Drifting snow and its sublimation in turbulent boundary layer

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Abstract. Drifting snow is a special process of mass-energy transport in hydrological cycle especially in alpine region. It can not only change the snow distribution, but also result in phase change of ice crystal into water vapour, which is so called drifting snow sublimation. Thus drifting snow is of glaciological and hydrological importance in cold regions. In this paper, recent research on drifting snow and its sublimation is reviewed, and some new progresses by our research team in Lanzhou University are also introduced.

1. Introduction
Snow distribution is an important part of eco-hydrology in alpine region, which can be influenced by many factors. Wind blowing snow acting with terrain is the major reason for snow redistribution [1]. Wind blowing snow is a specific hydrological phenomenon, which reflected in two aspects. One is change the distribution of precipitation by transporting the snow from one side to another [2-4]. The other is letting snow particles jump and suspend with high speed, to promote their sublimation, which can lead to mass loss even larger than surface sublimation [5-7]. And these two processes have great influence on other hydrology processes in alpine region. So it is of great significance on wind blowing snow study.

Research on wind blowing snow can be traced back to the early last century, when only observational or descriptive works on specific disasters were studied. Because of the great effects of drifting snow on global environment, human's production and life protection, in 1980s, more and more researchers focused on the forms and trajectory of snow particle motion by wind-tunnel, theoretical analysis and numerical simulation. However, idealized hypotheses are accepted by most previous researchers, for example snow particle is regarded as a sphere with equivalent volume, and wind speed is time-averaged. With the development of computer science, complex factors like turbulence and rugged terrain have been taken into consideration on modelling drifting snow. Then many drifting snow models were developed in the early 21st century [8-10]. But most of these models didn’t take into consideration of the coupling action between snow particles and wind field, as well as effects of turbulence on particle motion. In this paper, wind-blown snow movement in turbulent boundary layer is simulated, and some new ideas then are proposed.

2. Simulation methods
Based on ARPS (The Advanced Regional Prediction System), a non-hydrostatic regional prediction system that developed in Oklahoma University [11, 12], codes of two-phase flow considering coupling of wind and particles, grain-bed collision, air entrainment of snow particles, and drifting snow sublimation, are added to simulate the drifting snow and its sublimation in turbulent boundary layer. The filtered Navier-Stokes equations are as following:
\[ \frac{\partial \bar{\rho} \bar{u}_i}{\partial t} + \frac{\partial \bar{\rho} \bar{u}_i \bar{u}_j}{\partial x_j} = - \frac{\partial p^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + B \delta_{ij} + F_i \]  

(1)

Where \( \rho \) is air density, \( u \) is wind velocity, \( p \) is pressure, \( \tau_{ij} \) is sub-grid stress, \( B \) is buoyancy, \( F_i \) is the force that particles act on wind.

The particle motion equations are:

\[ \frac{d u_{pi}}{d t} = 3 \rho v (u_i - u_{pi})  \frac{C_D}{4 \rho_p d_p^2} C_p Re_p + g_i (1 - \frac{\rho}{\rho_p}) \]  

(2)

Where \( u_{pi} \) is snow particle velocity, \( v \) is kinematic viscosity of air, \( \rho_p \) is snow particle density, \( d_p \) is diameter of snow particle, \( C_D \) is drag coefficient, \( Re_p = \frac{(u_i - u_{pi}) d_p}{v} \) is particle Reynolds number, \( g \) is gravitational acceleration.

Splash function developed by Kok and Renno [13] is used to simulate grain bed collision, and semi-empirical formula proposed by Doorschot and Lehning [14] is used to model the air entrainment.

Thorpe and Mason [15] gave an expression of mass loss of an ice crystal by blowing sublimation:

\[ \frac{d m}{d t} = \frac{2 \pi r L_s}{K \theta \nu} (R_H - 1) + \frac{R_v T_a}{Sh De_s} \]  

(3)

Where \( m \) is the mass of ice crystal, \( R_H \) is relative humidity, \( T_a \) is air temperature, \( L_s \) is the latent heat of sublimation \( (2.84 \times 10^6 J/kg) \), \( K \) is the thermal conductivity of air, \( R_v \) is gas constant of water vapor \( (461.5 kg^{-1} K^{-1}) \), \( D \) is rate of molecular diffusion of water vapor, \( Nu \) and \( Sh \) are non-dimensional numbers relative to wind velocity, \( e_s = 610.78 \exp[21.87(T_a - 273.16)/(T_a - 7.66)] \) is saturated vapor pressure relative to ice surface.

In this paper, every snow particle is tracked to calculate its mass loss during its saltation, and then we get the sublimation rate by summing the mass lose of all saltating particles in the simulation domain.

Considering the negative feedback of sublimation process, we take the water heat balance equation into account [16]:

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y} \left( K_\theta \frac{\partial \theta}{\partial y} \right) - \frac{L_s S}{\rho c} \]  

(4)

\[ \frac{\partial q}{\partial t} = \frac{\partial}{\partial y} \left( K_q \frac{\partial q}{\partial y} \right) - \frac{S}{\rho} - Q \]  

(5)

Where \( \theta = T_a (\frac{1000}{\rho})^{0.286} \) is the potential temperature, \( q = 0.622 \cdot \frac{e_s}{p - e_s} \cdot RH \) is the specific humidity, \( K_\theta = \kappa u_s y + K_T \) and \( K_q = \kappa u_s y + K_v \) are diffusion coefficient of water vapor and heat [17]. \( S = \frac{1}{\nu} \frac{d m_i}{d t} \) is the sublimation rate, \( C \) is the specific heat of air, \( Q = u \nabla q \) is convection flux.

3. Results and discussions

3.1 Snow stripes

Uniform horizontal grids and refined vertical grids are used to simulate the wind of an 10m × 10m × 4m area, and grain size distribution obtained from natural snow by Omiya [18] is used to simulate drifting snow. Our simulated wind profile agrees well with the wind-tunnel experiment [19], shown as figure 1.
Figure 1. Computational domain. (a) Snow particle size distribution (b) Horizontal wind velocity profile in clear wind field.

Figure 2 shows that simulation results have good consistency with experiment data [20-22], while figure 3 (a) shows that mean particle spanwise horizontal velocity decreases with height for low wind friction velocity, and evolves with opposite phases for high wind friction velocity, which is firstly be detected; (b) shows that streamwise horizontal velocity of particles will concentrate with increment of wind velocity, while the peak value is nearly invariable.

Figure 2. (a) Transport rate with wind friction velocity (b) Particle size distribution with height

Figure 3. (a) Mean particle spanwise horizontal velocity distribution with height (b) Probability density distribution of particle streamwise horizontal velocity

Snow streamers are first reproduced in drifting snow simulation in this paper, and spectral analysis is used to explain the relationship between snow streamers and turbulent flow. Figure 4 shows similar spectrogram of snow streamer width and wind streamer width, which indicates that intermittency of turbulent flow may be the reason of formation of snow streamers.
3.2 Drifting snow sublimation

Figure 5(a) shows the sublimation rate versus friction velocity on situation one. It indicates that sublimation rate increases with friction velocity and air temperature, and decreases with relative humidity. Figure 5(b) shows that sublimation rate in saltation layer can be higher than that in suspension layer in low friction velocity, which indicates that sublimation rate in saltation layer cannot be ignored.

Figure 6 show the sublimation rate that sublimation rate will quickly reach a peak value and then decreased to zero at the circumstance without moisture transport, which is called a negative feedback effect. However, moisture and heat diffusion and advection will weaken the negative feedback effect, which leads to continuous sublimation events in saltation layer. So it is inadvisable to easily see no blowing snow sublimation in saltation layer.

Figure 5. (a) Sublimation rate change with friction velocity by fixed air temperature and relative humidity. (b) Sublimation rate change with friction velocity in different layers
4. Conclusions
In this paper, research on drifting snow and its sublimation in turbulent boundary layer is introduced. Snow streamer is reproduced and its formation mechanism is analysed. The mean particle spanwise horizontal velocity distribution with height is presented. Drifting snow sublimation in saltation layer is simulated, and the results show it is an indispensable part of snow sublimation, which is usually ignored before.

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