

Authors' Responses to the Comments on the Manuscript

“A simulation of the large-scale drifting snow storm in a turbulent boundary layer”

General Response to the Comments:

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 in tracking form). The detailed responses to comments of referees are as follows (see blue part in this reply):

Responses to Comments of Reviewer#1:

General comments:

[Comment] In this manuscript, the authors used the large eddy simulation combined with the Lagrangian particles motion model to calculate the large-scale drifting snow storm. While their basic idea is interesting, the paper needs a revision before been published. The points of criticism are discussed in more detail in the following.

[Response] Thanks for your careful reviews. A substantial revision to the original manuscript has been made according to your kind advice as listed in specific comments, as shown in the following responses.

Specific comments:

[Comment 1] The author simulates the drifting snow storm in the manuscript. What are the differences between the drifting snow storm and the general blowing snow on the physical mechanism? How is it reflected in the model of this manuscript?

[Response 1] Thanks for your this recommendations. The general blowing snow model pays attention to the particle motions at the near surface, and typically includes four sub-processes: aerodynamic entrainment, grain-bed collision, particle trajectory

and wind modification (Nemoto and Nishimura, 2004). However, the key physical process for a drifting snow storm is the particle's motion in atmospheric turbulences (especially the large-scale coherent structures), and a reasonable bottom boundary condition for particles is the basic.

From the view point of model, on the one hand, the three-dimensional large eddy simulation model combined with a proper model setting is necessary to produce large scale turbulent structures; on the other hand, a steady-state saltation condition is needed for the development of the drifting snow storm.

In the revised manuscript, the description 'The large-scale drifting snow storm is produced and its spatial structures and transport features are analyzed.' has been modified into 'The large-scale drifting snow storm is produced under the actions of large-scale turbulent structures combined with a steady-state snow saltation boundary condition for particles, and its spatial structures and transport features are analyzed.', as shown in line 69-72.

[Comment 2] The mesh size set in this manuscript is much larger than the particle size. How do you determine the wind speeds of the particles position when calculating the particles motion?

[Response 2] Thanks for your comment. In the process of calculating the particle's motion, the wind speed component at the particle's position is determined by the wind speeds at surrounding grid points through a linear interpolation algorithm. The sentence 'in which $\tilde{u}_i(\vec{x}(t))$ is determined by the wind speeds of surrounding grid points through the linear interpolation algorithm' has been added in line 126-128 of the revised manuscript.

[Comment 3] The author mentions that a particle represents one particle parcel in Section 2.4. How many particles does the particle parcel contain? What is the time step for calculating the particles?

[Response 3] Thanks for your comment. We use one particle parcel to represents 2.5×10^7 snow particles. The description 'In this simulation, each particle parcel contains 10^7 snow particles.' has been added in line 202-203 of the revised manuscript.

At the same time, the particle time step is determined by the minimum of particle relaxation time $T_p = \rho_p d_p^2 / 18 \rho \nu$ to ensure a smooth particle trajectory (Dupont et al., 2013). The description ‘The large time step and small time step (acoustic wave integral) for the wind field calculation are 0.1 s and 0.02 s, respectively, and the particle time step is determined by the minimum of particle relaxation time.’ has been added in line 203-205 of the revised manuscript.

[Comment 4] The author mentions that the bottom boundary condition of the particles is calculated by Section 2.3, but Equation 12 shows that the impact and lift-off particles are the same, how does the particle in the air increase?

[Response 4] Thanks for your careful reviewing. The steady-state saltation is set as the bottom condition for snow particles. For a steady-state saltation, the impact and lift-off particles should be equivalent, thus, Equation (12) are used to guarantee a steady-state saltation throughout the calculation. In this condition, if some of the snow particles within the saltation layer are transported to higher in the air (the saltation layer becomes undersaturated), more particles will lift-off from the surface to replenish the saltation layer until a saturated state is reached.

In order to make it more clearly, the descriptions ‘In this condition, if some of the snow particles within the saltation layer are transported to higher in the air by turbulent vortexes (the saltation layer becomes undersaturated), more particles will lift-off from the surface to replenish the saltation layer until a saturated state is reached.’ are added in line 179-182 of the revised manuscript.

[Comment 5] The author cites the work of Vinkovic et al. (2016) in Equation 4. The SGS velocity in the work of Vinkovic et al. (2016) is attached to the solid particles, but the author seems to attach it to the flow field. Why?

[Response 5] Thanks for your comment. The subgrid scale (SGS) velocity is related to the local turbulent kinetic energy, but it has no any impacts on the wind field. Thus, the SGS velocity is attached to the solid particles essentially. In order to make it more clearly, the contents about SGS velocity have been moved to section 2.2, and the description ‘Namely, the local wind velocity $\tilde{u}_i(\vec{x}(t))$ is composed of a resolved

Eulerian large-scale part $\tilde{u}_i(\vec{x}(t))$ (obtained from the linear weighting of surrounding grid points) and a fluctuating SGS contribution $u'_i(t)$ has been changed into ‘Namely, the local relative is expressed as $V_{ri} = \tilde{u}_i(x_p) - u_{pi} + u'_i$, in which $\tilde{u}_i(\vec{x}_p)$ is the resolved large-scale wind speed at the particle’s position and is determined by the resolved wind speeds of surrounding grid points through the linear interpolation algorithm.’, as shown in line 125-128 of the revised manuscript.

[Comment 6] The result that the proportion of particles below 100 m in the particle size distribution at 0.05 m in Figure 5 of this paper is obviously smaller than that of the experimental results. Why?

[Response 6] Thanks for your careful reviewing. In Fig. 5 of the original manuscript, the proportion of particles below 100 m in the particle size distribution at 0.05 m is smaller than that of the experimental results. The reason could be that mid-air collisions, occurred frequently within the high concentration saltating snow cloud at the near surface, play an important role in conveying larger particles to high altitude (Carneiro et al., 2013). However, the effect of mid-air collision mechanism is beyond the scope of the current study.

In the revised manuscript, the description ‘Besides, it can be seen that the proportion of particles below 100 μm in diameter at 0.05 m is smaller than that of the experimental result. The reason could be that mid-air collisions, occurred frequently within the high concentration saltating snow cloud at the near surface, play an important role in conveying larger particles to higher altitude (Carneiro et al., 2013). However, the mid-air collision mechanism is beyond the scope of the current study.’ has been added in line 261-266.

[Comment 7] Figure 6a shows that the rate of snow transport flux has a mutation at 1 m, while the rate of the average particle size of snow particles in Figure 4 also has a mutation at 1 m. Is there any relationship between them?

[Response 7] Thanks for your comment. Indeed, the snow transport flux profile is related to the average particle size profile. The transition of snow transport flux

profile at about 1 m should be caused by the different motion states of particles with different particle sizes. As shown in Fig. 4, the mean particle diameter decreases rapidly with height below the critical height of approximately 1 m, and almost keeps constant above this height. Above the critical height, the particle gravities and relaxation times are small, thus, particles follow the turbulent flow in the state of suspension. However, below this height, plenty of larger particles have much larger relaxation times and gravities, thus, there exist relative speed between particle and wind field because particle inertia plays an important role.

In the revised manuscript, the description ‘Besides, the transition of snow transport flux profile at about 1 m should be mainly caused by the different motion states of particles with different particle sizes, as shown in Fig. 4. Above the critical height, particles generally follow the turbulent flow in the state of suspension because their gravities and relaxation times are small enough. However, plenty of larger particles at the near surface make the particles velocity differs from the wind speed, since particle inertia plays an important role.’ has been added in line 281-286.

[Comment 8] Figure 10 shows that the thickness of drifting snow storm eventually developed to about 900m. Is this because the author set the upper boundary to 1000m? If the upper boundary is set higher, will the thickness of drifting snow storm continue to increase?

[Response 8] Thanks for your comment. Actually, the height of the domain is determined by a series of testing simulations with various domain heights. As shown in Fig. R1, under current model settings, the thickness of the fully developed turbulent boundary layer basically do not vary with the height of the domain. The reason could be that the turbulent boundary layer is a shear force dominated flow with constant initial boundary layer depth and the surface heat flux (Moeng and Sullivan, 1994). Drifting storm with different thicknesses may be achieved through changing the initial field and surface heat flux.

The description ‘Higher domain heights are also tested with the same model settings, and the thickness of the drifting snow seems basically unchanged. Drifting

snow storm with difference thicknesses may be achieved by changing the initial state of the air and surface heat flux.’ has been added in line 360-363 of the revised manuscript.

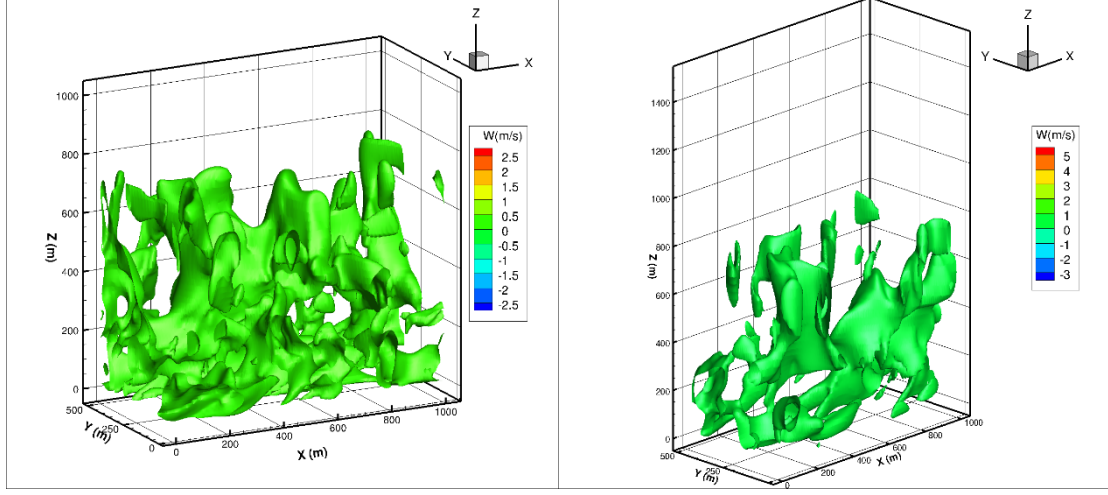


Figure R1. Iso-surfaces of vertical wind speed bubbles with a value of 1.0 ms^{-1} with different domain height (a) 1.0 km and (b) 1.5 km. All simulation settings are the same for both simulations except the height of the domain.

[Comment 9-1] The author mentions that the particles enter the high-altitude causing by large-scale turbulence structure. Therefore, the authors show the distribution of airborne particles with and without consideration of atmospheric turbulence in Figure 2 and Figure 8 respectively. What are the differences between the two examples in Figure 2 and Figure 8 when calculating the flow field? What equations are used to calculate atmospheric turbulence?

[Response 9-1] Thanks for your comment. First of all, the atmospheric turbulence is calculated by the large eddy simulation model (Equation 1~3) through wind shear combined with a small heat flux at the bottom (Moeng and Sullivan, 1994). Then, the only difference between the two examples in Fig. 2 and Fig. 8 is that the resolved wind speed at particle’s position ($\tilde{u}_i(\vec{x}_p)$) in Fig. 8 is replaced by a given value obtained from the standard logarithmic profile during calculating particle’s trajectory. In this way, the effect of resolved large-scale turbulent structures on the development of the drifting snow storm can be removed from the example in Fig. 8.

In the revised manuscript, the description ‘This simulation is achieved by

replacing the resolved wind speed at particle's position ($\tilde{u}_i(\vec{x}_p)$) with a given value obtained from the standard logarithmic profile, and the other model settings and simulation procedures stay the same with other simulations. In this way, the effect of large-scale turbulent structures on the development of the drifting snow storm vanishes.' has been added in line 311-316.

[Comment 9-2] In addition, the author should give a comparison of the flow field structure in these two cases, so that the readers can understand this part of the content more clearly.

[Response 9-2] Thanks for your suggestion. As discussed in [Response 9-1], the flow field structures in these two cases are the same. However, in order to make this part of the content more clearly, the description 'This simulation is achieved by replacing the resolved wind speed at particle's position ($\tilde{u}_i(\vec{x}_p)$) with a given value obtained from the standard logarithmic profile, and the other model settings and simulation procedures stay the same with other simulations. In this way, the effect of large-scale turbulent structures on the development of the drifting snow storm vanishes.' has been added in line 311-316 of the revised manuscript.

[Comment 10] The author gives the vertical wind speed bubbles (1 m/s) in Figure 9, indicating that the particles are substituted into the upper air by the ascending airflow. Why use a 1m/s here? Is it the critical speed at which the particles become suspended particles?

[Response 10] Thanks. The reviewer is right that the wind speed of 1m/s is approximately the critical speed at which the particles of mean particle size become suspended particles, because the maximum diameter of suspended particles is found to be approximately the mean particle size of the lift-off particles. The description '(corresponding to the critical wind speed at which the particle of mean particle size becomes suspended particle, since the maximum diameter of suspended particles is found to be approximately equals to the mean particle size of the lift-off particles)' has been added in line 339-342 of the revised manuscript.

[Comment 11] There are some writing errors in this manuscript. For example, 'is'

should be changed to ‘are’ in line 313 of page 19.

[Response 11] Thanks for your careful reviewing. The sentence ‘The thickness of saturated drifting snow storms is almost constant with a value approximately 900 m under different friction velocities’ has been changed into ‘The thicknesses of saturated drifting snow storms are almost constant with a value approximately 900 m under different friction velocities’ in line 358-359 of the revised manuscript.

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,

Zhengshi Wang, Shuming Jia

Reference:

1. Carneiro, M. V., Araújo, N. A., Pähtz, T., and Herrmann, H. J.: Midair collisions enhance saltation, *Phys.rev.lett*, 111, 058001, 2013.
2. Nemoto, M., and Nishimura, K.: Numerical simulation of snow saltation and suspension in a turbulent boundary layer, *Journal of Geophysical Research Atmospheres*, 109, D18206, 2004.
3. Moeng, C. H., and Sullivan, P. P.: A Comparison of Shear- and Buoyancy-Driven Planetary Boundary Layer Flows, *Journal of the Atmospheric Sciences*, 51, 999-1022, 1994.