertical direction. Accordingly, the intensity of the streamwise and spanwise E-fields is probably larger than that of the vertical E-field.

Please see pages 24-26.

Added text2: A detailed description of VREFM can be found in the Supplement of Zhang et al. (2017), but we describe it here briefly. The working principle of VREFM is based on the dynamic capacity technique, as illustrated in the inset of Fig. 1b. Unlike traditional atmospheric electric field mill, VREFM is composed of only one vibrating electrode. As the electrode oscillates, it charges and discharges periodically. The magnitude of the induced electric current $i(t)$ is proportional to the ambient E-field intensity E (Zhang et al., 2017), i.e.

$$i(t) \propto E\omega\cos(\omega t) \tag{1}$$

where ω is the vibration frequency of the electrode. The induced electric current is then converted to an output voltage signal, which is linearly proportional to the ambient E-field, through functional modules within VREFM. In addition, the length and diameter of the VREFM sensor are approximately 2.5 cm and 7 cm, respectively. This small size sensor allows us to measure E-field very close to ground but do not disturb the ambient E-field significantly.

Please see lines 11-26 in page 5.

2) The fig.4 can be more persuasive if you plot the DWT component of shaded area of E-field in all directions. And it lacks of explanation of how the shaded area is much more stable than other data.

Thanks for your important suggestions. A period is said to be relatively stationary if time-varying means of all quantities (including wind speed, number of saltating particle, and 3-D electric field) do not vary notably with time (Bendat and Piersol, 2011). As suggested, Fig.4 (i.e. Fig.5 in the revised manuscript) and its caption have been modified as follows:

Changes made:

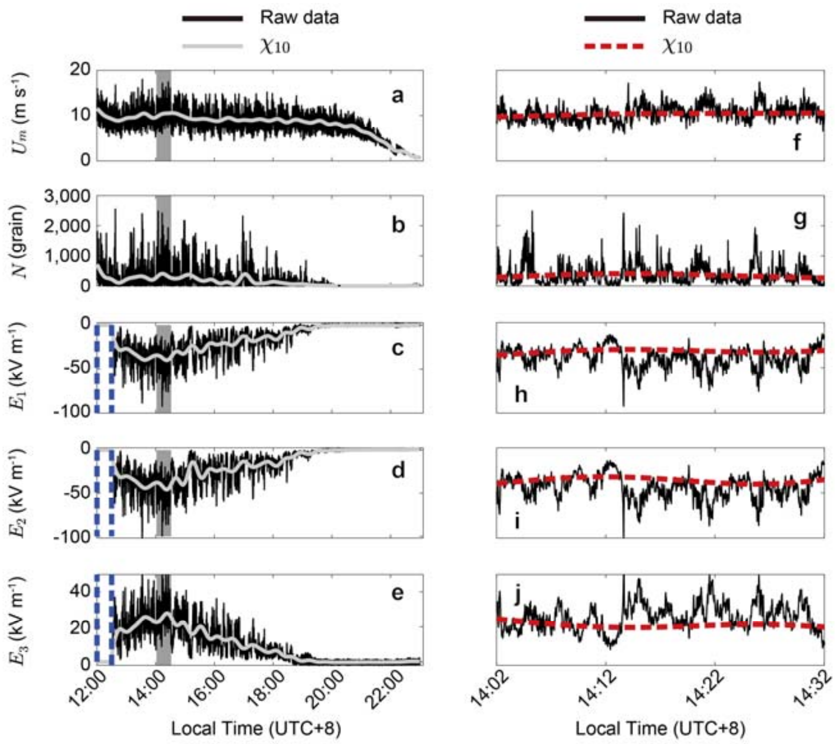

Figure 5. Measured results during a dust storm occurring on May 6, 2014, at the QLOA site. (a)-(e): the measured time series of the streamwise wind speed, u_m at 0.7 m; the number of saltating particle N at 0.15 m; streamwise E-field E_1, spanwise E-field E_2, and vertical E-field E_3 at 0.7 m. Unfortunately, owing to the interruption of power supply, the 3-D E-field data have not been recorded before ~12:30, as represented by a dashed box in the last three panels (from top to bottom). The shaded area denotes the relatively stationary period of the observed dust storm, because during this period the time-varying means of all quantities (i.e. χ_{10}) do not vary notably as time varies (Bendat and Piersol, 2011), as shown in (f)-(j).

3) the mass flux of sand particles is influenced by both the horizontal and vertical E-field, and from the measurement result we can see that the streamwise and spanwise E-field are mostly induced by the fluctuation of wind field. Thus, the horizontal wind field seems very important in calculating the mass flux. But in the calculation, the author used a 1D wind field implemented by the 3D E-field, which I think is not precise. From the fig. 8 we can see it the mass flux is almost the same with/without the vertical E-field. What if you implement the 3D E-field into a 3D wind-field? Will it be such a big difference between the vertical E- field and 3D E-field?

Thanks for your very important suggestions. We are sorry that, in this version of the manuscript, we cannot perform a simulation including the 3-D wind flow. Indeed, turbulent fluctuations (3-D wind field) play an important role in particle dynamics and charging processes. As we discussed in section 5.4 in the manuscript, inclusion of turbulence in the model of particle charging in dust events is challenging us because of the huge computational cost. So far, the simulation of particle charging considering turbulence is still limited to very low Reynolds number flows (see Renzo and Urzay, 2018). As many previous studies (e.g., Kok and Renno, 2009), this study is mainly concerned with the steady-state saltation. In steady-state saltation model, all statistics are averaged over 10 min timescale, and thus the governing equations of the wind flow can be reduced to a simple model. In future work, we plan to develop a tractable numerical model that incorporates the turbulent fluctuations into our saltation model and explores the coupling mechanisms between turbulent fluctuations, particle dynamics, and electric field.

In the revised manuscript, we have added a description of the limitations of our model.

Added text: One limitation of our model is that the effects of turbulent fluctuations on particle charging and dynamics are not explicitly accounted for. In actual conditions, saltation is unsteady and inhomogeneous at small scales, and the wind flow is mathematically described by the continuity and Navier-Stokes equations. However, in many cases, wind flow is statistically steady and homogeneous over a typical timescale of 10 min (Durán et al., 2011; Kok et al., 2012). For example, in the relatively stationary period in Fig.5, all long-period averaged statistics become independent of time. In this case, the governing equations of the wind flow can be reduced to a simple model described by equation Eq. (13). There is no doubt that 3-D turbulent fluctuations could affect particle charging and dynamics considerably (e.g. Cimarelli et al., 2013; Dupont et al., 2013). Further work is therefore needed to incorporate turbulence into the numerical model.
Please see pages 26-27.

4) In Figure 10, can you explain more about the results shown? Why does the mean charge to mass ratio decrease fast with a certain value of charge density? How did you calculated the mean charge to mass ratio? Does it depend on the particle size? Why there is a peak value for percent increases in saltation height when charge density is at one value? It seems like the increase rate for mass flux and saltation height will becomes a stable value with the increasing charge on particle, does it accordant with the actual situation?

Thanks for your important comments. As suggested, we have added more detailed discussions associated with Fig. 10 (Fig. 11 in the revised manuscript).

Frist, from eqs. (25)-(27), we can see that for small density of charged species ρ_h^0, charge transfer Δq_{ij} is proportional to ρ_h^0, leading to Δq_{ij} increases with increasing ρ_h^0. However, for large ρ_h^0, Δq_{ij} is independent of ρ_h^0 because Δq_{ij} is limited by the difference of species number between two colliding particles (i.e. $\rho_h^j S_j - \rho_h^i S_i$). A similar discussion can be found in Kok and Lacks (2009).

Second, the mean charge-to-mass ratio $\langle \zeta_p \rangle$ is defined as the ratio of charge flux to the mass flux in the range of $[z, z+\Delta z]$. It is independent of particle size.

Third, since there is a peak for $\langle \zeta_p \rangle$ at ρ_h^0 of about 10^{16}-10^{17}, percent increase in z_{salt} also has a peak at ρ_h^0 in the same interval. In addition, it is clear that the peak in percent increase is more apparent than in $\langle \zeta_p \rangle$. This is because z_{salt} is very sensitive to mass flux profile. A little change in mass flux profile would lead to an apparent change in z_{salt} (see Text S1 in the Supplement).

Fourth, in actual condition, charge on dust/sand particles does not increase indefinitely. In fact, dust/sand particles can acquire a certain amount of charge (termed equilibrium or saturation) after hundreds of collisions, please see the following studies for more details:

Méndez Harper, J., & Dufek, J. (2016). The effects of dynamics on the triboelectrification of volcanic ash. Journal of Geophysical Research: Atmospheres, 121(14), 8209-8228.
Zhang, H., & Zheng, X. (2018). Quantifying the large-scale electrification equilibrium effects in dust storms using field observations at Qingtu Lake Observatory. Atmospheric Chemistry and Physics, 18(23), 17087-17097.

We thus expect that the increase rate for mass flux and saltation height can reach a stable value.

Changes made:

$$\langle \zeta_p \rangle (z) = \frac{\sum \zeta_{p,i} m_{p,i} u_{p,i}}{\sum m_{p,i} u_{p,i}} \qquad (28d)$$

The $\langle \zeta_p \rangle$ is defined as the ratio of charge flux and mass flux in the range of $[z, z + \Delta z]$.
Please see lines 10-15 in page 18.

Added text: From Eqs. (25)-(26), it can be seen that the net charge transfer Δq_{ij} is proportional to the initial density ρ_h^0 so that $\langle \zeta_p \rangle$ increases rapidly with increasing ρ_h^0 for small values of ρ_h^0. However, for larger ρ_h^0, Δq_{ij} is no longer proportional to ρ_h^0 because Δq_{ij} is limited by the difference of the number of charged species (i.e. $\rho_h^j S_j - \rho_h^i S_i$) between two colliding particles (Kok and Lacks, 2009). Fig. 11c shows a peak of increase in z_{salt} at ρ_h^0 of about 10^{16}-10^{17} m^{-2}, because $\langle \zeta_p \rangle$ also exhibits a peak in the same range of ρ_h^0. In addition, the peak is more apparent in Fig. 11c. This is because z_{salt} is very sensitive to mass flux profile. A little change in mass flux profile can lead to an apparent change in z_{salt} (see Text S1 in the Supplement). For the larger height-averaged time-varying mean, the enhancements of the total mass flux Q and saltation height z_{salt} could exceed 20 % and 15 %, respectively.
Please see lines 2-12 in page 23.

5) In page 4, line 2, the author criticized the Schimidt et al.'s work as a wrong measurement. Actually, it is reasonable that Schimdt pointed out the finding of upward pointing electric field, for the measurements results show that the large particles (near the ground) carries the positive charge, and the small ones in high air carries the negative charge.

Thanks for your important suggestions. As suggested, the statement has been corrected as follows.

Amended to: Most field observations, such as Schmidt et al. (1998) and Bo et al. (2014), have studied the electrical properties of sand particles in dust events. However, many environmental (lurking) factors, such as relative humidity, soil moisture, surface crust, etc., cannot be fully controllable (recorded) in these field observations.
Please see lines 3-6 in page 4.

6) In Fig 7, the results show that only in very strong wind situation, the charge separation is a little bit obvious. The author should make more explanation about this figure.

Thank you for this suggestion. As suggested, a brief explanation has been added as follows.

Added text: As wind speed increases, the difference of the charge-to-mass ratio distribution between the cases with and without midair collisions is increasingly notable. This is because the probability of midair collisions become more significant for larger wind speed (Sørensen and McEwan, 1996; Huang et al., 2007).
Please see lines 2-5 in page 22.

7) In figure 10, the unit of mass to charge ratio should be uC/kg, not uC/m3.

Corrected as suggested.

8) Charge on particles is one of the most important parameters in the simulation of charged particle movement. In this manuscript, the author explained the model implemented but didn't compare the charge of particle with the measured value, and also the variation process of particle charge. This can be a part of the validation of calculation.

Thanks for your useful suggestions. To our best knowledge, there is no actual measurements of charge on a single particle because such measurements is too difficult in dust events (please see the review articles of Zheng, 2013 and Harrison et al., 2016 for more details). As suggested, we have estimated the mean charge on a single particle and comparted it with the empirical values (Merrison, 2012).

Added text: To our knowledge, so far there are no actual measurements of charge on a single sand particle in dust events. In the case of Fig. 7c, the magnitude of the simulated mean charge-to-mass ratio is around 100 μC kg^{-1}, corresponding to a mean charge of 1.64×10^{-12} C/particle. This is in accordance with the empirical values of 10^{-14}-10^{-12} C/particle (Merrison, 2012).
Please see lines 23-27 in page 21.

9) The dimension of equation of 26(d) is not correct, for it's not a dimension of speed in the right side.

Thanks for your important comments. This error has been corrected. In fact, mean particle horizontal speed is calculated as the ensemble mean of particle horizontal speed located in the range of $[z, z+\Delta z]$. We now include a description in the caption of Fig.10 in the revised manuscript.

Added text: 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 ensemble mean of particle horizontal speed located in the range of $[z, z+\Delta z]$. Insets show the same data and emphasize the local information.

10) In figure 9, the mass concentrations and mean particle horizontal speeds of the case

without E-field (case 1) and only with vertical component (case 2) are almost the same, but a little different from the 3-D E-field (case 3). However, in contradiction with it, figure 8 shows that the mass flux in case 1 is closer to case 3, not case 2. It doesn't make sense.

Thank you for this useful comment. In fact, the two figures are consistent. We explain the effect of 3-D electric field on saltation mass flux using the profiles of mean mass concentration, m_c, and mean particle horizontal speed, $\langle u_p \rangle$, just qualitatively not quantitatively. This is because the saltation mass flux is approximately but not exactly equal to equal to the product of mean mass concentration and mean horizontal speed (see eqs. 28 in the revised manuscript). As shown in Fig.10 in the revised manuscript (Fig.9 in the previous version of manuscript), let without electric field be case 1, with vertical component be case 2, and with 3-D electric field be case 3, the relationships for m_c and $\langle u_p \rangle$ are as follows:

above ~0.01 m $\begin{cases} m_c: case\ 2\ <\ case\ 1\ \approx\ case\ 3 \\ \langle u_p \rangle: case\ 2\ \approx\ case\ 1\ <\ case\ 3 \end{cases} \Rightarrow mass\ flux: case\ 2\ < case\ 1\ <\ case\ 3$

below ~0.01 m $\begin{cases} m_c: case\ 2\ <\ case\ 1\ <\ case\ 3 \\ \langle u_p \rangle: case\ 3\ \lesssim\ case\ 2\ \lesssim\ case\ 1 \end{cases} \Rightarrow mass\ flux: case\ 2\ < case\ 1\ <\ case\ 3$

Hence, from Fig. 10 we can infer that the relationships for mass flux among different cases are case 2 < case 1 < case 3, which is consistent with Fig. 9 in the revised manuscript (Fig. 8 in the previous version of manuscript). As stated above, however, the exact values for each case cannot be obtained from Fig.10. In the revised manuscript, we have added two insets in Fig. 10 in order to make the figure more clearly.

Changes made:

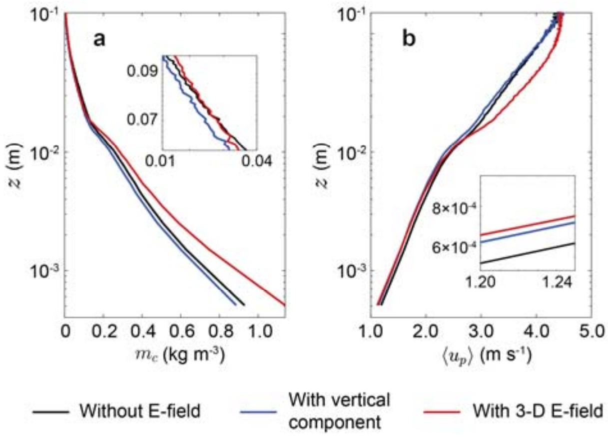

Figure 10. Vertical profiles of the particle mass concentration m_c (a) and mean particle horizontal speed $\langle u_p \rangle$ (b) for different cases, where $\langle u_p \rangle$ is calculated as the arithmetic mean of particle horizontal speed located in the range of $[z, z + \Delta z]$. Insets show 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.