Authors' Responses to the Comments on the Manuscript

"The role of a mid-air collision in drifting snow"

General Response to the Comments and the Editor's Suggestions:

According to your comments, we have made a substantial revision to the original manuscript such that a clear description on the research is displayed in the revised manuscript (the directly changes can be seen in the revised manuscript with changes highlights). The detailed responses to comments of referees are as follows (see blue part in this reply):

Responses to Comments of Editor F. Dominé:

[Comment 1] The reviewers note the interest and novelty of your paper. However, both are very critical regarding presentation and clarity. If you wish to submit a revised version, please answer in detail each reviewer's recommendation, and pay particular attention to clarity.

[Response 1] Thanks for your effort on handling our manuscript, and all the relevant comments from the reviewers. In the revised manuscript, the presentation and clarity are improved according to the reviewers' suggestions. We have also answered all the comments carefully. Please see our response on each comment below.

[Comment 2] All symbols and equations must be clearly explained and the whole paper needs major rewriting to better explain methods, results and their analysis. Finally, the discussion needs significant improvement.

[Response 2] Thanks for your recommendation. In the revised manuscript, all symbols and equations have been defined and explained, and we have also made a substantial revision to the methods, results and analysis according to the reviewer's comments. Please see our detailed responses below.

Responses to Comments of Reviewer#1:

General comments:

[Comment] This manuscript aims to investigate the effect of midair particle-particle collision on drifting snow using a three-dimensional numerical model. The theoretical frame work of the model is standard in recent numerical studies of drifting snow, but authors consider the collision between airborne particles, which is excluded from previous drifting snow models. Numerical simulations of the model adopt the non-periodic boundary condition in the streamwise direction. In addition, the realistic particle size distribution measured in wind tunnel experiments and field observations is used for simulations. Then, numerical results are compared with previous experimental and observational data to check the validity of the model. However, there are many lack of descriptions, analyses, and discussions as listed in specific comments. Therefore, the current manuscript fails to meet the publication quality of The Cryosphere.

[Response] Thanks for your careful reviews. More detailed and clearly descriptions, analyses, and discussions have been added in the revised manuscript according your kind advice as listed in specific comments, as shown in the following responses.

Specific comments:

1. Introduction

[Comment 1] Please explain that why authors focus on a role of a mid-air collision in wind-blown sand transport and drifting snow.

[Response 1] Thanks for your this recommendations. According to your suggestion, we have added the description ‘Inter-particle collision within aeolian snow/sand cloud changes trajectories of saltating grains, and further affects the structures and transportation features of the particle flow. Numerous of investigations have shown that mid-air collision effect plays an non-neglected role in wind-blown sand movement (Carneiro et al., 2013;Dong et al., 2005;Huang et al., 2007;Li et al., 2013). However, this mechanism has been rarely investigated in a drifting snow transport with more suspended grains and smaller particle response time.' in the introduction section, as shown in line 35-43 of the revised manuscript.

[Comment 2] Please refer to important previous studies for a mid-air collision in aeolian particle transport: for example, Carneiro, M. V. et al.: Midair Collisions Enhance Saltation, Physical Review Letters, 111, 058001:1-5, 2013. Li, D. et al.: Inter-particle collision effects on the entrained particle distribution in aeolian sand transport, International Journal of Heat and Mass Transfer, 58, 97-106, 2013.

[Response 2] Thanks for your recommendation. The recommended references and some other related references have been referred and discussed in the introduction of the revised manuscript. The sentences 'Numerous of investigations have shown that mid-air collision effect plays an non-neglected role in wind-blown sand movement (Carneiro et al., 2013;Dong et al., 2005;Huang et al., 2007;Li et al., 2013). However, this mechanism has been rarely investigated in a drifting snow transport with more suspended grains and smaller particle response time.' have been added in line 39-43 of the revised manuscript.

2. Model and method

[Comment 3] For the drag force acting on a particle F_D, the function of particle Reynolds number f(Re_p) and the particle relaxation time T_p are used. In general, the drag force is expressed using the drag coefficient C_D, the projected area of particle A, and the square of relative velocity between particle and wind as written in Yamamoto et al. (2001). What is different from the general formula? Please explain the physical meaning of f(Re_p) and T_p.

[Response 3] Thanks for your careful reviews. As the reviewer mentioned, the drag force is generally expressed using the drag coefficient C_D, the projected area of particle A, and the square of relative velocity between particle and wind V_r as [Anderson and Haff, 1991; Yamamoto et al., 2001]:

$$F_D = \frac{1}{2} C_D \rho A V_r^2 \quad \text{(R1)}$$

where $A=\left[\pi\left(\frac{d_p}{2}\right)^2\right]$ is the projected area of particle, C_D is a function of particle Reynolds number Re_p and can be expressed as (Bagnold, 1941):

$$C_D=\frac{24}{Re_p}f(Re_p) \tag{R2}$$

As a matter of fact, our formula for particle drag force is equivalent with equation (R1):

$$\begin{aligned} F_D &= m_p\frac{V_r}{T_p}f(Re_p) \\ &=\frac{1}{6}\pi d_p^3\rho_p\cdot V_r\cdot\frac{18\rho\nu}{\rho_p d_p^2}\cdot f(Re_p) \\ &=\frac{1}{2}\left[\pi\left(\frac{d_p}{2}\right)^2\right]\cdot V_r^2\cdot\rho\frac{24}{Re_p}f(Re_p) \\ &=\frac{1}{2}\rho A V_r^2\frac{24}{Re_p}f(Re_p) \end{aligned} \tag{R3}$$

where $T_p=\frac{\rho_p d_p^2}{18\rho\nu}$ is the particle relaxation time. In equation (R2) and (R3), $f(Re_p)$ is a correction factor of the drag coefficient C_D.

We express this formula in the form of generalized Newton's second law $F=ma$ for a better physical meaning, where the accelerated speed a is expressed as the ratio of V_r and T_p. Here, T_p represents the time of particle speed changing from one steady state to another.

For a better understanding of this equation, the sentences 'represents the time of particle speed changing from one steady state to another' and 'is a correction factor of particle drag coefficient and' have been added in the revised manuscript, as shown in line 83-84 and 86-87.

[Comment 4] In mid-air collision model, I cannot understand "To avoid repetition, there is the limitation condition of x_Ai < x_Bi". Please justify this limitation.

[Response 4] Thanks for your comment. In the process of determining the inter-particle collision, particle A only seeks for downstream particles ($x \geq x_A$) for the purpose of reducing computation. This option will not omit any collision events since particles seek contiguous partner in sequence. Thus we have the limitation condition of $x_{A1} < x_{B1}$.

In order to make it more clearly, the sentences ‘To avoid repetition, there is the limitation condition of $x_{A1} < x_{B1}$’ have changed into ‘Since mid-air particles judge collision event in sequence, each particle only seeks downstream particles to reduce computation’ in the revised manuscript, as shown in line 104-105.

[Comment 5] The change in particle velocity due to the mid-air collision is similar to the calculation process of discrete element method (DEM) without the friction. Please justify the midair collision model. Also, for {nlambda} and e of the recovery coefficient of ice, the applicable range should be rewritten on the basis of Supulver et al. (1995).

[Response 5] Thanks for your this recommendations. The reviewer is right that the mid-air collision is similar to the calculation process of discrete element method (DEM) without the friction. In the process of calculating inter-particle collision process, the coordinate system is rotated to the case of central collisions, and the rotations of particles are not included, thus, the collision process do not generate any friction force. In the revised manuscript, the description ‘Since central collisions without particle rotation do not generate any friction forces’ has been added in line 113-114 of the revised manuscript.

Besides, the applicable ranges of λ and e are added in the revised manuscript, the expression “where $\gamma = (1+e)/\left(d_A^3 + d_B^3\right)$ and e is the recovery coefficient of ice. According to Higa et al. (1998), the recovery coefficient of ice typically has a constant value e_{qe} at the quasi-elastic region and a decrement tendency at the inelastic region, which can be described by a piecewise function:

$$e=\begin{cases} e_{qe} & v_n < v_c \\ e_{qe}\left(\dfrac{v_n}{v_c}\right)^{-\log(v_n/v_c)} & v_n < v_c \end{cases}$$

in which $e_{qe}=0.27\left(1+\hat{d}^3\right)^{0.1}\left(1+\hat{d}\right)^{0.2}\left(d_A/0.05\right)^{-0.5}$ and $\hat{d}\equiv d_A/d_B$, v_n is the normal relative velocity of particle *A* and *B*, and v_c is the critical impact velocity for the transition from the quasi-elastic region to the inelastic region, which can be expressed as:

$$v_c=v_0\left(1+\hat{d}^3\right)^a\left(1+\hat{d}\right)^b\exp\left(\frac{c}{2RT}\right)\left(\frac{d_A}{d_0}\right)^{-0.5} \qquad T\geq 229K$$

where $v_0=5.72e-4$, $a=3/4$, $b=-7/4$ and $d_0=0.03$ are parameters, R is the gas constant and T is the temperature." has been added in line 118-129. The results with mid-air collisions has also been recalculated in the revised manuscript.

[Comment 6] Please describe boundary conditions at bottom and top. Is the boundary condition of snow particles same as wind?

[Response 6] Thanks for your careful reviewing. The stress-free boundary condition is applied at the top boundary, and a prescribed stress is added at the bottom boundary. Besides, During drifting snow simulation, the wind field and snow particles both have periodic boundary conditions. In order to make it more clearly, we have added the omit descriptions 'The bottom boundary is a rigid wall, and the top boundary obeys a stress-free boundary condition.' and 'Drifting snow simulation begins after the turbulent boundary layer is fully developed, and the lateral boundary conditions for snow particles are the same as the wind field.' in line 143-144 and 149-151 of the revised manuscript.

[Comment 7] The aerodynamic entrainment and the splash process are important sub-physical processes in drifting snow. Especially, Sugiura and Maeno (2000) measured two- dimensional particle motion near the snow surface; and then, they categorize splash functions according to the type of snow. Please write the detail of these two processes.

[Response 7] Thanks for your careful reviews. According to the reviewer's suggestion, the aerodynamic entrainment and splash scheme are supplied in App. 1 in the revised manuscript, as shown below:

Appendix 1

The aerodynamic entrainment scheme describes the information of fluid entrained particles from the bed surface. According to , the number of entrained particles per unit area per unit time can be written as (Anderson and Haff, 1991):

$$N_{ae} = \eta(\tau - \tau_t) \quad \text{(A1)}$$

where $\eta = C/(8\pi d_p^2)$ (Doorschot and Lehning, 2002) and $\tau_t = A^2 g \bar{d}_p (\rho_p - \rho)$ (Clifton et al., 2006), in which $C = 1.5$ and $A = 0.2$ are constants, and $\bar{d}_p$ is the mean diameter of snow particles.

The grain-bed interactions are described by the ejecta number, horizontal and vertical restituation coefficients, respectively. The ejecta number n_e follows the binomial distribution (Sugiura and Maeno, 2000):

$$S_e(n_e) = C_l^{n_e} q^{n_e} (1-q)^{l-n_e} \quad \text{(A2)}$$

where q and p are functions of impact velocity v_{in} and incident angle θ_{in}:

$$l = \frac{0.26 v_{in}^{1.2} \theta_{in}^{0.32}}{0.51 v_{in}^{0.6} \theta_{in}^{0.16} - 0.18 v_{in}^{-0.27} \theta_{in}^{0.05}} \quad \text{(A3)}$$

$$q = 1 - 0.35 v_{in}^{-0.87} \theta_{in}^{-0.11} \quad \text{(A4)}$$

At the same time, the horizontal restitution coefficient e_h and the vertical restitution coefficient e_v can be described by a normal and gamma distribution, respectively:

$$P(e_h)=\frac{1}{\sqrt{2\pi}\sigma}\exp(-\frac{(e_h-\mu)^2}{2\sigma^2}) \quad \text{(A5)}$$

$$P(e_v)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}e_v^{\alpha-1}\exp(-\frac{e_v}{\beta}) \quad \text{(A6)}$$

where μ, σ^2, α and β are all expressions of v_{in} and θ_{in}, as shown in Table A1.

Parameters	Compact snow	Fresh snow
α	$\begin{cases} 1.22\theta_{in}^{0.47} & v_{in} \geq 0.84\ ms^{-1} \\ 1.22(v_{in}/0.84)^{\log(v_{in}/0.84)}\theta_{in}^{0.47} & 0.84 < v_{in} \leq 1.23\ ms^{-1} \\ 1.22(v_{in}/0.84)^{\log(v_{in}/0.84)}(v_{in}/1.23)^{-2\log(v_{in}/1.23)}\theta_{in}^{0.47} & v_{in} \geq 1.23\ ms^{-1} \end{cases}$	
β	$\begin{cases} 12.85\theta_{c}^{-1.41} & v_{c} \geq 0.84\ ms^{-1} \\ 12.85(v_{c}/0.84)^{-\log(v_{c}/0.84)}\theta_{c}^{-1.41} & 0.84 < v_{c} \leq 1.23\ ms^{-1} \\ 12.85(v_{c}/0.84)^{-\log(v_{c}/0.84)}(v_{c}/1.23)^{\log(v_{c}/1.23)}\theta_{c}^{-1.41} & v_{c} \geq 1.23\ ms^{-1} \end{cases}$	
μ	$\begin{cases} 0.48\theta_{i}^{0.01} & v_{c} \leq 1.27\ ms^{-1} \\ 0.48(v_{c}/1.27)^{-\log(v_{c}/1.27)}\theta_{i}^{0.01} & v_{c} > 1.27\ ms^{-1} \end{cases}$	
σ^2	$\begin{cases} 0.17\theta_{c}^{-0.25} & v_{c} \leq 1.27\ ms^{-1} \\ 0.17(v_{c}/1.27)^{-\log(v_{c}/1.27)}\theta_{c}^{-0.25} & v_{c} > 1.27\ ms^{-1} \end{cases}$ ($u_{*} = 0.19\ ms^{-1}$) $\begin{cases} 0.08\theta_{c}^{0.01} & v_{c} \leq 1.34\ ms^{-1} \\ 0.08(v_{c}/1.34)^{-\log(v_{c}/1.34)}\theta_{c}^{0.01} & v_{c} > 1.34\ ms^{-1} \end{cases}$ ($u_{*} = 0.25\ ms^{-1}$)	$\begin{cases} 0.07\theta_{c}^{-0.06} & v_{c} \leq 0.52\ ms^{-1} \\ 0.07(v_{c}/0.52)^{-\log(v_{c}/0.52)}\theta_{c}^{-0.06} & v_{c} > 0.52\ ms^{-1} \end{cases}$

Table A1. Parameters of splash function.

3. Results

[Comment 8] Before the comparison with previous experiments and simulations, please justify if the mid-air collision model correctly works. In general, a very small value of time step {ndelta_t} is required in the calculation of the collision between particles: 10ˆ-6 s as the typical value.

[Response 8] Thanks for your comment. Generally, a very small value of time step is required in the calculation of the inter-particle collision by discrete element method. However, contact forces between particles are not necessary in this model, thus the time step is much larger. At the same time, this model judges collision event along the continuous particle trajectories within a typical particle integration time step, and thus the collision moment can be captured exactly, as shown in figure R1. And the effect of time steps on the simulation results are also examined in the revised manuscript, as shown below.

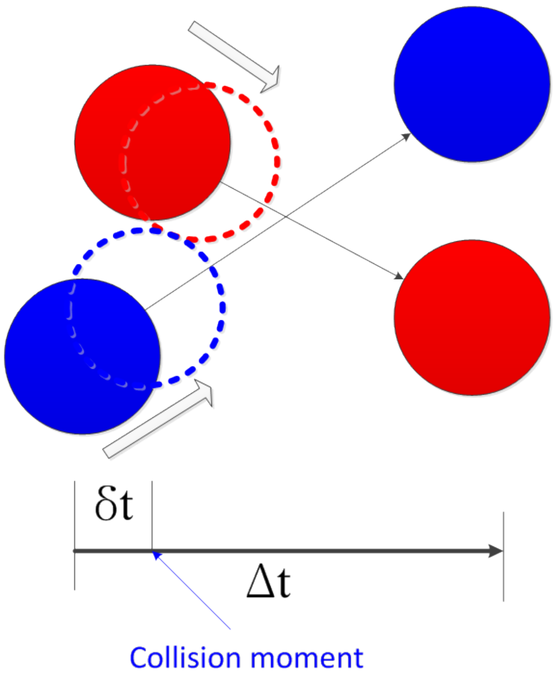

Figure R1. Diagram of the judgment of inter-particle collision within a particle integration time step.

Before calculating the drifting snow process with mid-air collision, the validity of the collision model is examined firstly. Since the collision model judges collisions along the continuous particle trajectories within a particle integral time step, thus, the time resolution of the particle trajectory determines the accuracy of the model. Fig. R2 shows the predicted collision frequency versus particle concentration under various particle integral time steps Δt_p, which is also compared with theoretical results. Here, collision frequency is defined as the mean collision times per unit time of a particle.

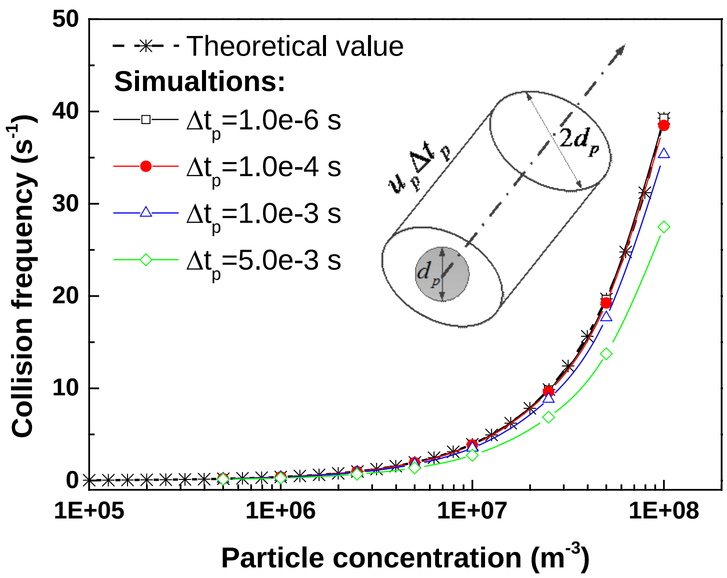

Figure R2. Comparison between theoretical collision frequency and simulation results under various particle integral time steps. The simulation condition is that a certain number of randomly released particles with uniform grain size moves in an airtight box (0.1 m×0.1 m×0.1 m). The initial velocity is 2.0 ms^{-1} with random directions, and the energy loss during inter-particle collision is neglected. The mirror reflection conditions without energy loss are adopted at boundaries. And the predicted collision frequency is the mean value of 10 s physical time. Besides, the theoretical collision frequency is calculated by the existence probability of particles in the control volume given by the inset ($\pi d_p^2 u_p \Delta t_p$). Thus, the theoretical collision frequency equals to $\pi d_p^2 u_p c$, where c is the number concentration of particles.

From Fig. R2, the predicted collision frequency is directly related to the particle integral time step, and the differences between various particle time steps increase with particle concentration. A critical value of Δt_p =1.0e-4 s is necessary to capture overall particle collisions. As a matter of fact, this critical value also ensures that most particle displacement increments are smaller than the mean inter-particle gap (e.g., a particle concentration of 1.25×10^8 m^{-3} corresponding a mean inter-particle gap of 1.75×10^{-3} m). However, a larger time step for particle may miss part of collisions, because the displacement increments of particle are larger than the mean inter-particle distance. In this simulation, the selected time step ensures that the error between simulation and theoretical results under extreme condition (maximum particle concentration and particle velocity) is smaller than 5%.

Above contents have also been added in line 179-207 of the revised manuscript.

[Comment 9] In the simulation setup, the length of streamwise direction is 2 m. This length is quite- short to analyze the transport property and structure. Indeed, the streamwise length of wind tunnel experiments exceeds approximately 10 m. Nishimura et al. (2014) compared vertical profiles of wind and particle speeds at 6 m and 12 m leeward from the wind tunnel entrance; then, they reported that the drifting snow does not reach the steady state at 6 m length. In addition, most of the drifting snow simulation utilize the periodic boundary condition in the streamwise direction, in order to reproduce well-developed drifting snow. Therefore, I don't understand the state of drifting snow calculated using the model. This doubt about the accuracy of simulation are found in many points of Results and Discussions.

[Response 9] Thanks for your careful reviews. As stated in [Response 6], we actually use periodic boundaries at lateral in our drifting snow simulation. In order to make it more clearly, the sentences 'It is notable that the combined boundary conditions along streamwise are only used to generate some initial wind fluctuations, and the periodic boundary conditions are adopted after that. The evolution time equals to 10 times of the large-eddy turnover time t_* ($t_* \equiv H/u_*$, where u_* is the friction velocity) under periodic boundary conditions. Drifting snow simulation begins after the turbulent boundary layer is fully developed, and the lateral boundary conditions for snow particles are the same as the wind field.' has been added in line 145-151 of the revised manuscript.

[Comment 10] Please write the gamma function of particle diameter.

[Response 10] Thanks for your this recommendations. According to the reviewer's suggestion, the gamma function has been added in the revised manuscript. The description 'The gamma function can be written as:

$$P(d_p) = \frac{1}{\beta_p^{\alpha_p}\Gamma(\alpha_p)} d_p^{\alpha_p - 1} \exp(-\frac{d_p}{\beta_p})$$

where $\alpha_p = 5$ and $\beta_p = 50$ are parameters.' has been added in line 175-177 of the revised manuscript.

[Comment 11-1] In Fig. 3, data of previous wind tunnel experiments and numerical simulations are shown. Here, Nemote and Nishimura (2004) considered the suspension layer up to 20 m height. Thus, the experiment and simulation situations of drifting snow are different. Why authors compare these previous studies?

[Response 11-1] Thanks. From the simulation results of Nemote and Nishimura (2004), the transport flux at higher altitude is much smaller than that at the near surface. As shown in figure R3, the transport flux profile shows that the snow transport rate per unit area per unit time above 1 m is almost 3~4 magnitude smaller than that at the near surface. Thus, the integral transport flux above 1 m generally not affect the total transport flux significantly. In this way, our results is comparable with the simulation results of Nemote and Nishimura (2004) and other wind tunnel experiments.

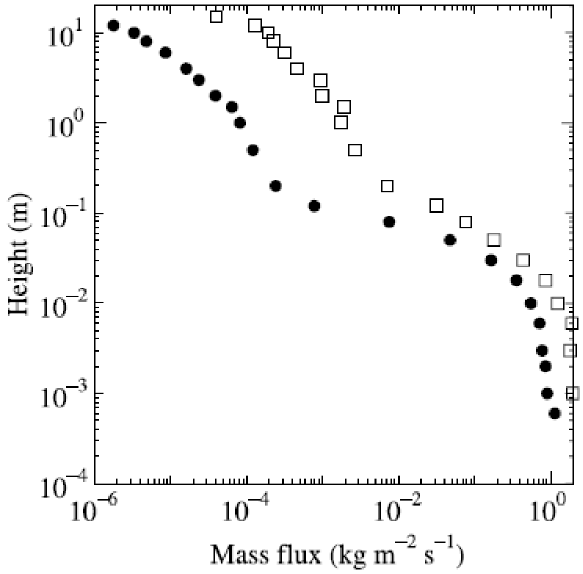

Figure R3. Snow transport flux profile under various friction velocities (circle: 0.32 ms^{-1}; square: 0.39 ms^{-1}). Origin: figure 18 of Nemote and Nishimura (2004).

[Comment 11-2] Although numerical data without and with the mid-air collision are drawn as solid and dashed lines, please draw data points.

[Response 11-2] Thanks for your this recommendations. According to the reviewer's suggestion, data points of the simulation results are also added in Fig. 4 in the revised manuscript. The replotted figure is shown below.

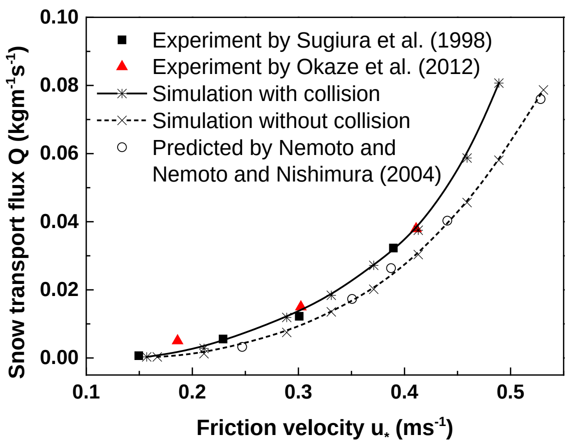

Figure R4. Snow transport flux versus friction velocity.

[Comment 11-3] How the friction velocity of x-axis are estimated?

[Response 11-3] Thank you for this comment. As discussed in response 6, periodic boundaries are used to produce a fully developed turbulent boundary layer. The friction velocity is obtained from the time and spatial averaged wind profile of a fully developed turbulent boundary layer without drifting snow according to the logarithmic law:

$$U(z) = \frac{u_*}{\kappa} \ln(\frac{z + z_0}{z_0})$$

where $\kappa = 0.4$ is the Karman constant, and z_0 is the roughness height.

In the revised manuscript, above description has been added in line 151-155.

[Comment 12] "the snow transport flux at various friction velocities are consistent with the simulation results of Nemoto and Nishimura (2004), mainly because the same splash function is adopted." Recent numerical study with this splash function (Niiya et al.: Spatiotemporal Structure of Aeolian Particle Transport on Flat Surface, J. Phys. Soc. Jpn., 86, 054402:1-11, 2017.) reported that the splash function of snow underestimates the snow transport flux at higher friction velocities. To avoid this, the current drifting snow model divides the splash process into two types: rebound and splash (Nemoto and Nishimura (2004), Zwaaftink et al., (2014)). Please discuss the reason that this simulation obtains the same level of snow transport flux as previous model.

[Response 12] Thanks for your comment. The splash function of Nemoto and Nishimura (2004) is obtained from wind tunnel observations at lower friction velocities, thus, only the simulation results under smaller friction velocities (e.g., $u_* < 0.5 ms^{-1}$) are discussed in this work. Under this wind condition, the predicted mass flux is credible, and thus is comparable to other simulations and wind tunnel measurements. The description "Since the splash function is obtained from wind tunnel observations at low friction velocities, only the results at lower friction velocities (e.g., smaller than 0.5 ms^{-1}) are mainly discussed." has been added in line 160-162 of the revised manuscript.

At the same time, the snow transport flux is very sensitive to the particle size. The exponent of the predicted mass flux by Niiya et al. (2017) and Nemoto and Nishimura (2004) is different because their size distribution is different. Measurements also show that the snow transport flux varies significantly with different particle size under the same wind condition (Sugiura et al., 1998). The sentences "As a matter of fact, measurements of have shown that the total mass flux (including saltation and suspension) is rather sensitive to the particle size, because the suspension mass flux varies significantly." has been added in line 374-377 of the revised manuscript.

[Comment 13] In Fig. 4, the collision frequency is measured. Please define it. "one particle may experience over 10 collisions per second when the particle concentration is 10ˆ8 mˆ-3" This meaning changes depending on the definition of collision frequency.

[Response 13] Thank you. The collision frequency indicates the collision times per unit time of a saltating particle. In the revised manuscript, the description 'Here, the collision frequency is defined as the collision times per unit time of a saltating particle' has been added in line 231-232.

[Comment 14] Elghobashi, S.: On predicting particle-laden turbulent flows. Appl. Sci. Res., 52, 309- 326, 1994. presented a classification map for the types of interaction between particles and turbulence. In the paper, the particle-particle interaction (i.e., collision) is not negligible when the particle volume fraction exceeds 10ˆ-3. Also, the granular temperature, is fluctuation of particle velocity, plays an important role in the particle collision of granular gas. Please check the collision frequency from the view point of particle volume fraction, and quantify the particle activity as the granular temperature.

[Response 14] Thank you. According to your suggestion, the collision frequency is reanalyzed form the view point of particle volume fraction. The description "As a matter of fact, the particle volume fraction of snow cloud reflects the gaps among solid particles, and determines the collision frequency more directly. Elghobashi [1994] reported that the inter-particle collision effect is not negligible when the particle volume fraction exceeds 10ˆ-3, which corresponds to a particle concentration of $\sim 10^8$ m^{-3} in our simulation. For a drifting snow process, only the near surface transport particle cloud achieves this condition, and our simulation results also show that the structures of near surface snow cloud are largely reshaped by mid-air collisions. From Fig. 5, it can be seen that the collision frequency is about 10 per second, which implies that almost each saltation process is affected by mid-air collisions (the time scale of a saltation process is approximately 0.1s)." has been added in line 248-257 of the revised manuscript.

At the same time, the effect of subgrid-scale fluctuating velocity of particles is also discussed in the revised manuscript. The description "Under this grid resolution, the subgrid-scale (SGS) fluctuating velocity of particles has a negligible impact on particle motions, because the lifetime of SGS eddies is much smaller than the particle response time-scale (Dupont et al., 2013)" has been added in line 136-139.

[Comment 15] In Fig. 5, the critical height is calculated from the vertical profile of the particle concentration. Please show it. Vertical profiles of wind speed, friction velocity, particle speed, particle concentration, and so on are key to understand the mechanism of drifting snow; however, they are not shown in current manuscript.

[Response 15] Thanks for your this recommendations. We have added the particle concentration profiles in the revised manuscript, as shown in Fig. R5.

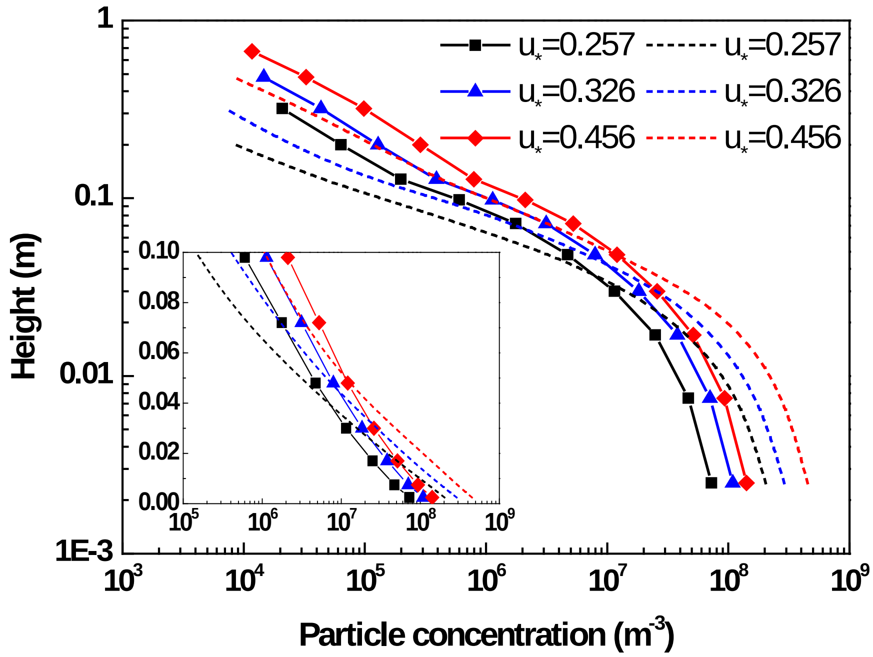

Figure R5. Profiles of particle number concentration with and without mid-air collisions under various friction velocities (Solid lines: with mid-air collisions; dashed lines: without mid-air collisions).

The description "Since mid-air collisions plays an important role in conveying particles to high altitude, the enhanced total transport flux under mid-air collision should be mainly contributed by the increased transport flux higher in the air. This is substantially accord with the findings of Carneiro et al. (2013). In this way, the particle concentration profile is also modified by mid-air collisions. As shown in Fig. 8, part of the near surface particles are transported to higher altitude by inter-particle collision, and the particle concentration profiles is largely changed by mid-air collision effect. The inset shows the particle concentration profile at the near surface.

Seen from Fig. R5, the thickness of the drifting snow layer is increased by mid-air collision effect under the same friction velocity, which is also a positive contribution to the increment of the total mass flux. Mid-air collisions also increase the particle concentration higher in the air but reduce that at the near surface, agree well with the mass flux profiles." and corresponding figure have been added in line 280-296 of the revised manuscript.

4. Discussions

[Comment 16] Only the skin friction velocity in drifting snow is focused in Discussions. Since this manuscript aims to the role of a mid-air collision, authors should discuss deeply the mid- air collision from various viewpoints.

[Response 16] The suggestion is implemented. According to the reviewer's suggestion, more discussions about the role of a mid-air collision are added in the revised manuscript. The effect of mid-air collision on the structure of drifting snow has been added in section 4.1 of the revised manuscript, as shown in line 263-340.

[Comment 17] If authors study the skin-friction velocity in drifting snow as the additional discussion, please refer the recent experiment (Walter et al.,: Experimental assessment of Owen's second hypothesis on surface shear stress induced by a fluid during sediment saltation, Geophys. Res. Lett., 41, 6298-6305, 2014.).

[Response 17] Thanks for your suggestion. In the revised manuscript, the recommended reference has been cited in the revised manuscript. The sentences "However, several recent physically based numerical saltation models indicate that τ_f in fact decreases with the friction velocity mainly because the larger wind speed higher in the saltation layer should be compensated by a decrease in the wind speed lower in the saltation layer (Kok et al., 2012)" has been modified into "However, several recent physically based numerical saltation models and measurements indicate that τ_f in fact decreases with the friction velocity mainly because the larger wind speed higher in the saltation layer should be compensated by a decrease in the wind speed lower in the saltation layer (Kok et al., 2012;Walter et al., 2015)" in line 318-322 of the revised manuscript.

[Comment 18] P.13, L. 205: "because frequent inter-particle collisions can produce many high energy particles..." Particles lose the energy by the energy dissipation due to the collision. Please explain the meaning of sentence.

[Response 18] Thank you. Mid-air collisions plays an important role in conveying particles to high altitude, as shown in [Response 15]. Thus, more particles can acquire energy from the wind higher in the air. Thus, the overall energy is increased by inter-particle collisions. In the revised manuscript, the sentences "mainly because frequent inter-particle collisions can produce many high energy particles under the actions of momentum transfer among the particles and thus enhances saltation." have been changed into "mainly because frequent inter-particle collisions convey part of particles to higher in the air where the wind speed is larger, the overall particle energy and thus the saltation is enhanced.", as shown in line 334-336.

[Comment 19] The particle transport flux increases as the square of friction velocity in recent studies, but also it is strongly depending on the particle diameter according to Sugiura et al. (1998). In this simulation, the polydisperse particles of 100-600 m diameter is considered. Please discuss more carefully this point.

[Response 19] Thank you for this relevant comment. The particle transport flux is indeed very sensitive to particle size. According to the reviewer's suggestion, more descriptions about this points have been supplied in the revised manuscript. The sentences 'As a matter of fact, measurements of Sugiura et al. (1998) have shown that the total mass flux (including saltation and suspension) is rather sensitive to the particle size, because the suspension mass flux varies significantly. From this study, the suspension and saltation snows also influence each other.' has been added in line 374-377 of the revised manuscript.

Technical corrections:

[Comment 20] Is F_di of Eq. (6) same as F_D of Eq. (3)?

[Response 20] Thanks for your careful reviews. F_{di} of Eq. (6) is same as F_D of Eq. (3). We have change 'F_{di}' into 'F_{Di}' in Eq. (6) of the revised manuscript.

Responses to Comments of Reviewer#2:

General comments:

[Comment 1] In this paper a process is proposed that should improve the simulation of the transport of blown snow particles. The paper is interesting but as it is submitted to TC, some terms must be defined. Also the role of atmospheric turbulence should be discussed, and not only implicitly linked to the friction velocity.

[Response 1] Thanks for your recommendation. The reported terms in the specified comments are defined or explained in the revised manuscript. At the same time, the effect of atmospheric turbulence on the structure of drifting snow is discussed. The description "At the same time, the thickness of the drifting snow layer with atmospheric turbulence is much larger than that without turbulence, which also increases with friction velocity. The reason could be that turbulent vortex brings particles to higher in the air when the local vertical wind speed exceeds the particle's terminal velocity, and turbulent intensity also increases with friction velocity." has been added in line 299-303 of the revised manuscript.

The points of criticism are discussed in more detail in the following:

[Comment 1] In the whole paper: "drifting snow" has different meanings in the literature so that it must be defined. What is its difference with saltation and suspension?

[Response 1] Thanks for your this recommendations. According to your comment, the definition of drifting snow is added in the revised manuscript, the sentences "Drifting snow in the turbulent boundary layer contains both saltation particles that jumps towards downwind at the near surface and suspension particles higher in the air" have been added in line 35-36 of the revised manuscript.

[Comment 2] p.2, line 18 and p.15, line 261: "particle activity" should be defined.

[Response 2] Thanks for your comment. For a better understanding, the "particle activity" has been modified into "particle velocity" throughout the manuscript.

[Comment 3] p.3, line 44: a reason should be cited why the process is important.

[Response 3] Thanks for your careful reviews. According to the reviewer's suggestion, the description "Inter-particle collision within aeolian snow/sand cloud changes trajectories of saltating grains, and further affects the structures and transportation features of the particle flow. Numerous of investigations have shown that mid-air collision effect plays an non-neglected role in wind-blown sand movement (Carneiro et al., 2013;Dong et al., 2005;Huang et al., 2007;Li et al., 2013). However, this mechanism has been rarely investigated in a drifting snow transport with more suspended grains and smaller particle response time." has been added in line 37-43 of the revised manuscript.

[Comment 4] p.5, line 6: what is the meaning of Fdi ?

[Response 4] Thanks for this comment. F_{di} is the drag force F_D along the *i*-th direction. We have change 'F_{di}' into 'F_{Di}' in Eq. (6), and the sentence "F_{Di} is the drag force component along the *i*-th direction" has been added in line 95-96 of the revised manuscript.

[Comment 5] p.7, line 105: gamma is not defined and lambda is not used.

[Response 5] Thanks for your careful reviews. The expression "$\lambda = (1+e)\big/\left(d_A^3 + d_B^3\right)$" has been modified into "$\gamma = (1+e)\big/\left(d_A^3 + d_B^3\right)$" in the revised manuscript.

[Comment 6] p.7, line 119: the surface boundary conditions of the model should be specified.

[Response 6] The suggestion is implemented. The surface boundary conditions are specified in the revised manuscript. The sentence "The bottom boundary is a rigid wall, and the top boundary obeys a stress-free boundary condition." has been added in line 143-144 of the revised manuscript.

[Comment 7] p.9, line 144: why "obviously"?

[Response 7] Thanks for your careful reviews. In order to make it more clearly, the word "obviously" has been deleted in the revised manuscript.

[Comment 8] p.9, line 149: "critical friction velocity" should be defined.

[Response 8] The suggestion is implemented. We have added the description "(the smallest friction velocity for a drifting snow)" in line 219-220 of the revised manuscript.

[Comment 9] p.9, lines 152-154: the slowing down of the airflow by the blown snow particles is not discussed.

[Response 9] Thanks for your careful reviews. According to the reviewer's suggestion, the slowing down of the airflow by the blown snow particles is discussed in the revised manuscript. The sentences "At the same time, saltating particles reduce the wind at the near surface, however, mid-air collisions reduce the surface wind speed to a more smaller value, which also implies that the mass flux is enhanced by mid-air collision effect, detailed discussion can be seen in Sec. 4.2." have been added in line 225-229 of the revised manuscript.

[Comment 10] p.10, line 168: the sentence "The reason could be ..." is not clear; what is the link between the particle activity and the friction velocity?

[Response 10] Thanks for your this recommendations. As a matter of fact, the particle activity indicates the mean particle momentum. In order to make it more clearly, the sentence "The reason could be that particles are more active with larger friction velocity" has been changed into "The reason could be that the mean particle momentum increases with friction velocity" in the revised manuscript, as shown in line 244-245.

Finally, once again we appreciate you for your good and comprehensive comments. Those revisions according to your comments really make this manuscript improve a lot.

Thank you!

Yours sincerely,

Shuming Jia, Zhengshi Wang, Shumin Li

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