A 3D simulation of drifting snow in the turbulent boundary layer

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Abstract. The drifting snow is one of the most important factors that affect the global ice mass balance and hydrological balance. Current models of drifting snow are usually one- or two-dimensional, focusing on the macroscopic quantities of drifting snow under temporal average flow. In this paper, we take the coupling effects between wind and snow particles into account and present a 3-D model of drifting snow with mixed grain size in the turbulent boundary layer. The Large Eddy Simulation (LES) method is used for simulating the turbulent boundary layer of the wind field and the 3-D trajectory of every motion snow particle is calculated through Lagrangian Particle Tracking method. Both simulation and experimental results agree well. The results indicated that the motion trajectories of snow particles, especially the small snow particles, are obviously affected by the turbulent fluctuation and the particle movement enhance the turbulent fluctuation in turn. ~~the~~ The visualized observation of drifting snow in the turbulent boundary layer demonstrates ~~has~~ apparent 3-D structure and snow streamers, which lead to an intermittent transport of the snow particles and spatial inhomogeneity. ~~, and the motion trajectories of snow particles, especially the small snow particles, are obviously affected by the turbulent fluctuation.~~ The macro statistics of drifting snow indicates that the variation of spanwise velocity of snow particles ~~increases with~~along height depends on the friction velocity and is one order smaller than that of streamwise velocity. ~~Furthermore, the diameter distribution of snow particles in the air along the height shows a stratification structure.~~

1 Introduction

The phenomenon of the loose snow particles traveling near the land surface under the action of wind is known as drifting snow. As a typical two-phase flow, drifting snow is widely distributed in the globe and has significant impacts on the natural environment and the social economy. On one hand, drifting snow is one of the main causes of the temporal and spatial variation of snow distribution, contributes greatly to the mass balance of the ~~Antarctic~~ ice sheets (Gallée et al., 2013), and further affects global climate system. The seasonal snow cover also deeply affects the hydrological balance in cold regions, thus is of glaciological and hydrological importance. On the other hand, drifting snow causes snow accumulation on the road and reduces visibility, which may seriously affect the traffic and human activities, and its resultant non-uniform distribution of snow layer may induce and aggravate various natural disasters, such as flood, avalanche, mudslides and landslide (Michaux et al., ~~2002~~2001). These disasters may result in not only huge direct and indirect economic losses, but also human casualties. Thus, in-depth study on the drifting snow is considered to be essential to comprehensively understanding the ice mass balance and hydrological balance.

The transport processes of snow grains have been extensively investigated (Pomeroy et al., 1993; Clifton and Lehning, 2008~~Lehning et al., 2002; Bavay et al., 2009~~). Many models were proposed by taking the snow particles as continuous phase (Uematsu et al., 1993; Mann, 2000; Taylor, 1998; Déry and Yau, 1999; Fukushima et al., 1999, 2001; Xiao et al., 2000; Bintanja, 2000a, 2000b). ~~Obviously, the above assumption is not in agreement with the real situation. In addition, these models could reveal neither the movement mechanisms of snow particles nor the factors affecting the behaviors of snow particles.~~ These models have a significant role in promoting the drifting snow research although some information can not be acquired from these models, for example, the trajectory of particle and its movement mechanisms. Subsequently~~Recently~~, Nemoto and Nishimura (2004) studied the snow drifting process based on particle tracking in a turbulent boundary layer and their 1-D model included four sub-processes: the aerodynamic entrainment of snow grains, grain-bed collision, grain trajectories and wind modification. Later, Zhang and Huang (2008) presented a steady state snow drift model combined with the initial velocity distribution function and analyzed the structure of drifting snow at steady state.

However, neither the details of the spatial variation of snow drifting nor the whole turbulent structure of wind field can be described due to limitation of their models. 3-D simulation of drifting snow gradually carried out in recent years. Gauer (2001) first simulated the blowing and drifting snow in Alpine terrain with Reynolds Averaged Navier-Stokes (RANS) approaches. Also, Schneiderbauer and Prokop (2011) developed the SnowDrift3D model based on RANS. Vionnet et al. (2014) went on a study of large-scale erosion and deposition using a fully coupled snowpack/atmosphere model. Groot et al. (2014) simulated the small-scale drifting snow with a Lagrangian stochastic model based on LES and the intermittency of drifting snow was mainly analyzed. ~~Furthermore~~And~~,~~ snow particles were uniform size in most previous models, which is different from the natural situation. To date, a comprehensive study on drifting snow in the turbulent field is indispensable for a thorough understanding of the complex drifting snow.

In this paper, based on the model of Dupont et al. (2013) that developed for blown sand movement, the Advanced Regional Prediction System (ARPS, version 5.3.3), which is a middle-scale meteorological model, is applied in a small-scale for drifting snow and a series of adaptations are made for drifting snow simulation. ~~we~~ We performed a numerical study of~~present a physical 3-D numerical model for~~ drifting snow in the turbulent boundary layer ~~based on the LES of Advanced Regional Prediction System (ARPS, version 5.3.3)~~ by taking the 3-D motion trajectory of snow particles with mixed grain size, the grain-bed interaction, and the coupling effect between snow particles and wind field into consideration and used it to directly calculate the velocity and position of every single snow particle in turbulent atmosphere boundary layer, the transport rate and velocity distribution characteristics of drifting snow, and the mean particles size at different heights. The paper is structured as follows: Section 2 briefly introduces the model and methods; Section 3 illuminates the model validations; Section ~~3~~ 4 presents the simulation results and discussions, and Section ~~4~~ 5 is the conclusion.

2 Model and Methods

2.1 Turbulent boundary layer

The ARPS developed by University of Oklahoma is a three-dimensional, non-hydrostatic, compressible LES model and has been used for simulating wind soil erosion (Vinkovic et al., 2006; Dupont et al., 2013). In this paper, it is used for modeling the drifting snow.

Snow saltation movement in the air is a typical two-phase movement, in which the coupling of particles and the wind field is a key issue. Vinkovic et al. (2006) introduced the volume force caused by the particles into Navier-Stokes equation of ARPS and The conservation equations of momentum and subgrid scale (SGS) turbulent kinetic energy (TKE) after filtering ~~with considering the impact of the presence of particles on the flow field~~ can be expressed as (Vinkovic et al., 2006; Dupont et al., 2013):

$$\frac{\partial \tilde{u}_i}{\partial t}+\tilde{u}_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\bar{\rho}}\frac{\partial}{\partial x_i}\left(\tilde{p}''-\alpha_{div}\frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_i}\right)-g\left(\frac{\tilde{\theta}''}{\bar{\bar{\theta}}}-\frac{c_p}{c_v}\frac{\tilde{p}''}{\bar{p}}\right)\delta_{i3}-\frac{\partial \tau_{ij}}{\partial x_j}-f_i \tag{1}$$

$$\begin{aligned}\frac{\partial e}{\partial t}+\tilde{u}_j\frac{\partial e}{\partial x_j}=-\tau_{ij}\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial}{\partial x_j}\left(2\left(\left(1-\delta_{j3}\right)\nu_{th}+\delta_{j3}\nu_{tv}\right)\frac{\partial e}{\partial x_j}\right)\\ -\frac{g}{\bar{\theta}}\tau_{3\theta}-\varepsilon-\frac{1}{V_{grid}}\sum_{s=1}^{N_p}\frac{m_p}{\bar{\rho}}\frac{2e}{T_P+T_L}f\left(Re_p\right)\end{aligned} \tag{2}$$

where the tilde symbol indicates the filtered variables and the line symbol represents grid volume-averaged variables. $x_i\,(i=1,2,3)$ stand for the streamwise, lateral, and vertical directions, respectively, u_i refers to the instantaneous velocity component of three directions, δ_{ij} is the Kronecker symbol, α_{div} means the damping coefficient, p and ρ are the pressure and density of air, respectively; g is the gravity acceleration, θ indicates the potential temperature, c_p and c_v are the specific heat of air at constant pressure and volume, respectively; t is time, τ_{ij} denotes the subgrid stress tensor, and f_i is the drag force caused by the particles and can be written as (Yamamoto et al., 2001):

$$f_i=\frac{1}{\rho V_{grid}}\sum_{s=1}^{N_p}m_p\frac{u_i(x_p(t),t)-u_{pi}(t)}{T_p}f(Re_p) \tag{3}$$

where V_{grid} is the grid cell volume, N_P stands for the number of particles per grid, m_p means the mass of particles, $u_{pi}(t)$ and $u_i(x_p(t),t)$ represent the velocity of particles and the wind velocity at grain location at time t, respectively, and $f(Re_p)$ is an empirical relation of the particle Reynolds number Re_p (Clift et al., 1978):

$$f(Re_p) = 1 \qquad (Re_p < 1)$$
$$f(Re_p) = 1 + 0.15 \mathrm{Re}_p^{0.687} \qquad (Re_p \ge 1) \tag{4}$$

In the equation (2), e is the SGS TKE, ν_{th} and ν_{tv} stand for the horizontal and vertical eddy viscosities, respectively, $\tau_{3\theta}$ is the subgrid heat flux, and ε indicates the dissipation rate of SGS TKE. T_p and T_L represent the particle response time and the Lagrangian correlation timescale, respectively, and can expressed as

$$T_p = \frac{\rho_p d_p^2}{18\rho\nu} \quad \text{and} \quad T_L = \frac{4e}{3C_0\varepsilon} \tag{5}$$

where C_0 is the Lagrangian constant and ν denotes the molecular kinematic viscosity.

2.2 Governing equation of particle motion

Because snow particles have much higher density ρ_p than air ($\rho_p/\rho \approx 10^3$) and much smaller diameter d_p than Kolmogorov scale, in this~~our~~ simulation, they are approximately regarded as a sphere and only possess gravity and drag force. Thus, their motion governing equation can be expressed as (Vinkovic et al., 2006)

$$\frac{d\vec{x}_p(t)}{dt} = \vec{v}_p(t) \tag{6}$$

$$\frac{d\vec{v}_p(t)}{dt} = \frac{\vec{v}(\vec{x}_p(t),t) - \vec{v}_p(t)}{T_p} f(Re_p) + \vec{g} \tag{7}$$

where $\vec{v}_p(t)$ and $\vec{v}(\vec{x}_p(t),t)$ are the velocity of the particle and the fluid velocity of particle position at time t, respectively.

It is worth noting that the inertia effect of snow particles is considered by evaluating the maximum particle response time, so the particle motion is the dynamical calculation of time step, which is guaranteed to be less than the maximum particle response time.

2.3 Grain-bed interactions~~Rebound and splash~~

2.3.1 Aerodynamic Entrainment

Snow particles will be entrained into the air if the shear force produced by air flow is large enough. The number of entrainment N (per unit area per unit time) can be express as (Anderson and Haff, 1991):

$$N = \eta(\tau - \tau_t) \tag{8}$$

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where τ is the local surface shear stress and τ_t is the threshold shear stress. Obviously, if τ of every position in the computation domain is always smaller than τ_t, no particle can start-up and the drifting snow will not happened. The threshold shear stress can be described as

$$\tau_t = A^2 gd(\rho_p - \rho) \qquad (9)$$

in which $A = 0.2$ is more suited to snow as reported by Clifton et al. (2006). The coefficient takes the form of $\eta = C/(8\pi d_p^2)$ (Doorschot and Lehning, 2002) and $C = 1.5$.

The initial velocity of entrained particles follows a lognormal distribution with mean value $3.3u_*$ (u_* is the friction velocity), which is consistent with the measurements of saltating snow in wind tunnel (Nishimura and Hunt, 2000) and has been adopted by drifting snow studies (Clifton and Lehning, 2008; Groot et al., 2014). And the initial take-off angle can be described by a lognormal distribution with a mean value of $(75-55(1-\exp(-\langle d_p\rangle/1.75\times10^{-4})))$ (Clifton and Lehning, 2008).

~~The collision of saltating particles with the bed surface is a key physical process in saltation, as it will rebound with a certain probability and may splash new saltating particles into the air (Shao and Lu, 2000). Kok and Renno (2009) have proposed a physical splashing function based on the conservation of energy and momentum. Thus, the saltation process under various physical environments can be accurately simulated and applied to the mixed soils and drifting snow.~~

2.3.~~1~~ 2 Rebounding

~~The grain-bed interaction is a stochastic process, in which the impact~~ When a moving particles~~s~~ impact on the bed, it may rebound into air again~~may rebound with a certain probability~~. If a particle rebounds into the air, it can be described using three variables: the velocity v_{reb}, the angle toward the surface α_{reb} and the angle toward a vertical plane in the streamwise direction β_{reb}.

The rebound probability can be expressed as (Anderson and Haff, 1991):

$$P_{reb} = B[1-\exp(-\gamma v_{imp})] \qquad (10)$$

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where v_{imp} is the impact velocity of particle, B and γ are the experienced parameters. Here, $\gamma = 2s/m$ and $B = 0.90$ are employed as Groot et al.(2014) indicate that these value are more accurate for drifting snow.

~~where v_{imp} is the impact velocity of particle, B and γ are the experienced parameters. Here, $B = 0.95$ and $\gamma = 2s/m$ are employed.~~

Recent experiment shows that the fraction of kinetic energy retained by the rebounding particle approximately follows normal distribution (Wang et al., 2008):

$$\mathrm{prob}(v_{reb}^2) = \frac{1}{\sqrt{2\pi}\sigma_{reb}} \exp\left(-\frac{(v_{reb}^2 - \langle v_{reb}^2 \rangle)^2}{2\sigma_{reb}^2}\right) \qquad (11)$$

where $\langle v_{reb}^2 \rangle = 0.45 v_{imp}^2$ and $\sigma_{reb} = 0.22 v_{imp}^2$ (Kok and Renno, 2009).

The angle α_{reb} approximately follows an exponential distribution. Although Kok and Renno (2009) suggest the mean value of α_{reb} is 45° and it was used by Groot et al. (2014) for drifting snow, we choose a mean value depending on the mean particle size because many researches indicate that α_{reb} relay on particle size (Rice et al., 1995; Zhou et al., 2006):

~~For the velocity after rebound v_{reb}, Kok and Renno (2009) indicate that the fraction of kinetic energy retained by the rebounding particle approximately follows normal distribution as follow:~~

$$\cancel{v_{reb}^2 = ((45 \pm 22)\%) v_{imp}^2} \qquad \cancel{(11)}$$

~~Two angles are introduced in the rebound process to describe the rebound direction as mentioned above. The angle α_{reb} approximately follows an exponential distribution. Although it is not affected by the impact velocity, it decreases exponentially with the increase of particle diameter (Rice et al., 1995; Zhou et al., 2006). The relationship of average value of rebound angle to particle diameter can be expressed as:~~

$$\langle \alpha_{reb} \rangle = 161.46 e^{-\frac{d_p}{250\times 10^{-6}}} + 0.15 \qquad (12)$$

~~where d_p is measured in the unit of micrometer.~~

However, the angle β_{reb} was rarely involved in previous studies and may not

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strongly affect the saltation process (Dupont et al., 2013). Here we choose $\beta_{reb} = 0^{\circ} \pm 15^{\circ}$.

2.3.~~2~~3 Splashing

The newly ejected particles and the 'dead particles' (not rebounded) will reach equilibrium when the saltation process becomes stable.

The number of newly ejected particles is usually proportional to the impact velocity and can be written as (Kok and Renno, 2009):

$$N = \frac{a}{\sqrt{gD}} \frac{m_{imp}}{\langle m_{ej} \rangle} v_{imp} \tag{13}$$

where a is a dimensionless constant in the range of 0.01– 0.05. This value affect the 'saturation length' (total transport rate of drifting snow reached equilibrium) to a great extent. We find that $a = 0.03$ is closer to the observation of drifting snow in the wind tunnel (Okaze et al., 2012). While this parameter will not influence the steady state of drifting snow because we found the percentage of eject particles is always less than 3% in the fully developed drifting snow. D is the typical particle size ($\langle d_p \rangle$ in this paper), m_{imp} is the mass of impacting particle and $\langle m_{ej} \rangle$ is the average mass of ejection grains. ~~where a is a dimensionless constant in the range of 0.01– 0.05 (here $a = 0.03$), D is the typical particle size ($\langle d_p \rangle$ in this paper, m_{imp} is the mass of impacting particle and $\langle m_{ej} \rangle$ is the average mass of ejection grains.~~

Once a new particle is splashed into the air, it can also be characterized by its velocity v_{ej}, its angle toward the surface α_{ej} and its angle toward a vertical plane in the streamwise direction β_{ej}.

The speed of the ejected particles is exponentially distributed. Kok and Renno (2009) developed a physical expression of the average dimensionless speed of the ejected particle as follow:

$$\frac{\langle v_{ej} \rangle}{\sqrt{gD}} = \frac{\langle \lambda_{ej} \rangle}{a} \left[1 - \exp\left(-\frac{v_{imp}}{40\sqrt{gD}} \right) \right] \tag{14}$$

where $\langle \lambda_{ej} \rangle$ is the average fraction of impacting momentum applied on the ejecting surface grains. We choose $\langle \lambda_{ej} \rangle = 0.15$ in this paper, which corresponds to the experimental observation of sand by Rice et al. (1995).

~~where $\langle \lambda_{ej} \rangle$ is the average fraction of impacting momentum applied on the ejecting surface grains. We choose $\langle \lambda_{ej} \rangle = 0.15$ in this paper.~~

Kok and Renno (2009) indicated that the angle α_{ej} approximately follows an exponential distribution and its mean value is 50°, which was also adopted by Groot et al. (2014). In addition, the angle $\beta_{ej} = 0^{\circ} \pm 15^{\circ}$, similar to Dupont et al. (2013).

~~$\beta_{ej} = 0^{\circ} \pm 15^{\circ}$~~.

2.4 Simulation Details

In this paper we have performed some wind tunnel experiments to obtain the initialization data for the simulation as well as to compare the simulated results with experiment results. The ~~The blowing snow process in the turbulent boundary layer is simulated and the simulation results are compared with the existent experiment results. Computational~~ computational region is set as $16m \times 1.0m \times 1.5m$ and divided into two sections, as show in Figure 1. The first zone extending from $x = 0m$ to $x = 5m$ is used for the development of the ~~fully developed~~ turbulent wind field ~~region with a steady turbulent boundary layer~~ and provides a steady turbulent boundary layer~~extending from $x = 0m$ to $x = 5m$ and a flow field cycle at $x = 1m$~~. In this simulation, the turbulent characteristics separating from our wind tunnel results are added on the initial logarithmic velocity profile at beginning and the inlet velocity of fluid will be equal to the wind velocity at the location of $x = 5m$ after 5 seconds which realizes a long distance development of the turbulent boundary layer. The second zone is the blowing snow ~~blowing~~ region from $x = 6m$ to $x = 16m$, where a ~~sufficient~~ loose snow layer is set on the ground.

In this model, the grid has a uniform size of $\Delta x = \Delta y = 0.05m$ in the horizontal direction, and the average mesh size of $\Delta z = 0.03m$ in the vertical direction. The grid is stretched by cubic function to acquire ~~more~~ detailed information of the surface layer and the smallest grid is $\Delta z_{min} = 0.002m$.

~~A turbulent boundary layer over a snow bed is generated using t~~The actual computation time is 30 seconds, in which the first 10s and the second 10s are respectively used for the development of turbulent boundary layer and the drifting snow, and the last 10s for data statistics. The dynamic Smagorinsky-Germano

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subgrid-scale (SGS) model is used in the simulation. ~~by setting the soil type, reasonable roughness and an initial field with turbulent fluctuations.~~ For the flow field, we applied the rigid ground boundary condition at the bottom, the open radiation boundary in the top, the periodic boundary condition in the spanwise direction, the open radiation boundary condition at the end of the domain along the streamwise direction. The forced boundary is applied in the inflow as mentioned above. ~~and the periodic boundary condition in the inflow with the cycle location at $x=5.0m$. The initial wind database is obtained from the experimental results of wind tunnel.~~ Additionally, ~~The~~ the snow particles have circulatory motion in the lateral boundary and they will disappear when moving out of the outlet in the end of the domain.~~.~~

The size distribution of snow particles in this paper is fitted to the experiment results obtained from field observations of SPC (Schmidt, 1984), that is

$$f(d_p)=\frac{d_p^{(\alpha-1)}}{\beta^{\alpha}\Gamma(\alpha)}\exp(-d_p/\beta) \tag{15}$$

where α and β are the shape and scale parameters of gamma-function distribution and we choose a value of 4.65 and 75.27, respectively. Every new ejection or entrainment particle will be given a random size from above distribution and will be tracked separately. The sizes of snow particles in the air are stochastically collected and the size distribution is presented in figure 2. The mean diameter is about $\langle d_p \rangle = 350\mu m$. The results are in consistence with those observational results of the natural snow (Omiya et al., 2011).~~where α and β are the shape and scale parameters of gamma-function distribution, respectively. Here, the diameters of 2617 snow particles are counted and their distribution is presented in Figure 2. The mean diameter is $\langle d_p \rangle = 350\mu m$. The results are in consistence with those observational results of the natural snow (Omiya et al., 2011).~~

The density of snow particles and air are $912kg/m^3$ and $1.225kg/m^3$, respectively. And the surface roughness and the molecular kinematic viscosity of snow particles are $z_0=\langle d_p \rangle/30$ and $\nu=1.5\times10^{-5}$, respectively. ~~Several particles will be forced to take off from bed surface with random velocities ($u_{pi}=(0\sim1)m/s$) at random positions in the domain at the initial moment of drifting snow.~~

The processes of snow blowing with the friction wind velocity of

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$u_* = 0.179 \sim 0.428\ m/s$ are performed with the environmental temperature of $-10^\circ C$ and initial relative humidity of 90%. And we found the lower bound of friction velocity for a drifting snow is approximately 0.18 m/s for this situation.~~The processes of snow blowing with the wind velocity of~~ $\cancel{u_* = 0.179 \sim 0.428\ m/s}$ ~~are performed at environmental temperature of~~ $\cancel{-10^\circ C}$ ~~and initial relative humidity of 90%.~~

3 Model validations

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The wind profile is firstly obtained by the time averaging and spatial averaging of a time-series of wind velocities ($t = 5 \sim 10\, s$ and the time interval is $0.01s$). As shown in figure 3, the method leads to similar wind profiles to that of wind tunnel experiment at different wind speeds.

Snow transport rate (STR) is one of the most important indicators of the strength of the drifting snow. Figure 4(a) shows the evolution of STR per width along streamwise in different friction wind velocity. It can be seen that the STR per width increases along with the streamwise and gradually reaches a steady state, which is basically consistent with the observation in the wind tunnel by Okaze et al. (2012). And it appears that the distance needed to reach the state is increase with the increasing of friction wind speed. The STR per width (averaging from $x = 14m$ to $x = 15m$) versus friction velocity is presented in figure 4(b). It can be observed that the STR per width increases with friction wind velocity increasing. The relationship of STR per width Q and friction velocity u_* can be expressed as

$$Q = 1.94 u_*^{4.51}$$

which is consistent with the experiment results of Sugiura et al. (1998) and the simulation results of Nemoto and Nishimura (2004).

Then, figure 5 shows the relationship of STR per unit area to the saltation height. As shown in figure 5, the variations in the STR per unit area with height at different friction wind speeds are equivalent, that is, the STR per unit area decreases with height increasing. The comparison of the simulation and experiment results of Sugiura et al. (1998) is also displayed in the inset map of figure 5 and they are in a good agreement.

Subsequently, the velocity distribution of snow particles in the air is shown in figure 6, in which (a) is the average velocity of snow particles along the streamwise direction as a function of height and (b) displays the corresponding velocity probability distribution of snow particles. It can be observed from figure 6(a) that the average velocity of snow particles along the streamwise direction increases with the height increasing, in which the experiment data has been calibrated by wind speed. Good accordance with the experimental results until below 0.02m mainly because mid-air collision near bed surface is high frequency and loses energy.

It can be seen from figure 6(b) that the probability distribution of snow particles' velocity along the streamwise direction obeys the unimodal distribution. In other words, it distributes mainly at $0 \sim 4\,m/s$ and the amount of snow particles moving in the opposite direction is basically less than 3% of the total snow particles. Meanwhile, the probability distribution basically does not change with the friction wind speed, in agreement with our experiment. It should be noted that the high-speed particles in this simulation are significantly more than those captured in the experiments (figure 6(b)). This is mainly because the mean velocity of snow particles increases with height increasing, our measurement is mainly set at lower positions due to the limitation of instrument and thus part of high-speed particles are not being captured.

A more detailed statistics of the percentages of particles that moving at different velocities are showed in figure 6(c). The field observation of Greeley et al. (1996) showing that the proportions of saltating sand particles with velocity smaller than $1.5m/s$ and greater than $4\,m/s$ are greater than 59% and smaller than 3%, respectively. However, the proportion of snow particles with the velocity smaller than $1.5m/s$ is in general smaller than 48% and the percentage of particles with velocity greater than $4\,m/s$ increase with the increasing friction velocity. It can be found that the drifting snow has more high-speed particles than saltating sand, which is mainly because the density of snow particles are significant smaller than sand and they are more easily suspended and followed.

Finally, figure 7 shows the mean size of snow particles along height in the air at different friction velocities and compared with the experimental result of Gromke et al. (2014). All the data have been normalized to the average diameter of overall snow particles. It is clearly that the mean diameter of snow particles in the saltation layer slightly decreases with the height increasing, which is also consistent with the observation of previous works (Nishimura and Nemoto, 2005). However, it appears that the mean diameter increase with increasing height above the saltation layer. The main reason may be that the small particle trends to carry smaller inject velocity, while the larger particle is just the opposite due to the stronger inertia. The rebound velocity is proportional to the incident velocity and thus larger snow particle will rebound with a bigger initial velocity.

~~3~~ 4 Results and discussions

~~3~~4.1 ~~Analysis of the flow field~~The interaction between turbulent and particle motion

Almost all the flows at atmospheric boundary layer are turbulent. ~~Therefore, the simulation of turbulent boundary layer is the key and basis for accurately simulating the drifting snow. Enough time is supplied for forming a stable turbulent boundary layer before particles taking off. The computational region is relative small and the inflow contains the real turbulent fluctuation.~~The turbulent fluctuations will affect the movement of snow particles and the particle motion will influence the development of turbulent.

Figure ~~3~~ 8 shows the cloud map of velocity along the streamwise direction ($u_* = 0.428\,m/s$) (a) before the snow particles take off (t=~~5s~~10s) and (b) when the drifting snow has been sufficiently developed (t=~~20s~~25s). The slice ~~elicited by arrows~~ displays the velocity cloud map of ~~U~~ U-direction at height $H = 0.001\,m$. Figures ~~3~~8(a-1) and ~~3~~8(a-2) show the contour surface map ($\pm 0.5\,m/s$) of wind velocity along spanwise direction and vertical direction, respectively, at time $t = 10s$, and ~~Figures~~ figures ~~3~~8(b-1) and ~~3~~8(b-2) show the corresponding results at time $t = 25\,s$. At the same time, the typical trajectories of snow particles are represented in figure 9, in which the diameter of (a) and (b) are 100 μm and 300 μm, respectively. The blue dotted line denotes the motion trajectory that is not affected by the turbulence and it is calculated by another drifting snow model (Zhang and Huang, 2008) with the same take-off velocity and wind profile.

It can be seen from figure 9 that turbulence can significantly affect the trajectories of snow particles with diameter smaller than 100 μm, and may drive these snow particles moving up to 5~6 m during one saltation process. By contrast, the trajectories of larger snow particles are less affected by the turbulent fluctuation, showing only slight influence on the saltation height, saltation distance and landing position of snow particles. This is consistent with the sand saltation in the turbulent boundary layer performed by Dupont et al. (2013). On the other hand, we can see from figure 10 that the wind velocity is significantly decreased in the drifting snow region due to the reaction force of the snow particles, while the TKEs are obviously enhanced during snow drifting. This result is attributed to the fact that velocity gradient is obviously changed when the drifting snow formed (Okaze et al., 2012).

~~It can be observed from Figure 3 that homogeneous turbulent fluctuations are distributed in the fully developed boundary layer. When the stable drifting snow is formed, the wind velocity will significantly decrease in the drifting snow region due to the reaction force of the snow particle and the turbulent fluctuations gradually become non-uniform in the drifting snow region. This is mainly due to the presence of the snow streamers resulted great difference in the number concentration of snow particles at different positions (details are shown in Section 3.2).~~

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~~In addition to the turbulent fluctuation, the wind profile can also be obtained by the time averaging and spatial averaging of a time-series of wind velocities ($t = 3 \sim 5\,s$ and the time interval is $0.01\,s$). As shown in Figure 4, the method leads to similar wind profiles to that of wind tunnel experiment at different wind speeds.~~

~~When the turbulent boundary layer is fully developed, the snow particles will be released and the motion feature of snow particles could be further obtained.~~

3.~~2~~ 1 The formation of ~~Snow~~ snow streamers

The saltation process, either in the field or in the wind tunnel, exhibits a temporospatial discontinuity. This discontinuity is affected by many factors such as turbulent fluctuation, topography, surface moisture, roughness elements, etc (Stout and Zobeck, 1997; Durán et al., 2011). ~~Different from~~Most previous models ~~which~~ are unable to clearly describe the drifting snow structure~~,~~. ~~our 3-D model could be used to directly calculate the~~ The ~~3-D~~motion trajectory of every snow particle is calculated and further ~~intuitively demonstrate~~ the overall structure of snow saltation layers could be intuitively demonstrated because it describes the macroscopic performance of a large amount of ~~drifting snow~~saltating particles.

~~Figure 5(a) and 5(b) show the typical trajectories of snow particles with diameter of 100 μm and 300 μm, respectively, in which the blue dotted line denotes the motion trajectory that is not affected by the turbulence. It can be seen that turbulence can significantly affect the trajectories of snow particles with diameter smaller than 100 μm, and may drive snow particles with diameter of 100 μm moving 5~6 m during one~~

~~saltation process. By contrast, the trajectories of larger snow particles are less affected by the turbulent fluctuation, showing only slight influence on the saltation height, saltation distance and landing position of snow particles.~~

~~A large amount of snow particles move complexly in the turbulent boundary layer, constituting the overall structure of the drifting snow. Figure 6 shows the top view of the snow-driving particles concentration and the horizontal cloud map of streamwise wind velocity at corresponding moment, in which, (a) and (b) represent the moment of $t = 8\ s$ and $t = 12\ s$, respectively.~~

It can be observed from Figure ~~6~~ 11 that snow streamers with high saltating particle concentration obviously swing forward along the downwind direction, merging or bifurcating during the movement. It can also be found that the snow streamers with elongated shape differ greatly in length, but only 0.1~0.2 *m* in width. From the corresponding slices of wind velocity cloud map, it can be seen that many low-speed streaks exist in the near-wall region of the turbulent boundary layer. By comparing the concentration and corresponding velocity cloud map, it is hard to decide the relationship between particle concentration and local wind velocity, which is just like the sand streamers reported by Dupont et al. (2013). This may be due to the complex motion of the snow particles and hysteretic change of local wind. However, the shapes of snow streamers are quite different from that of sand streamers. For example, the snow streamers trend to be longer and thinner in the turbulent boundary layer.~~it can be found that the particle concentration shows a direct proportional relationship with the local wind velocity, that is, only few snow particles present in the low-speed streaks.~~

The in-homogeneous take off and splash of the snow particles in the turbulent wind field are the main reasons for the formation of snow streamers. The shape and size of streamers largely depend on the flow structure of the turbulent boundary layer. In addition, during the full development of drifting snow, the saltating particles and wind field are in the state of dynamic balance due to the feedback effect of each other. When the number concentration of snow particles at a certain position is high enough, the local wind velocity will be significantly reduced, resulting in a lower splash level. Thus the streamer will gradually weaken or even disappear. In contrast, the local wind speed in the low concentration region will increase, which enhances the splash process, so the snow particles will grow rapidly and form a streamer. Furthermore, the fluctuating velocity may also change the movement direction of snow particles. All the above reasons together cause the serpentine forward of the snow streamers.

~~3.3 Snow transport rate~~

~~Snow transport rate (STR) is one of the most important indicators of the strength of the drifting snow. In this simulation, the snow particles will be collected if they pass through the section located at $x = 3\,m$ during the time of $t = 10 \sim 20\,s$. Figure 7(a) shows the time evolution of STR per width in different friction wind velocity. It can be seen that the STR per width increases rapidly and reaches a dynamic equilibrium state in a short time. With the friction wind speed increasing, the time needed to reach the equilibrium state also increases. During the transport process, STR per width also slightly fluctuates and its fluctuation amplitude is proportional to the friction wind velocity, mainly owing to the intermittent behavior of drifting snow. At the same time, it can be observed from Figure 7(b) that the STR per width increases with friction wind velocity increasing, in consistence with the existing experiment results.~~

~~The average particle concentrations under different friction wind velocities as a function of height are shown in Figure 8(a). It is clear from the figure that the average particle concentrations at different friction wind velocity similarly fluctuate with height, that is, they decrease with height increasing. And the greater the friction wind velocity, the greater the maximum height the snow particles can achieve. Further analysis shows that the difference of average particle concentrations under different friction wind speed is proportional to height. For example, at the height of 0.001 m, the average particle concentration at friction wind velocity of $u_* = 0.361\,m/s$ is 2.86 times greater than that at friction wind velocity of $u_* = 0.215\,m/s$; while at the height of 0.2 m, the former is 176.32 times greater than the latter. Therefore, it is concluded that the significant increase of snow particles at the higher position is the major contributor to the increase of STR at higher wind speed mainly because the snow particles in the higher speed flow field can acquire more energy from the air and will rebound with a higher velocity.~~

~~Figure 8(b) shows the relationship of STR per unit area to the saltation height. As shown in Figure 8(b), the variations in the STR per unit area with height at different friction wind speeds are equivalent, that is, the STR per unit area decreases with height increasing. However, the STRs per unit area differ greatly at the same height at different friction wind speeds. In the same condition, the STRs per unit area at height~~

~~h=0.01 m under friction wind velocity of $u_* = 0.215\,m/s$, $u_* = 0.252\,m/s$, $u_* = 0.288\,m/s$ and $u_* = 0.361\,m/s$ are 0.028 $kg/m^2/s$, 0.057 $kg/m^2/s$, 0.102 $kg/m^2/s$ and 0.378 $kg/m^2/s$, respectively.~~

~~3.4~~4.3 Velocity of snow particles

As one of the most important aspects to evaluate the accuracy of a drifting snow model, the velocity information (especially in the spanwise direction) of snow particles in the air is worthy of attention although it is seldom given in previous models. ~~The location and velocity of every snow particle can be obtained, and the most important of all, the spanwise velocity of snow particles can be directly obtained in our simulation. The velocity distribution of snow particles in the air and the initial take-off velocity of the ejected particles are given in Section 3.4.1 and Section 3.4.2, respectively.~~

~~3.4.1 Velocity of snow particles in the air~~

~~The velocity distribution of snow particles in the air is shown in Figure 9, in which (a) is the average velocity of snow particles along the streamwise direction as a function of height and (b) displays the corresponding velocity probability distribution of snow particles. It can be observed from Figure 9(a) that the average velocity of snow particles along the streamwise direction increases with the height increasing and with the friction wind velocity at the same height increasing. It can be seen from Figure 9(b) that the probability distribution of snow particles' velocity along the streamwise direction obeys the unimodal distribution. In other words, it distributes mainly at $0 \sim 3\,m/s$ and the amount of snow particles moving in the opposite direction is less than 3% of the total snow particles. Meanwhile, the probability distribution does not change with the friction wind speed, in agreement with our experiment. In this work, at friction wind velocity of $u_* = 0.288\,m/s$, the proportions of snow particles with the velocity smaller than $1.5\,m/s$ and greater than $4\,m/s$ are 65.07% and 1.76%, respectively, consistent with a field observation of Greeley et al. (1996) showing that the proportions of saltating particles with velocity smaller than $1.5\,m/s$ and greater than $4\,m/s$ are greater than 59% and smaller than 3%, respectively.~~

~~It should be noted that the high-speed particles in our simulation are significantly more than those captured in the experiments (Figure 9(b)). This is mainly because the~~

~~concentration of snow particles decreases with height increasing, making it increasingly difficult to be captured the high-speed snow particles.~~

Firstly, the spanwise velocity of snow particles in the air is analyzed. As shown in ~~Figure~~ figure ~~10~~ 11~~shows the spanwise velocity of snow particles in the air~~, ~~where~~ (a) is the distribution of the absolute value of spanwise velocity along the elevation and (b) is the corresponding probability distribution~~ of snow particles' velocity~~. It is observed from figure 12(a) that the mean velocity along spanwise basically increases with the increasing wind speed. This can also be certified from figure 12(b) that the proportion of snow particles in the air with higher spanwise velocity increases with friction velocity increasing. Furthermore, it can be seen that when the friction velocity is small, the absolute value of spanwise velocity ~~increases~~ decreases with increasing height; while the law is just the opposite for large friction velocity. And the spanwise velocity of snow particles is ~~in~~ an order of magnitude less than that of the streamwise in general~~ velocity~~.~~ The variation in the spanwise velocity with height at different friction wind velocity is not obvious.~~ The main reason for this is that turbulent fluctuations are fairly minimal when the wind speed is small, and they exert an increasingly stronger with the growing wind speed.

~~From the above analysis it is quite evident that the velocity distribution of snow particles in the air is not sensitive to the wind velocity. The main reason for that is the wind velocity in the full development drifting snow slightly varies due to the reaction force of snow particles in the air.~~

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~~3.4.2 Take-off velocity of snow particles~~

Then, the ~~The~~ initial take-off ~~velocities~~ speed distributions of snow particles in three directions are acquired due to they are ~~(including rebound particles)~~ widely used in the numerical model. The probability distributions of lift-off velocity in a fully developed drifting snow field are presented in Figure ~~11~~13, in which the (a), (b), (c) and (d) show the distributions of streamwise, spanwise, vertical and resultant velocities, respectively. It is clear that all the velocity components obey the unimodal distribution. The vertical lift-off velocity ~~and are~~is basically not affected by the friction wind velocity while the initial take-off speed along streamwise and spanwise trend to increase with the increasing wind speed. This provides a reference for use the probability distributions of initial take-off speed.

~~Although there is no obvious difference in take-off velocity at different wind velocity, we can see that a large amount of particles may saltate at higher saltation~~

~~height and greater friction wind speed. It may be inferred that turbulent fluctuation plays an important role in the lifting of snow particles.~~

~~3.5 Diameter distribution of snow particles in the air~~

~~The snow particles with mixed size close to natural situation are applied in our simulation. In this section, the size distribution of snow particles in the air is analyzed.~~

~~Figure 12 shows the size distributions of snow particles in the air at different friction velocities, and their comparison with the experimental results. All the data have been normalized to the average of overall snow particles due to different characteristics of snow particles in different experiments. To avoid the random error, those data with snow particle influx less than 10^4 $(m^{-2}s^{-1})$ have been eliminated. It is clearly that the mean diameter of snow particles near ground (with height below 0.05 m) is unchanged with the height increasing, which is consistent with the conclusion obtained by Gromke et al. (2014). However, the mean diameter of snow particles with height above 0.05 m exhibits a growing trend with height increasing, similar to the results observed by Sedmit (1984). This is mainly because larger particles withstand greater drag force in the air during the movement process and have higher impact velocity. Therefore, they will rebound with higher initial velocity because the rebound velocity is proportional to the incident velocity.~~

~~4~~ 5 Conclusions

In this study, the~~we establish a~~ 3-D drifting snow ~~model~~ process with mixed particle size in the turbulent boundary layer is performed~~, simulate the development process of drifting snow with mixed particle size~~ and draws the following main conclusions:

(1) Turbulent fluctuation may significantly affect the trajectory of small snow particles with equivalent diameter $d_p \leq 100\ \mu m$, while has little influence on that of particles with larger size. And the saltating particles can strengthen the turbulent fluctuation.

(2) ~~The drifting snow in a turbulent boundary layer is very intermittent.~~ Fully developed drifting snow swings forward toward the downwind in the form of snow streamers and the wind velocity is proportional to the concentration of snow particles at different locations of the turbulent boundary layer.

(3) The change of spanwise velocities of snow particles along ~~streamwise and spanwise directions increase with the~~ height relay on the friction velocity~~,~~. and the

~~latter~~ spanwise velocity is one order of magnitude less than the ~~former~~ streamwise direction in general. ~~In addition, the velocity distribution is not sensitive to the wind speed.~~

~~(4) The mean diameter of snow particles in the air is obviously distributed in layers. It is constant for snow particles with height less than 0.05 m, but shows a gradual increase trend for snow particles with height above 0.05 m.~~

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Figures:

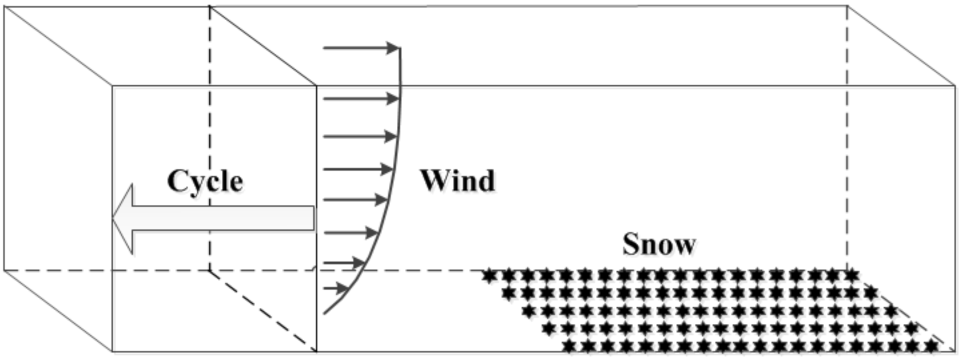


Figure 1. Diagram of computational region.

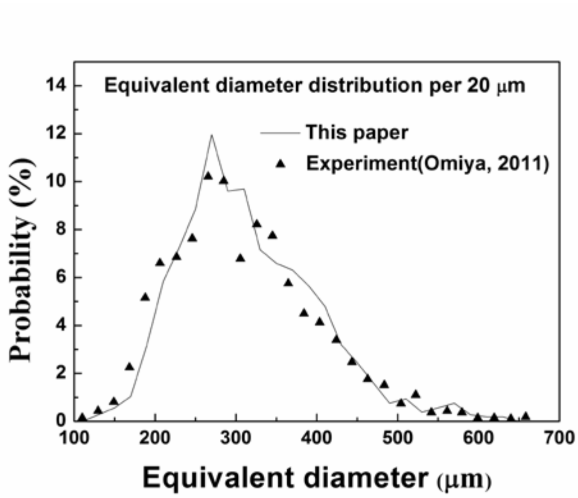


Figure 2. Equivalent diameter probability distribution of snow particles.

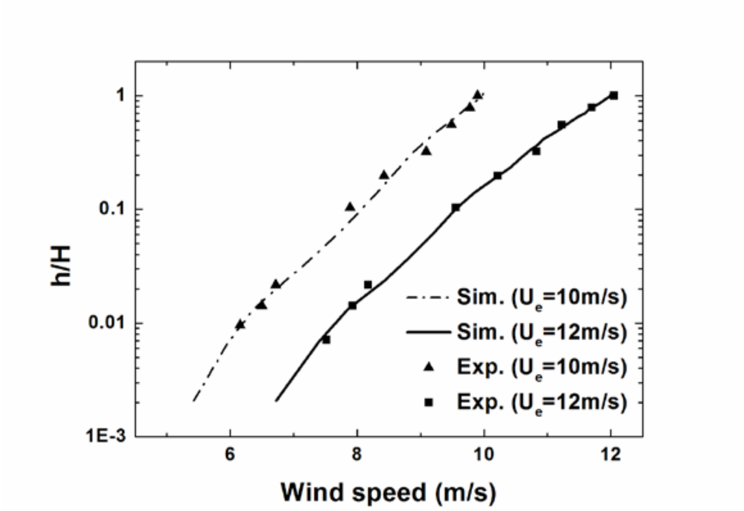


Figure 3. The wind profile at (a) U_e=10m/s and (b) U_e=12m/s.

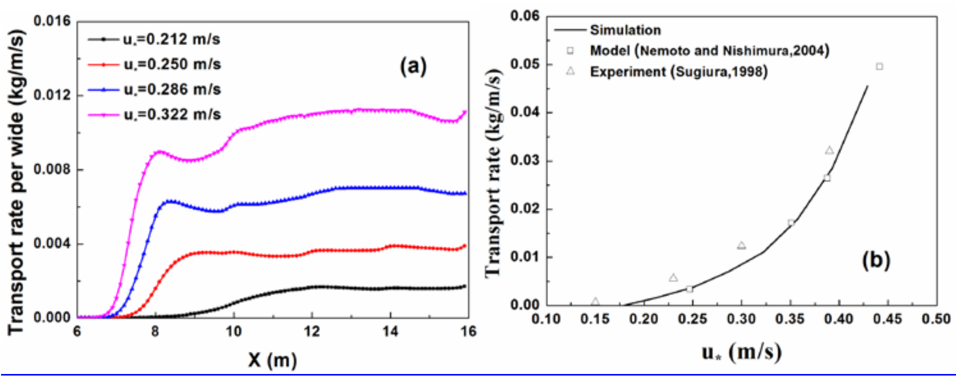


Figure 4. Variation of the snow transport rate (STR) per width with (a) development distance and (b) friction wind velocity.

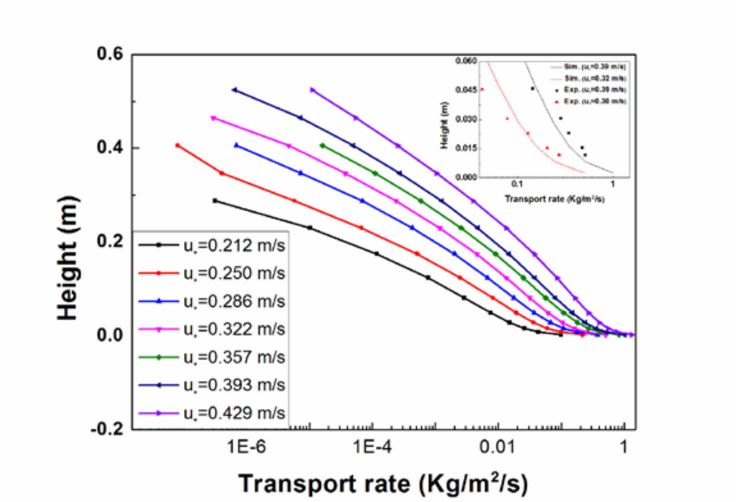
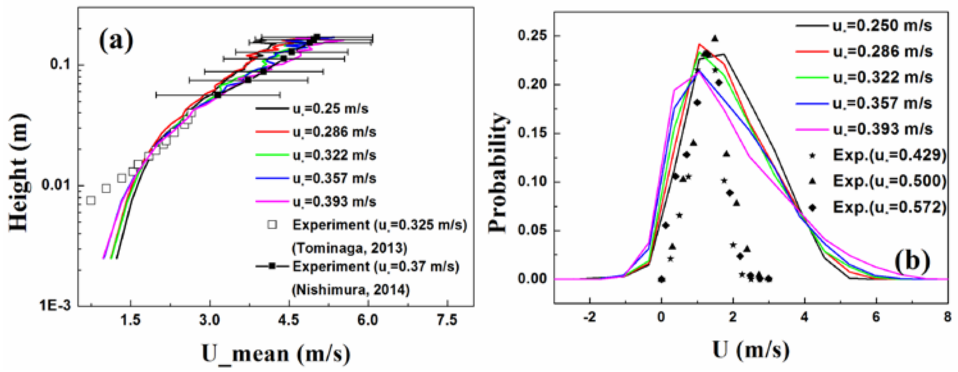


Figure 5. The STR per unit area versus height at different friction wind velocities.



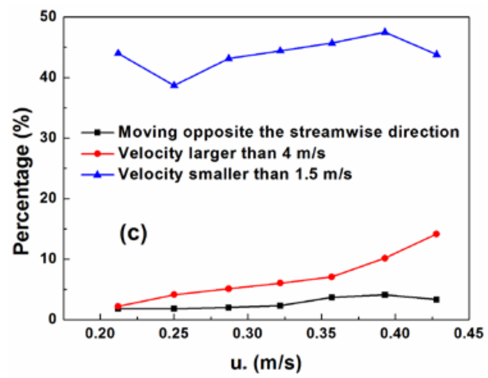


Figure 6. (a)Variation of the average velocity of snow particles along streamwise direction as a function of height, (b) the velocity probability distribution of snow particles and (c) the percentage of particles in different velocity vs friction wind velocities.

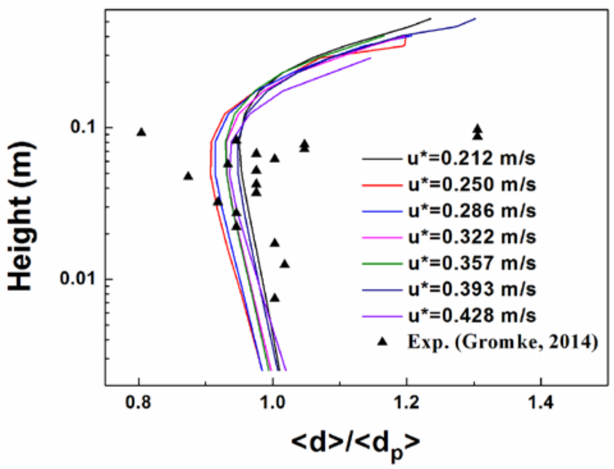
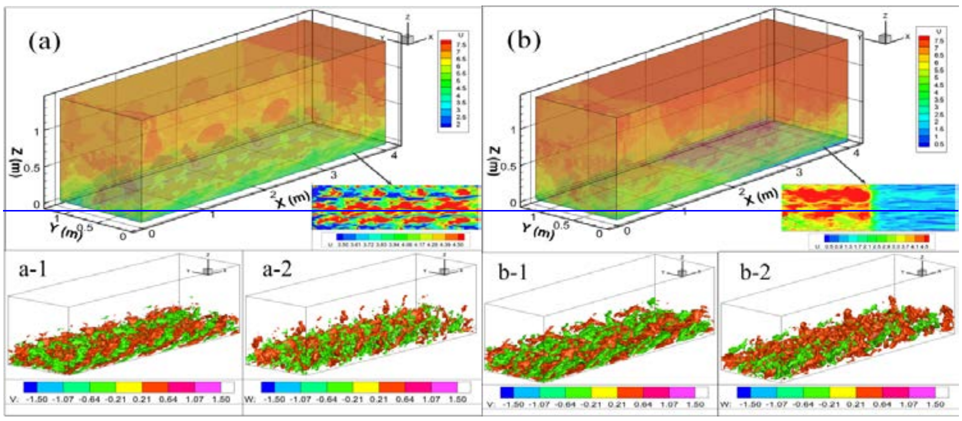


Figure 7. The mean equivalent diameter distribution of snow particles in the air vs height.



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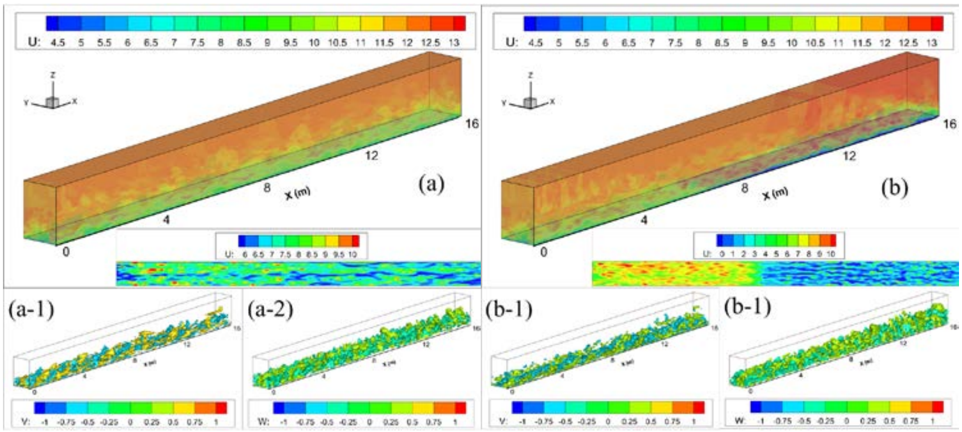
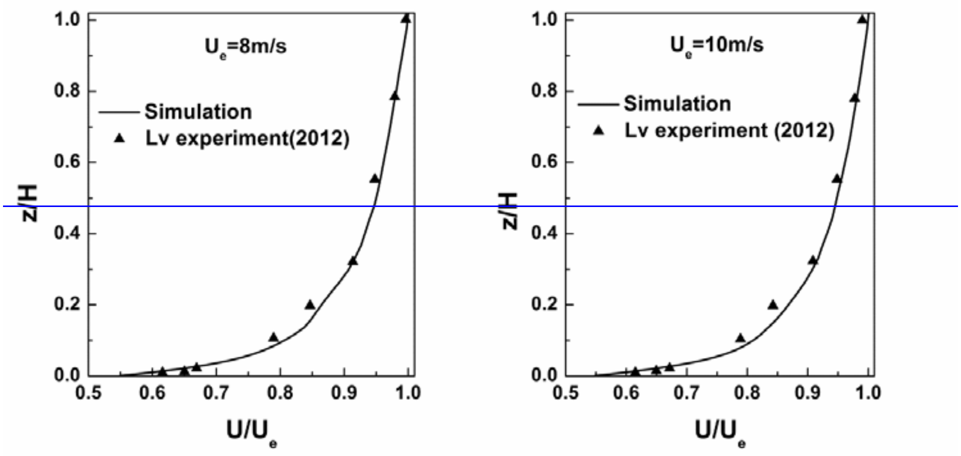


Figure ~~3~~8. The cloud map of flow field at (a) t=~~5s~~ 10s and (b) t=~~20s~~25s.



~~**Figure 4.** The wind profile at (a) U_e=8m/s and (b) U_e=10m/s.~~

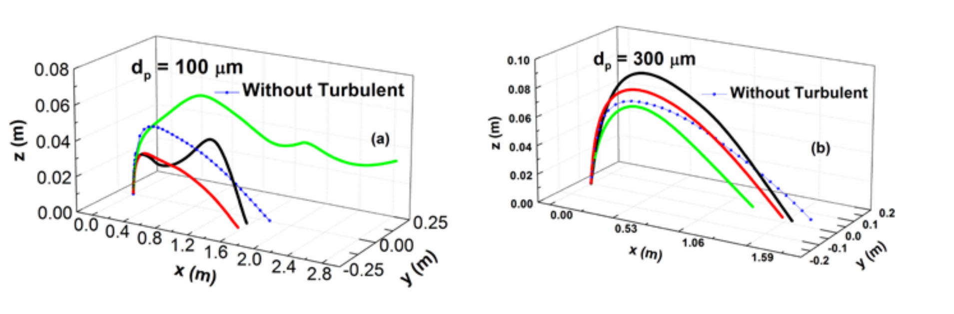


Figure ~~5~~9. The 3-D trajectories schematic diagram of snow particles with different diameters ~~($u_* = 0.35\, m/s$)~~.

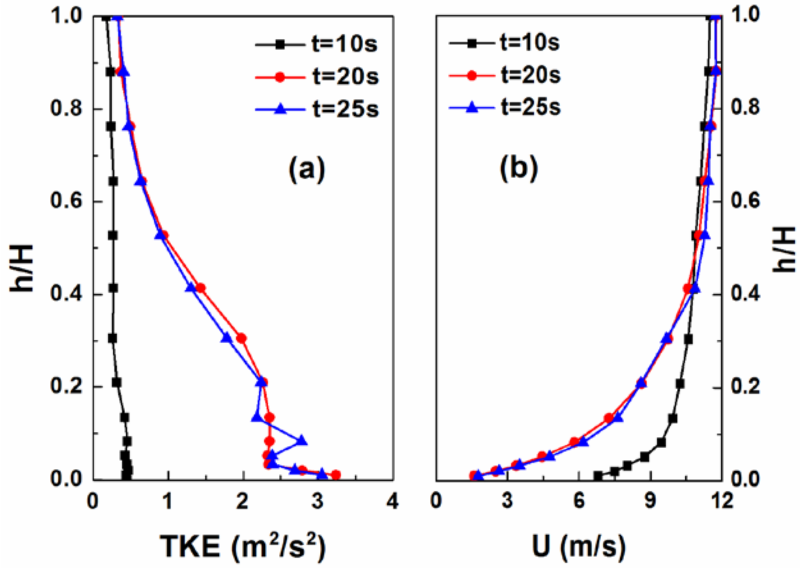
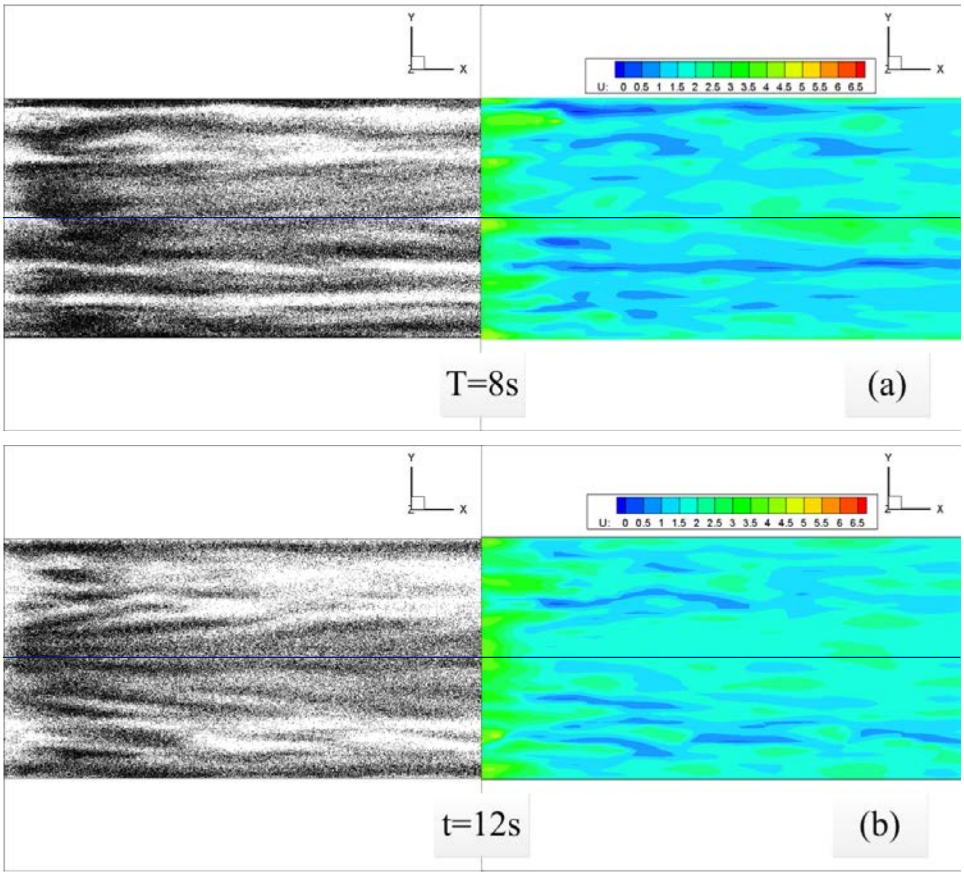


Figure 10. The TKE profile (a) and wind profile (b) at different time, in which the wind data between 13~15m along the downstream is used ($u_* = 0.428\, m/s$).


Y
X
U: 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5
T=8s
(a)
Y
X
U: 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5
t=12s
(b)

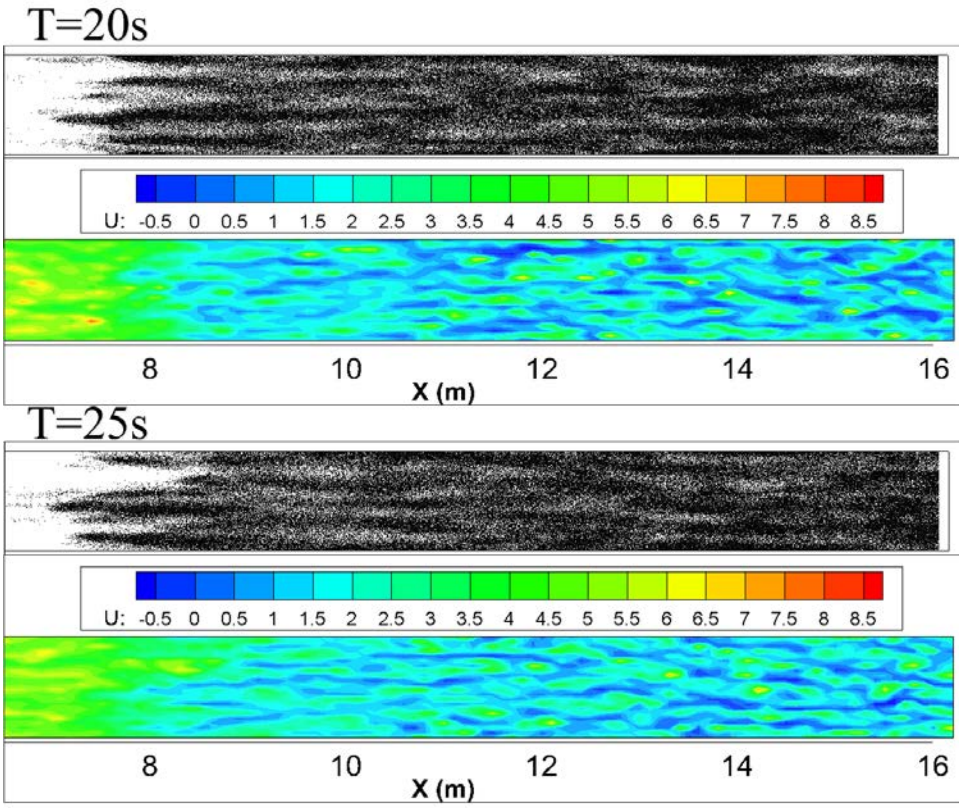
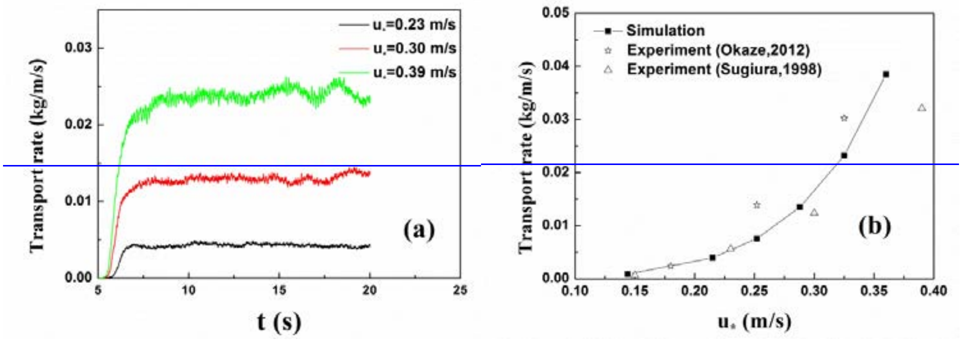
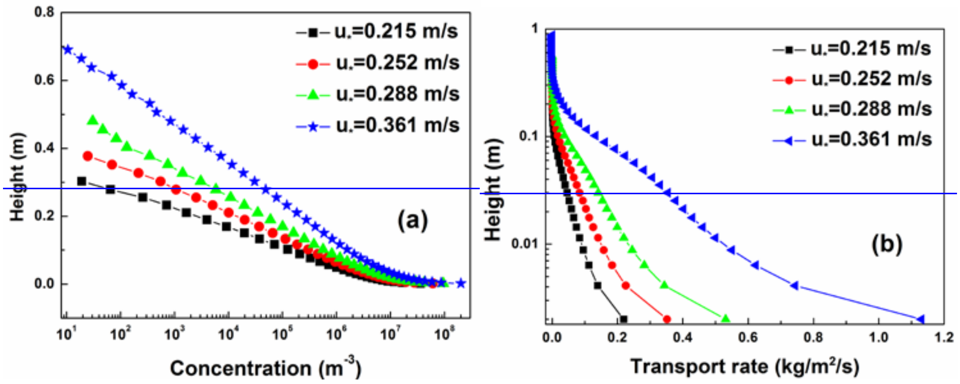


Figure ~~6~~11. The top view of the particle concentration and the horizontal section of wind velocity cloud map at corresponding moment ($u_* = 0.357\, m/s$, one dark spot stands for a snow particle and the height of horizontal section is $H = 0.001\, m$).

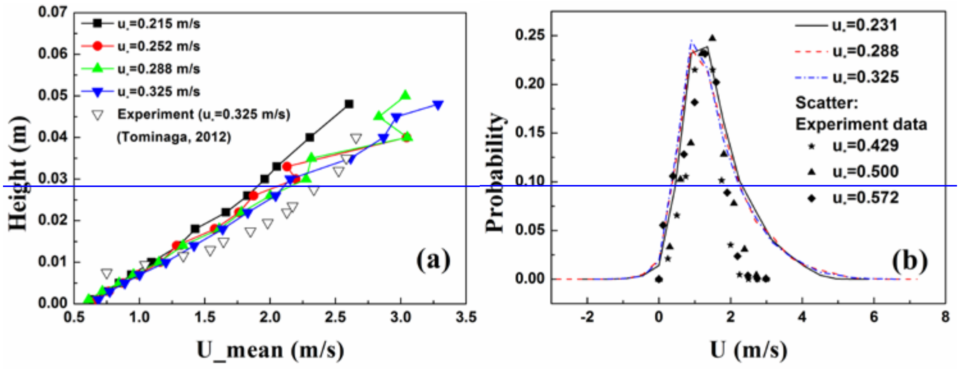


~~**Figure 7.** Variation of the snow transport rate (STR) per width with (a) time and (b) friction wind velocity.~~

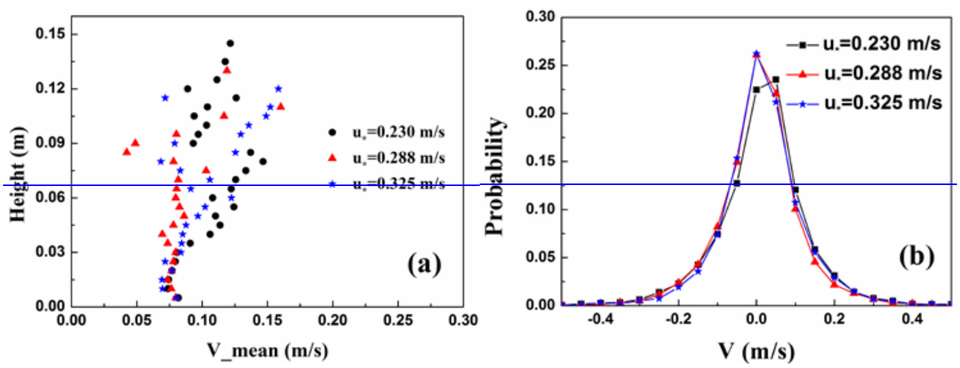


带格式的：两端对齐

~~**Figure 8.** (a) The average particle concentrations and (b) STR per unit area versus the height at different friction wind velocities.~~



~~**Figure 9.** (a)Variation of the average velocity of snow particles along streamwise direction as a function of height and (b) the velocity probability distribution of snow particles.~~



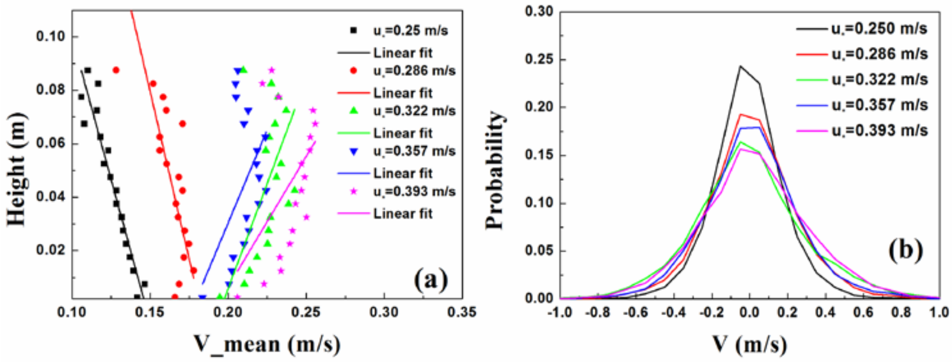
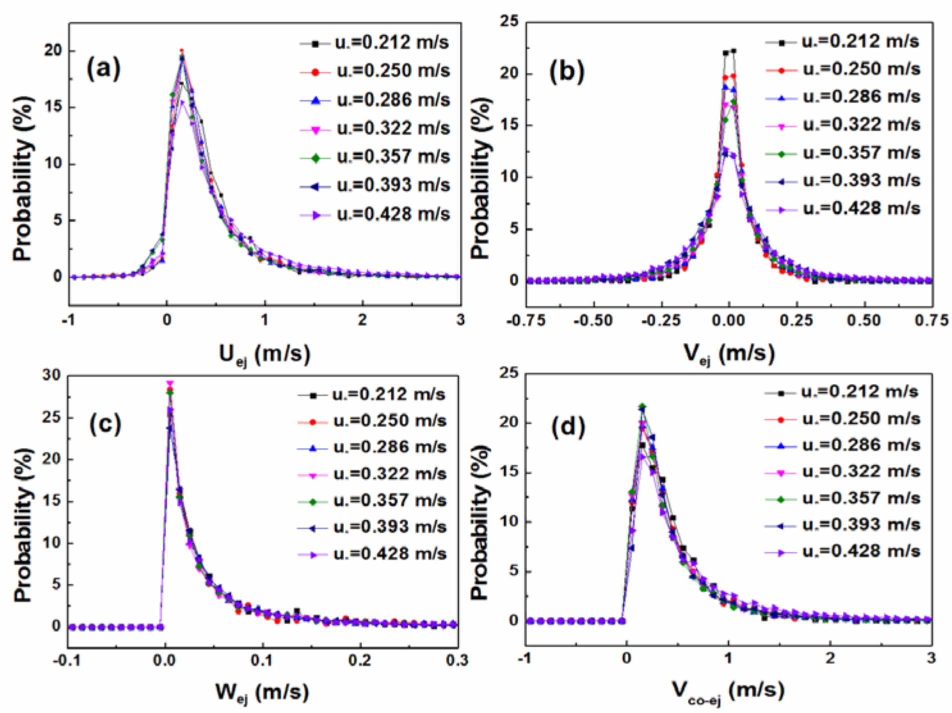


Figure ~~10~~12. Distribution of (a) the absolute value of spanwise velocity along the elevation and (b) the corresponding probability distribution of snow particles in the air.



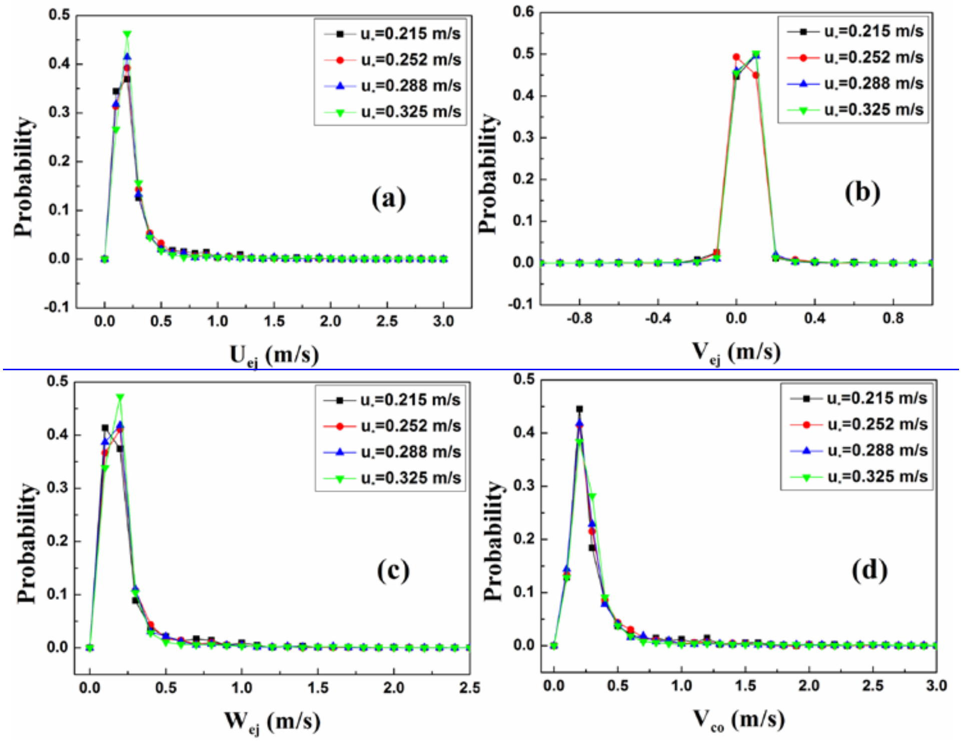
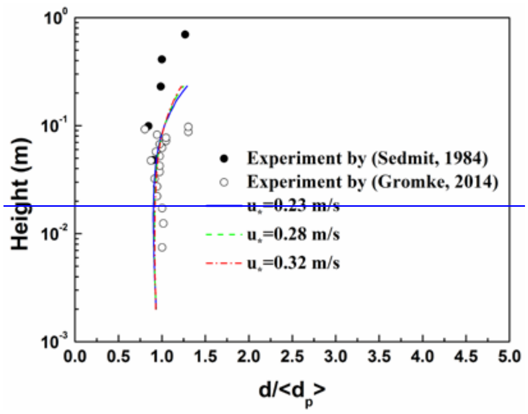


Figure ~~11~~13. Distribution of the initial (a) streamwise, (b) spanwise, (c) vertical directions and (d) resultant take-off velocity of snow particles.



~~**Figure 12.** The mean equivalent diameter distribution of snow particles in the air vs height.~~