Aeolian Research 23 (2016) 1–10

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

The formation of snow streamers in the turbulent atmosphere boundary layer

Ning Huang, Zheng-Shi Wang *

Key Laboratory of Mechanics on Disaster and Environment in Western China (Lanzhou University), The Ministry of Education of China, 730000, China
Department of Mechanics, School of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, 730000, China

ARTICLE INFO

Article history:
Received 20 March 2016
Revised 9 September 2016
Accepted 9 September 2016
Available online 1 October 2016

Keywords:
Drifting snow
Large Eddy Simulation (LES)
Turbulent boundary layer
Snow streamers

ABSTRACT

The drifting snow in the turbulent atmosphere boundary layer is an important type of aeolian multiphase flow. Current theoretical and numerical studies of drifting snow mostly consider the flow field as steady wind velocity. Whereas, little is known about the effects of turbulent wind structures on saltating snow particles. In this paper, a 3-D drifting snow model based on Large Eddy Simulation is established, in which the trajectory of every snow grain is calculated and the coupling effect between wind field and snow particles is considered. The results indicate that the saltating snow particles are reorganized by the suction effect of high-speed rotating vortexes, which results in the local convergence of particle concentration, known as snow streamers. The turbulent wind leads to the spatial non-uniform of snow particles lifted by aerodynamic entrainment, but this does not affect the formation of snow streamers. Whereas the stochastic grain-bed interactions make a great contribution to the final shapes of snow streamers. Generally, snow streamers display a characteristic length about 0.5 m and a characteristic width of approximately 0.16 m, and their characteristic sizes are not sensitive to the wind speed. Compared to the typical sand streamer, snow streamer is slightly narrower and the occurrence of other complex streamer patterns is later than that of sand streamers due to the better follow performance of snow grains with air flow.

1. Introduction

Drifting snow is a typical two-phase flow that frequently occurred at high latitudes and its studies are of glaciological and hydrological importance (Zhou et al., 2014). The drifting snow process carries snow grains from one place to another and results in a redistribution of snow cover. On one hand, the non-uniform distribution snow layer caused by drifting snow on mountains may induce and aggravate various natural geologic hazards (Michaux et al., 2001). On the other 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 ice sheets (Gallée et al., 2013). Thus, the dispersion and transport characteristics of snow particles in the turbulent boundary layer require in-depth research.

Many drifting snow models have been proposed to investigate this comprehensive phenomenon. Most of them are two-fluid models assume snow particles a continuous phase (Uematsu et al., 1991; Mann et al., 2000; Taylor, 1998; Déry and Yau, 1999; Fukushima et al., 1999, 2001; Xiao et al., 2000; Bintanja, 2000a, 2000b; Gauer, 2001; Lehning et al., 2008; Schneiderbauer and Prokop, 2011; Vionnet et al., 2014). These models have greatly improved our understanding of drifting snow process. However, snow grains can also saltate downflow due to the gravitational effect. The movement of mid-air snow particles and the interaction between snow grains and turbulent structures are essential for understanding the natural drifting snow process and its spatial structure under the action of turbulent wind. In recent years, some Euler-Lagrange models have been explored to investigate the drifting snow process, in which the snow particles were tracked with Lagrange method. Nemoto and Nishimura (2004) studied 2-D snow particle motions in the 1-D turbulent boundary layer based on particle tracking with consideration of the aerodynamic entrainment and wind modification. Later, Zhang and Huang (2008) presented a steady state snow drift model and analyzed the features of the steady state of drifting snow.

The studies on the dispersion of solid particles in the 3-D turbulent boundary layer based on Large Eddy Simulation (LES) have also been conducted by researchers. Vinkovic et al. (2006) studied

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* Corresponding author at: Key Laboratory of Mechanics on Disaster and Environment in Western China (Lanzhou University), The Ministry of Education of China, 730000, China.

E-mail address: wangzhsh2013@lzu.edu.cn (Z.-S. Wang).

http://dx.doi.org/10.1016/j.aeolia.2016.09.002
1875-9637/

the dispersion of solid particles in a turbulent boundary layer based on the large-eddy simulation combined with the dynamic Germano subgrid-scale (SGS) model, while the spatial structure of the sand flow was not discussed. Then, Dupont et al. (2013) simulated the wind-blown sand movement in the near surface turbulent flow layer and found the process of sand saltation is very intermittent in time and space due to the turbulence of the flow. Groot Zwaaftink et al. (2014) simulated the small-scale drifting snow in the turbulent boundary layer and analyzed the intermittency of drifting snow by simplifying the coupling effect between particles and wind field as a uniform roughness modification. This may be inaccurate since the saltating snow particles are non-uniform distributed in the turbulent flow. Huang and Wang (2015) performed the behaviors of snow particle in a fully developed turbulent boundary layer and snow streamers were reproduced. Up to now, the characteristic sizes of snow streamer and its formation mechanisms require further exploration. In addition, all above studies didn't adopt an adequate SGS model to reflect the influence of non-uniform distributed saltation particles on the wind field, which will affect the final structure of the drifting snow to a great extent.

Here, we investigate the influence of turbulent structures on saltating snow using a Lagrangian dynamic subgrid-scale (SGS) model (Meneveau et al., 1996). This model averages the Smagorinsky coefficient in time following fluid pathlines and can match the non-uniform drag force due to the saltating snow particles essentially. The coupling effect between snow particles and wind field is explicitly considered. Each saltating snow particle is tracked using a Lagrangian approach and a splash scheme is used to describe the grain-bed interactions. The development of drifting snow in the turbulent boundary layer with mixed grain size is numerically studied and 'snow streamers' in the turbulent boundary layer are reproduced. The most important improvement of this model is that the reaction force of each saltating particle is calculated and imposed on the wind field and each single particle is tracked separately in order to obtain the detail structure of blown snow in the turbulent boundary layer. The spatial distribution characteristic of snow streamers and its relevance with turbulent wind structure are analyzed in detail.

2. Model and methods

2.1. Turbulent boundary layer

The ARPS (Advanced Regional Prediction System, version 5.3.3) developed by University of Oklahoma is a middle-scale meteorological model, and the three-dimensional, non-hydrostatic, compressible Navier-Stokes equation is solved using the 'split-explicit' time integration method (Xue et al., 2000, 2001). After introduce the reaction force of saltating snow particles into the Navier-Stokes equation, the fluid governing equations can be expressed as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho \bar{u}_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i)+\frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j)=-\left(\frac{\partial \overline{p^*}}{\partial x_i}+g\frac{\rho'}{\rho}\right)-\frac{\partial \tau_{ij}}{\partial x_j}-F_i \tag{2}$$

where the line symbol indicates the filtered variables. $x_i(m)$ is the position coordinates and $i = 1, 2, 3$ stand for the streamwise, lateral, and vertical directions, respectively; u_i ($\mathrm{ms^{-1}}$) refers to the instantaneous velocity component of three directions, t (s) is time, $p^* = p' - \alpha\nabla(\bar{\rho}\mathbf{u})$ (Nm^{-3}) contains the pressure perturbation and a divergence damping terms, the ρ' and ρ ($\mathrm{Kg\,m^{-3}}$) are the perturbance density and grid-averaged density of air, respectively; g ($\mathrm{ms^{-2}}$) is the gravitational acceleration, and $\tau_{ij} = \rho\overline{u_i u_j} - \rho\bar{u}_i\bar{u}_j$ is the subgrid stress, according to Smagorinsky (1963):

$$\tau_{ij} = -2(C_s\Delta)^2|\bar{S}|\bar{S}_{ij} \tag{3}$$

where Δ (m) is the filter scale, $\bar{S}_{ij} = (\partial\bar{u}_i/\partial x_j + \partial\bar{u}_j/\partial x_i)/2$ is the strain rate tensor, and C_s is the Smagorinsky coefficient, which is dynamically determined according to the Lagrangian dynamic SGS model (Meneveau et al., 1996).

F_i is the reaction force per unit volume of saltating particles and should be equal and opposite in direction of the drag force of snow particle (Anderson and Haff, 1991):

$$F_i = \frac{1}{V_{grid}}\sum_{s=1}^{N}\frac{3}{4}m_p C_D V_{ri}^2/d_p \tag{4}$$

where V_{grid} (m^3) is the volume of grid cell, N is the total number of particles in a grid, m_p (kg) means the mass of particles, C_D is the drag coefficient and V_r ($\mathrm{ms^{-1}}$) represents the relative velocity between the particle and air flow.

2.2. Governing equation of particle motion

The Lagrangian Particle Tracking Method combined with fourth order Ronge-Kutta method is used to track the snow grains. As the particle density ρ_p is much larger than the air ($\rho_p = 912\ kgm^{-3}$ and $\rho = 1.225\ kgm^{-3}$) and its diameter d_p (m) is much smaller than the Kolmogorov scale, every snow particle is regarded as a sphere and only possesses gravity and drag force (Anderson and Haff, 1988). The static electric force is not included in this simulation. Thus, the equation of particle motion can be written as:

$$\frac{du_{pi}}{dt} = \frac{3\rho\mu V_{ri}}{4\rho_p (d_p)^2}C_D Re_p + g_i\left(1-\frac{\rho}{\rho_p}\right) \tag{5}$$

$$C_D Re_p = \begin{cases} 24 + 3.6(Re_p)^{0.687}, (Re_p \leqslant 1000) \\ 0.44Re_p, (Re_p > 1000) \end{cases} \tag{6}$$

where $Re_p = d_p V_r/\nu$ is the particle Reynolds number and $\nu = 1.5 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$ is the kinematic viscosity of air.

2.3. Grain-bed interactions

Snow particles will be entrained into the air if the shear force generated by air flow is above threshold. The aerodynamic entrainment scheme of Groot Zwaaftink et al. (2014) is adopted to describe the quantity and initial velocities of entrained particles.

When a moving particle impacts on the bed, it may rebound into air again and eject new particles into the air due to momentum transfer. The rebound probability can be expressed as (Anderson and Haff, 1991):

$$P_{reb} = B[1 - exp(-\gamma v_{imp})] \tag{7}$$

where $v_{imp}(\mathrm{ms^{-1}})$ is the impact velocity of particle, $B = 0.9$ and $\gamma = 2\ sm^{-1}$ are empirical parameters (Groot Zwaaftink et al., 2014).

The number of newly ejected particles can be expressed as (Kok and Renno, 2009):

$$N_{ej} = \frac{a}{\sqrt{gD}}\frac{m_{imp}}{\langle m_{ej}\rangle}v_{imp} \tag{8}$$

where a is a dimensionless constant in the range of 0.01–0.05. A value of $a = 0.03$ is in accordance with the observation of drifting snow in the wind tunnel (Okaze et al., 2012). D (m) is the typical particle size ($\langle d_p\rangle$ in this paper), m_{imp} (kg) is the mass of impacting particle and $\langle m_{ej}\rangle$ (kg) is the average mass of ejection grains.