# Snow Particle Fragmentation Enhances Snow Sublimation

Ning Huang[1,3], Jiacheng Bao[1,3], Hongxiang Yu[2], and Guang Li[2]

[1]College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, China

[2]College of Atmospheric Sciences, Lanzhou University, Lanzhou, China

[3]The Ministry of Educational Department, Key Laboratory of Mechanics on Disaster and Environment in Western China, Lanzhou, China

**Correspondence:** Hongxiang Yu (yuhx2023@lzu.edu.cn)

**Abstract.** Fragmentation of snow particles, where dendritic snowflakes transform into rounded shapes upon impact with surface and other particles during drifting and blowing snow events, plays a critical role in shaping snow dynamics. However, existing models of drifting and blowing snow often neglect the effects of snow particle fragmentation, introducing uncertainties in the prediction of flow dynamics and sublimation rates. In this study, we incorporate a snow particle fragmentation model into a well-developed wind blowing snow model to quantitatively investigate the influence of fragmentation under varying wind conditions. Our results reveal that fragmentation within the saltation layer generates smaller particles, leading to an increase in mass flux and subsequently enhancing sublimation rates in drifting and blowing snow. Notably, the effects of fragmentation on sublimation are more pronounced for suspension particles than saltation particles, particularly under low wind conditions. This work highlights the critical role of collision-induced fragmentation, wherein dendritic snowflakes are shattered into smaller particles during transportation. This quantitative assessment of fragmentation impact on snow sublimation underscores its importance for improving the physical representation of drifting and blowing snow. These findings have important implications for improving the snow transport models, with potential applications in snow hydrology and climate modeling.

## 1 Introduction

Snow plays an important role in Earth's climate system because of its wide coverage and seasonal variation, leading to variable surface conditions. Sublimation is a significant process for snow surface to exchange heat, mass, and energy with the atmosphere. Snow sublimation includes static surface sublimation and dynamic airbrone particle sublimation. The latter process usually happens in drifting and blowing snow (DBS), in which snow particles follow the air flow, driven by the wind. Water vapor transport created by snow sublimation has a significant influence on the local hydrological cycle and distribution, especially in polar and high alpine regions. For example, in the coastal area of Antarctica, ice sheet mass loss caused by DBS reaches 18.3 % of the whole DBS amount each year (Pomeroy and Jones, 1996). In Antarctica, snow sublimation depleted approximately 17 - 20 % of its annual precipitation (Déry and Yau, 2001). In Mongolia, snow sublimation depleted 20.3 - 21.6 % of annual snowfall (Zhang et al., 2008).

On the Tibetan Plateau, due to its extremely dry, cold, and windy environmental condition, the sublimation amount is very high, up to about 50 % of the amount of snow cover every year (Ueno et al., 2007).

DBS sublimation fluxes (40 - 60 $W/m^2$) are more than twice as high as surface sublimation fluxes (20 - 30 $W/m^2$) (Pomeroy and Essery, 1999). DBS sublimation is obviously stronger than surface snow sublimation for: 1) The turbulence is stronger during DBS events. 2) Aerodynamically entrained particles from the surface enlarge the contact surface with air. 3) The relative humidity decreases during DBS, which promotes a faster sublimation process. Therefore, investigating the role of sublimation in DBS is the forehead to accurately assess the water equivalent and understand the interaction between land surface and atmosphere in cold areas, especially for polar regions.

In DBS, mass, momentum, and energy are transferred between the surface and atmosphere accompanied by snow particle movement. Snowfall is the initial source of snow particles on the ground. Once the snow particles deposit on the surface, they either start rolling on the ground, saltating near the surface entrained by the wind force, or suspending in high air when wind speed exceeds the threshold value. During particle saltating, they jump on the ground surface and may bring up more particles to start to move, which is called splash. The above processes have been well described in the current numerical models of DBS (Pomeroy and Male, 1992; Taylor, 1998; Lehning et al., 2008; Vionnet et al., 2014; Sigmund et al., 2021; Yu et al., 2022; Melo et al., 2022). Early saltation models are usually empirical mass transport equations, which are functions related to surface shear stress (Pomeroy et al., 1993; Déry and Yau, 2001). These models are susceptible to the empirical parameters. JDoorschot et al. (2004) developed a numerical model for steady-state saltation by considering the aerodynamic entrainment and rebound processes, which shows a more physical picture. Nemoto and Nishimura (2004) developed a new numerical model for saltation and suspension that considers aerodynamic entrainment, grain-bed collision, and wind modification processes with a distribution of grain sizes. Based on their model, a few improved works by Zhang and Huang (2008), Wang and Huang (2017), Yu et al. (2022), Hames et al. (2022), and Melo et al. (2022) are carried out. However, the role of sublimation in drifting snow has not been demonstrated in these models.

For a single snow particle sublimation process, the sublimation rate is well described in the model proposed by Thorpe and Mason (1966), in which the sublimation rate is related to the particle size and environmental conditions. This T-M model has been implemented in the current snow model to estimate the sublimation in DBS, to assess the amount of sublimation amount caused by DBS on a small scale (meters) (Groot Zwaaftink et al., 2011; Huang and Shi, 2017; Dai and Huang, 2014; Vionnet et al., 2014; Sharma et al., 2018) and middle scale (kilometers) (Sharma et al., 2023; Gadde and Berg, 2024). The numerical simulation results from the above models all show that snow sublimation is an important snow physical process that cannot be ignored in DBS. In these small-scaled snow models, they track each single snow particle's trajectory, by considering particle diameter is unchanged. Also, the parameterization of sublimation in those middle-scaled snow models is from these small-scaled snow models, based on the same assumption.

In fact, snow particles, one of the most easily deformable and fragile granular systems, inevitably undergo fragmentation - a process that occurs during saltating, where particle-particle and particle-surface collision cause snowflakes to break apart and deform into smaller particles. This fragmentation not only alters their dynamic behavior by changing particle size (Sato et al., 2008; Walter et al., 2024) but also significantly impacts the sublimation rate, as the sublimation of snow particles is closely linked to their size, shape, and specific surface area (Domine et al., 2009). For a moving particle in the air, the reduction in size of a moving particle in the air is a joint effect of breakage and sublimation. In turn, the dynamically varying size of snow particles will affect their moving rules such as changing their trajectories, which further influences the mass flux and sublimation rate. However, this mutual physical feedback caused by fragmentation in DBS has never been reported, and the relevant model is still lacking.

To date, there is only one model (Comola et al., 2017) considering the fragmentation of snow particles during drifting snow. That study, using a statistical mechanics model, calculates the fragmented number of particles from the perspective of energy and mass balance and analyzes the effect of fragmentation on the particle size distribution. However, it did not explore the impact of fragmentation on drifting snow flux or the subsequent sublimation of snow particles.

In this work, we introduce the snow fragmentation model into the drifting snow model, enabling a more realistic representation of the movement and dynamic size changes of individual particles in the air. This advancement allows for a more accurate prediction of snow particle sublimation rates, offering critical insights into the micro-scale processes that govern snow-atmosphere interactions.

## 2 Model description

The model by Huang and Shi (2017) is a simulation framework for DBS, which is able to simultaneously describe the behavior of both saltation and suspension particles. In our model, the saltation particles are described using an Euler-Lagrangian tracking method, which captures the saltating motion of particles. For suspension particles, which are typically smaller in size, we employ a dispersion function to characterize their movement dynamics. A threshold grain size was used to separate the saltating and suspended particles. The Thorpe and Mason model (Thorpe and Mason, 1966) is used to calculate the sublimation of DBS. The feedback of particle motion and particle sublimation to the wind field, air temperature, and air humidity are also considered.

Comola's model, as the only one drifting model that consider snow particle fragmentation, is a one-dimensional, non-CFD (computational fluid dynamics) statistical approach. While it incorporates particle fragmentation, it does not couple the particles with the wind field. As a result, the effects of fragmentation on the wind field cannot be evaluated in their framework.

Building on the previous model developed by Huang and Shi (2017), we incorporated the fragmentation model proposed by Comola et al. (2017) and set up a comprehensive DBS model. This new model addresses the limitations of Comola's model and provides a more comprehensive description of the interactions between particle fragmentation and the wind field. The particle fragmentation is now newly taken into consideration in the saltation splash process.

Here, we reintroduce them briefly.

### 2.1 Air flow

Considering the steady state of saltation, the horizontal wind field satisfies the following equations (Nemoto and Nishimura, 2004):

$$\frac{\partial}{\partial z}(\rho_f \kappa^2 z^2 |\frac{du}{dz}|\frac{du}{dz}) + f_p = 0 \tag{1}$$

where $z$ is height above the surface, $\rho_f$ is the air density, $\kappa$ is the von Karman constant, $u$ is the wind speed, and $f_p$ is the feedback force of the airborne snow particles.

The air temperature and humidity equations are Eq. (2) and (3), respectively, satisfying the horizontal uniformity condition are formulated according to (Bintanja, 2000):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(K_\theta \frac{\partial \theta}{\partial z}) + S_\theta \tag{2}$$

where $\theta$ is the air potential temperature, $K_\theta = \kappa u_* z + K_T$ is the turbulent heat exchange coefficient, $K_T$ is the molecular diffusion coefficients of heat, and $S_\theta$ is the sublimation heat feedback of the airborne snow particles $u_*$ is the friction velocity.

$$\frac{\partial q_v}{\partial t} = \frac{\partial}{\partial z}(K_q \frac{\partial q_v}{dz}) + S_q \tag{3}$$

where $q_v$ is the water vapor mixing ratio, $K_q = \kappa u_* z + K_v$ is the water vapor turbulent exchange coefficient, $K_v$ is the molecular diffusion coefficient of water vapor, $S_q$ is the sublimation humidity feedback of the airborne snow particles.

### 2.2 Snow saltation

The motion of saltating snow particles can be described as five sub-processes, which are aerodynamic entrainment, particle trajectory, splash function, sublimation, and feedback to air.

(1)Aerodynamic entrainment

The snow particles start to move when the wind speed reaches a critical value (namely fluid threshold, usually presented by friction velocity) for a given snow surface; this is called aerodynamic entrainment. The rate of aerodynamic entrainment is known as a linear function of the surface shear stress $\tau$ (Anderson and Haff, 1991):

$$N_a = A(\tau - \tau_t) \tag{4}$$

where $N_a$ is the number of aerodynamic entrainment particles per unit area per unit time, $A[N^{-1}s^{-1}]$ is an empirical coefficient, and $\tau_t$ is threshold surface shear stress. The particle size distribution $f(d)$ follows a Gamma Distribution:

$$f(d) = \frac{d^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} e^{-d/\beta} \tag{5}$$

where $\alpha$ and $\beta$ are shape and inverse scale parameters, $d$ is particle diameter.

There are two ways to describe the motion pattern of snow particles. The most used way is to define a threshold height to divide the saltation and suspension layers, which is easy to apply. However, the threshold value is empirical and varies significantly in the existing literature. The other way is determined by the particle size, which is based on the traceability. The lifting velocity of aerodynamic entrainment particles is set to $\sqrt{2gd}$ (Dai and Huang, 2014), where $g$ is gravitational acceleration, which is not sensitive to the steady state of saltation.

(2) Particle's trajectory

After the snow particles are lifted into the air, their ballistic trajectories can be described by Newton's second law:

$$m\frac{d\boldsymbol{r}}{dt} = \boldsymbol{f_d} - m\boldsymbol{g} \tag{6}$$

where $m$ is the mass of the snow particle, $\boldsymbol{r}(x,z)$ is the location of the particle, $\boldsymbol{f_d}$ is the drag force by fluid, $\boldsymbol{g}$ is the gravitational acceleration.

(3) Splash function

In this model, we use probability functions to describe the movement after particles impacting the surface (Sugiura and Maeno, 2000). The restitution coefficient in the vertical direction $S_v(e_v)$, the restitution coefficient in the horizontal direction $S_h(e_h)$ and the number of particles ejected from the surface $n_e$ are defined as follows:

$$S_v(e_v) = \frac{e_v^{a-1}}{b^a\Gamma(a)} e^{-\frac{e_v}{b}} \tag{7}$$

$$S_h(e_h) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(e_h-\mu)^2}{2\sigma^2}} \tag{8}$$

$$n_e = C_m^{n_e} p^{n_e} (1-p)^{m-n_e} \tag{9}$$

where $v_{ix}$ is the horizontal component velocity of the impacting grain, $v_{iy}$ is the vertical component velocity of the impacting grain, $v_{ex}$ is the horizontal component velocity of the ejected grain, and $v_{ey}$ is the vertical component velocity of the ejected grain. $e_v = v_{ey}/v_{iy}$ is the vertical recovery coefficient, $e_h = v_{ex}/v_{ix}$ is the horizontal recovery coefficient, $n_e$ is the number of ejected snow grains. $S_v(e_v)$ is the probability distribution function of $e_v$, $S_h(e_h)$ is the probability distribution function of $e_h$, and $S_e(n_e)$ is the probability distribution function of $n_e$. $\Gamma(a)$ is the gamma function, $C_m^{n_e} = m!/[n_e!(m-n_e)!]$ is the combination number.

Particle fragmentation was not considered in Sugiura and Maeno's splash function. We added it when a particle-bed collision happens. The probability for particles breaking after impact is calculated according to Comola et al. (2017):

$$p(f) = 1 - \frac{1}{\sqrt{1+\frac{\sigma^2}{w_s}}} \tag{10}$$

where $\sigma^2 = 2.5u_*^2$ is the turbulence velocity variance which refers to the fluctuations in velocity caused by turbulent eddies (Stull, 1988). $w_s$ is the settling velocity of snow particles. When a snow particle falls back to the ground (initial velocity $v_i > 0.5$ m/s), Equation 10 is used to determine whether it breaks, and then the number of snow particles $N$ is calculated by Eq. (11), and $\lambda$ is the ratio of particle size before and after fragmentation, again following Comola et al. (2017), by Eq. (12):

$$\begin{cases} N = 15v_i - 2.5, & 0.5 < v_i < 1.5 \\ N = \frac{5}{7}(6v_i + 19), & v_i > 1.5 \end{cases} \tag{11}$$

$$\begin{cases} \lambda = -0.4v_i + 0.7, & 0.5 < v_i < 1.0 \\ \lambda = -0.1v_i + 0.4, & 1.0 < v_i < 1.5 \\ \lambda = 0.25, & v_i > 1.5 \end{cases} \tag{12}$$

The velocity and the direction angle of the newly produced snow particles is kept same as that of the original snow particles.

(4) Sublimation

The drifting snow sublimation is calculated using the Thorpe and Mason model (Thorpe and Mason, 1966):

$$\frac{dm}{dt} = \frac{\pi d(RH-1) - \frac{Q_r}{KNuT}(\frac{L_s}{R_vT} - 1)}{\frac{L_s}{KNuT}(\frac{L_s}{R_vT} - 1) + \frac{R_vT}{ShDe_s}} \tag{13}$$

where $m$ is the particle mass, $d$ is the particle diameter, $T$ is the air temperature, RH is the air relative humidity, $Q_r$ is the solar radiation which snow particles absorb, $K$ is the heat conductivity, $R_v$ is the gas constant of water vapor (461.5 J/kg//K), $D$ is the molecular diffusivity of water vapor, $e_s$ is the saturated vapor pressure relative to the ice surface, $Nu$ is the Nussel number and $Sh$ is the Sherwoods number.

(5) Feedback to air

The airborne particles have a significant effect on airflow. To consider this effect, we equivalent body force one grid is calculated as:

$$\boldsymbol{f_p} = -\frac{1}{V}\sum_{i=1}^{N}\boldsymbol{f_{di}} \tag{14}$$

$V$ is the volume of the grid, $N$ is the total number of the airborne particles in the grid, $\boldsymbol{f_{di}}$ is the drag force of the $i_{th}$ particle in the grid.

The volume sublimation rate in each control volume mesh can be calculated as:

$$S = -\frac{1}{V}\sum_{i=1}^{N}\frac{dm_i}{dt} \tag{15}$$

where $m_i$ is the mass of the $i_{th}$ particle in the grid.

Then, the sublimation feedback to air temperature and humidity are:

$$S_\theta = -\frac{L_s S}{\rho_f C} \tag{16}$$

$$S_q = \frac{S}{\rho_f} \tag{17}$$

where $L_s = 2.84 \times 10^6$ J/kg is the latent heat of sublimation, $S$ is the volume DBS sublimation rate, and $C = 1006$ J/kg//K is the specific heat of air.

### 2.3 Snow suspension

In the simulation, we define a diameter threshold for distinguishing suspension and saltation particles (Huang and Shi, 2017), the threshold diameter is calcualted based on the Rouse number:

$$R_N = \frac{w_s}{\kappa u_*} \tag{18}$$

Therefore, the conditions for determining the saltation and suspension snow particles are (Scott, 1995) :

$$\begin{cases} R_N > 1, saltation \\ R_N \leq 1, suspension \end{cases}$$

The suspended snow follow the vertical diffusion equation (Déry and Yau, 2002):

$$\frac{\partial q_s}{\partial t} = \frac{\partial}{\partial z}(K_s\frac{\partial q_s}{dz} + w_s q_s) + S \tag{19}$$

where $q_s$ is the suspended snow particle mixing ratio, $K_s = \delta\kappa u_* z$ is the diffusion coefficient of suspended particles, $w_s$ is the terminal velocity. The $\delta$ follows (Csanady, 1963):

$$\delta = \frac{1}{\sqrt{1 + \frac{\beta^2 f^2}{w'^2}}} \tag{20}$$

where $\beta = 1$ is the proportionality constant, $w'$ is the vertical turbulent fluid velocity, and we set $\overline{w'^2} = u_*^2$. A flowchart of the model is shown as Fig. 1 to illustract the new splash function.

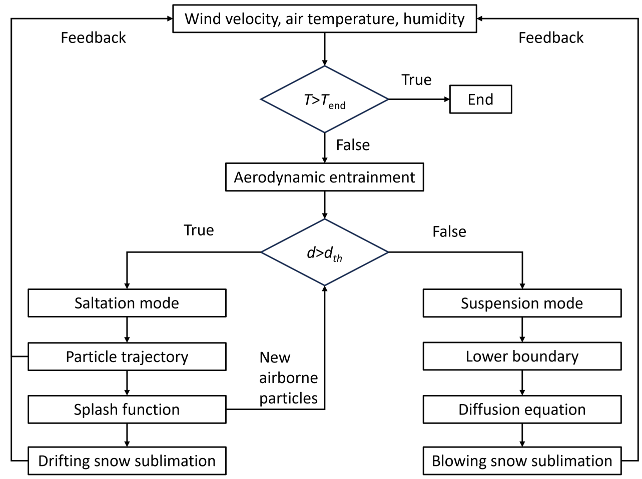


**Figure 1.** Flowchart of the drifting and blowing snow model.

### 2.4 Model verification

To verify the model, we compared simulated particle size distribution, sublimation rate, and mass concentration to observational data. We first compare the particle size distribution at all heights with field observation data of Gordon and Taylor (2009) and Nishimura and Nemoto (2005), shown in Fig. 2. The simulated results are in consistent with size distribution range and variation trend, compared to field observation. Overall, the size distribution variation with height deviates more significantly in the near-surface (0.02 m to 0.1 m), compared to that in higher space (0.12 m to 1.13 m). The proportion of smaller-sized particles increases when considering the fragmentation (blue columns in Fig. 2), which is closer to the observation results (white columns in Fig. 2). For particles in height between 0.12 m to 1.13 m, particle size is in a narrow range of 0-90 $\mu$m. In contrast, within the saltation layer (up to 0.1 m in height), particle sizes display a broader distribution, ranging from 50-450 $\mu$m, and the simulated average particle size decreases with increasing height. However, this trend is not evident in the field, which might be due to the complexities of the field environment compared to ideal simulation, as well as limitations in the accuracy of measurement sensors.

Fig. 3 shows the comparison of the total sublimation rate between the numerical simulation and the field observation data (Schmidt, 1982). Comparing theses two curves, we see that the sublimation rate is the same order of magnitude, which shows that the model is suitable for calculating the sublimation rate of blowing snow. The mass concentration from the simulation and from field observations for the same friction velocity and temperature is shown in Fig. 4 (measured by Pomeroy and Male (1992) near Saskatoon).

The suspension sublimation rate from this paper and from other sublimation models under the same conditions are compared (Fig. 5). The black line is the sublimation rate of suspension in the case of fragmentation of snow particles, and the other five curves are the simulation results of suspension sublimation of jump without breaking

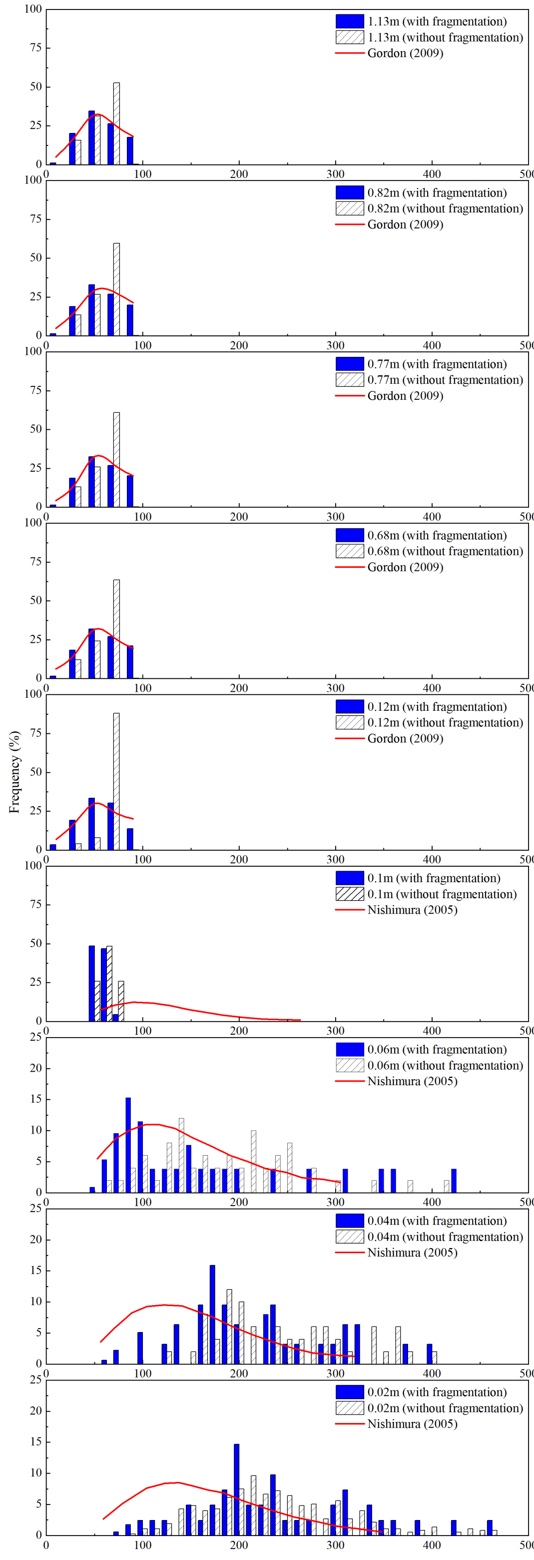


**Figure 2.** Particle size distribution at all heights.

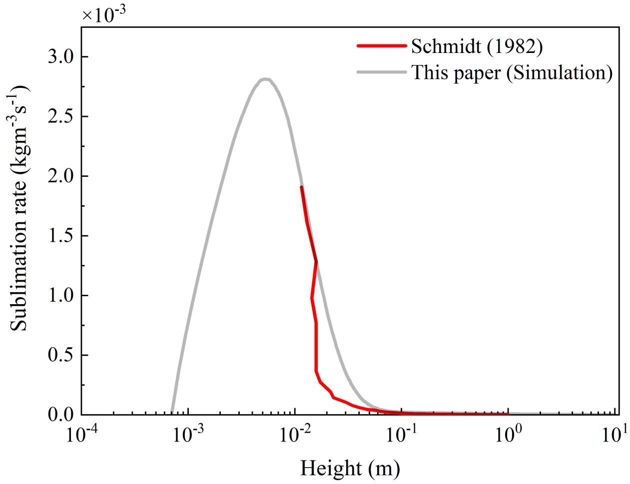


**Figure 3.** Comparison of total sublimation rate for this paper and field observations. (Schmidt, 1982) ($u_* = 0.63$ m/s, $z_0 = 7 \times 10^{-4}$ m, $T = 267.45$ K)

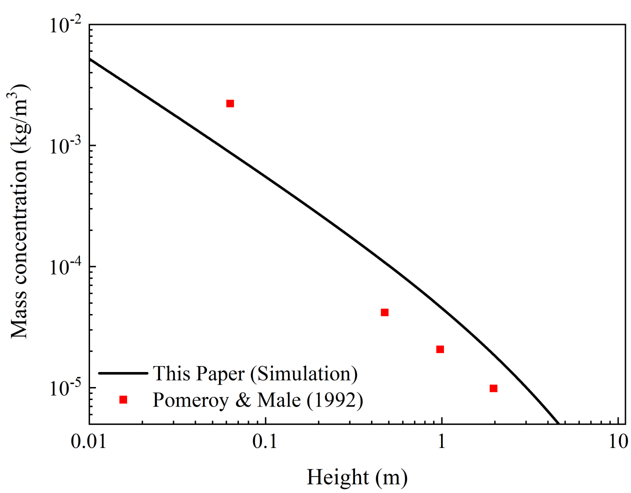


**Figure 4.** Comparison of mass concentration for this paper and field observations. (Pomeroy and Male, 1992) ($u_* = 0.31$ m/s, $T = 265$ K)

of snow particles (Xiao et al., 2000; Huang and Shi, 2017). The results demonstrate that drifting snow sublimation is important, particularly in the near-surface saltation layer. However, most previous models underestimate the sublimation rate near the surface, which significantly impacts the assessment of the drifting snow sublimation. Accounting for fragmentation increases the sublimation rate by approximately 1.3 times, which suggests that it is necessary to conclude snow particle fragmentation in DBS models.

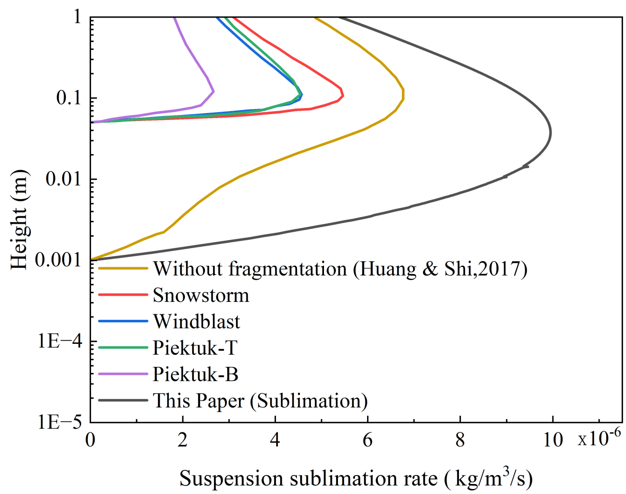


**Figure 5.** Comparison of suspension sublimation rates with other blowing snow models. (Xiao et al., 2000; Huang and Shi, 2017) ($u_* = 0.87$ m/s, $z_0 = 0.001$ m, $T_0 = 253.16$ K)

## 3 Results

### 3.1 Fragmentation effects on particle size distribution

The fragmentation of snow particles first leads to changes in their size distribution, releasing numerous smaller particles. Simulations were conducted to analyze the effect of fragmentation on particle size distribution.

Simulations are conducted with a same friction velocity $u_* = 0.45$ m/s, and a same initial mean particle size $\bar{d} = 200$ $\mu$m. As shown in Fig. 6, the size distribution pattern for particles, without considering fragmentation, follows the log-normal distribution function (blue bar). When considering fragmentation, the proportion of smaller-sized particles ($< 100$ $\mu$m) increases, while the overall proportion of larger-sized particles decreases. This results in a decrease in the average particle size.

### 3.2 Fragmentation effects on snow particle number

Fig. 7 presents the temporal evolution of the concentration of snow particles suspended in the air. It is observed that the number of saltation particles increases over time until reaching a steady state, regardless of the presence of fragmentation. It is noted that when fragmentation processes are taken into consideration, the steady-state concentration of snow particles is consistently higher at all wind speeds. Under low wind speed ($u_* = 0.3$ m/s), the particle number increases by 42 %. Under high wind speed ($u_* = 0.5$ m/s), the particle number increases by 26 %. This suggests that the fragmentation contributes to the total number of snow particles in the air. Furthermore, Fig. 7 also reveals that the increase of particle number resulting from fragmentation is notably more pronounced at lower wind speeds. However, the increase rate of the particle number is lower than that of the high wind speed.

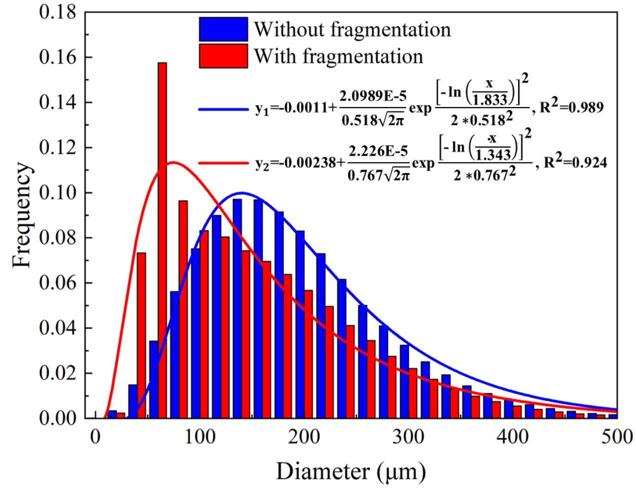


**Figure 6.** Size distribution with and without considering the particle fragmentation.

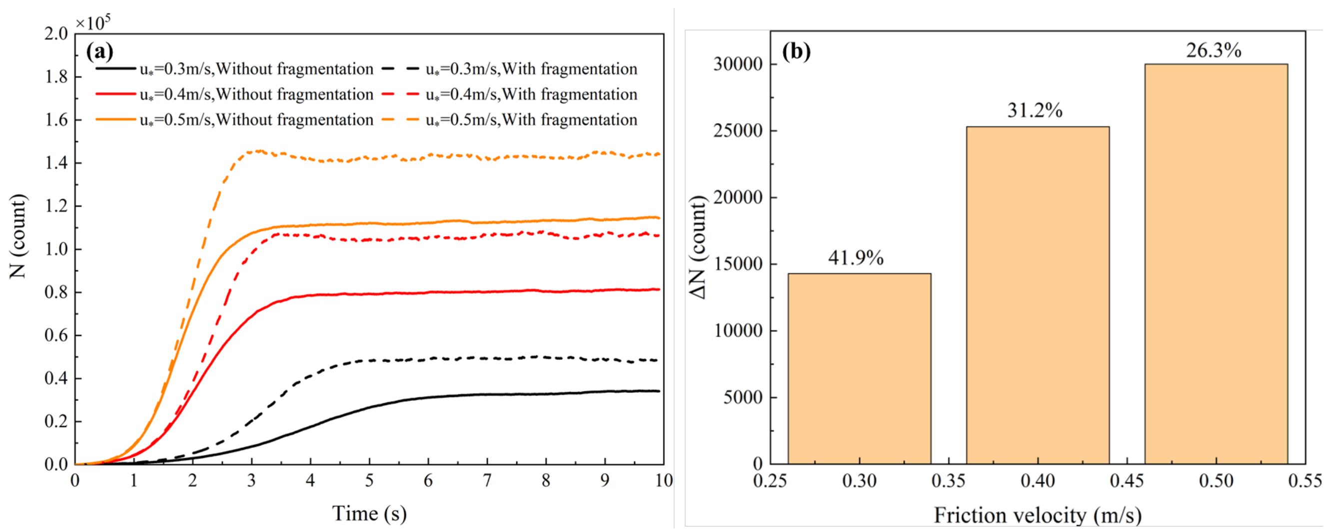


**Figure 7.** (a) Saltating particle number variation with time under wind conditions of $u_* = 0.3$, 0.4 and 0.5 m/s. (b) Increment number and ratios of saltation snow particles in the air.

This indicates that at higher wind speeds, the degree of fragmentation becomes more intense due to the transfer of kinetic energy to the internal energy of the particles. Therefore, during the processes of particle-bed surface and particle-particle collisions, the release rate of particles from snow particle fragmentation is higher under stronger wind conditions.

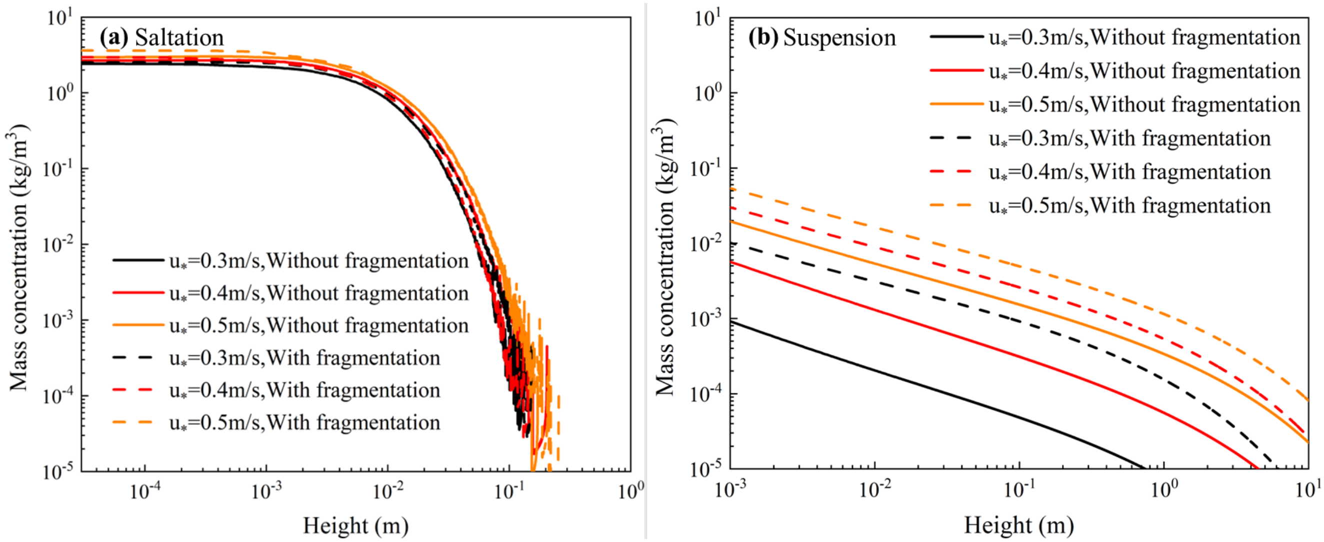


**Figure 8.** Mass concentration of (a) saltating and (b) suspension particles with/without considering fragmentation, under wind conditions of $u_* = 0.3$, 0.4 and 0.5 m/s.

### 3.3 Fragmentation effects on mass concentration and mass flux

For near-surface saltation particles, Fig. 8 illustrates that the variation in the mass concentration of saltating and suspended particles with height. The fragmentation of snow particles enhances the concentration of both saltating and suspended particles, at levels close to the surface. Fig. 8(a) depicts the mass flux versus height above the surface, showing that fragmentation enhances the transport of saltating particles near the ground. This is because the fragmentation of snow particles increases the number of air-borne saltation particles, more saltation particles take part in the splash process, further increasing the air saltation particle number. When the friction velocity varies from 0.3 m/s to 0.5 m/s, the increment proportion of fragmentation mass concentration increases from 19 % to 3 %, which means the fragmentation only has strong effects on the mass concentration under weak wind conditions.

For particles suspended further aloft, it is shown in Fig. 8(b) that the mass concentration of the suspended snow particles at the same height is higher and the overall suspension height is higher, when considering snow particle fragmentation. This is because of smaller and lighter particles created by snow fragmentation, which have higher possibility to be entrained and suspended to higher levels.

Under the same friction velocity, the mass flux of near-surface ($< 0.01$ m) snow particles is larger with snow fragmentation than without, as shown in Fig. 9. It is concluded that fragmentation increases snow particles transport.

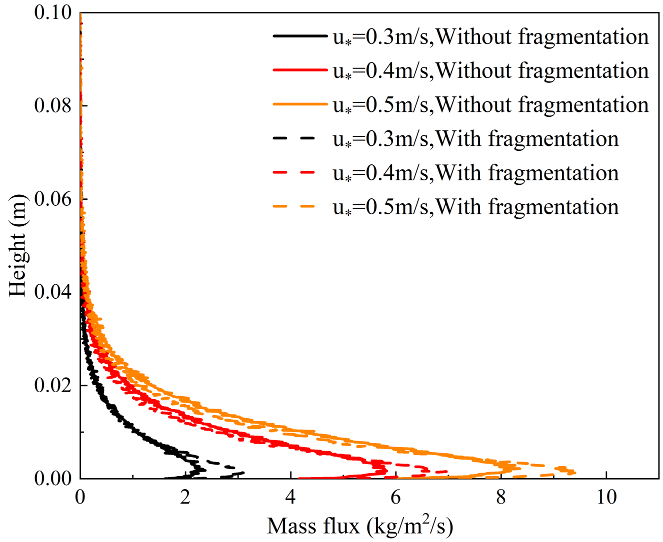


**Figure 9.** Vertical mass flux distribution of snow particles with/without considering fragmentation, under wind conditions of $u_* = 0.3$, 0.4, and 0.5 m/s.

## 3.4 Fragmentation effects on sublimation rate

The sublimation rates of saltating and suspended snow particles increase with fragmentation implemented in the model, as shown in Fig. 10. This enhancement is more significant at lower friction velocity, indicating that snow particle fragmentation has a more profound effect on sublimation under such conditions.

When the wind speed is 0.3 m/s, the average sublimation rate of saltation particles increases by 20 % due to fragmentation, from $1.56\times10^{-2}$ $kg/m^2//s$ to $1.87\times10^{-2}$ $kg/m^2//s$. However, as the wind speed increases to 0.5 m/s, this increase drops to 3 %, from $4.37\times10^{-2}$ $kg/m^2//s$ to $4.49\times10^{-2}$ $kg/m^2//s$, indicating that the impact of fragmentation on the sublimation rate diminishes under stronger wind conditions. This trend can be attributed to the fact that higher wind speeds enhance particle transport and mixing, which reduces the relative contribution of fragmentation to the overall sublimation process.

A similar trend is observed for suspension particles at higher altitudes. At a wind speed of 0.3 m/s, the average sublimation rate of suspension particles increases by 8 times, from $1.09\times10^{-6}$ $kg/m^2//s$ to $9.8\times10^{-6}$ $kg/m^2//s$ when fragmentation is considered. As the wind speed increases to 0.5 m/s, this growth decreases to 50 %, from $3.7\times10^{-6}$ $kg/m^2//s$ to $5.7\times10^{-6}$ $kg/m^2//s$. While the effect of fragmentation on sublimation remains significant at higher wind speeds, the reduction in growth indicates that other factors, such as increased turbulence and particle dispersion, may play a more prominent role in driving sublimation under these conditions.

Overall, snow fragmentation has a more pronounced effect on sublimation rate of suspension particles than for saltation particles. This difference can be attributed to the longer residence time and greater exposure of suspension

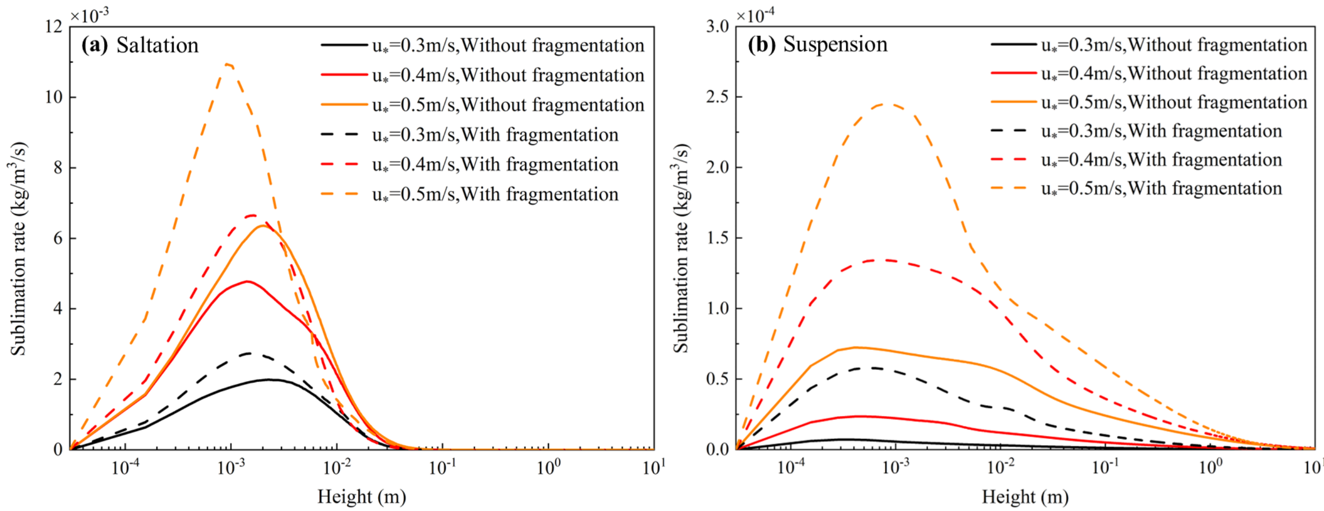


**Figure 10.** Sublimation rate versus height. (a) Saltation particles. (b) Suspension particles.

particles to the airflow, which amplifies the impact of fragmentation on their sublimation rates. In contrast, saltation particles, which are closer to the surface and are subject to more frequent impact and splash processes, experience a relatively weaker influence from fragmentation as wind speed increases.

### 3.5 Effects of size distribution on fragmentation

The averaged particle diameter is defined as $\overline{d} = \alpha \times \beta$, where $\alpha$ and $\beta$ are the shape and scale parameter, respectively. $\alpha$ adjusts the peak position and $\beta$ controls the width of the distribution (the higher the value, the wider the size distributes).

#### 3.5.1 Average particle diameter

As is shown in Fig. 11(a) and (b), with the increasing value of $\alpha$ or $\beta$, the number of fragmented snow particles increases, and the fragmentation efficiency is higher. This indicates that the larger particles have a higher fragment extent, and this is because larger particles can produce more small snow particles.

#### 3.5.2 Size proportion

We set up three cases with the same mean diameter $\overline{d} = 200\ \mu$m but different $\alpha$ and $\beta$, parameters. These differences in $\alpha$ and $\beta$ result in particle systems with varying size distributions. In these three cases, the proportion of particles with diameter larger than the threshold diameter is 73 % (blue), 85 % (green), and 96 % (purple), respectively.

As shown in Fig. 11(c), the fragmentation is significant under the same mean averaged diameter when the large particles take a higher proportion in a granular system. The fragmentation number of snow particles with different

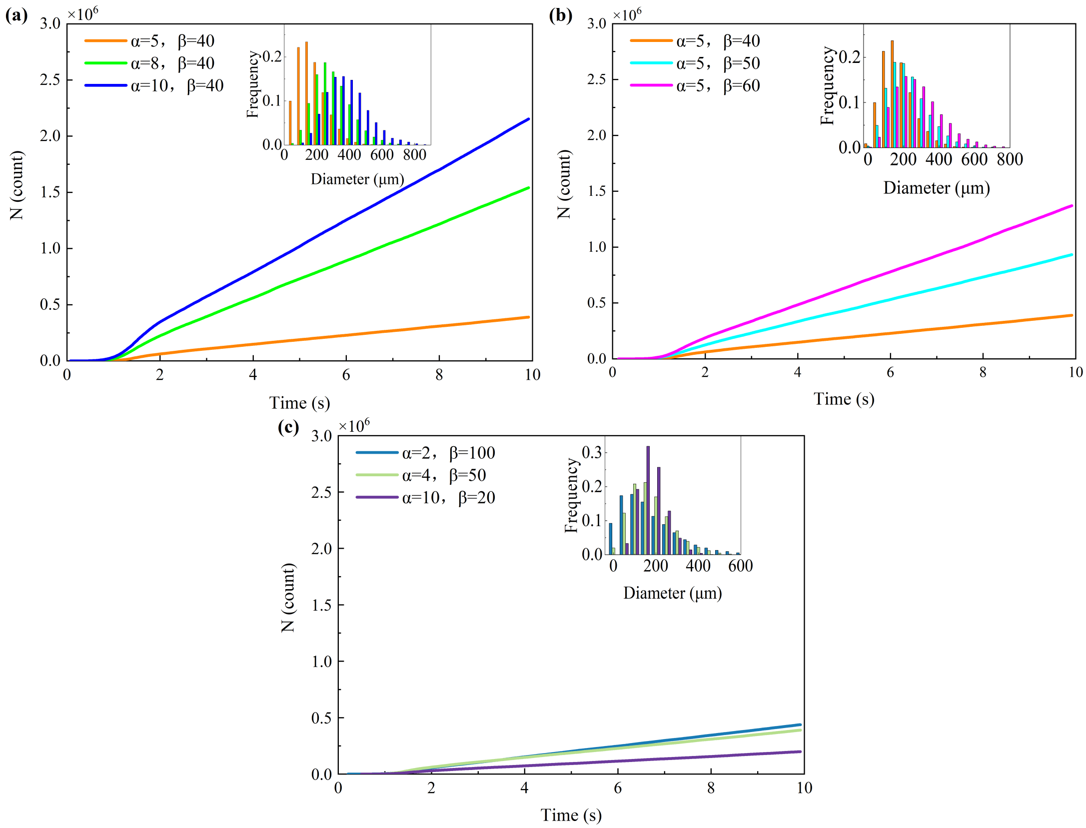


**Figure 11.** Number of snow particles as a function of time. (a) variation of shape parameter $\alpha$, scale parameter $\beta = 40$, const. (b) variation of shape parameter $\beta$, scale parameter $\alpha = 5$, const. (c) Average diameter $\bar{d} = 200\ \mu$m.

particle size distribution increases almost linearly with time. This is because, only snow particles with a larger size than threshold diameter, more snow particles will join the fragmentation.

## 4 Discussion

In this study, we investigated how particle fragmentation affects snow transport and sublimation processes. We found that when fragmentation is considered, the particle size distribution is modified, leading to an expected increase in snow sublimation during DBS. This occurs because fragmentation generates a greater number of smaller-sized particles, which increases the average specific surface area of transported snow. Since the sublimation rate is directly proportional to the specific surface area, the presence of smaller particles enhances sublimation. Additionally, the smaller particles produced by fragmentation reduce the averaged diameter of surface snow particles, leading to a lower threshold velocity of aerodynamic entrainment. As a result, more particles are lifted from the surface and transported by wind, further increasing the number of particles available for sublimation during transport. Moreover, the sublimation rate is directly proportional to the mass concentration of drifting snow particles, amplifying the overall sublimation effect.

However, fragmentation has a limited impact on the overall mass flux profile, with notable changes primarily observed in the near-surface layer. Specifically, when fragmentation is considered, the mass flux below 0.01 m increases. This increase is mainly attributed to changes in mass concentration of suspension particles, for the mass concentration of saltation particles remains largely unchanged. This indicates that fragmentation predominantly occurs within the saltation layer but primarily contributes to the mass in the suspension layer. This is because smaller fragmented particles are more easily transported by wind forces, exhibiting greater flowability in air and reaching higher altitudes.

Moreover, the fragmentation of the snowflakes produces smaller-sized particles that remain in saltation and suspension, while deposited particles alter the surface size distribution. These changes in particle size distribution influence snow surface properties, such as albedo (Manninen et al., 2021), snow microstructure, static snow cover sublimation rate (Albert and Mcgilvary, 1992), and surface roughness. Larger snow particles reduce multiple scattering events because light travels longer paths within larger particles, leading to increased absorption, particularly in the near-infrared spectrum. Thus, larger snow particles have a low snow albedo. Smaller snow particles, with their higher specific surface area, allow light to undergo more scattering events within the snowpack and reduce the absorption of solar radiation, typically having a high albedo, especially in the visible spectrum. The variation of snow surface size distribution due to fragmentation in DBS influences the surface energy balance by changing the snow surface albedo. Additionally, smaller grains affect the snow thermal conductivity, mechanical stability, and the retention of impurities, which can further reduce albedo and accelerate snowmelt. Therefore, this variation of snow surface properties plays a critical role in determining the energy exchange between the snowpack and the atmosphere.

These findings highlight the importance of incorporating particle fragmentation processes into spatially distributed surface energy balance models. This can improve the accuracy of snowpack mass balance assessments, enhance predictions of seasonal snow dynamics, and better represent snow transport and sublimation processes in atmospheric and climate models.

## 5 Conclusion

In this study, we carried out a numerical simulation to investigate the snow particle fragmentation and sublimation during DBS. The model is based on an Euler-Lagrangian method to track the trajectories of individual snow particles. To account for sublimation processes, we implemented the T-M model, which calculates the sublimation rate of snow particles based on their size, temperature, and the surrounding environmental conditions.

The simulation incorporates key physical processes in DBS, including particle-particle interactions, fragmentation due to collisions. The model was validated with experimental data from previous studies. This integrated method provides a detailed understanding of the dynamics of snow particles and their sublimation during snow particle transport.

In this study, we developed a drifting snow model that incorporates the snow particle fragmentation process. This model simultaneously accounts for both the dynamic processes, including the movement of saltation and suspension particles, and the thermodynamic processes, such as snow sublimation. The model was validated using experimental data from previous studies, ensuring its reliability. This integrated approach, the model offers a comprehensive understanding of snow particle dynamics and sublimation during transport in DBS events.

Based on this model, this work investigates the significant role of snow particle fragmentation in DBS. We find that fragmentation not only alters the particle size distribution but also increases the number, concentration, and mass flux of particles in DBS. Subsequently, this phenomenon affects the sublimation rate of airborne snow particles. Specifically, fragmentation reduces the average particle size, creating smaller particles that are more prone to sublimation. The effects of fragmentation on sublimation are more pronounced for suspension particles than saltation particles, particularly under low wind conditions.

Investigating the effects of particle size distribution on the sublimation rates, we find that the sublimation rate is enhanced for particles with a larger average diameter and a higher proportion of larger particles. These results underscore the importance of accurately representing fragmentation and size distributions in snow transport models.

Our simulation results are consistent with previous observational data, suggesting the validity of the model. Furthermore, a comparison of simulation results considering or ignoring fragmentation of snow particles, shows that our sublimation rates are 2-4 times higher than other previous model results. This is because fragmentation reduces the snow particle's size, and increases the number of airborne particles, which are more susceptible to sublimation. By integrating fragmentation into the numerical model, this study marks a significant step forward in understanding and quantifying the effects of particle dynamics on snow sublimation.

Our work provides insights into the complex dynamics of DBS. It provides a deeper understanding of the physical process of snow particle fragmentation during saltating/suspending in the air. This indicates the importance of fragmentation in the numerical models of DBS. However, the used model is a two-dimensional numerical model, which could not be applied to larger regions, especially for complex terrains. Therefore, the expansion of this model into a three-dimensional drifting snow model in the future is necessary. Moreover, crystal habits is another important factor in influencing the sublimation rate of snow particles, such as density, size, and specific surface area. Future numerical simulation should be carried out regarding crystal habits factors.

The simulation results provide detailed insights into the physical processes of particle-atmospher momentum transfer, heat and mass transfer, from a single particle perspective. This work provides the theoretical foundation and prediction method for accurately assessing the accurate amount of snow sublimation during DBS. These findings have important implications for imporiving the representation of snow transport and sublimation processes in atmospheric and climate models, which can enhance predictions of snow mass balance and its broader environmental impacts.

*Author contributions.* N H designed the conception, JC B contributed to the programming and numerical calculation, HX Y contributed to the conception, first draft and revision, G L designed the conception and revised the manuscript.

*Competing interests.* All authors declare that no competing interests are present.

*Acknowledgements.* This work was supported by the Third Comprehensive Scientific Expedition and Research Program in Xinjiang (grant no.: 2022xjkk0101), the National Natural Science Foundation of China (grant no.: 42476251, 42406255, U22A20564), and the China Postdoctoral Science Foundation (grant no.: 2024M751257). The data and code will be uploaded to the Dryad repository after the paper is published. Additionally, we are deeply grateful to the two anonymous reviewers for their insightful comments and constructive suggestions, which have greatly contributed to improving the quality and clarity of this paper.

## References


Albert, M. R. and Mcgilvary, W. R.: Thermal effects due to air flow and vapor transport in dry snow, Journal of Glaciology, 38, 273–281, https://doi.org/10.3189/S0022143000003683, 1992.

Anderson, R. S. and Haff, P. K.: Wind modification and bed response during saltation of sand in air, Acta Mechanica Suppl, 1, 21–51, 1991.

Bintanja, R.: Snowdrift suspension and atmospheric turbulence. Part I: Theoretical background and model description., 2000.

Comola, F., Kok, J., Gaume, J., Paterna, E., and Lehning, M.: Fragmentation of wind-blown snow crystals: Blowing snow fragmentation, Geophysical Research Letters, 44, https://doi.org/10.1002/2017GL073039, 2017.

Csanady, G. T.: Turbulent Diffusion of Heavy Particles in the Atmosphere, Journal of Atmospheric Sciences, 20, 201 – 208, https://doi.org/10.1175/1520-0469(1963)020<0201:TDOHPI>2.0.CO;2, 1963.

Dai, X. and Huang, N.: Numerical simulation of drifting snow sublimation in the saltation layer, Scientific Reports, 4, https://api.semanticscholar.org/CorpusID:14720403, 2014.

Domine, F., Taillandier, A.-S., Cabanes, A., Douglas, T. A., and Sturm, M.: Three examples where the specific surface area of snow increased over time, The Cryosphere, 3, 31–39, https://doi.org/10.5194/tc-3-31-2009, 2009.

Déry, S. and Yau, M.: Simulation Of Blowing Snow In The Canadian Arctic Using A Double-Moment Model, Boundary-Layer Meteorology, 99, 297–316, https://doi.org/10.1023/A:1018965008049, 2001.

Déry, S. J. and Yau, M. K.: Large-scale mass balance effects of blowing snow and surface sublimation, Journal of Geophysical Research: Atmospheres, 107, ACL 8–1–ACL 8–17, https://doi.org/https://doi.org/10.1029/2001JD001251, 2002.

Gadde, S. and Berg, W.: Contribution of blowing-snow sublimation to the surface mass balance of Antarctica, The Cryosphere, 18, 4933–4953, https://doi.org/10.5194/tc-18-4933-2024, 2024.

Gordon, M. and Taylor, P. A.: Measurements of blowing snow, Part I: Particle shape, size distribution, velocity, and number flux at Churchill, Manitoba, Canada, Cold Regions Science and Technology, 55, 63–74, https://doi.org/https://doi.org/10.1016/j.coldregions.2008.05.001, 2009.

Groot Zwaaftink, C., Löwe, H., Mott, R., Bavay, M., and Lehning, M.: Drifting snow sublimation: A high-resolution 3-D model with temperature and moisture feedbacks, Journal of Geophysical Research, 116, https://doi.org/10.1029/2011JD015754, 2011.

Hames, O., Jafari, M., Wagner, D. N., Raphael, I., Clemens-Sewall, D., Polashenski, C., Shupe, M. D., Schneebeli, M., and Lehning, M.: Modeling the small-scale deposition of snow onto structured Arctic sea ice during a MOSAiC storm using snowBedFoam 1.0., Geoscientific Model Development, 15, 6429–6449, https://doi.org/10.5194/gmd-15-6429-2022, 2022.

Huang, N. and Shi, G.: The significance of vertical moisture diffusion on drifting Snow sublimation near snow surface, The Cryosphere Discussions, pp. 1–28, https://doi.org/10.5194/tc-2017-116, 2017.

JDoorschot, J., Lehning, M., and Vrouwe, A.: Field measurements of snow-drift threshold and mass fluxes, and related model simulations, Boundary-Layer Meteorology, 113, 347–368, https://doi.org/10.1007/s10546-004-8659-z, 2004.

Lehning, M., Löwe, H., Ryser, M., and Raderschall, N.: Inhomogeneous precipitation distribution and snow transport in steep terrain, Water Resources Research, 44, https://doi.org/https://doi.org/10.1029/2007WR006545, 2008.

Manninen, T., Anttila, K., Jääskeläinen, E., Riihelä, A., Peltoniemi, J., Räisänen, P., Lahtinen, P., Siljamo, N., Thölix, L., Meinander, O., Kontu, A., Suokanerva, H., Pirazzini, R., Suomalainen, J., Hakala, T., Kaasalainen, S., Kaartinen, H., Kukko, A., Hautecoeur, O., and Roujean, J.-L.: Effect of small-scale snow surface roughness on snow albedo and reflectance, The Cryosphere, 15, 793–820, https://doi.org/10.5194/tc-15-793-2021, 2021.

Melo, D., Sharma, V., Comola, F., Sigmund, A., and Lehning, M.: Modeling Snow Saltation: The Effect of Grain Size and Interparticle Cohesion, Journal of Geophysical Research: Atmospheres, 127, https://doi.org/10.1029/2021JD035260, 2022.

Nemoto, M. and Nishimura, K.: Numerical simulation of snow saltation and suspension in a turbulent boundary layer, Journal of Geophysical Research, 109, https://doi.org/10.1029/2004JD004657, 2004.

Nishimura, K. and Nemoto, M.: Blowing snow at Mizuho Station, Antarctica, Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, 363, 1647–62, https://doi.org/10.1098/rsta.2005.1599, 2005.

Pomeroy, J. and Male, D.: Steady-state suspension of snow, Journal of Hydrology, 136, 275–301, https://doi.org/https://doi.org/10.1016/0022-1694(92)90015-N, 1992.

Pomeroy, J., Gray, D., and Landine, P.: The Prairie Blowing Snow Model: Characteristics, Validation, Operation, Journal of Hydrology, 144, 165–192, https://doi.org/10.1016/0022-1694(93)90171-5, 1993.

Pomeroy, J. W. and Essery, R. L. H.: Turbulent fluxes during blowing snow: field tests of model sublimation predictions, Hydrological Processes, 13, 2963–2975, https://doi.org/https://doi.org/10.1002/(SICI)1099-1085(19991230)13:18<2963::AID-HYP11>3.0.CO;2-9, 1999.

Pomeroy, J. W. and Jones, H. G.: Wind-Blown Snow: Sublimation, Transport and Changes to Polar Snow, https://api.semanticscholar.org/CorpusID:11700473, 1996.

Sato, T., Kosugi, K., Mochizuki, S., and Nemoto, M.: Wind speed dependences of fracture and accumulation of snowflakes on snow surface, Cold Regions Science and Technology, 51, 229–239, https://doi.org/https://doi.org/10.1016/j.coldregions.2007.05.004, international Snow Science Workshop (ISSW) 2006, 2008.

Schmidt, R. A.: Vertical profiles of wind speed, snow concentration, and humidity in blowing snow, Boundary-Layer Meteorology, 23, 223–246, 1982.

Scott, W. D.: Measuring the erosivity of the wind, CATENA, 24, 163–175, https://doi.org/https://doi.org/10.1016/0341-8162(95)00022-K, 1995.

Sharma, V., Comola, F., and Lehning, M.: On the suitability of the Thorpe–Mason model for calculating sublimation of saltating snow, The Cryosphere, 12, 3499–3509, https://doi.org/10.5194/tc-12-3499-2018, 2018.

Sharma, V., Gerber, F., and Lehning, M.: Introducing CRYOWRF v1.0: multiscale atmospheric flow simulations with advanced snow cover modelling, Geoscientific Model Development, 16, 719–749, https://doi.org/10.5194/gmd-16-719-2023, 2023.

Sigmund, A., Dujardin, J., Comola, F., Sharma, V., Huwald, H., Melo, D., Hirasawa, N., Nishimura, K., and Lehning, M.: Evidence of Strong Flux Underestimation by Bulk Parametrizations During Drifting and Blowing Snow, Boundary-Layer Meteorology, 182, https://doi.org/10.1007/s10546-021-00653-x, 2021.

Stull, R. B.: An Introduction to Boundary Layer Meteorology, An Introduction to Boundary Layer Meteorology, 1988.

Sugiura, K. and Maeno, N.: Wind-Tunnel Measurements Of Restitution Coefficients And Ejection Number Of Snow Particles In Drifting Snow: Determination Of Splash Functions, Boundary-Layer Meteorology, 95, 123–143, https://doi.org/10.1023/A:1002681026929, 2000.

Taylor, P.: The Thermodynamic Effects of Sublimating, Blowing Snow in the Atmospheric Boundary Layer., Boundary-Layer Meteorology, 89, 251–283, https://doi.org/10.1023/A:1001712111718, 1998.

Thorpe, A. and Mason, B.: The Evaporation of Ice Spheres and Ice Crystals, British Journal of Applied Physics, 17, 541–548, https://doi.org/10.1088/0508-3443/17/4/316, 1966.

Ueno, K., Tanaka, K., Tsutsui, H., and Li, M.: Snow cover conditions in the Tibetan Plateau observed during the winter of 2003/2004, ARCTIC ANTARCTIC AND ALPINE RESEARCH, 39, 152–164, https://doi.org/10.1657/1523-0430(2007)39[152:SCCITT]2.0.CO;2, 2007.

Vionnet, V., Martin, E., Masson, V., Guyomarc'h, G., Naaim-Bouvet, F., Prokop, A., Durand, Y., and Lac, C.: Simulation of wind-induced snow transport and sublimation in alpine terrain using a fully coupled snowpack/atmosphere model, The Cryosphere, 8, 395–415, https://doi.org/10.5194/tc-8-395-2014, 2014.

Walter, B., Weigel, H., Wahl, S., and Löwe, H.: Wind tunnel experiments to quantify the effect of aeolian snow transport on the surface snow microstructure, The Cryosphere, 18, 3633–3652, https://doi.org/10.5194/tc-18-3633-2024, 2024.

Wang, Z. and Huang, N.: Numerical simulation of the falling snow deposition over complex terrain, Journal of Geophysical Research: Atmospheres, 122, 980–1000, https://doi.org/https://doi.org/10.1002/2016JD025316, 2017.

Xiao, J., Bintanja, R., Déry, S., Mann, G., and Taylor, P.: An Intercomparison Among Four Models Of Blowing Snow, Boundary-Layer Meteorology, 97, 109–135, https://doi.org/10.1023/A:1002795531073, 2000.

Yu, H., Li, G., Huang, N., and Lehning, M.: Idealized Study of a Static Electrical Field on Charged Saltating Snow Particles., Frontiers in Earth Science, 10, https://doi.org/10.3389/feart.2022.880466, 2022.

Zhang, J. and Huang, N.: Simulation of Snow Drift and the Effects of Snow Particles on Wind, Modelling and Simulation in Engineering, 2008, https://doi.org/10.1155/2008/408075, 2008.

Zhang, Y., Ishikawa, M., Ohata, T., and Oyunbaatar, D.: Sublimation from thin snow cover at the edge of the Eurasian cryosphere in Mongolia, Hydrological Processes, 22, 3564–3575, https://doi.org/https://doi.org/10.1002/hyp.6960, 2008.