Please note that the line numbers in this response is associated to the attached marked-up version.

Response to anonymous referee's #1

General comments:

Zhang et al. 2016 present an analysis of wind tunnel experiments to examine the role of three dust emission mechanisms. While the authors try to address the role of surface renewal in dust emission, they also place much emphasis on the importance of aerodynamic entrainment compared to other emission mechanisms. I think this is the first study to address the surface renewal process based on wind tunnel experiments. I find that the paper is generally well written although some sections need to be restructured. The methods need improvements in several places. Often, I feel that the statements drawn by the authors lack sufficient evidence. More proper interpretations and in-depth discussions on the experimental data are needed in many places to support their conclusions. One big issue is that, although the wind tunnel experiments are well designed, the collected data sample is too small to tell real differences between the regression fitting of various dust flux formulations. Plus, no statistics are given by the authors to judge the performance of regression analysis. I recommend publishing this paper after the following issues are addressed.

Response: We much appreciate the positive and insightful comments from the anonymous referee #1. These comments have motivated us to examine and revise the manuscript. Some sections of the manuscript have been restructured, according to the suggestions of the referee. The details of responses are shown as following.

Detailed comments:

(P-page, L-line; note that the ACPD public version is used in this review)

My very first comment is that, please use continuous line numbering (instead of restarting numbering on every page) in your future manuscripts. This really helps the review process. Regardless whether the journal has such a requirement or not, using continuous line numbering is always a good practice.

Response: Thanks for the reminding, the advice has been accepted.

Section 2 reads more like literature review, rather than a well-organized methods section. I encourage the authors to add a few sentences right after the section heading to explain how section 2 is organized before diving into the subsections. Another serious issue of section 2 is the use of symbols and abbreviations that are difficult to follow, because the authors give a review of so many dust schemes. Are they all necessary to be included in the paper? The authors need to make it clear why having an entire section for literature review of these specific dust flux methods is needed, and how they are going to connect with the wind tunnel experiments.

Response: Thanks for the suggestions. Following the reviewer's comment, section 2 has been restructured (Line 49-143). The title of this section is changed to "Background of Dust Emission Mechanisms" (Line 49). Some sentences have been added before the section heading (Line 50-55); we deleted unnecessary equation and checked the symbols (Line 84-87, Line 93) and abbreviations to make the statement be clear.

Equation 2: Why do the authors refer to the Gillette & Passi vertical flux parameterization, and then relate it to the Marticorena & Bergametti method of the F-Q relationship? Marticorena & Bergametti had their own parameterization for Q and F. That being said, equation 3 only applies for the Q parameterization in Marticorena & Bergametti, not necessarily the schemes from other studies.

Response: We listed typical achievement on vertical flux parameterization here. Marticorena & Bergametti considered F was a fraction of Q and the value of F/Q being imposed by the soil clay content. Actually, Marticorena & Bergametti had their own parameterization, which was not employed in the manuscript. So we removed Eq. (3) to avoid misunderstand (Line 84-87).

Equation 4: Is this Fb or Fc? Later in eq. 8, you used Fc, but never defined Fc.

Response: Eq. (4) is the result of F_b and Eq. (7) including the contributions of F_b and F_c. We have made the equations clear and defined the variables in the revised manuscript (Line 50-53, Line 101).

Equation 5-7: Should all the F in these equations be Fc? Also explain what F(di) and F(di, ds) are.

Response: Thanks. Eq. (7) including the contributions of F_b and F_c (Line 101). We have made all of the variables clear.

Equation 8 is questionable. My expression is that there are no distinct differentiations between the three emission mechanisms in the model parameterizations. After all, they are mostly derived from wind tunnel experiment data, which most likely represent all three dust emission schemes. It is difficult to separate the different processes in field measurements or wind tunnel experiments. Even if Fa, Fb and Fc are specifically defined for the three processes, they formulations share the same parameters. However in fact, the validity of these formulations is only limited to certain conditions (e.g., wind speed, soil sizes), which are not discussed in the paper at all.

Response: Thanks. It was true that dust emission mechanism was only conceptually divided into three parts for it was hard to distinguish the contribution of these three sub-mechanisms from experimental data. Based on previous measurements, the vertical dust flux F was found to be proportional to u_*^n with varying values of n, which was ascribed the different contributions of the sub-mechanisms under different conditions. But we still didn't know the actual reasons in detail, which limited the knowledge of dust emission. In this paper, we designed a serial of experiments to separate the contributions of the three sub-mechanisms, and thus to improve the understanding on dust emission. We agreed with the referee that the validity of the existing emission formulations was only limited to certain conditions (e.g., wind speed, soil sizes). Following the reviewer's comment, we have added some necessary explanations and discussions in lines 120-123.

But it appeared to be unnecessary to valid the formulations in this paper, which did not closely relate to the topic. Thus we deleted section 4.5 in the revised manuscript (Line 426-443).

Equation 9: I think it is necessary to show a plot on regression analysis on calculating u* and z0 for all three experiments. Show the statistics from the regressions as well.

Response: Thanks. Following the reviewer's comment, we have added the results of wind profiles and the information of regression analysis (Line 236-240, 609-611 (Figure 3), 701-703 (Table 1)).

Equation 10: You never explained what the Pm(d) and Pf(d) are, and where they come from. I suppose that they come into play in Eq. 6. If so, define them after Eq. 6.

Response: Thanks for the careful reviewing. Following the reviewer's comment, some adjustments have been made in the revised manuscript and $p(d_s)$, $P_m(d)$ and $P_f(d)$ are defined in Line 106-107

P6L3: How long does it take the fan to reach the target wind speed?

Response: It usually needs several seconds.

Section 3.1: Explicitly describe the purpose of the three experiments, for example, what dust emission mechanism(s) are each experiment corresponding to? What real-world conditions (e.g., supply limited in S1, supply limited but with renewal in S2, unlimited supply in S3?) do the experiments represent? I think having one or two statements like that can help readers easily understand the purpose of the experiment setup.

Response: Thanks. Following the reviewer's comment, we added the purpose of each experiment in the last paragraph of section 3.1 (Line 160-168).

Equation 15 and Figure 3: Equations (15-19) should not be in the Results section. Move them to Section 2. I encourage the authors to rewrite Section 2 and logically introduce the dust schemes/equations (remove those not needed).

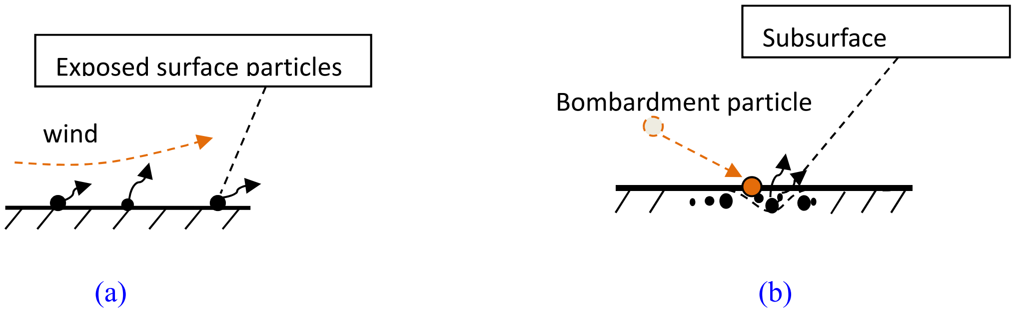
Response: Thanks. Following the reviewer's comment, we have moved Equations (15-19) to section 2 and rewritten Section 2 to logically introduce the dust schemes/equations (Line 49-144).

In Fig. 3: Why are there only 4 u*/Q values (same for other figures)? I do not think 4 runs for each surface type is sufficient to provide a meaningful data sample for regression analysis. Also, no statistics of regression (e.g., RMSE) are given. You can show them in the Fig.3. In P7L25, it is hard to "see" performance difference of two regression methods because of lack of statistical metrics. And the statistics should make more sense if a larger data sample is collected. If the wind tunnel can be configured to reach any target wind speeds, it should not be difficult to make more measurements at variable wind speed conditions in order to collect a sufficiently large data sample. I think this is a big weakness of the paper.

Response: Thanks. Our experiment was mainly limited by the amount of prepared soil material. To satisfy the requirement of experiment, the surface was made of soil material, with size of 9 m long, 1 m wide and 5 cm deep. Every surface was disposable and the soil material could not be used again, because of the changed dust content. That was why we only set 4 runs for each surface type. In the paper, we have 2 regression coefficients, and we thought the data of 4 runs were enough to run the regression analysis. But we still agreed that the performance of regression analysis should be better, if more data sample is collected. The advice should be applied in future studies. Following the reviewer's comment, we have added more statistics information of regression in the revised manuscript (for example, the coefficient of determination R^2 in Figure 3, 4, 6, 7, 8) such that it would be easy to judge the performance difference of two regression methods

P8L15: The way the aerodynamic entrainment is calculated (F0-3min minus F3-10min) is not convincing. Please explain why there is no significant difference between the saltation flux between 0-3 min (unlimited supply condition) and 3-10 min (supply limited condition)?

Response: Thanks. Based on the definition of aerodynamic entrainment and saltation bombardment (as shown in the following picture), the emitted dust via aerodynamic entrainment depends on the amount of exposed surface dust, and saltation bombardment dust relates to the dust content of subsurface. For the case without surface renew (i.e. S1), as result of dust emission, the exposed surface dust is exhausted and supply-limit occurs. But the content of subsurface should not change significantly during the measurement time of 10 minutes, due to the lack of motion of large surface particle, which may renew surface. So it is reasonable to assume that there is no significant difference between the saltation bombardment emission flux during the period of 0-3 min and 3-10 min. Following the reviewer's comment, we added explanation for the data-processing method (Line 318-326)



Sketch map of (a) aerodynamic entrainment and (b) saltation bombardment

P9L1-7: This part of discussions is questionable. The authors state that "with intensified surface renewal from S1 to S3, the relationship between dust flux and friction velocity increasingly resembled the aerodynamic entrainment under unlimited supply." The authors show that the vertical dust flux is proportional to u*ˆ10 in S1 strong saltation condition, u*ˆ4 in S1 week saltation condition, u*ˆ6 in S2, and u*ˆ7 in S3. These n values still substantially deviates from the n=3 in Eq. 1. That means the F-u* relationship does not fall in the aerodynamic entrainment regime. By the rule, S1 supply limit state (n=4) is most close to the aerodynamic entrainment regime.

Response: Thanks. The vertical dust flux, which was proportional to u*ˆ10 in S1 (0-3 min, under unlimited supply), was actually caused by aerodynamic entrainment for the contribution of saltation bombardment has been subtracted. For the case of weak saltation condition (S1, 3-10 min), the vertical dust flux was proportional to u*ˆ4, which was only caused by saltation bombardment and aggregates disintegration for aerodynamic entrainment is exhausted because of supply-limit. For the case of strong saltation condition (S2, 3-10 min), the vertical dust flux was proportional to u*ˆ6, which was mainly caused by saltation bombardment though a few contribution of aerodynamic entrainment was included. And for the case of strong saltation and surface renew condition (S3, 3-10 min), the vertical dust flux was proportional to u*ˆ7, which was caused by both saltation bombardment and aerodynamic entrainment. The value of *n* changes from 4 to 7, and was closed to 10 for aerodynamic entrainment under unlimited supply. Based on above results we stated that "with intensified surface renewal from S1 to S3, the relationship between dust flux and friction velocity was more and more close to that of the aerodynamic entrainment under unlimited supply." Eq. 2 (n = 3) was not the reference of aerodynamic entrainment in our paper. And also we noted that our result of aerodynamic entrainment dust was obviously bigger than the value of LH2000 (i.e. Eq. 2, the comparison was shown in Fig. 6). That divergence may be caused by different experimental conditions, such as surface roughness and surface particle distribution. The exactly reason will be exposed in future study.

The authors also states that "From this point of view, dust emission can be considered to be mainly driven by aerodynamic entrainment, whereas saltation and creep are responsible for surface renewal which restores the availability of dust for emission. In general, dust emission can be seen as the result of restricted aerodynamic entrainment." I agree that saltation and creep is responsible for surface renewal; but that does not lead to the conclusion that during that process, aerodynamic entrainment is the main mechanism for dust emission. Saltation and aggregates disintegration are contributing to emission while they replenish the surface at the same time. The conclusion by the authors is not supported by any quantitative analysis that can prove the dominant role of aerodynamic entrainment in dust emission. Also, explain what 'restricted aerodynamic entrainment' means.

Response: Thanks. Following the reviewer's comment, we added some conceptual explanation for that (Line 345-360). The regression equation in Fig. 6 (as shown in following) could be considered as the general formation for dust emission. The coefficient C relates to available dust content and the powder n relates to the mechanism of emission. Based on our measurements, n equals to 10 for aerodynamic entrainment and to 4 for saltation bombardment (also including the contribution of aggregates disintegration which is not identified in our work). Then the total dust flux could be expressed by

$$F = F_a + F_{b+c} = c_1 \cdot u_*^{10}\left(1 - \frac{u_{*t}}{u_*}\right) + c_2 \cdot u_*^4 \left(1 - \frac{u_{*t}}{u_*}\right) \quad (17)$$

where c_1 relates to exposed dust content and c_2 to subsurface dust content and impact energy of saltators. The first term on the right hand side of Equation (17) is attributed to aerodynamic entrainment and the second to saltation bombardment and aggregates disintegration. We now use Equation (17) to predict the vertical dust fluxes over the different surfaces. The values of u_{*t} are assumed to be the same as in Figure 6 and c_1 and$c_2$are obtained by regression analysis. As shown in Figure 7, Equation (17) can well describe the experimental data. And based on the estimated values of c_1 andc_2,the ratio of F_a/F can be readily estimated, as shown in Figure 7 (dashed lines). It is seen that, sometimes (e.g. high u_* over S2 and S3) the contribution of aerodynamic entrainment can exceed saltation bombardment ($F_a/F > 0.5$) and be the dominate mechanism for dust emission. It appears that saltation not only causes dust emission, but also surface renewal which restores the availability of dust for the emission.

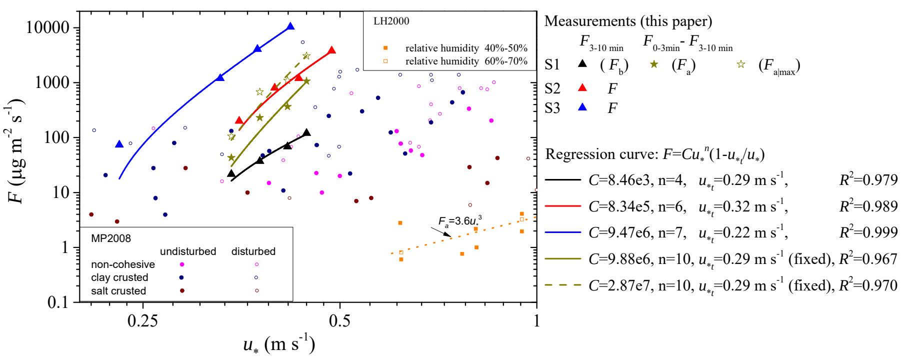


Figure 6. Measured vertical dust fluxes over the three different surfaces in the wind-tunnel experiment (triangles), together with the measurements of Loosmore & Hunt (2000, LH2000) and Macpherson et al. (2008, MP2008), labeled as LH2000 and MP2008, as well as the various regression curves.

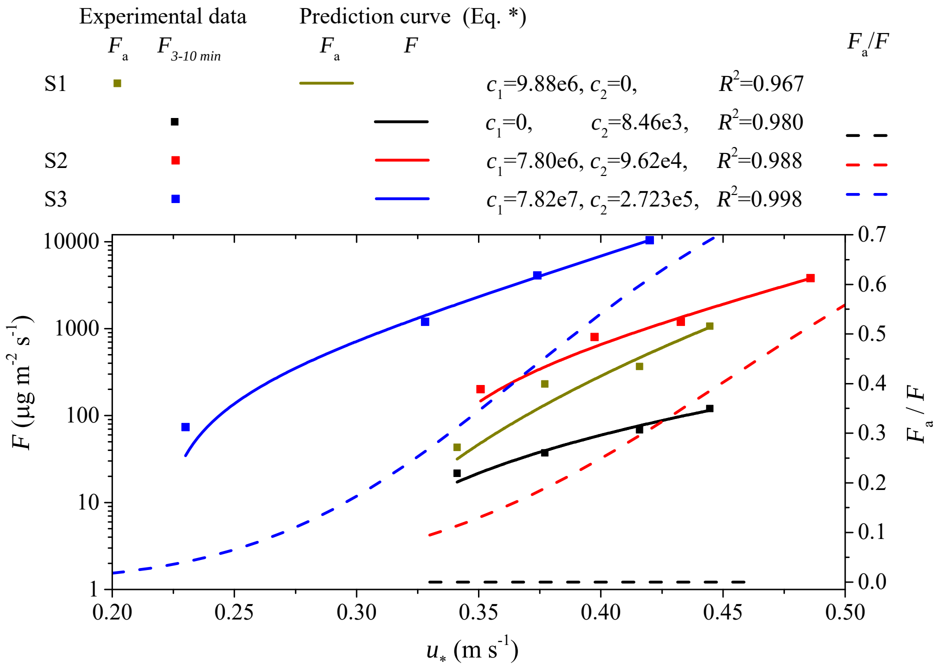


Figure 7. Predictions of Equation (17) and the predicted contribution of aerodynamic entrainment F_a is illustrated as the dashed lines with the right vertical coordinate. u_{*t} is valued as the same to figure 6.

P9L32, the authors' claim that "the last stage of S2 must be due to the contribution of aerodynamic entrainment" is not convincing. I understand that at high u* (last state of S2), surface renewal provides more erodible materials which increases the dust vertical flux. However, it is not necessarily due to the mechanism of aerodynamic entrainment. I think the authors are trying to emphasize the role of aerodynamic entrainment, but their analysis is groundless.

Response: Thanks. We added Fig. 7 to support this statement.

Considering the above comments, the abstract and conclusion sections of this paper must be rewritten. The summary #2 in the Section 5 is groundless and misleading. The authors state that n = 10 in the case of aerodynamic entrainment, but Eq. 1 shows n = 3 in the aerodynamic regime (Eq.1 was used throughout the paper to separate the aerodynamic entrainment regime). The authors state that aerodynamic entrainment is even a dominant process under certain circumstances. Please elaborate on that. What specific circumstances are they? I think the authors made lots of efforts to relate their experiments to aerodynamic entrainment, but the focus of this paper is on surface renewal. Many issues around that are not addressed, such as the renewal rate, dependence on wind speed/soil texture/soil size distribution/vegetation, biases in current dust schemes due to lack of surface renewal, and possible ways to introduce to dust schemes.

Response: Thanks. Actually, we didn't use Eq. 1 (i.e. Eq. 2 in the revised version) to separate the aerodynamic entrainment regime, but via $F_{0\text{-}3\ min}$ - $F_{3\text{-}10\ min}$ over S1. And as we stated before, the divergence between Eq. 1 (i.e. Eq. 2 in the revised version) and our results will be study in future work. The results of Fig. 7 should be good to prove the statement 'aerodynamic entrainment is even a dominant process under certain circumstances' and the relevant expression has been rewritten (Line 336-381).

We appreciate that the referee give us some good advices on surface renew research in future. But the main work of this paper is to point out the significant of surface renewal in dust emission mechanism. The detail study of surface renewal will be implemented in next.

Minor comments:

Section 2.1, explicitly state that F is the vertical dust flux.

Response: Thanks. We stated the relationship of emission flux and vertical flux in line 199-201.

P1L24: there is -> there are.

Response: Thanks. It has been changed (Line 25).

P2L14: uplifted->uplift.

Response: Thanks. It has been changed (Line 57).

P2L15: inconsequential->insignificant.

Response: Thanks. It has been changed (Line 58).

P3L3: in equation 3, η_c is the soil clay content in percentage101.

Response: Thanks. We deleted this unnecessary equation 3 (Line 85-87).

Equation 4: η is already used in eq.3, use a different symbol.

Response: Thanks. η is replaced with ξ here (Line 94, 109).

P3L20: you already defined u*t above.

Response: Thanks. It has been removed (Line 127).

P5L21: if -> of.

Response: Thanks. It has been changed (Line 197).

P5L25: use dust vertical flux (not dust emission rate) to be consistent throughout the manuscript.

Response: Thanks. Actually, emission flux and vertical flux are two different concepts and we gave the relationship of these two variables in line 199-200.

P9L9: η is already used in other places. use a different symbol.

Response: Thanks. We changed the symbol of the Eq. (4) and (7).

P9L20: limit->limited.

Response: Thanks. It has been changed (Line 402).

Comments on Figures and figure/table captions:

Add S1, S2, S3 labels on the Fig. 2.

Response: Following the reviewer's comment, we added some descriptions of the surfaces in the caption of Fig. 2 (Line 590-593).

Add regression equations in Fig. 3.

Response: Thanks. It has been changed (Line 617).

Describe the horizontal dash lines in Fig. 4 caption.

Response: Thanks. It has been added (Line 636-637).

Change 'dust emission' to 'dust vertical flux' in the Fig. 6 caption.

Response: Thanks. It has been changed (Line 636).

Table 2: Explain the meaning of the symbols in the caption (i.e. the parameters in the log normal size distribution).

Response: Thanks. It has been added (Line 725-726).

Response to anonymous referee #2

This is an interesting paper that uses wind-tunnel experiments to put forth the hypothesis that the renewal of fine particles in a soil's top layer is critical to dust emissions. This is an appealing hypothesis and this process is currently missing from models. They test this hypothesis using a series of wind tunnel measurements, which seem well designed. This article thus has the potential to be an important contribution.

Response: We greatly appreciate the positive comments from referee 2#.

However, there are several major issues with the article. Paramount is a major deficiency in how the results and discussion are presented. Almost throughout the "Results and Analysis" and "Conclusions" sections, the authors present hypotheses, of which their (otherwise very interesting) data are merely suggestive, as facts. Words such as "show" and "demonstrate" are used abundantly. This is not appropriate considering the level of evidence the authors present, and the enormous complexity of dust emissions. I will give a few (of many) examples of this below. The authors need to completely rewrite these sections. In particular, they should split up the "Results" and "Discussion" sections, to make it clear what are indisputable facts from their experiments, and what is their interpretation of these facts.

Response: Many thanks for the constructive comments which have been adopted in the revised version. We split up the "Results" and "Discussion" into different paragraphs and the details of the changes are shown in following.

In addition, there are some major scientific issues:
- The saltation bombardment section has major issues, which I'll list below:
* "c0 reflects the fraction of effective saltators, namely, grains available for saltation at a given friction velocity". This is inconsistent with Owen (1964), and also with the paper's own Eq. 18, where c0 is linked to the terminal velocity.

Response: Thanks. Following the reviewer's comment, we made some modifications for this part and the explanations of c_0 followed the physical meaning of Owen (1964) (Line 251-253).

* P. 7, lines 10-11: I'm not aware of any measurements supporting the idea that the number of available saltators depends on the (theoretical) thresholds for individual particles. Rather, when saltation is initiated, the splashing process can mobilize particles of a wide range of sizes (e.g., Rice et al., 1995). The authors should either provide experimental evidence for their viewpoint, or note the opposing view (even if they do not adopt it).

Response: Thanks for the comment. The unreasonable explanations have been deleted in the revised version (Line 276-279).

P. 7, lines 13-14: Did the authors directly measure what particles constituted the saltators? If not, this is interpretation, yet as presented as fact.

Response: Thanks. Following the reviewer's comment, we modified this part which is not measurement result but added some discussions for the regression parameters (Line 251-253).

P. 7, lines 14-15: This similarly is interpretation presented as fact. The saltation flux depends on many closely coupled and complex processes. Linking a change in the flux to any one parameter (the fraction of effective saltators in this case) without directly measuring it is speculative. That's fine to do in the discussion section, but should be presented as such.

Response: Thanks. Following the reviewer's comment, we split up "Results" and "Discussion" into different paragraphs (Line 242-253).

* For the fitting with equation (15), how was u*t obtained? Was it fit as well? And how was

v_t calculated?

Response: Thanks. For the dashed lines in Fig. 4, u_{*t} and c_0 were obtained from regression analysis; for the solid line in Fig. 3, c_0 was calculated by Eq. (8), and v_t was calculated by $v_t = 1.66(\sigma_\varphi g d_s)^{1/2}$ (Shao, 2008) which have been added in the revised version (Line 112).

The use of Eq. (16) – (19) is very interesting. However, the procedure here is very unclear to me, and might have some scientific flaws. My primary concern is that the parameters in the u*t relation seem to be fit to the measurements, such that Eqs. (16) – (19) have, as far as I can tell, three tunable parameters (proportionality constant (c0?), r, and An). Since the data they fit to are only four data points, these fits are statistically not that meaningful (only 1 degree of freedom). Thus the conclusion that "the above method gives a more accurate estimate of Q than Equation (15)" needs to be put on a more solid statistical basis.

Response: Thanks. Actually, here c_0 was determined by Eq. (8) (v_t was calculated by $v_t = 1.66(\sigma_\varphi g d_s)^{1/2}$ as stated above) and there were only two tunable parameters (r and A_n) left. We have added the coefficient of determination R^2 in the revised version (Line 617), to judge the performance of different regression methods.

* Related to the above comment, please provide the fitted u*t(d) relationships for the three soils so that the reader can judge whether they are reasonable. This is necessary to judge whether the visually good agreement is due to a good description of the physics, or because of a sufficient number of tuning parameters. You could provide these fits in a supplement to the paper.

Response: Thanks. Following the reviewer's comment, we have added the fitted $u_{*t}(d)$ relationships for the three soils in Figure 4 of the revised version (Line 617).

- Sections 4.3 and 4.4: A central argument of the authors here is that the dust supply for aerodynamic entrainment is maintained by the intense sand flux for S2 and S3, but not for S1, which has lower sand flux at a given u*. However, the authors should compare apples to apples here and thus compare data with similar sand fluxes, for instance u* = 0.37 m/s for S1 and u* = 0.23 m/s for S3. The S1 data point shows a large dust flux decrease during the first minutes, whereas the S3 data point does not. This is not explained by their hypothesis, and should be clarified.

Response: Thanks. Following the reviewer's comment, we compared data with similar sand fluxes and explained why dust supply for aerodynamic entrainment was not maintained for S1 (Line 330-332).
"a large dust flux decrease during the first minutes" indicated that supply limit occurred and surface renewal didn't work over S1. This was consistent with our hypothesis.

- I found section 4.4 very difficult to follow. Please use paragraphs in this section and make sure that the text flows smoothly. More importantly, this section again uses many interpretations of the data and would benefit enormously from separation into a results (facts) section and a discussion (interpretations and hypotheses) section. As it is written, I cannot sufficiently judge the scientific merit of this section.

Response: Thanks. The suggestions have been accepted. We split up the part of "results" and "discussion" for this section (Line 387-424).

- Section 4.5 suffers from similar issues as the other sections, with many hypotheses presented as though they were measured experimentally (line 9-11 "Due to the neglect of the supply-limiting effect and of the variation of bombardment efficiency, all three models underestimated the dust flux at low friction velocity, but slightly overestimated at high friction velocity"; line 14-15 "With the increase of u*, the bombardment efficiency decreases because of changed surface property due to intrusive sand particles." ; line 18-19 "S04 appears to perform somewhat better than the others due to improved treatment for saltation bombardment and aggregates disintegration."; line 21- 22 "This shows that threshold friction velocity u*t represents different properties of the soil surface in the Owen model and the GP88 model.")

Response: Thanks for the comment. We deleted this part which was not necessary for the topic of the paper (Line 426-444).

Other comments:

- Please make line numbers continuous in revised article to make the review easier.

Response: Thanks for the suggestion which has been applied in the revision version.

- In the literature I'm familiar with, the term "supply limited" is generally used to refer to a lack of supply of saltators, not a lack of supply of fine soil particles. The authors should clarify this point.

Response: Thanks. Following the reviewer's comment, we added a note to clarify this point. (Line 29)

- Line 31-32, p. 1: Why do differences in dust emission after disturbing a soil indicate the importance of aerodynamic entrainment? This should be clarified or removed.

Response: Thanks. Following the reviewer's comment, we added some explanation for this part. (Line 34-36)

- Sections 2.2 and 2.3: While the authors cannot be expected to compare their data against every single dust emission model, they should at least mention the other ones (e.g., Marticorena and Bergametti (1995); Alfaro and Gomes (2001); Kok et al. (2014)).

Response: Thanks. Following the reviewer's comment, we briefly reviewed the other people's work, in sections 2.2 and 2.3 (Line 80-83; Line 118-120).

- Eq. (9): What is the averaging time for u(z)?

Response: Thanks. The wind speed was averaged over three minutes.

- Line 15, p.5: This statement on sonification requires justification. For instance, the impact of saltating particles can chip and break them, which does not occur during sonification. Therefore, whereas sonification disaggregates particles, won't grinding result in the wearing down of individual (disaggregated) particles, thereby changing the size distribution?

Response: Thanks. Following the reviewer's comment, we added more appropriate explanations for the method selecting (Line 184-187).

- Please add a brief discussion whether the use of the gradient method is reasonable for your experiment. Compared to field measurements, your fetch is very small (a few meters, compared to 100s or 1000s of meters in the field). You partially compensated for this by moving your dust sensors close to the ground, but can you expect dust to be well-mixed (and thus follow a logarithmic profile) at only a few meters of fetch? How will this affect your results?

Response: Thanks. Following the reviewer's comment, we added some discussions on the rationality of gradient method (Line 200-2054).

- Section 3.3: was the wind flow seeded with particles in your experiments? If not, do you expect your sand flux to be saturated? The results of Shao and Raupach (1992) suggest that you need more length than the 8 m of your set-up.

Response: Thanks. Actually, the wind flow was not seeded with particles. So we could not assure that the sand flux was saturated. That why we measured the saltation flux directly and strived to searched a good formulation of Q.

- P. 7: please define d1 and d2 in Eq. 16. Also, the last d should be d_s

Response: Thanks. Following the reviewer's comment, d_1 and d_2 were defined in Line 106-107 and the relevant equation has been corrected.

- P. 7: Please provide the value of the particle-to-air density

Response: Thanks. Following the reviewer's comment, it has been added in the revised version. (Line 112).

- In general, how exactly is the fitting performed? What quantity is minimized? Given that the data spans several orders of magnitude, it makes most sense to me to minimize the squared distance in log space, not in linear space (as the authors seem to have done).

Response: Thanks. Actually, we used 'Origin' (software) with the function of 'nonlinear curve fit' to implement data fitting. The iteration algorithm is set as 'Levenberg Marquardt'.

- P. 8, line 3: does this refer to radius or diameter? Does this mean that the reported dust fluxes are limited to D (or r) < 15 um? Please clarify.

Response: Thanks. That refers to diameter and the reported dust fluxes are limited to D < 15 um. Following the reviewer's comment, it has been clarified (Line 294).

- P. 8, line 10-15: There are a lot of hypotheses used here to interpret the data in terms of arising from either aerodynamic entrainment or saltation bombardment, and whether or not the dust supply was limited. These factors were not measured directly, so these interpretations should be presented conservatively, rather than as statements of facts.

Response: Thanks. Following the comment, we have rewritten this part carefully （Line 293-364）.

- P. 10: The scaling of aerodynamic entrainment with u* to the 10th power seems a bit extreme. Can you put uncertainty bounds on this result? How does this compare against other literature measurements such as Shao et al. (1993) and Loosmore and Hunt (2000)? What could explain the differences? Also, since you did not actually measure just aerodynamic entrainment (saltation was always present, as far as I understand), this conclusion should be more conservative.

Response: Thanks for the insightful comment. The value of the power was obtained by regression analysis and we added the relevant coefficient of determination in the revised version. Due to the limitation of soil materials, the experiments for each surface and wind condition only performed once. So the uncertainty analysis was not included in the paper. This was indeed a shortage of the work, which may be improved in future.

Actually we compared our results to Loosmore and Hunt (2000). The differences were attributed to different surface roughness (Line 300-301; 334-338).

Although saltation was always present, we subtracted the contribution of saltation from total emission flux to obtain the quantity of aerodynamic entrainment (Line 320-325).

- P. 11: “Supply limit is the major reason to restrict dust emission.” This statement illustrates the main problem with the paper in its present form. Your measurements do not show this because you did not directly measure the supply limitations. You are merely hypothesizing this based on other measurements. I think it’s a reasonable hypothesis, but needs to be presented as such, and not as a fact or hard conclusion. This problem is persistent throughout the entire paper.

Response: Thanks, According to the suggestion of the referee, we have been checked the manuscript carefully and revised the relevant presentation (Line 447, 452, 455).

The detailed modifications are shown in the marked-up version attached below.

Surface Renewal as a Significant Mechanism for Dust Emission

Jie Zhang[1,2], Zhenjiao Teng[2], Ning Huang[1,2], Lei Guo[2], Yaping Shao[3]

[1]Key Laboratory of Mechanics on Disaster and Environment in Western China~~, ~~ (Lanzhou University~~, ~~), Ministry of Education, 730000 Lanzhou, China
[2]School of Civil Engineering and Mechanics, Lanzhou University, ~~730000~~ 730000 Lanzhou, China
[3]Institute for Geophysics and Meteorology, University of Cologne, 50937 Cologne, Germany

Correspondence to: N~~. ~~.ing ~~ing~~Huang (huangn@lzu.edu.cn)

Abstract. Wind-tunnel experiments of dust emissions from different soil surfaces are carried out to better understand dust emission mechanisms. The effects of surface renewal on aerodynamic entrainment and saltation bombardment are analysed in detail~~, and the measurements are used to test published dust models~~. It is found that flow conditions, surface particle motions (saltation and creep), soil dust content and ground obstacles ~~may~~ all strongly affect dust emission, causing ~~dust emission~~its rate to vary over orders of magnitude. Aerodynamic entrainment is highly effective, if dust supply is unlimited, as in the first 2-3 minutes of our wind-tunnel runs. While aerodynamic entrainment is suppressed by dust supply limit, surface renewal through the motion of surface particles appears~~is found~~ to be an effective pathway to remove the supply limit. Surface renewal is also found to be important to the efficiency of saltation bombardment. We demonstrate that surface renewal is a significant mechanism affecting dust emission and recommend that this mechanism be included in future dust models.

Keywords: dust emission; surface renewal; aerodynamic entrainment; wind tunnel; supply limit

1. Introduction

Three dust emission mechanisms have been identified, including (1) aerodynamic entrainment; (2) saltation bombardment; and (3) aggregates disintegration (Shao, 2008; Kok et al., 2012; Újvári et al., 2016). In spite of much research effort, many questions remain unanswered in relation to the process of dust emission~~ mechanisms~~. For example, in most existing dust emission schemes, aerodynamic entrainment is assumed to be small and negligible. It is however questionable, to what extent and under what conditions this assumption is justified, because there are ~~is~~hardly any data which enable a rigorous comparison of aerodynamic entrainment from natural soil surfaces with the other dust emission mechanisms. For natural soils, dust emission is usually ~~"~~“supply limited~~"~~” (Shao, 2008; Macpherson et al., 2008; Újvári et al., 2016), i.e., the emission is limited by the availability of free particles on the soil surface, rather than by the shear stress that wind exerts (note that ‘supply limited’ in this paper only refers to a lack of supply of fine soil particles, but not saltators). However, “supply limit” is not a quantified term in published emission models, as little is known about its spatial and temporal variations. The argument for the neglect of aerodynamic entrainment is that dust particles have relatively large cohesive forces and are resistant to aerodynamic lift, and thus saltation bombardment and aggregates disintegration are the dominant mechanisms for dust emission (Greeley and Iversen, 1985; Shao et al., 1993). Researchers have noted there are obvious differences in dust emission from disturbed and undisturbed soils (Macpherson et al., 2008, MP2008 hereafter~~),~~). This is because soil disturbance replenishes dust supply to aerodynamic entrainment and modifies the aerodynamic properties of the surface, which may enhances momentum transfer from the atmosphere to the surface~~which indicates that aerodynamic entrainment can play an important role if the supply of dust is less limited~~. Further, in existing dust models, the conditions of the surface subjected to erosion are assumed to be stationary. In reality, during an erosion event, surface self-disturbance occurs due to top soil removal and particle impact, i.e., a surface renewal process takes place, which in general enhances the supply of dust for aerodynamic entrainment. We argue that under the conditions of strong surface renewal, aerodynamic entrainment may be a significant mechanism for dust emission.

In this work, we simulate three typical landforms in a wind-tunnel experiment, namely, a farmland surface, a desert surface and a loess surface (see Section 3 for details). We then ~~sought~~ seek to quantify the contributions of three dust emission mechanisms to the total dust flux for the different landforms. Using the wind-tunnel observations, we demonstrated that supply limit of free dust is ~~the primary~~a major factor which suppresses aerodynamic entrainment, but surface renewal through saltation and creep provides an important pathway to enhance the free dust supply for aerodynamic entrainment. Thus, for surfaces with strong renewal and sufficient free dust supply, aerodynamic entrainment becomes a non-negligible process for dust emission.

2. Background of Dust Emission Mechanisms~~Model and Method~~

In general, dust emission flux, F, is considered to be caused by three mechanisms and can be expressed as

$$F = F_a + F_b + F_c \qquad (1)$$

where F_a, F_b, F_c are respectively the fluxes arising from aerodynamic entrainment, saltation bombardment and aggregates disintegration. F_a is directly relate~~s~~d to surface shear stress, while F_b and F_c depend on saltation. Here ~~W~~we will briefly review the studies on ~~these~~ dust emission mechanisms and summarize the dust emission flux formulations. We will then introduce the basic assumptions of our study.

2.1 Aerodynamic Entrainment

Aerodynamic entrainment refers to direct dust uplift~~uplifted~~ from the surface into the atmosphere by aerodynamic forces. It has been suggested that the dust flux arising from aerodynamic entrainment is insignificant~~inconsequential~~, because aerodynamic lift force for small particles is in general small compared to inter-particle adhesion. Loosmore and Hunt (2000, LS2000 hereafter) suggested based on their wind-tunnel experiments that

$$F_a = 3.6\, u_*^3$$

(12)

Wherewhere F_a is in (μg·m^{-2}·s^{-1}) is dust emission flux due to aerodynamic entrainment and u_*(m·s^{-1}) is friction velocity. Shao (2008) suggested thatHowever, inter-particle cohesive force is a stochastic variable, such that there always exists in nature a proportion of dust which is free, i.e., dust for which inter-particle cohesion is weak (Shao, 2008). Several studies have demonstrated that F_a is not always negligible (Kjelgaardet al., 2004; MP2008Macpherson et al., 2008; Klose and Shao, 2012; Sweeney and Mason, 2013), but the key factors which determine aerodynamic entrainment remain poorly understood. Moreover, Loosmore and Hunt (2000) conducted the wind tunnel experiments by using "Arizona Test Dust" (ISO-12103-1) to produce very smooth test beds. The investigation of dust emission caused by aerodynamic entrainment over natural and rough surfaces is still lacking.

2.2 Saltation Bombardment

Saltation bombardment is considered as the central mechanism of dust emission and has been extensively studied. Based on field experiments (Gillette, 1974, 1977 and 1981), Gillette & Passi (1988, GP88 hereafter) proposed an empirical formula for dust flux due to saltation bombardment, F_b, as a function of friction velocity

$$F_b = c \cdot u_*^n \left(1 - \frac{u_{*t}}{u_*}\right) \qquad (3)$$

$$F_b = c \cdot u_*^4 \left(1 - \frac{u_{*t}}{u_*}\right) (23)$$

Wwhere c is an empirical constant and n is suggested to be 4 (GP88). According to existing field measurements, Shao (2008) stated that dust emission flux can be proportional to u_*^n but with n varying between 2.9 and 4.4 and depending on soil type and soil-surface conditions. Many other studies have been carried out on sandblasting dust emission. For example, Marticorena and Bergametti (1995) suggested that dust emission flux is dependent on streamwise saltation flux and soil clay content, and Alfaro and Gomes (2001) suggested that sandblasting results in dust emission from three separate lognormal particle-size modes, and the contribution of the modes depends on the particle binding energy and the kinetic energy of impacting saltators.

whereu_{*t} is threshold friction velocity and c an empirical constant. Marticorena and Bergametti (1995) suggested that $F_b$is dependent on streamwise saltation flux (Q), and soil content (η_c),

$$F_b = a_1\, e^{a_2 \eta_c + a_3}\, Q \, (3)$$

wherea_1, a_2 and a_3 are empirical constants. Based on the wind-tunnel observations by Rice et al. (1996a, b) and Shao (1993, 1996), Lu & and Shao (1999, LS99 hereafter) and Shao (2000, 2001) argued that a blasting saltator, upon its impact, causes a bombardment effect which results in dust emission. The latter authors derived a physical ~~an~~ expression for dust emission by saltation

$$F_b = \frac{c_b g \xi \rho_b}{P}\left(1 + 14u_*\sqrt{\frac{\rho_b}{P}}\right) Q \qquad (4)$$

~~$F_b = \frac{c_b g \xi \rho_b}{P}\left(1 + 14u_*\sqrt{\frac{\rho_b}{P}}\right) Q F = \frac{c_b g \eta \rho_b}{P}\left(1 + 14u_*\sqrt{\frac{\rho_b}{P}}\right) Q$ (4)~~

where c_b is a constant, g is gravitational acceleration, ξ ~~η~~ is the mass fraction of dust inside the crater, ρ_b is the soil bulk density, P is the horizontal component of soil plastic pressure determined by soil property and Q represents saltation intensity which can be estimated by using the Owen model as shown in the next section.

2.3 Aggregates Disintegration

Studies on aggregates disintegration are rare. Shao (2001) presented a dust emission model which accounts for both the effect of saltation bombardment and aggregates disintegration. This model, as simplified in Shao (2004, S04 hereafter), can be summarized as follows:

$$F_b + F_c = \sum_{i=1}^{I} F(d_i) \qquad (5)$$

$$F(d_i) = \int_{d_1}^{d_2} F(d_i, d_s) p(d_s)\, \delta d_s \qquad (6)$$

$$F(d_i, d_s) = c_y \xi_{fi} \left[(1-\gamma) + \gamma\sigma_p\right](1+\sigma_m)\frac{gQ(d_s)}{u_*^2} \qquad (7)$$

$$Q(d_s) = c_0 \frac{\rho}{g} u_*^3 \left(1 - \frac{u_{*t}^2(d_s)}{u_*^2}\right), \text{ with } c_0 = 0.25 + \frac{v_t}{3u_*} \quad \text{(Owen, 1964)} \qquad (8)$$

where d_i is the particle size of the ith bin out of the total I bins, d_s is the particle size of the saltator, $F(d_i)$ represents the flux of dust of size d_i, and $F(d_i, d_s)$ represents the fraction of $F(d_i)$ which is caused by saltators of size d_s. d_1 and d_2 are the lower and upper limits of d_s. $p(d_s) = \gamma p_m(d_s) + (1-\gamma)p_f(d_s)$ is the particle size distribution of d_s, $p_m(d_s)$ and $p_f(d_s)$ are respectively the distributions of saltators with statuses of minimally and fully disturbances, $\gamma = \exp[-(u_* - u_{*t})^3]$ (Shao et al., 2011), c_y is a dimensionless coefficient, ξ_{fi} is total dust fraction of the ith bin, σ_p is the ratio of aggregated dust to free dust, σ_m is the mass ratio of ejectiles to saltators (i.e., bombardment efficiency) derived from the saltation model by Lu and Shao (1999). Saltation intensity $Q(d_s)$ is evaluated by Owen model (Equation 8, where ρ is air density, 1.25 kg·m^{-3}) and the particle terminal velocity is calculated by $v_t = 1.66(\sigma_\varphi g d_s)^{1/2}$ (Shao, 2008), with particle-to-air density ratios σ_φ=2120. Equation (5) sums the dust fluxes of all size bins and Equation (6) gives the dust flux of particles in the ith bin. In the end, emission dust flux is found to be proportional to $Q(d_s)$, but the proportionality depends on soil texture and soil plastic pressure. Further simplification indicates that at high soil plastic pressure (>3×10^5 Pa), σ_m becomes negligibly small (<0.1) under normal wind conditions, and saltation bombardment diminishes to such an extent that aggregates disintegration prevails.

Kok et al. (2014) proposed a physically based dust emission parameterization by using a combination of theory and numerical simulations. Their model primarily considers dust emission by aggregates disintegration and is in good agreement with a quality-controlled compilation of experimental measurements. But an indisputable fact is that it is ~~really~~ difficult to distinguish the contributions of the different dust emission mechanisms from experimental data (especially for field measurement). And it appears to be untenable to assume that dust emission is mainly caused by sandblast~~ing or~~ed fragmentation. We argue that aerodynamic entrainment should not be simply ignored and a series wind tunnel experiments are designed to verify our argument.

~~where F is total dust flux, d_i is the particle size of the ith bin out of the total I bins, d_s is the particle size of the saltator, d_1 and d_2 are the lower and upper limits of d_s, $p(d_s)$ is the particle size distribution of d_s, c_y is a dimensionless coefficient, η_{fi} is total dust fraction of the ith bin, $\gamma = \exp[-(u_* - u_{*t})^3]$ in which u_* is the friction velocity and u_{*t} is the threshold friction velocity, σ_p is the ratio of aggregated dust to free dust, σ_m is the mass ratio of ejectiles to saltators (i.e., bombardment efficiency) derived from the saltation model by Lu and Shao (1999), and $Q(d_s)$ is the flux of the saltators. Equation (5) sums the dust fluxesover allsize bins and Equation (6) gives the dust flux of particles in the ith bin.~~

~~In the end, F is found to be proportional to $Q(d_s)$, but the proportionality depends on soil texture and soil plastic pressure. Further simplification indicates that at high soil plastic pressure (>3×10^5 Pa), σ_m becomes negligibly small (<0.1) under normal wind conditions, and saltation bombardment diminishes to such an extent that aggregates disintegration prevails.~~

~~In this work, we consider the total dust flux, F, as the sum of contributions from the three individual mechanisms~~

~~$F = F_a + F_b + F_c$ (8)~~

Our basic assumptions of this paper are as follows. Let the dust exposed on a bare soil surface be the available dust for aerodynamic entrainment~~emission~~. Then, the thoroughly disturbed soil possesses the maximum amount of available dust. As dust emission proceeds, supply limit for aerodynamic entrainment occurs when the available dust falls below a critical level. We define the replenishment of available dust as surface renewal. Then, saltation and creep enable surface renewal in several ways: (1) remove particles on the surface to expose the underlying dust; (2) spear into the soil to dislodge the dust initially not available; and (3) blast onto aggregates and break them to release new surface dust. Surface renewal does not directly cause dust emission but recover surface available dust, which is the main difference from normal saltation bombardment mechanism. The total emitted dust is divided into two parts: one part is attributed to aerodynamic entrainment (F_a) and the other to sandblasting (F_{b+c}, including the contribution of saltation bombardment, F_b, and aggregates disintegration, F_c).

3. Wind Tunnel Experiment

We conducted the experiments in the wind tunnel of Lanzhou University. This open-return blow-down low-speed wind tunnel is 22 m long (only for work section) with a cross section of 1.3 m wide and 1.45 m high. The operational wind speed can be adjusted in the range of 4-40 m·s^{-1}. The wind tunnel has excellent performance in simulating atmospheric boundary-layer flows for near-surface wind environment studies. The detailed information of the wind tunnel could be found in Zhang et al. (2014).

3.1 Experimental Setup

The setup for the experiments is as shown in Figure 1. Roughness elements are placed 6 m upstream the working section to initiate a turbulent boundary layer. Their heights are adjusted to ensure a logarithmic wind profile (up to 20 cm above ground) in the downstream measurement area under all applied flow speeds. A test surface is located immediately downstream the roughness elements, which is 9 m long, 1 m wide and 5 cm deep and is paved with a soil. For measuring saltation, a sand trap is installed 8 m downstream from the frontal edge of the test surface. Two dust concentration probes are placed at 7 cm and 14 cm above the surface, each connected to a 1.109 Grimm aerosol spectrometer (Grimm Aerosol Technik GmbH & Co. KG). A Pitot tube is anchored to an adjustable frame for measuring the profile of the flow speed at 10 sampling points at 10, 15, 20, 30, 50, 70, 100, 130, 160 and 200 mm above the surface.

A farmland soil collected from Minqin in GansuMinqin of Gansu Province of China (natural soil hereafter) and natural sand collected from the Tengger Desert (natural sand hereafter) are used for the preparation of the test surfaces. Three land surfaces are tested as shown in Figure 1. In Setting 1 (S1), the natural soil is used for the entire test bed to simulate a farmland surface, on which supply limit may commonly occur. In Setting 2 (S2), the first 4 m of the test bed is paved with the natural sand ahead of 5 m natural soil, to examine how enhanced saltation affects dust emission with respect to S1. The S2 case corresponds to a desert-edge surface, on which saltation is significant to cause dust emission. In Setting 3 (S3), the natural soil is first sieved with a 20 mesh (841 μm) sieve (sieved soil hereafter) and then paved to simulate a loess surface which has sufficient dust content and low restriction for saltationsieved soil. In this setting, the lumpy aggregates are removed. S1 represents a farmland surface, S2 a desert-edge surface and S3 a loess surface.

3.2 Instruments and Measurements

By regression of the Prandtl–von Kármán equation

$$u(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right) \quad (9)$$

$$u(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right) \quad (9)$$

to the Pitot-tube measurements, the friction velocity, u_*, and surface roughness, z_0, are calculatedestimated. In Equation (9), z is height, $u(z)$ is the mean flow velocity at height z and κ=0.4 is the von Kármán constant.

The particle size distributions of the natural soil, natural sand and sieved soil were analysed by using a Microtrac S3500 Laser Diffractometer (Microtrac, Montgomeryville, PA, USA) and approximated with an overlay of multiple log-normal distributions

$$d \times p(d) = \sum_{j=1}^{N} \frac{W_j}{\sqrt{2\pi}\sigma_j} exp[-\frac{(lnd-lnD_j)^2}{2\sigma_j^2}] \quad (10)$$

$$d \times p(d) = \sum_{j=1}^{N} \frac{W_j}{\sqrt{2\pi}\sigma_j} exp[-\frac{(lnd-lnD_j)^2}{2\sigma_j^2}] (10)$$

where N is the number of log-normal distribution modes ($N \le 4$), W_j is the weight of the jth model of the particle size distribution$j$th normal distribution, D_j and σ_j are the parameters in the jth normal distribution. The particle size distribution of minimally disturbed soil $p_m(d)$ and fully disturbed soil $p_f(d)$are measured similarly to Shao et al. (2011). The soil sample is dispersed in water and the resulting particle size distribution taken as $p_m(d)$. The soil is firstly ground in a mortar and then be dispersed in 2% sodium hexametaphosphate to prepare the measurement for $p_f(d)$. Although ultra-sonication is an effective method to break solid particles, the effect of chipping and attrition induring particle collision process does not occur during sonication which may result in wearing down individual particles and changing the size distribution. Therefore, the sonication step in Shao et al. (2011) is replaced with grinding in measuring $p_f(d)$.The sonication step in Shao et al. (2011) is replaced with grinding in measuring $p_f(d)$ because sonication has incomparably stronger power than the particle collision during saltation.

The saltation flux is measured using a sand trap adapted from the WITSEG sampler designed by Dong et al. (2003). Facing the wind stream are 38 stacked collectors (2 cm × 2 cm opening), each of which collects sand to its chamber. The streamwise saltation flux, Q, is then determined by weighing the sand in the chambers after each run:

$$Q = \sum_{i=1}^{38} q_i \Delta h_i \quad (11)$$

$$q_i = \frac{m_i}{t_s A_i} \quad (12)$$

$$Q = \sum_{i=1}^{38} q_i \Delta h_i (11)$$

$$q_i = \frac{m_i}{t_s A_i} (12)$$

where Δh_i is the vertical size ofsize if inlet for collector $i$$i$ mounted at height h_i above the surface, q_i is the saltation flux at h_i, m_i is the mass of sand collected at h_i, t_s is the time duration of sand collection and A_i is the inlet area of the collector.

Once emitted, dust is transported vertically by turbulent diffusion. Assuming steady state and horizontal homogeneity, the vertical diffusive flux is equal to dust emission flux and can be evaluated by the gradient method which has been applied in previous wind-tunnel studies on dust emission (Fairchild and Tillery, 1982; Borrmann and Jaenicke, 1987). Our environmental wind-tunnel is designed for simulating atmospheric boundary layer flows and its performance has been validated. We also tested the performance of this wind-tunnel in simulating well-mixed dust cloud with ~~a~~an 8 m fetch in a previous study on dust deposition (Zhang, 2013). Thus, the condition of our laboratory satisfies the requirements of the gradient method~~, which can be calculated using the gradient method~~. In our experiments, dust concentration, C, is measured at z_1 = 7 cm and z_2 = 14 cm above the surface, and thus dust emission rate can be calculated as

$$F = -K_p \frac{C(z_2)-C(z_1)}{z_2-z_1} \quad (13)$$

~~$$F = -K_p \frac{C(z_2)-C(z_1)}{z_2-z_1} \quad (13)$$~~

where K_p is the turbulent diffusion coefficient for dust particles, which can be approximated as

$$K_p = K_m = u_* l \quad (14)$$

~~$$K_p = K_m = u_* l \quad (14)$$~~

with l being the mixing length, taken here as $\kappa(z_1+z_2)/2$.

3.3 Procedures of Wind-tunnel Experiments

The wind-tunnel experiments are carried out according to the settings given in Table 1 and the following procedures:

1. Prepare soil and pave test bed as shown in Figure 1;
2. Set up instruments as shown in Figure 1;
3. Set fan to target flow speed; measure dust concentration and wind speed over 10 minutes; end run early if test bed is blown bare or sand chambers are filled;
4. Turn off fan; record time duration for saltator collection; weigh mass of collected saltators; save dust concentration data measured with aerosol spectrometer;
5. Restart fan set to the same target speed as Step 3, and measure wind profile;
6. Remove paved soil (soil must not be reused because emission has changed dust content). Start over from Step 1 for next run.

4. Results and Analysis

4.1 Particle Size ~~Distribution~~ Distribution of Source Materials and Wind Profiles

The particle size distributions of the natural soil, natural sand and sieved soil are shown in Figure 2. The dots represent the measured values, while the lines ~~represent~~ Equation (10) fitted to the measurements (see Table 2 for fitting parameters). For the natural sand, the fraction of particles in the size range of 10-200 μm increased due to grinding, while for the natural soil and sieved soil in the 1-10 μm and 30-60 μm size ranges.

The natural soil contained many lumps (diameter in centimetre scale) that can be easily broken by external impact or abrasion. These lumps disperse in water and thus the similarity in $p_m(d)$ between the natural and sieved soils does not reflect the existence of the large lumps in the natural soil. However, the lumps may significantly influence dust emission by causing spatial shear stress variations and by sheltering the surface from erosion. It was also found that the soil lumps were easily destroyed during the sieving process and the characterization of large soil lumps remains a problem to be better solved in future research.

The wind ~~profiles~~velocities~~,~~ measured in the height range ~~from~~of 10~~-mm to-~~-160 mm (the data obtained at the topmost measurement point are erratic and therefore not included) are shown in Figure 3. The dots are averaged wind speeds over 3 minutes measured ~~by using~~with Pitot tubes and the lines are the regressions using Equation (9). As shown, the profiles of the horizontal wind velocity follow the logarithmic law and ~~fit~~can be well fitted with the Prandtl–von Kármán equation very well. The values of the regression parameters are listed in Table 1.

4.2 Streamwise Saltation Flux~~Saltation Bombardment~~

The measured streamwise saltation fluxes are shown in Figure 4. For all three surfaces, saltation flux increased with friction, but the saltation flux of S2 (natural soil surface under sand bombardment) was significantly larger than that of S1 (natural soil surface) by more than an order of magnitude, due to the impact of saltating sand particles. No saltation was detected over S1 and S2 for $u_* < 0.34$ m·s^{-1}. But over S3, significant saltation was measured for $u_* > 0.23$ m·s^{-1}. For $u_* > 0.35$ m·s^{-1}, the saltation flux ~~over~~of S3 obviously exceeded that ~~over~~of S1, but is smaller than that o~~ver~~f S2.

It is necessary to ~~estimate~~validate first the formulations of streamwise saltation flux which is closely related to most dust emission models (e.g. LS99, S04). In case of saltation of uniform particles, saltation flux can be estimated using the Owen model (i.e. Equation 8), but c_0 and u_{*t} are tuneable parameters ~~which are~~ to be determined by regression to the observations. The model-simulated results are shown in Figure 4 (Regression 1, dotted curves) together with the regression parameters c_0 and u_{*t} and determination coefficient, R^2. As c_0 is related to the terminal velocity of the saltating particles, it is obviously big for S2 (corresponding to big sand particles). u_{*t} is effected by the size of soil particles and surface roughness, and is therefore large for S1 (because of high surface roughness) and for S2 (because of big size of sand particles).

The above fitting is straightforward and gives reasonable results except for the cases when the friction velocity is close to the threshold friction velocity. An alternative method is to calculate the saltation fluxes for different particle size bin by Equation (8) and then integrate over the size bins to obtain the total saltation flux

$$Q = \int_{d_1}^{d_2} Q(d_s)\, p(d_s)\, \delta d_s \qquad (15)$$

$Q = \int_{d_1}^{d_2} Q(d_s)\, p(d_s)\, \delta d_s$ (15)

The threshold friction velocity is evaluated by (Shao and Lu, 2000)

$u_{*t}(d_s) = \sqrt{u_{*t}(d_s) = \sqrt{A_n(\sigma_\varphi g d_s + \frac{r}{\rho d_s})}\ A_n(\sigma_\varphi g d_s + \frac{r}{\rho d_s})}$ (16)

(16)

where A_n and r are the regression parameters. The threshold friction velocities calculated using Equation (16), together with the regression parameters A_n and r, are shown in Figure 4. It is seen that the second method (Regression 2, solid curves) gives a more accurate estimate of Q than the first (Regression 1). And the threshold friction velocity appears to be influenced by not only particle size but also surface conditions, as the different values of A_n and r imply.

The measured and predicted streamwise saltation fluxes are shown in Figure 3. For given friction velocity, the sieved soil (S3) has slightly higher saltation flux than the natural soil under sand bombardment (S2), but both are much higher than the natural soil (S1). The Owen (1964) saltation model (dotted curve in Figure 3)

$Q = c_0 \frac{\rho}{g} u_*^3 \left(1 - \frac{u_{*t}^2}{u_*^2}\right)$ (15)

fits well to the measured fluxes, where c_0 is the Owen coefficient and u_{*t} is the threshold friction velocity and ρ is air density. The Owen saltation model is best applied to describe the saltation of uniform particle sizes, for which the two important parameters, namely, c_0 and u_{*t}, are well defined. For a surface with mixed particles, u_{*t} can be interpreted as a mean threshold friction velocity over a particle size range and c_0 reflects the fraction of effective saltators, namely, grains available for saltation at a given friction velocity, u_*. The fraction of effective saltatorsdepends on the size distribution of the surface soil, the threshold friction velocity for each particle size bin and the spatial variation of u_*.

In S1, the presence of soil lumps not only increased significantly the threshold frictionvelocity compared with the sieved soil in S3, but also reduced the fraction of effective saltators as manifested in the low c_0 values. In S2, the saltators were mainly the natural sand particles which have a higher threshold friction velocity than the sieved soil. Because the natural sand has a narrow size range, the fraction of effective saltators was high once u_* exceeded u_{*t}, as seen in the high c_0 value.

The above fitting is straightforward and gives reasonable results except for the cases when the friction velocity is close to the threshold friction velocity and the Owen coefficient is mainly dependent on the fraction of effective saltators. To further verify the prediction of the regression function, we calculated the saltation fluxes for different particle size bin and their integral over the size bins as follows:

$Q = \int_{d_1}^{d_2} Q(d_s)\, p(d_s)\, \delta d$ (16)

$Q(d_s) = c_0 \frac{\rho}{g} u_*^3 \left(1 - \frac{u_{*t}^2(d_s)}{u_*^2}\right)$ (17)

$$c_0 = 0.25 + \frac{v_t}{3u_*} \quad (18)$$

$$u_{*t}(d_s) = \sqrt{A_n\left(\sigma_\varphi g d_s + \frac{r}{\rho d_s}\right)} \quad (19)$$

where $p(d_s)$ is the measured soil size distribution (Figure 2), σ_φ the particle to air density ratio, v_t the particle terminal velocity and A_n and r the regression parameters (Shao and Lu, 2000). It is seen in Figure 3 that the above method gives a more accurate estimate of Q than Equation (15). Note that the key difference here is an improved estimate of u_{*t} for different particle size groups, as the values of A_n and r differ for different soils.

4.3. Vertical Dust Flux

Vertical dust fluxes can be calculated with Equations (13) and (14) using the measured dust concentrations at the levels of 7 cm and 14 cm. In this study, dust is defined as particles with diameter smaller than 15 μm, such that the requirements for using the gradient method are satisfied (Shao et al., 2011). It can be seen from Figure 4 5 that for S1, dust emission has an initial sharp increase followed by a rapid decline (Figure 5aFig. 4a). The same phenomenon has been reported in earlier studies and is considered to be characteristic of aerodynamic entrainment under limited supply of free dust (Shao, 1993; Loosmore and Hunt, 2000). After 3 minutes, the vertical dust flux tends to be stable. Therefore, we calculated the average dust flux over the interval of 3 to 10 minute (dashed lines in Figure 5) for all cases and plotted the results in Figure 6 (triangles). For comparison, the data of LH2000 and MP2008 are plotted as circles and squares respectively. As shown, our results are comparable with MP2008 but obviously greater than LH2000. Generally, dust vertical fluxes increase with friction velocity by following a power function. But the results for the three surfaces differ by several orders of magnitudes.

By considering that S1 resembled the unperturbed surface in MP2008, whereas S2 and S3 resembled the renewed surface in MP2008, and consequentlythe soilS2 surface was indeed renewed in S2 by external sand bombardment and inthe S3 by the spontaneous saltation and creep of big particles. Thus, the vertical flux indust emission of S2 iswas about one order of magnitude greaterlarger than that inof S11 because the former hasexperienced stronger saltation bombardment,. and tThe results indust flux of S3 arewas another order of magnitude greaterlarger than that inof S21 because of the higher dust content of effectiveat the surface dust(Shao, 1993; Loosmore and Hunt, 2000).

In our experiments, paving the test bed causes caused mechanical disturbances to the soil. Thus, at the beginning of the run, the amount of free dust available for aerodynamic entrainment should bewas close to the maximum for the given soil. As the dust emission continued, the amount of available free dust thus iwaswas gradually depleted and eventually exhausted. -That appears to be a reasonable explanation of the phenomenon that occurred in S1 in the first three minutes. After about three minutes, dust emission was mainly attributed to weak saltation bombardment (Figure 5aFig. 4). We therefore separate the time series into the two sections of 0-3 min and 3-10 min. The vertical dust flux averaged over the 0-3 min section, $F_{0\text{-}3\text{min}}$, is the dust emission due to both aerodynamic entrainment and saltation bombardment with unlimited dust supply. The dust flux averaged over the 3-10 min section, $F_{3\text{-}10\text{min}}$ (F_b), is the dust emission due to saltation bombardment under limited dust supply (here, the effect of aggregates disintegration is not discussed individually and the related contribution is involved in F_b). Based on the theory of dust emission described in Section 2, dust emission via aerodynamic entrainment depends on the amount of exposed surface dust, and saltation bombardment dust relates to the dust content of subsurface. For the case without surface renewal (S1), as result of dust emission, the exposed surface dust iwas exhausted and supply-limit occursed. But the dust content of the subsurface should not have changed significantly during the measurement time of 10 minutes, due to the lack of motion of large surface particles, which- renews the surface. So it is reasonable to assume that there iwas no significant difference in dust emission via saltation bombardment during the measurement time, and the difference between the average vertical dust fluxes over the first 3 minutes ($F_{0\text{-}3\text{min}}$) and over the last 7 minutes ($F_{3\text{-}10\text{min}}$) is therefore considered as the dust emission caused by aerodynamic entrainment (F_a) under unlimited dust supply (Figure 6, pentagram dots).Thedifference$F_{0\text{-}3\text{min}}$-$F_{3\text{-}10\text{min}}$($F_a$)is then considered the dust emission due to aerodynamic entrainment under unlimited dust supply (Fig. 5).

In contrast, S2 and S3 did not show such a remarkable decrease of dust flux after the initial phase, probably due to the intensive saltation (see Figure 4Fig. 2) which timely replenished the dust supply. But in general, it is not possible to separate the contributions due to aerodynamic entrainment and saltation bombardment. We have noted that the comparable saltation flux over S1 did not lead to surface renewal but over S3. This shows that surface renewal is affected both by saltation intensity and surface properties (i.e. S1 is more resistant to be renewed).Also for S2 and S3, we consider the dust flux averaged over the period of 3 to 10 minute as the dust emission for the corresponding surfaces (Fig. 5).

The results show that, the dust flux due to aerodynamic entrainment in S1 under unlimited supply was far greater than that in LH2000 (Fig.ure 5) and the maximum value ($F_{a|\max}$, which is about three times the average flux) even exceeded the dust flux due to strong saltation bombardment in S2. This may be due to the uneven distribution of surface shear force over the coarserough soil surface in S1. Thus, we conclude that flow conditions, surface particle motion, dust availability and surface roughness can jointly cause dust fluxes to differ by orders of magnitudes.

The measurement data of average verticald dust fluxes averaged over the period of 3 to -10 minutes are ththaen discussedexamined bywith regression analysis. Equation (3) is chosen as the regression equation and the regression curves are shown as solid lines in fFigure 6. For S1, the natural soil with weak saltation bombardment had a dust flux proportional to u_*^4, in agreement with Gillette and Passi (1988). The introduction of saltation bombardment in S2 increased dust emission by one order of magnitude, with dust flux proportional to u_*^6. In S3, dust flux increased by two orders of magnitude compared to S1, with dust flux proportional to u_*^7. But under unlimited supply in S1, the dust flux was proportional to u_*^{10}, if the threshold friction velocity is set to the same value as in the first case of S1 with the period of 3-10 minutes (i.e. u_{*t} = 0.29 m·s^{-1}). The regression analysis shows that with intensified surface renewal from S1 to S3, the relationship between dust flux and friction velocity increasingly resembled the aerodynamic entrainment under unlimited supply. An interpretation of this could be that strong saltation bombardment and creep enabled surface renewal, thusereby removing supply limit and maintaining dust emission at a high level. From this point of view, dust emission can be considered to be driven by a combination of aerodynamic entrainment and saltation b~~lasting~~ombardment. In consideration of that saltation and creep are responsible for surface renewal which restores the availability of dust for emission, the contribution of aerodynamic entrainment should not be ignored and may be domina~~ted~~nt under s~~a~~ome conditions.

To test the above hypothesis, the total dust vertical flux is considered as the sum of two parts

$$F = F_a + F_{b+c} = c_1 \cdot u_*^{10}\left(1 - \frac{u_{*t}}{u_*}\right) + c_2 \cdot u_*^4 \left(1 - \frac{u_{*t}}{u_*}\right) \qquad (17)$$

~~$$F = F_a + F_{b+c} = c_1 \cdot u_*^{10}\left(1 - \frac{u_{*t}}{u_*}\right) + c_2 \cdot u_*^4 \left(1 - \frac{u_{*t}}{u_*}\right) \qquad (17)$$~~

where c_1 relates to exposed dust content and c_2 to subsurface dust content and impact energy of saltators. The first term on the right hand side of Equation (17) is attributed to aerodynamic entrainment and the second to saltation bombardment and aggregates disintegration. We now use Equation (17) to predict the vertical dust fluxes over the different surfaces. The values of u_{*t} are assumed to be the same as in Figure 6 and c_1 and c_2 are obtained by regression analysis. As shown in Figure 7,~~-~~ Equation (17) can well describe the experimental data. And based on the estimated values of c_1 and c_2, the ratio of F_a/F can be readily estimated, as shown in Figure 7 (dashed lines). It is seen that, sometimes (e.g. high u_* over S2 and S3) the contribution of aerodynamic entrainment can exceed saltation bombardment ($F_a/F > 0.5$) and be the dominate mechanism for dust emission. It appears that saltation not only causes dust emission, but also surface renewal which restores the availability of dust for the emission.

~~The results of Loosmore&Hunt (2000) and Macpherson et al. (2008), denoted as LH2000 and MP2008, respectively, are also shown in Figure 5. It can be seen that dust fluxes increase with friction velocity by following a power function, but the results for the three surfaces differ by several orders of magnitudes. S1 resembled the unperturbed surface in MP2008, whereas S2 and S3 resembled the renewed surface in MP2008, indicating that the soil surface was indeed renewed in S2 by external sand bombardment and in S3 by spontaneous saltation and creep of big particles. The flux in S2was about one order of magnitude greater than that in S1 because the former had stronger saltation bombardment. The flux in S3was another order of magnitude greater than that in S2 because of the higher content of effective surface dust. We also noted thatthe dust flux of S1 under unlimited supply was far greater than that in LH2000 (Fig. 5) and the maximum flux ($F_{a|max}$, which is about three times the average flux) even exceeded the dust flux due to strong saltation bombardment in S2. This should be due to the uneven distribution of surface shear force over the coarse soil surface in S1.Thus, the flow conditions, surface particle motion, dust availability, surface roughness and other factors can all cause dust fluxes to differ by orders of magnitudes.~~

~~Regression analysis shows that in S1, the natural soil with weak saltation bombardment had a dust flux proportional to u_*^4, in agreement with Gillette and Passi (1988). The introduction of saltation bombardment in S2 increased dust emission by one order of magnitude, with dust flux proportional to u_*^6. In S3, dust flux increased by two orders of magnitudecompared to S1, with dust flux proportional to u_*^7.But under unlimited supply in S1, the dust flux was proportional to u_*^{10}. We note that with~~

~~intensified surface renewal from S1 to S3, the relationship between dust flux and friction velocity increasingly resembled the aerodynamic entrainment under unlimited supply. An interpretation of this can be that strong saltation bombardment and creep enabled surface renewal, thus removing supply limit and maintaining dust emission at a high level. From this point of view, dust emission can be considered to be mainly driven by aerodynamic entrainment, whereas saltation and creep are responsible for surface renewal which restores the availability of dust for emission. In general, dust emission can be seen as the result of restricted aerodynamic entrainment.~~

4.4. Bombardment Efficiency

Bombardment efficiency~~Figure 6 shows how bombardment efficiency~~, $\eta = F/Q$, (Gillette, 1979; Marticorena and Bergametti, 1995; Shao, 2008; Macpherson et al., 2008) is a key parameter for the saltation bombardment process~~varies with friction velocity, u_*~~. Previous studies suggested that dust emission is mainly due to saltation bombardment and for a given surface η appears to be a relatively stable constant (Marticorena and Bergametti, 1995; Houser and Nickling, 2001). Others found that η increases with u_* (Nickling et al., 1999; Kok et al., 2012) and this increase ~~should be~~ depend~~ents~~s on surface conditions (Shao, 2001). However, measurements are so far insufficient to verify this theory. In MP2008 (Macpherson et al., 2008), as the surface conditions were very complex, the measured bombardment efficiency scattered over a ~~wide~~ range of 4 orders of magnitude and did not show a fixed relationship with friction velocity.

The bombardment efficiencies we measured are shown as dots in Figure 8~~in Figure 6~~. It is observed that around the threshold friction velocity for each setting~~for all settings~~, η ranged between 2.0 and 3.0 × 10^{-4} m^{-1}, which is close to the result of MP2008~~,~~. ~~at small u_*.~~ However, it behaved differently as u_* increased. In S1, it decreased exponentially with u_*. But in S2, η firstly decreased and then increased with increasing u_*. For the case of S3, it monotonically increased with u_*.

We now analyse the possible reasons for the ~~unexpected~~ behaviour of η. In S1, the~~This~~ decrease cannot be explained using the existing dust emission modes (Lu and Shao, 1999; Shao, 2001, 2004). It is likely that as saltation bombardment was weak in S1 and could only lift the dust in a thin soil layer. Once the dust in this thin layer was depleted, the surface became dust supply limited. ~~Although both surface types are natural soil, the moving sand particles may be more effectivein the bombardment process (or aggregates disintegration process), and thus enhance the bombardment efficiency.That’s why the bombardment efficiency of S2 was slightly higher than in S1 at low friction velocity~~~~limit. The bombardment efficiency of S2 was slightly higher than in S1 at low friction velocity.Although both surface types are natural soil, the moving sand particles may be more effectivein the bombardment process (or aggregates disintegration process), and thus enhance the bombardment efficiency.~~ In S2, with the increase of u_*, the large amount of saltators from the upstream may have buried the dust on the surface of the test bed and changed its properties, thus leading to the decline in bombardment efficiency similar to S1. As u_* further increased, the sand particles would not settle on the test bed, but continue to strike the surface and expose more dust to air, and thus increasing the bombardment efficiency. It implies that~~Hence,~~ the degree of surface renewal may significantly affect~~s~~ the bombardment efficiency. In S3, the available dust content is high and the bombardment efficiency is much higher than that in S1 and S2. The sieved soil used in S3, free from the sheltering of the lumps, is very mobile. Thus, as wind speed increased, the sieved soil particles may undertook strong bombardment over the surface and enhanced surface renewal. This allowed an unlimited dust supply to maintain the bombardment efficiency. But even this does not seem to explain the increase of η with exponent of u_* (blue line in Figure 8Fig. 6). While the decline of η with u_* in S1 and the preceding stage of S2 may be due to the inadequate replenishment of dust supply, the increase of η with u_* in S3 and the last stage of S2 must be due to the contribution of aerodynamic entrainment., this appears to be in line with the previous discussion of Figure 7.

In short, we conclude that the strong saltation bombardment enabled surface renewal and dust supply to maintain saltation bombardment efficiency; if the surface renewal is inadequate, then η decreases with u_*; inFigure 5 also shows that the powerof u_* is 7 in S3, which is close to the model flux equation of aerodynamic entrainment (F_a). This implies that the strong saltation bombardment enabled surface renewal and dust supply to maintain saltation bombardment efficiency. If the surface renewal is inadequate, then η decreases with u_*. In contrast, the saltation and creep generate sufficient surface renewal and hence dust supply, then η increases with u_*.

4.5. Comparison with Model Predictions

Figure 7 shows the averaged dust flux over the time interval from 3 to 10 min and the predictions using the models of GP88, LS99 and S04. As shown, the differences between the predictions of GP88 and the measured data near critical friction velocity are obviously bigger than the results of other two models for all three settings. That is caused by the indefinableempirical coefficient, c, for mixed-particle surfaces. In S1, dust emission occurred in the case of limited supply.Due to the neglect of the supply-limiting effect and of the variation of bombardment efficiency, all three models underestimated the dust flux at low friction velocity, but slightly overestimated at high friction velocity. For S2, all three models underestimated dust flux at low and high friction velocities but overestimated dust flux at intermediate level of friction velocity. At low u_* (just above u_{*t}), the saltating sand impacts on soil surface with relative high bombardment efficiency to cause dust emission. With the increase of u_*, the bombardment efficiency decreases because of changed surface property due to intrusivesand particles.At high u_*, wind was strong enough to move deposited sand particles and renewal surface. For the latter case, the performances of models are better. But, as all three models do not consider surface renewal and the consequent parametric change, the deviation of the predictions from the measurements naturally occurs. In S3, notable saltation and creep took place, which generated significant surface renewal. S04appears to perform somewhat better than the others due to improved treatment for saltation bombardment and aggregates disintegration. Note that for the fitting of GP88 to the dust flux data (Figure 7), a very different u_{*t} was used than that for the fitting of the Owen model to the saltationflux data (Figure 3 and Figure 5). This shows that threshold friction velocity u_{*t} represents different properties of the soil surface in the Owen model and the GP88 model.

5. Conclusions

Three soil surfaces, representing farmland, desert-edge and loess, were tested in a wind-tunnel experiment to examine the dust emission mechanisms. It has been found that:

(1) Flow conditions, saltation bombardment, surface dust content and ground obstacles ~~can~~ may all significantly affect dust emission, causing dust emission to change over orders of magnitude;

(2) Dust emission due to aerodynamic entrainment from the natural soil surface is proportional to u_*^{10}, if the supply of free dust is unlimited, as in the initial phase (typically the first 2-3 minutes) of the wind-tunnel runs. This shows that in general, aerodynamic entrainment can be an important (even a dominant) process for dust emission under certain circumstances;

(3) Supply limit appears to be~~is~~ the major reason to restrict dust emission. In nature, dust emission may be~~is~~ often supply limited and hence the contribution of aerodynamic entrainment is determined by the renewal of the surface which results in increased availability of free dust for emission;

(4) Surface renewal through saltation and creep of surface particles should be~~is~~ the major pathway to ease the supply limit for dust emission. Surface renewal is not only important to the availability of dust for aerodynamic entrainment, but also important to the efficiency of saltation bombardment, η. It is shown that η depends on friction velocity, and the dependency differs for different surfaces reliant on the process of surface renewal~~;~~.

~~(5) Existing dust emission schemes do not account for the effects of surface renewal on aerodynamic entrainment and saltation bombardment efficiency, making the accurate prediction of dust emission from different surfaces difficult.~~

Dust emission seems to be~~is~~ a process driven by fluid motion and restricted by dust supply. The saltation and creep of large particles can generate surface renewal and restore the dust supply. Thus, the contribution of aerodynamic entrainment cannot be overlooked and the processes of supply limitation and surface renewal must be given due attention. Our experiment has shown that aerodynamic entrainment is highly efficient when dust supply is sufficient. Since surface renewal often does not fully liberate the potential of aerodynamic entrainment, dust emission in general can be seen as limited aerodynamic entrainment, and the extent of restriction depends on the degree of surface renewal.

This study does not contradict the earlier perception that saltation plays a fundamentally important role in dust emission, because saltation not only generates bombardment emission and aggregates disintegration, but also provides power for creep and contributes directly or indirectly to surface renewal. What is new in this paper is that we have been able to demonstrate the importance of surface renewal to aerodynamic entrainment in dust emission process~~dust emission~~.

In addition to the surface renewal by saltation and creep, or dynamic surface renewal, other processes, such as dust deposition and weathering, also contribute to surface renewal. Further experimental observations and theoretical analysis are necessary to establish a general surface renewal model.

Acknowledgments

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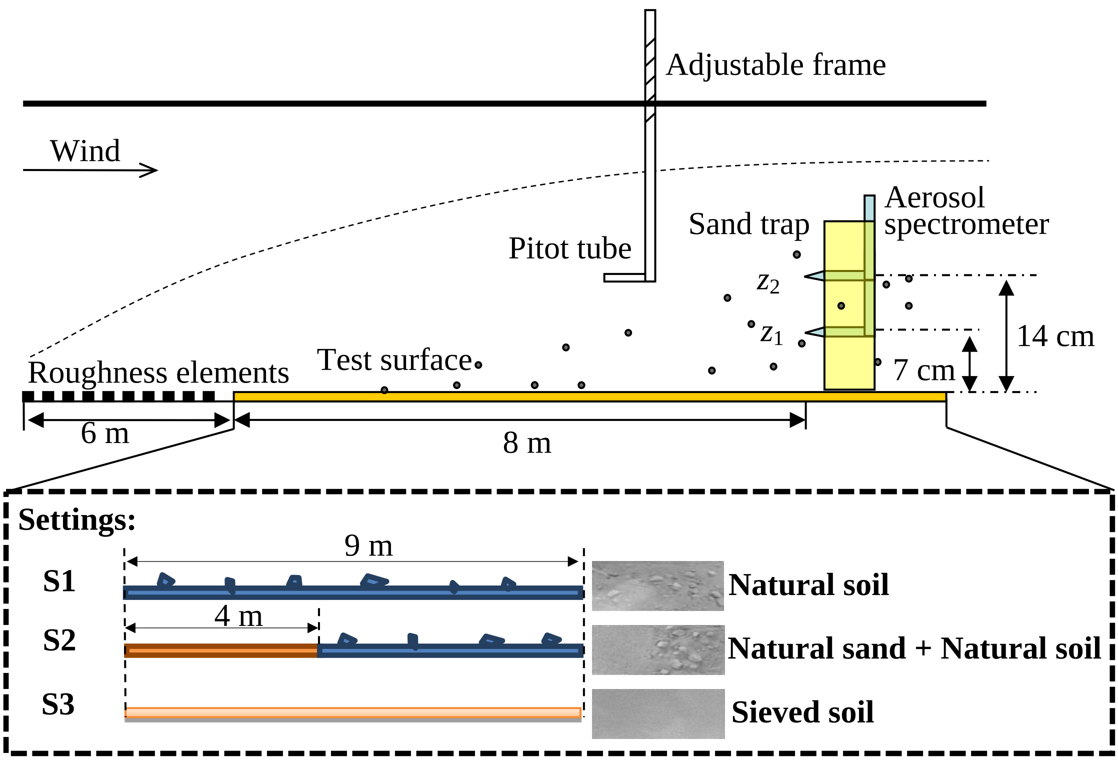


Figure 1. Wind tunnel configuration and simulated soil surfaces. The test surface of 9 m long, 1 m wide and 5 cm deep is located immediately downstream the roughness elements. A position-adjustable Pitot tube is used to measure wind profile. A dust trap is installed 8 m downstream from the frontal edge of the test surface. Two GRIMM probes are fixed at 7 cm and 14 cm above the surface to measure dust concentration gradient.~~**Figure 1: Wind tunnel configuration and simulated soil surfaces.**~~

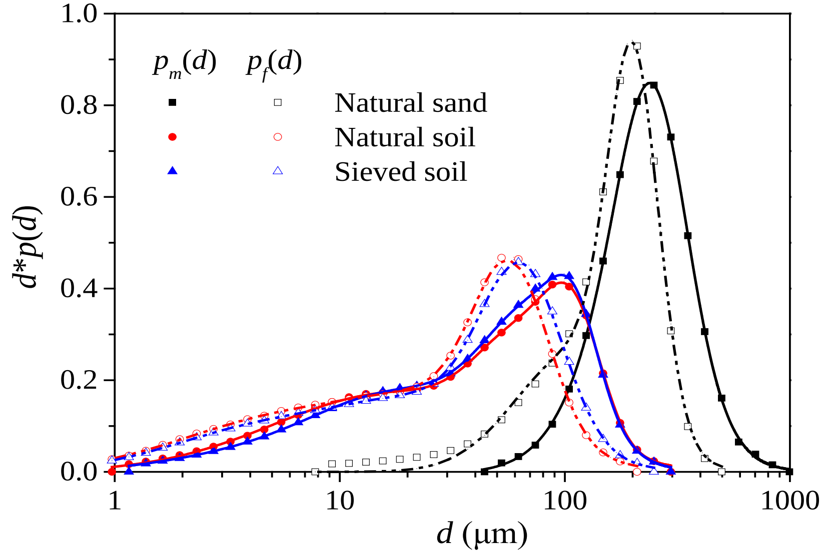


Figure 2. Minimally- and fully-disturbed particle-size distributions of the source materials which are used to simulated the three surfaces illustrated in Figure 1, namely, the natural sand, natural soil and sieved soil. The dots represent the measured values, while the lines Equation (10) fitted to the measurements. The fitting parameters are shown in Table 2.~~**Figure2: Minimally- and fully-disturbed particle-size distributions of the source materials, namely, the natural sand, natural soil and sieved soil.**~~

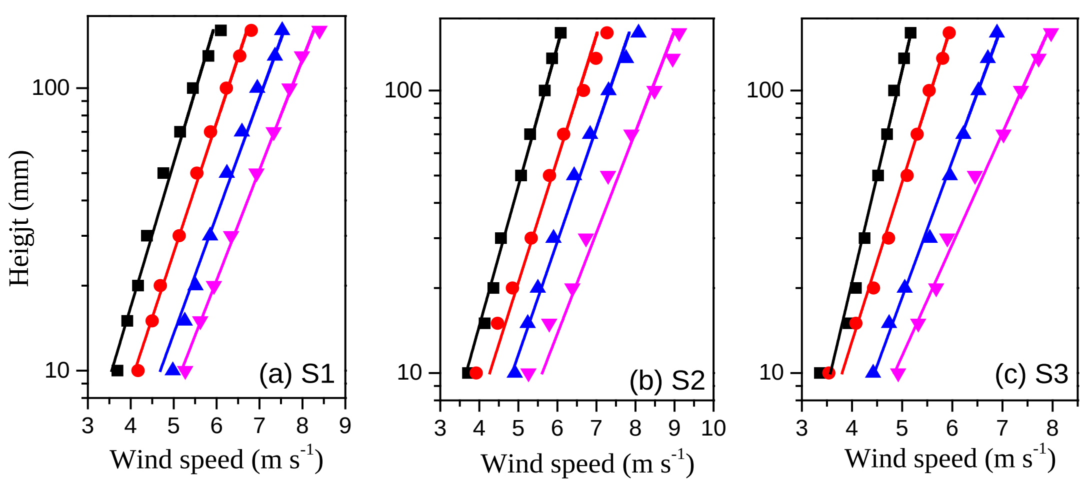


Figure 3. Wind profiles over three different surfaces. The dots are experimental data and lines are regression curves from Equation (9). The regression parameters are listed in Table 1.

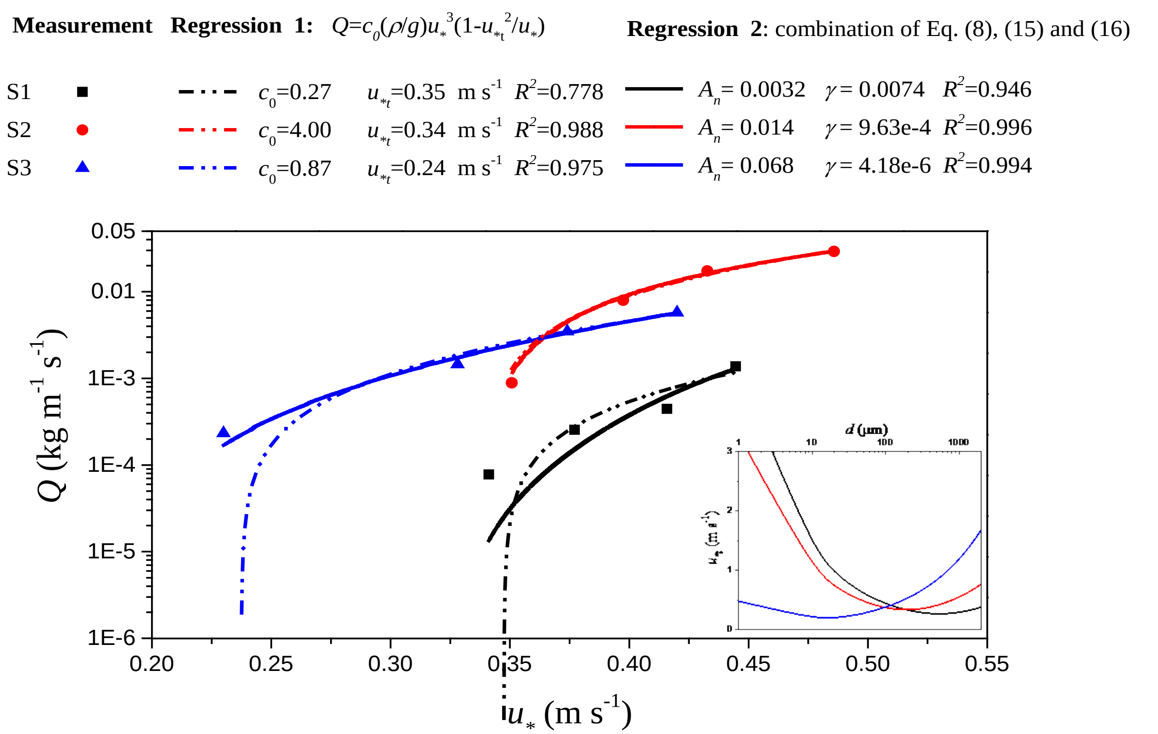
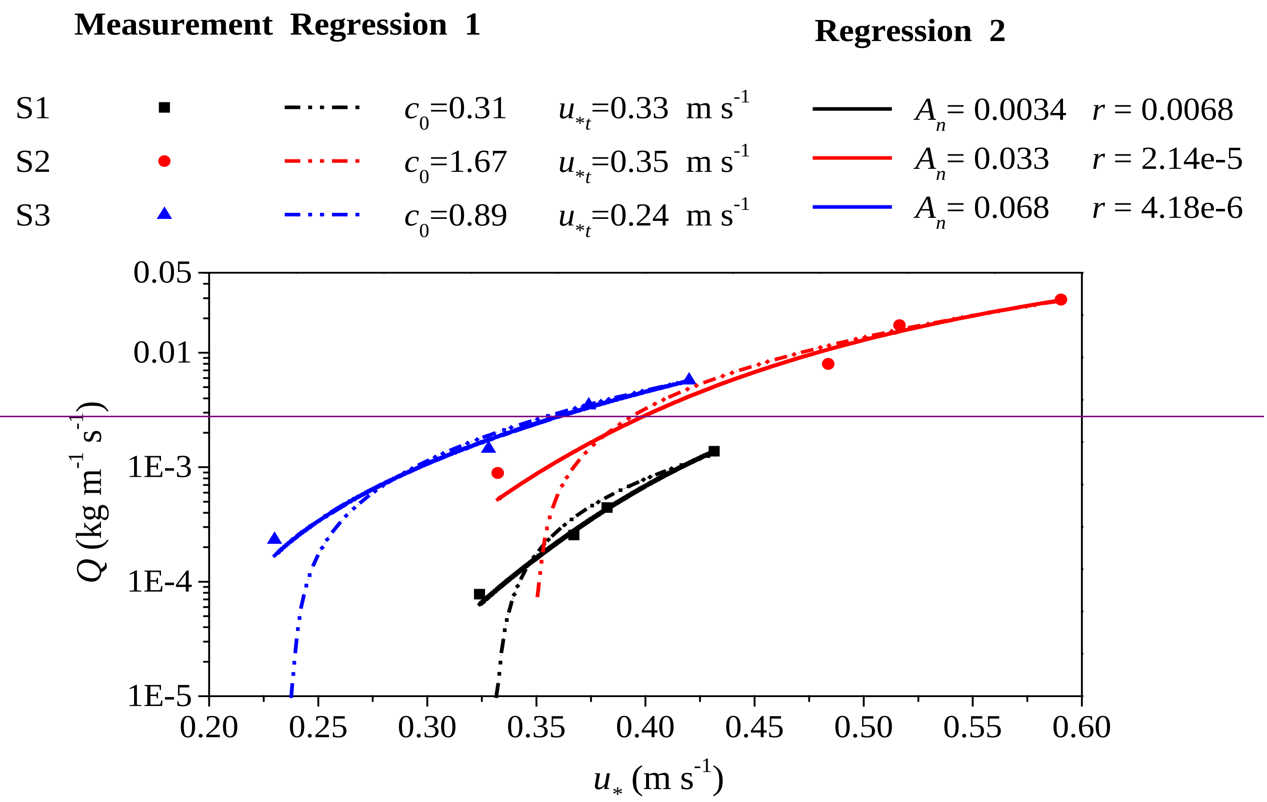


Figure 4. Streamwise saltation flux over the three soil surfaces tested in the wind-tunnel experiment. The symbols are experimental data. The dot-dashed lines are regressions with Equation (8); c_0 and u_{*t} are treated as regression parameters. The solid lines correspond to the combinations of Equation (8), (15) and (16). A_n and r are the regression parameters, which determine the friction velocities shown in the inserted graph.



~~Figure3:Streamwise saltation flux over the three soil surfaces tested in the wind-tunnel experiment.~~

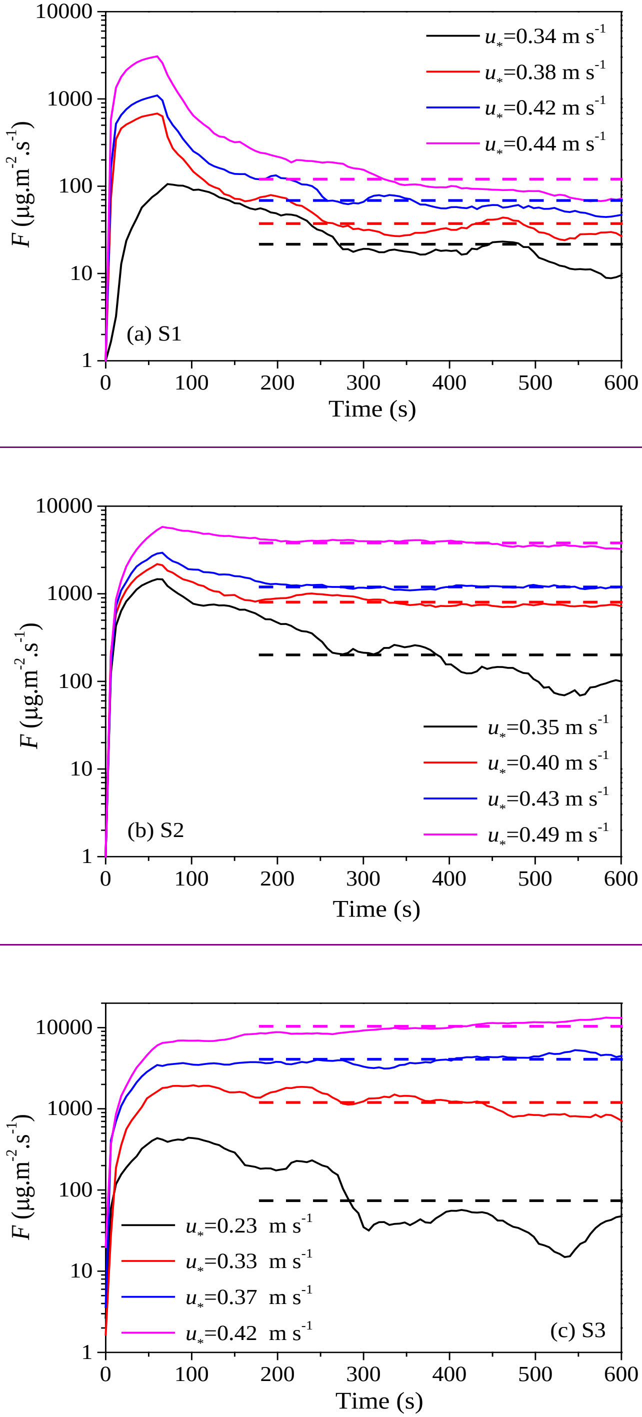

(a) S1
u_*=0.34 m s^{-1}
u_*=0.38 m s^{-1}
u_*=0.42 m s^{-1}
u_*=0.44 m s^{-1}
F (μg.m^{-2}.s^{-1})
Time (s)
(b) S2
u_*=0.35 m s^{-1}
u_*=0.40 m s^{-1}
u_*=0.43 m s^{-1}
u_*=0.49 m s^{-1}
F (μg.m^{-2}.s^{-1})
Time (s)
(c) S3
u_*=0.23 m s^{-1}
u_*=0.33 m s^{-1}
u_*=0.37 m s^{-1}
u_*=0.42 m s^{-1}
F (μg.m^{-2}.s^{-1})
Time (s)

Figure 5. Vertical dust flux series over the three surfaces tested in the wind-tunnel experiment. The dashed lines represent average values form 3 to 10 minutes.

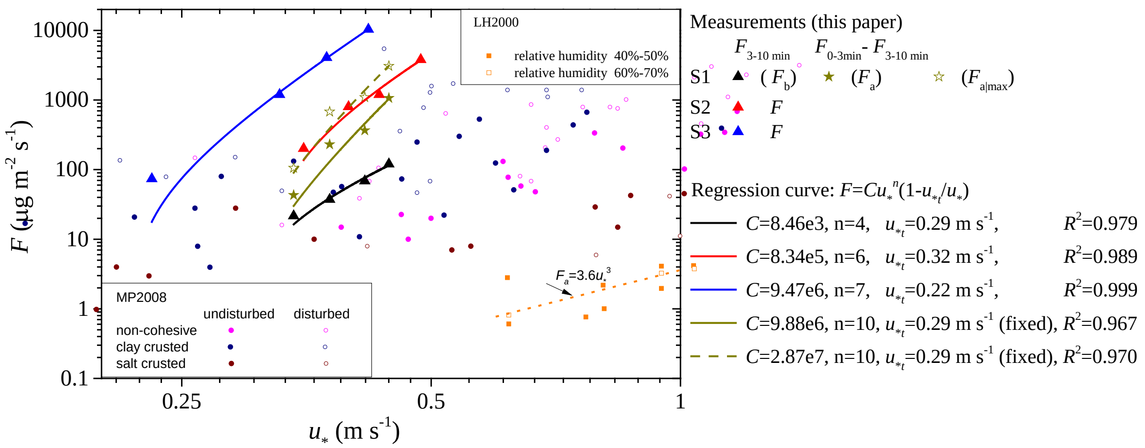
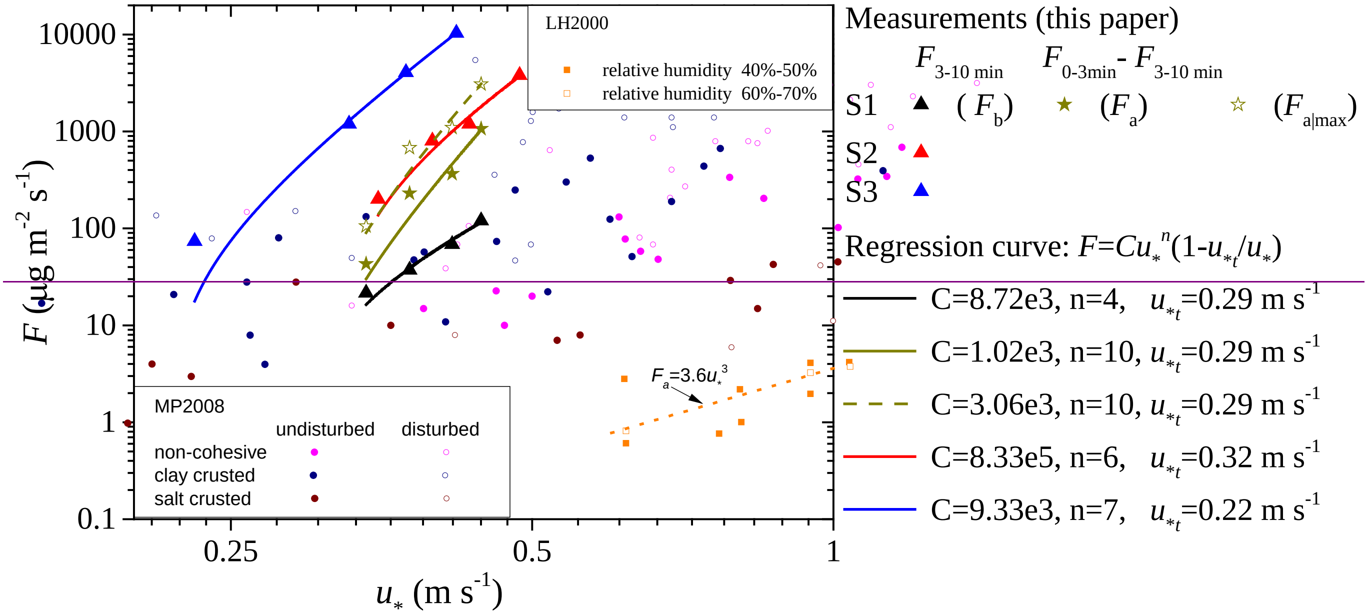


Figure 6. Measured vertical dust fluxes over the three different surfaces in the wind-tunnel experiment (triangles), together with the measurements of Loosmore & Hunt (2000) and Macpherson et al. (2008), respectively labeled as LH2000 and MP2008, as well as the various regression curves.



~~**Figure 5: Measured dust emission fluxes over the three different surfaces in the wind-tunnel experiment (triangles), together with the measurements of Loosmore& Hunt (2000, LH2000) and Macpherson et al. (2008, MP2008), labeled as LH2000 and MP2008, as well as the various regression curves.**~~

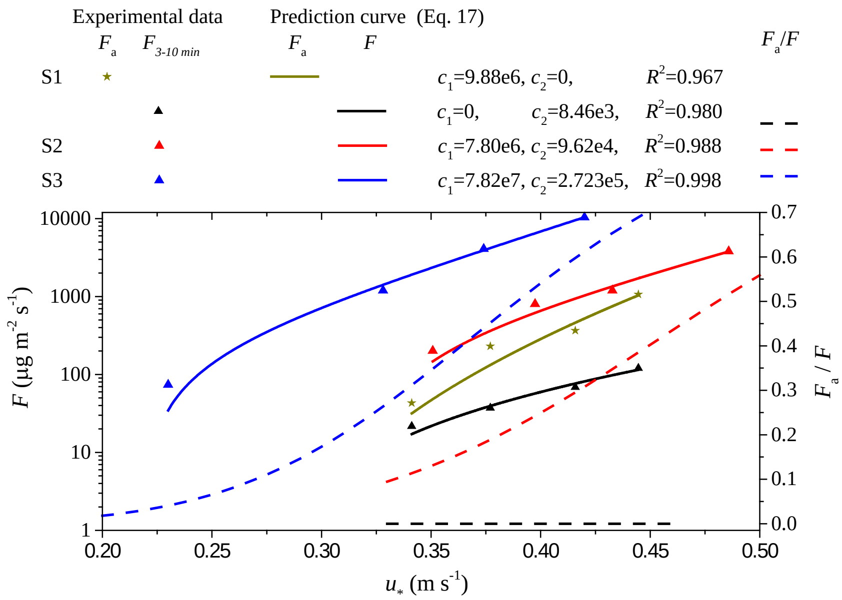


Figure 7. Predictions of Equation (17) and the predicted contribution of aerodynamic entrainment F_a is illustrated as the dashed lines with the right vertical coordinate. u_{*t} is valued as the same to Figure 6. The solid lines and symbols are the same as in Figure 6.

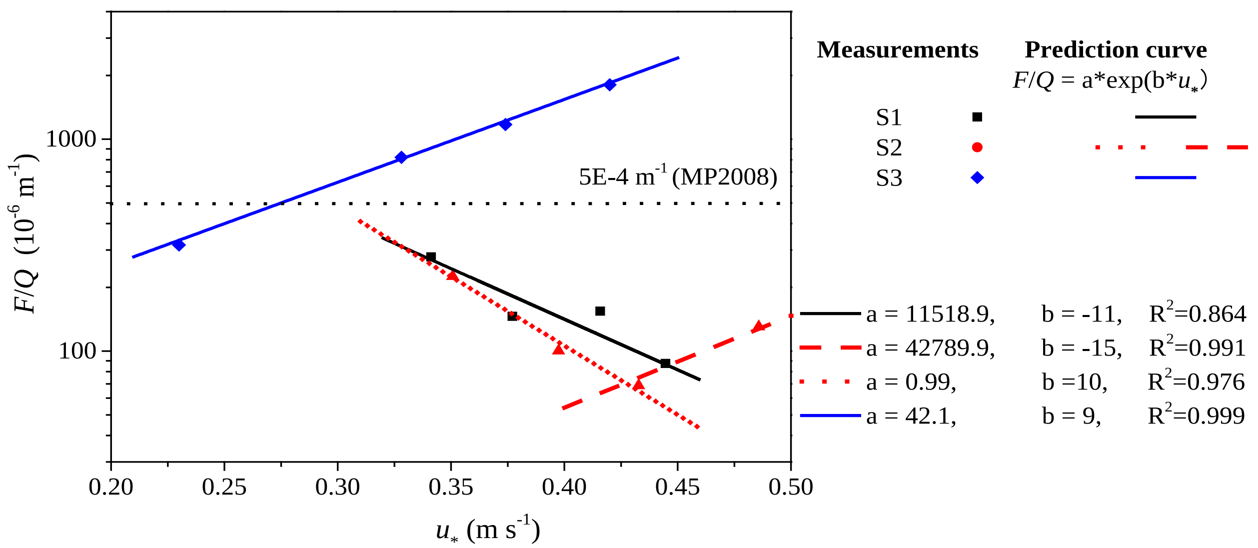
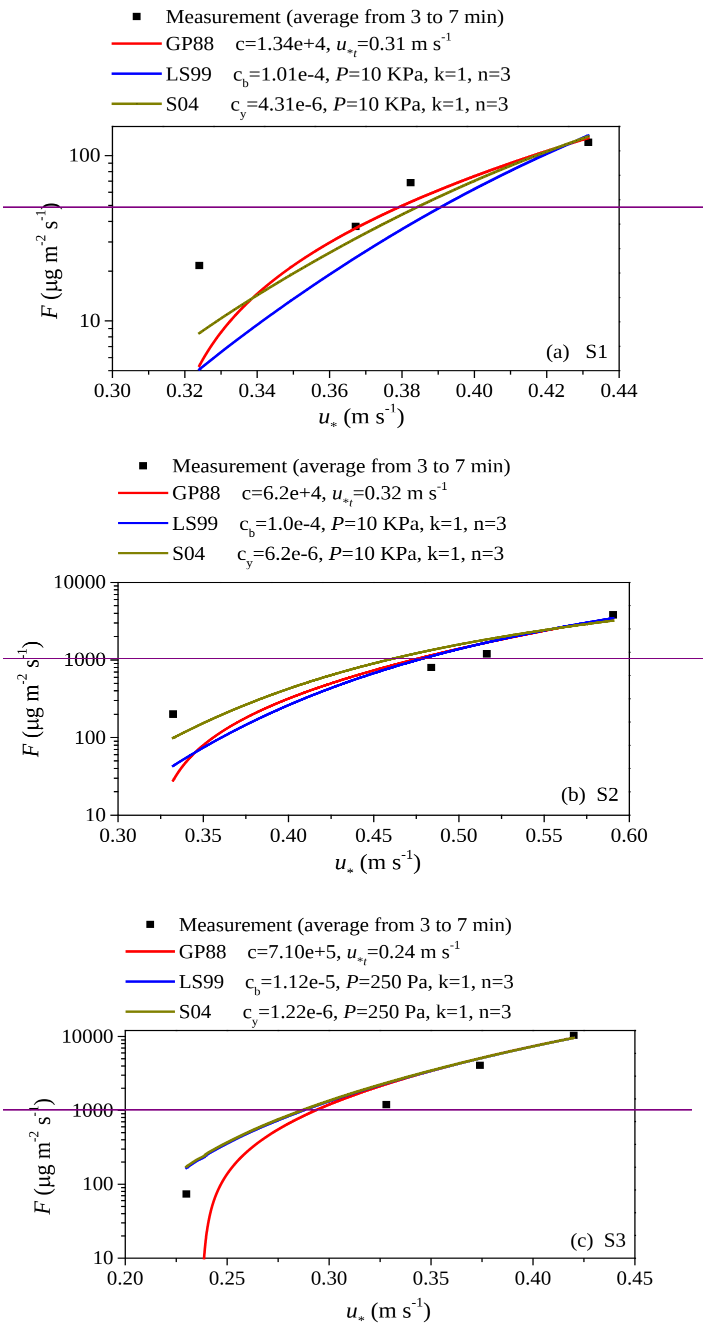


Figure8. The ratio of dust- emission to streamwise saltation flux. The symbols are experimental results and lines are prediction curves with the equation shown in the legend.



~~**Figure 7:Comparison between measurements and predictionsof dust emission fluxes, averaged over the measuring time interval of 3 to 10 min,for the three different surfaces.**~~

Table1. Runs for the dust-emission experiments and the regression parameters for wind profile over the three different surfaces. Four kinds of wind friction velocities are simulated for each surface. R^2 is determination coefficient of the regression.

Surface	runs	u_* (m s^{-1})	z_0(mm)	R^2	Configuration
S1	1	0.34	0.15	0.98	Natural soil
	2	0.38	0.13	0.99	
	3	0.42	0.11	0.98	
	4	0.44	0.09	0.99	
S2	5	0.35	0.15	0.99	Natural soil +natural sand for bombardment
	6	0.40	0.14	0.97	
	7	0.43	0.11	0.99	
	8	0.49	0.10	0.95	
S3	9	0.23	0.02	0.97	Sieved soil
	10	0.33	0.10	0.98	
	11	0.37	0.09	0.99	
	12	0.42	0.09	0.99	

~~**Table 1: Runs for the dust-emission experiments.**~~

~~Surfaces~~	~~Runs~~	~~Friction Velocity (m s^{-1})~~	~~Configuration~~
~~S1~~	~~1,2,3,4~~	~~0.33,0.48,0.52,0.59~~	~~Naturalsoil~~
~~S2~~	~~5, 6, 7, 8~~	~~0.32,0.37,0.38,0.43~~	~~Natural soil +natural sand for bombardment~~
~~S3~~	~~9, 10, 11, 12~~	~~0.23,0.33,0.37,0.42~~	~~Sieved soil~~

Table 2. Log-normal ~~D~~distribution ~~P~~parameters for the three kinds of soils used in the experiments. *d* is particle diameter, W_j is the weight of the *j*th ~~normal~~ distribution, D_j and σ_j are the parameters in the *j*th ~~normal~~ distribution, j (≤4) refers to *j*th model.

Material		**Mode 1**			**Mode 2**			**Mode 3**			**Mode 4**		
		W_1	$\ln(D_1)$	σ_1	W_2	$\ln(D_2)$	σ_2	W_3	$\ln(D_3)$	σ_3	W_4	$\ln(D_4)$	σ_4
Sand	$p_m(d)$	0.471	5.51	0.34	0.529	5.34	0.54						
	$p_f(d)$	0.570	5.31	0.26	0.430	4.70	0.60						
Natural Soil	$p_m(d)$	0.196	4.70	0.29	0.229	4.42	0.43	0.575	2.88	1.23			
	$p_f(d)$	0.357	4.06	0.37	0.314	3.44	0.86	0.329	1.73	1.06			
Sieved Soil	$p_m(d)$	0.109	4.72	0.24	0.372	4.31	0.49	0.488	2.95	1.02	0.031	0.88	0.70
	$p_f(d)$	0.408	4.17	0.41	0.364	3.29	0.92	0.228	1.49	0.94			