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Abstract

This study developed a new snowdrift model to evaluate the snowdrift height around a snow fence, often installed along a road in a snowy and windy environment. The model consisted of the conventional computational fluid dynamics (CFD) solver by the Lattice Boltzmann method (LBM) and a module for snow particles' motion and accumulation. The calculation domain was a half channel with a flat free-slip boundary on the top and a non-slip boundary on the bottom, imposing an inflow with artificially generated turbulence from one side to the other outlet side. Besides the reference experiment with no fence, the experiment was set up with a two-dimensional and a three-dimensional fences normal to the dominant wind direction in the channel center. The estimated wind

flow over the two-dimensional fence was characterized by a swirling eddy in the cross-section, whereas the wind flow in the three-dimensional fence experiment was horizontally diffluent with a dipole vortex pair in the leeward of the fence. As a result, almost all of snowdrift was formed in the windward of the two-dimensional and three-dimensional fences, but it was also formed as the split streak in the leeward of the three-dimensional fence. The result suggested that the fence should be as long as possible to avoid the snowdrift on roads.

Keywords

Drifting Snow, Blowing Snow, Snow Fence, Lattice Boltzmann Method

1 Introduction

Snowdrift is a patchy accumulation of snow, resulting from the redistribution of snow particles on the ground mainly caused by drifting snow, which is the horizontal movement of snow particles by creeping and saltation on the surface. Snowdrift affects human activities through its mass often being an obstacle. For example, snowdrift in mountainous terrain triggers avalanche and influences the mass balance of water (Lehning et al. 2006; Lehning et al. 2008; Mott et al. 2010; Vionnet et al. 2017). Moreover,

snowdrift causes traffic disruption because vehicles tend to stack and stagnate on a road with a snow depth of 15 cm (Kaneko et al. 2011). Snow fence is one of the solutions to mitigate the problem of the snowdrift, especially on roads under a snowy and windy environment. Snowdrift distribution around snow fences strongly depends on parameters in their designs, such as height, thickness, bottom gaps, space between panels or a penetration rate of porous fences, and distance from the road (Tabler 1986; Uematsu et al. 1991; Alhajraf 2004). Some studies examined the onset of drifting snow and snow accumulation by wind-tunnel experiments (Delpech et al. 1998; Okaze et al. 2012; Zhou et al. 2014). Other studies reported the difference in the amount of snowdrift on roads according to snow fence design through field observation (Tabler 1980; Takeuchi 1980; Takeuchi et al. 1986; Tabler 1994). However, the field observation limited the sampling chance of drifting snow events at a certain site, and wind-tunnel experiments did not always assure similarity to a real situation by their scaling. Moreover, these methods generally required a large cost to obtain enough amount of data to design snow fences. On the other hand, the recent growth of computer technology enabled us to perform a set of numerical simulations of developing snowdrift to search an optimal snow-fence design at a target site.

The numerical simulation on drifting snow requires the computational fluid

dynamics (CFD) and the estimate of snowdrift distribution. Studies on numerical simulation of drifting snow were started in the 1990s by Uematsu et al. (1991) and Liston et al. (1993). These studies succeeded in the wind simulation based on the Reynolds averaged Navier-Stokes (RANS) equations model with turbulence parameterizations such as K-theory and the $k-\varepsilon$ model. These models targeted a reproduction of snowdrift distribution around a simple snow fence. Some studies evolved these models to combine more complicated processes of drifting snow due to multiple snow events (Beyers et al. 2004; Tominaga et al. 2011a, 2011b). The large-eddy simulation (LES) has been recently applied to snow transport simulation, in order to describe turbulence more accurately (Okaze et al. 2018; Wang and Jia 2018). For example, Zwaafink et al. (2014) combined the LES and a Lagrangian stochastic model and succeeded in describing the temporal and spatial variability of drifting snow by their model. Some studies considered the momentum exchange between particles and background wind (Elghobashi 1994). Moreover, the turbulent wind is seriously influenced by not only the fixed boundary including topography and artificial obstacles but also temporally varying snow surfaces due to snowdrift. However, previous studies did not update the snow-surface boundary in the calculation because the conventional CFD algorithm needed high computational cost and one might face technical complexity in updating boundary conditions during the

simulation.

The Lattice Boltzmann method (LBM) is a brand-new CFD algorithm for a quick calculation with a simpler treatment for complicated boundary conditions like snow fences [McNamara and Zanetti (1988) for an original introduction and Benzi et al. (1992), Qian et al. (1995) and Chen and Doolen (1998) for comprehensive reviews]. The fundamental idea of the LBM is to equivalently replace the Navier-Stokes equation with the distribution function equation, called lattice Boltzmann equation, by regarding fluid flow as microscopic fictitious particles in the space lattice (Chen et al. 1992; Qian et al. 1992); the lattice Boltzmann equation can be numerically solved with the translation of distribution function and the relaxation to the equilibrium state. The LBM algorithm characterizes simpler implementation, more suitability for complicated boundary conditions, and higher efficiency in parallel computation, than the conventional CFD one (Chen and Doolen 1998). These advantages of the LBM algorithm are suitable for calculating wind flow around snowdrift when we update the surface boundary condition following snowdrift forms and when we calculate snowdrift around various types of road structures. The LBM was so applied to various fields such as wind flow in the urban environment with 1-m resolution (Onodera et al. 2013), the canopy turbulence in neutrally-satisfied condition (Watanabe et al. 2020), the flow in the porous media (Liu et

al. 2016), and the flow in the blood vessel (Zhang et al. 2008; Bernasch et al. 2009). These studies are the achievements of the LBM to be adopted to complicated boundary conditions. In the cryology field, Wang et al. (2006) simulated the change of snowing scene in various weather conditions and snow crystal types with LBM. Lu et al. (2009) also applied it to reproduce dendric snow crystal growth in the cloud. However, no studies applied LBM to compute blowing snow and snowdrift distribution.

This paper aims to develop a new LBM-based model for snowdrift distribution around an artificial snow fence. The model consists of the CFD module based on the LBM and the module of snow particles' motion and accumulation following Nishimura and Hunt (2000). Although temporally varying boundary conditions can be easily attached to this model, this paper is limited to the development of the core code for the first estimate of snowdrift distribution without any interactions between wind and snowdrift. We now implement a simple algorithm for snow particles' motion and accumulation. The remaining part of this paper is organized as follows: Sections 2 and 3 are the detail description of the developed model and experiments; in section 4, we show the result of the model simulation in comparison with previous studies of observation and numerical simulation, and we discuss the effect of snow fences to the snowdrift distribution; and section 5 concludes the paper.

2 Model

2.1 CFD module

The CFD module in the model we developed was based on a 3-dimensional LBM model with delivering microscopic fictitious particles to 19 neighbor nodes, usually referred as a D3Q19 configuration (Fig. 1). The discretized lattice Boltzmann equation is a prognostic equation of the distribution function for particles to the i -th direction, f_i , written as

$$f_i(\mathbf{r} + \mathbf{c}_i \Delta t, t + \Delta t) = f_i(\mathbf{r}, t) + \Omega_i \Delta t, \quad (1)$$

where $\mathbf{r}$ is the particle position vector, Δt is the time increment, Ω_i is the collision term, and $\mathbf{c}_i$ is the particle velocity vector.

The Bhatnagar-Gross-Krook approximation reduced the collision term Ω_i to the relaxation to the equilibrium state of distribution function (Chen et al. 1992; Qian et al. 1992):

$$\Omega_i = -\frac{1}{\tau} (f_i - \hat{f}_i). \quad (2)$$

Here τ is the relaxation time as a function of kinematic viscosity ν :

$$\tau = \frac{1}{2} + \frac{3\nu}{c^2 \Delta t}, \quad (3)$$

141 and $\hat{f}_i$ is the equilibrium distribution function for particles to the i -th direction calculated
 142 in the D3Q19 configuration as

$$\hat{f}_i = w_i \rho \left[1 + \frac{(\mathbf{c}_i \cdot \mathbf{u})}{c_s^2} + \frac{(\mathbf{c}_i \cdot \mathbf{u})^2}{2c_s^4} - \frac{|\mathbf{u}|^2}{2c_s^2} \right], \quad (4)$$

143 where

$$w_i = \begin{cases} \frac{1}{3} & (i = 0) \\ \frac{1}{18} & (i = 1, 2, \dots, 6), \\ \frac{1}{36} & (i = 7, 8, \dots, 18) \end{cases} \quad (5)$$

144 the lattice speed of sound $c_s = 1/\sqrt{3}$, and ρ and $\mathbf{u}$ are respectively the macroscopic
 145 density and velocity, computed in the D3Q19 configuration as

$$\rho = \sum_{i=0}^{18} f_i, \quad \text{and} \quad \mathbf{u} = \frac{1}{\rho} \sum_{i=0}^{18} f_i \mathbf{c}_i. \quad (6)$$

146 The sub-grid scale (SGS) parameterization (Feng et al. 2007; Onodera et al.
 147 2013; Wang et al. 2014; Suga et al. 2015) was implemented to estimate the eddy kinematic
 148 viscosity. We used Smagorinsky model (Smagorinsky 1963), where the eddy kinematic
 149 viscosity is related to the velocity gradient tensor $\mathbf{S}$:

$$\nu_t = C \Delta^2 |\bar{\mathbf{S}}|, \quad (7)$$

150 where Smagorinsky coefficient $C = 0.12$ (Tominaga et al. 2008) and $C = 60$ in the
 151 damping zone, 15 grids from the outlet boundary to damp the numerical oscillation near

152 the outlet (Inagaki et al. 2017). Δ is the cubic root of local mesh volume. $|\bar{\mathbf{S}}|$ was
 153 estimated in D3Q19 configuration as

$$|\bar{\mathbf{S}}| = \frac{3}{2\rho\tau} \sqrt{2 \sum_{k=1}^3 \sum_{j=1}^3 \sum_{i=0}^{18} (f_i - \hat{f}_i) c_{ij} c_{ik}}, \quad (8)$$

154 where c_{ij} and c_{ik} are the j -th and k -th component of $\mathbf{c}_i$, respectively.

155 The model domain was a finite channel in the 3-dimensional space spanned by
 156 wind direction as x , the horizontal direction normal to x (or fence direction) as y , and
 157 vertical direction z . Hereafter, only for convenience, the negative and positive ends of x
 158 in the domain are called western and eastern boundaries, those of y are southern and
 159 northern boundaries, and those of z are bottom and top boundaries, respectively. It is
 160 noted that the horizontal direction is rotational invariant in this system.

161 The LBM represents the western boundary condition with inflow $u_0 =$
 162 $(u_0(y, z), v_0(y, z), w_0(y, z))$ (Section 2.2) as

$$\begin{aligned} f_1 &= f_2 + \frac{\rho u_0}{3}, \\ f_7 &= f_{10} + \frac{f_4 + f_{17} + f_{18} - f_3 - f_{15} - f_{16}}{2} + \frac{\rho(u_0 + v_0)}{6} + \frac{\rho v_0}{3}, \\ f_8 &= f_9 + \frac{f_3 + f_{15} + f_{16} - f_4 - f_{17} - f_{18}}{2} + \frac{\rho(u_0 - v_0)}{6} - \frac{\rho v_0}{3}, \\ f_{11} &= f_{14} + \frac{f_6 + f_{16} + f_{18} - f_5 - f_{15} - f_{17}}{2} + \frac{\rho(u_0 + w_0)}{6} + \frac{\rho w_0}{3}, \end{aligned} \quad (9)$$

and

$$f_{13} = f_{12} + \frac{f_5 + f_{15} + f_{17} - f_6 - f_{16} - f_{18}}{2} + \frac{\rho(u_0 - w_0)}{6} - \frac{\rho w_0}{3}.$$

163 On the other side, the LBM represents the free-flow condition at the eastern boundary

164 (Hecht and Harting 2010) as,

$$\begin{aligned} f_2 &= f_1 - \frac{u_e}{3}, \\ f_{10} &= f_7 - \frac{f_4 + f_{17} + f_{18} - f_3 - f_{15} - f_{16}}{4} - \frac{u_e}{6}, \\ f_9 &= f_8 - \frac{f_3 + f_{15} + f_{16} - f_4 - f_{17} - f_{18}}{4} - \frac{u_e}{6}, \\ f_{14} &= f_{11} - \frac{f_6 + f_{16} + f_{18} - f_5 - f_{15} - f_{17}}{4} - \frac{u_e}{6}, \text{ and} \\ f_{12} &= f_{13} - \frac{f_5 + f_{15} + f_{17} - f_6 - f_{16} - f_{18}}{2} - \frac{u_e}{6}, \end{aligned} \tag{10}$$

165 where

$$\begin{aligned} u_e &= -1 + f_0 + f_3 + f_4 + f_5 + f_6 + f_{15} + f_{16} + f_{17} + f_{18} \\ &\quad + 2(f_1 + f_7 + f_8 + f_{11} + f_{13}). \end{aligned} \tag{11}$$

166 The southern and northern boundaries were cyclic: The distribution functions f_3 , f_7 , f_9 ,

167 f_{15} , and f_{16} at the southern boundary were respectively equal to those at the northern

168 boundary; and f_4 , f_8 , f_{10} , f_{17} , and f_{18} at the northern boundary were respectively equal

169 to those at the southern boundary. The top boundary was free-slip, *i.e.*, $\frac{du}{dz} = 0$. The LBM

170 representation was

$$f_6 = f_5, f_{13} = f_{11}, f_{14} = f_{12}, f_{16} = f_{15}, \text{ and } f_{18} = f_{17}. \quad (12)$$

171 The bottom boundary was no-slip, *i.e.*, $\mathbf{u} = 0$, so that the LBM represented it as bounce-
172 back,

$$f_5 = f_6, f_{11} = f_{14}, f_{12} = f_{13}, f_{15} = f_{18}, \text{ and } f_{17} = f_{16}. \quad (13)$$

173 The boundary on the fence was also no-slip as bounce-back, similarly given to Eq. (13).
174

175 **2.2 Inflow turbulence generation**

176 We generated the artificial inflow turbulence and imposed it as the inflow on the western
177 boundary. The inflow turbulence was generated as two-dimensional digital-filtered
178 random data by controlling time and spatial autocorrelations of the resultant inflow
179 turbulence (Okaze and Mochida 2017; Xie and Castro 2008). Now the total inflow
180 $\mathbf{u}_0(y, z, t)$ from the western boundary was divided into the time average $\langle \mathbf{u}_0 \rangle$ and the
181 deviation from it $\mathbf{u}'_0$. Here we assumed that the model domain is the constant flux layer.
182 The time-averaged vector was just eastward and the wind speed followed the logarithmic
183 profile of

$$\langle u_0(z) \rangle = \frac{u_*}{\kappa} \ln \left(\frac{z}{z_0} \right), \quad (14)$$

184 where u_* is the friction velocity (a parameter to be given), z_0 is roughness length for

185 flat snow surface (0.1 mm; Hiroo and Ishida 1973), and κ is the von Karman's constant
 186 (0.4). With more assumptions often used (Okaze and Moshida 2018), Reynolds stress
 187 tensor $\mathbf{R}$ for the inflow turbulence was parameterized as

$$\mathbf{R} = \begin{pmatrix} \langle u'_0 u'_0 \rangle & \langle u'_0 v'_0 \rangle & \langle u'_0 w'_0 \rangle \\ \langle v'_0 u'_0 \rangle & \langle v'_0 v'_0 \rangle & \langle v'_0 w'_0 \rangle \\ \langle w'_0 u'_0 \rangle & \langle w'_0 v'_0 \rangle & \langle w'_0 w'_0 \rangle \end{pmatrix} = u_*^2 \begin{pmatrix} 10/3 & 0 & -1 \\ 0 & 5/3 & 0 \\ -1 & 0 & 5/3 \end{pmatrix}. \quad (15)$$

188 The deviation from the time average is computed as $\mathbf{u}'_0(y, z, t) = \tilde{\mathbf{R}} \boldsymbol{\Psi}(y, z, t)$, where $\tilde{\mathbf{R}}$
 189 is the Cholesky decomposition of $\mathbf{R}$ and $\boldsymbol{\Psi}$ is the numerical solution of the stochastic
 190 equation (Xie and Castro 2008) of

$$\begin{aligned} \boldsymbol{\Psi}(y, z, t + \Delta t) \\ &= \boldsymbol{\Psi}(y, z, t) \exp\left(-\frac{\Delta t}{T}\right) \\ &+ \boldsymbol{\psi}(y, z, t + \Delta t) \left\{1 - \exp\left(-\frac{2\Delta t}{T}\right)\right\}^{1/2}, \end{aligned} \quad (16)$$

191 from the initial condition of $\boldsymbol{\Psi}(y, z, 0) = \boldsymbol{\psi}(y, z, 0)$. Here T is the characteristic
 192 timescale and $\boldsymbol{\psi}$ is digital-filtered normal random numbers that satisfy a spatial
 193 autocorrelation with the characteristic length L (Klein et al. 2003). $\boldsymbol{\psi}(y, z, t)$ was
 194 generated at each time step with the different random number. Here, following a modified
 195 Prandtl theory (Okuma et al. 1996), characteristic length L was parameterized as

$$L = \frac{1}{3} \kappa z. \quad (17)$$

196 Then, by assuming Taylor's hypothesis of frozen turbulence, the characteristic timescale

T was parameterized as

$$T = \frac{1}{3} \kappa z \langle u_0(z) \rangle. \quad (18)$$

It is noted that the inflow was numerically generated with the same grid spacing and the same time interval as the CFD module.

2.3 Snow particle module

The snow particle module in the model followed Nishimura and Hunt (2000) and Nemoto and Nishimura (2004). Assuming that drifting snow particles were spherical ice, electrically neutral, and not driven by the lift force, the motion equation for the particle was written as

$$\frac{d\mathbf{u}_p}{dt} = -\frac{3}{4} \left(\frac{\rho_a}{\rho_p d} \right) C_d V_R (\mathbf{u}_p - \mathbf{u}) - g \mathbf{k}, \quad (19)$$

where $\mathbf{u}_p$ (m s^{-1}) is the particle velocity vector, $\mathbf{u}$ (m s^{-1}) is the wind vector, $V_R = |\mathbf{u}_p - \mathbf{u}|$, g is gravity (9.8 m s^{-2}), ρ_a and ρ_p are respectively the density of the air (1.34 kg m^{-3}) and that of the particle (910 kg m^{-3}), d is the diameter of the particle ($100 \text{ }\mu\text{m}$; Nishimura et al. 2014), and C_d is the drag coefficient for the particle (White 1974) as,

$$C_d = \frac{24v_0}{V_R d} + \frac{6}{1 + V_R d / v_0} + 0.4, \quad (20)$$

211 where ν_0 is viscosity $10^{-5} \text{ m}^2 \text{ s}^{-1}$. The terminal fall velocity of a snow particle was 0.30
 212 m s^{-1} .

213 Observation results indicated that accumulated snow particles jumped out from
 214 the snow surface when the friction velocity was enough high to lift them (Shao and Li
 215 1999; Nemoto and Nishimura 2004). Based on this result, we assumed that a snow particle
 216 fell on the bottommost level and occupied a surface gridpoint when the friction velocity
 217 at the bottommost level was lower than the threshold. Here the friction velocity u_* (m
 218 s^{-1}) was computed by a different way from the inflow generation algorithm (Werner and
 219 Wegle 1991) as,

$$u_* = \begin{cases} \sqrt{\frac{2\nu_0|\mathbf{u}(z_b)|}{z_b}} & \text{for } |\mathbf{u}(z_b)| \leq \frac{\nu_0}{2z_b} A^{\frac{2}{1-B}} \\ \left\{ \frac{1-B}{2} A^{\frac{1+B}{1-B}} \left(\frac{\nu_0}{z_b}\right)^{1+B} + \frac{1+B}{A} \left(\frac{\nu_0}{z_b}\right)^B |\mathbf{u}(z_b)| \right\}^{\frac{1}{1+B}} & \text{for } |\mathbf{u}(z_b)| \geq \frac{\nu_0}{2z_b} A^{\frac{2}{1-B}} \end{cases}, \quad (21)$$

220 where z_b is the height of the bottommost grid just above the snow surface, $A = 8.3$, and
 221 $B = 1/7$. The threshold of friction velocity u_{*t} was computed following Bagnold
 222 (1941) and Clifton et al. (2006):

$$u_{*t} = 0.2 \sqrt{\frac{\rho_p - \rho_a}{\rho_a} g d} \sim 0.163 \text{ m s}^{-1}. \quad (22)$$

223 It is remarked that aerodynamic entrainment, rebound, splash, mass loss by sublimation

and disruption, the drag force to fluid, and coalescence of snow particles by the collision were all neglected.

3 Experiments

We performed three experiments with no fence, with a two-dimensional fence, and with a three-dimensional fence of its width of 1.5 m (Fig. 2). The fence was set at 4 m from the western boundary and was centered in the channel. The fence was non-porous, solid, and the thickness was 0.1 m and the height was 1 m. The following model settings were independent of the fence existence. The channel size was $15.75 \text{ m} \times 5 \text{ m} \times 5 \text{ m}$, with the grid spacing at 0.05 m. The origin of x -coordinate was 4 m from the western boundary, just at the position of the fence if any. In the CFD calculation, the integration time was 24 s and the time interval was 4 ms; the results were sampled every 0.08 s from the initial time. In the generation of the inflow turbulence, the total 40 s data was stored with an interval of 4 ms. The inflow turbulence was generated with the friction velocity such that the time averaged wind speed was 6 m s^{-1} westerly at 10 m aloft in the log-profile and the initial wind profile over the calculation domain was imposed as the same value. We used 24 s data of the generated inflow turbulence after the spin-up as the western boundary condition.

242 We numerically integrated the motion equation of snow particles [Eq. (19)]
 243 with the time interval being 1 ms. The particle was uniformly distributed on the western
 244 boundary plane per 2.5 cm height at the initial time, but we assumed that a single particle
 245 in the snow module represented snow-mass corresponding to snow volume flux
 246 depending on the height (Fig. 3b) as

$$v_f(z) = \alpha \frac{n(z)\langle u_0(z) \rangle}{\rho_p}. \quad (23)$$

247 Here $\alpha = 1500$ to accelerate the snow accumulation, and snow concentration $n(z)$ (g
 248 m^{-3}) is given (Fig. 3a; Shiotani 1953; Matsuzawa and Takeuchi 2002) by

$$n(z) = \min \left(30, 30 \left(\frac{z}{0.15} \right)^{\frac{0.30}{\kappa u_*}} \right), \quad (24)$$

249 where friction velocity u_* was estimated by Eq. (14). The snow particles' motion was
 250 driven by the sampled time segments of wind data obtained from each experiment with
 251 or without a fence; several snow-particle integrations were conducted with the CFD
 252 output starting from a different time. The initial wind profile based on the CFD module
 253 was given to the snow module every 0.4 s and the wind profile in the snow module was
 254 renewed every 0.08 s. The integration ended when all snow particles were fallen or flowed
 255 out of the calculation domain. Accumulated snow particles gave height on the grid
 256 corresponding to snow volume per grid area. Snow particles within the snowdrift did not

move, not collapse, not melt, and not sublimate.

4 Results

4.1 Artificial inflow turbulence

We first checked whether inflow turbulence successfully followed the target wind profile [Eq. (14)] and its corresponding Reynolds stress tensor [Eq. (15)]. Time-averaged inflow turbulence has a quite similar vertical profile to the target log-profile with 6 m s^{-1} westerly at 10 m height (not shown). The Reynolds stresses roughly agreed to prescribed values of $\langle u'u' \rangle \sim 10/3 u_*^2$, $\langle v'v' \rangle \sim \langle w'w' \rangle \sim 5/3 u_*^2$, $\langle u'w' \rangle \sim -u_*^2$, and $\langle v'u' \rangle \sim \langle v'w' \rangle \sim 0$ (Fig. 4).

4.2 No-fence experiment

The reference experiment without a fence was performed to demonstrate the validity of the new model and to check the spin-up time. Figure 5a displays the time series of wind speed at the center of the calculation domain over the integration period. We can see that the calculation is computationally stable during the period. Moreover, since the initial profile was all over the calculation domain, it almost took 2.6 s to run the information from the western boundary to the eastern end. This time span is regarded as the spin-up

period of the model. The effect of inflow turbulence was hence observed at the central position after half of the period (Fig. 5a). Therefore, the wind data calculated in the CFD module was discarded before 4 s, and the data segment selected after 4 s input the snow module. The vertical profile of the wind speed at the final time step was moreover suggestive of the effect of the non-slip bottom boundary. The westerly wind was considerably weaker than the initial log-profile (Fig. 5b).

The resultant snowdrift distribution is shown in Figure 6. Reminding Eqs. (19) and (24), the terminal fall velocity of snow particles was 0.3 m s^{-1} , and snow particles below 0.5 m height at the initial position had large volume flux. Snow particles were advected by the background flow $\sim 4 \text{ m s}^{-1}$ until deposition. Hence most of the snow particles fell within 6.7 m distance from the western boundary (Fig. 6). The horizontal distribution of snowdrift is dependent on the vertical distribution of snow volume flux. Snowdrift is expected to be uniformly about 0.3 m height in the calculation domain if the upper level on the western boundary has the same amount of snow volume flux as the lower level in the initial time. We can hereafter test the block effect of a fence at $x = 0$, because snowdrift was formed beyond the point without the fence.

4.3 Two-dimensional fence experiment

The horizontal wind like the no-fence experiment was distorted by the fence. Two-dimensional fence normal to the dominant wind direction created an ascending motion in the windward and a swirling eddy on the cross-section in the leeward (Fig. 7). The upper-level wind was intensified around the top of the fence. These features of wind profile corresponded to the previous studies (Uematsu et al. 1991; Liu et al. 2016). However, it is worthwhile remarked that the eddies were successively generated from the leeward of the fence. These eddies flowed to downstream following the dominant wind flow and the size and position on the cross-section irregularly varied in time (Figs. 7). At 8 s, a single eddy extended 2 m from the fence and another large eddy was found from $x = 2$ m to $x = 5$ m. The size of the latter eddy almost doubled to the former (Fig. 7a). The latter flowed to eastern direction and went out of the domain after 16 s (not shown). At 24 s, we found eddies on just right of the fence and on father downstream from $x = 7$ m to $x = 9$ m (Fig. 7b). An eddy was successively separated from the eddy right on the fence. The eddies excited by the fence augmented the fluctuations with a larger scale and a longer timescale.

The snowdrift distribution in this two-dimensional fence experiment is quite different from that in the no-fence experiment (Fig. 8a). Almost all of the snowdrift was

distributed on the windward of the fence, because surface wind speed was attenuated just left on the fence. The highest snowdrift had about 0.5 m height at $x = -1.0$ m. These results were consistent with the previous studies based on the conventional numerical simulation (Uematsu et al. 1991; Alhajraf 2004) and observation (Tabler 1994). On the leeward of the fence, there was few snowdrifts to be formed. This distribution is consistent with the first step of snowdrift development in Tabler (1994), which will be explained in detail in Section 5. There were three reasons for this result. First, most of snow particles climbing over the fence did not accumulate on just east of the fence, because strong wind above the fence accelerated snow particles. Figure 8b shows trajectories of three snow particles driven by the wind profile starting from 20 s. Particle starting from higher than 0.35 m height climbed over the fence and most of them were blown through the calculation domain, such as a particle starting from 1.25 m. Second, successively generated eddies on the leeward of the fence disturbed development of snowdrift on the certain point. A particle starting from 0.4 m height subsequently followed the streamline of the swirling eddy and fell on around 8 m east of the fence in Figure 8b, but a particle starting from 0.4 m height did not fell there in another time of wind profile because eddies moved, shown in the former paragraph. Third, some snow particles accumulating on the leeward of the fence had small snow volume flux, such as a particle

starting from 0.4 m height. Snowdrift on the point where this particle fell was only under 2.5 cm height (Fig. 8a), because this particle took a little snow volume flux. In contrast, a snow particle starting at 0.3 m height with a large snow volume flux fell on the surface of the windward. The two-dimensional snow fence was hence an effective obstacle to snowdrift development on the leeward, compared with the snowdrift distribution in the no-fence experiment (Fig. 6).

4.4 A three-dimensional fence experiment

The three-dimensional fence greatly changed the wind flow around the fence (Figs. 9,10). Quite different from the two-dimensional fence experiment, the wind flow vector had a 3-dimensional feature in the three-dimensional fence experiment. The along the center of the fence exhibited a weaker reverse flow than that of the two-dimensional fence experiment around the surface in the leeward from $x = 0$ m to $x = 3$ m at 8 s (Fig. 9a). At the same time, low-level wind flow was horizontally diffluent to go round the fence and a dipole pattern was noticeable in the leeward, with weak wake flow toward the center of the fence on the horizontal plane at $z = 0.5$ m (Fig. 10a). The wind flow at 24 s has weak eddy from $x = 1$ m to $x = 3$ m on the vertical plane (Fig. 9b). On the horizontal plane, a dipole pattern was still noticeable at the same time, but turbulent flow on 4 m

east of the fence was more intense than that of at 8 s due to the spread of turbulence generated by eddies on the horizontal plane in the leeward (Fig. 10b).

In the three-dimensional experiment, snowdrift had two-dimensional distribution (Fig. 11a). Snowdrift along the center of the y-axis in the windward was similar to that in the two-dimensional fence experiment (Fig. 11b). On the leeward, snowdrift was not formed behind the fence along the center of the y-axis, but it was formed in the no-fence zone (Fig. 11c). This snowdrift was developed ahead of the split flow (Figs. 10a, c) because there were constantly weak flow lines around the surface. This profile of snowdrift was consistent with previous studies regarding snowdrift around the cubes (Beyer et al. 2004; Okaze et al. 2013). Snow particles clarified the three-dimensional trajectories for snow deposition. A snow particle starting from 0.4 m height fell on the windward of the fence (Fig. 12a), whereas the particle from the same height climbed over the fence in the two-dimensional fence experiment. This difference was probably caused by weaker wind speed just above the three-dimensional fence due to energy loss accompanied with the horizontal diffluent (Fig. 10). Snow particle trajectories on a horizontal plane indicated the process of the formation of the snowdrift along the split streaks in the leeward. For example, a snow particle from $(y, z) = (1.5 \text{ m}, 0.1 \text{ m})$ did not collide with the fence and fell at a point along the stream of the horizontal diffluent

flow (Fig. 12b). These low-level particles formed the forking snowdrift in the leeward.

5 Conclusions and discussion

We developed the CFD and snow particle modules to evaluate the snow accumulation around snow fences. The snow particles were driven by the wind flow in the channel sampled from the CFD model experiment with LBM, and the snowdrift height was evaluated based on the previous study method. We designed the experiment with no fence, and the experiments with a two-dimensional fence or a three-dimensional fence, both installed normal to the dominant wind direction. The snowdrift distributions in both of the two-dimensional fence and the three-dimensional fence experiments were high in the windward of the fences, because most snow particles from lower levels did not climb over the fence due to weak wind and otherwise a varying, strong swirling eddy right on the fence often blew snow particles from higher level to out of the domain. However, it is noted that around the three-dimensional fence, the snow accumulation was found in the leeward along the horizontally diffluent wind flow. The CFD integration in the three-dimensional fence experiment increased the vorticity activity of a vertical component, whereas that in the two-dimensional fence experiment increased the vorticity activity of a horizontal component. The three-dimensional fence experiment was designed with the

fence blocking 30% of the channel width, but the ratio of fence length to channel width was probably related to which horizontal or vertical vorticity was dominant in the downward energy cascade for the existence of fences.

Snowdrift generation has three steps around the solid fence (Tabler 1994). Tabler (1994) showed that almost all of the snowdrift was developed in the windward of the fence. Tabler (1994) also argued that the top of snowdrift height was 0.6 times the height of the fence and there was the cavity between the snowdrift and the windward of the fence in the first step. The result of snowdrift distribution around the two-dimensional fence in our study was the part of the first step of snowdrift generation because snowdrift distribution in our study was consistent with the characteristics of the first step (Fig. 8a). The second of snowdrift generation, which step is filling the cavity, might be formed in our model when more snow particles flow in the calculation domain. However, in order to reproduce the snowdrift distribution of the third step, which step is developing snowdrift in leeward of the fence, the boundary condition in the CFD module should be renewed following the snowdrift surface in the windward and the process of particles' resuspension and redeposition should be included in the snow particle module.

We showed only the results in Section 4 under the condition that finite snow particles flowed in the calculation domain during finite time. However, the probability of

snowdrift development is also a point to evaluate the effect of the fence because a little height of snowdrift causes traffic disruption, reminding Section 1. Here, we introduced the snowdrift potential, based on 51 pieces of snowdrift simulation using different initial background flow sampled from the CFD calculation from 4 s to 24 s. For example, 50 % of snowdrift potential means that about 25 cases of the initial wind profile satisfied the condition of development of snowdrift height > 5 cm, just a single vertical grid interval, when infinitely number of snow particles flowed in from the western boundary. Figure 13 shows the results of snowdrift potential in the three experiments. Snowdrift potential in the no-fence experiment was more than 80 % over the calculation area because friction velocity under about 0.3 m was less than the threshold. This result indicated that snowdrift was possibly formed anywhere in the calculation domain by accumulating snow particles blowing from the western boundary. In contrast, snowdrift potential around the three-dimensional fence decreased so much on the leeward of the fence, less than 20 % just 4 m distance right on the fence. This feature suggested that snow particles were not likely to fall on the leeward. If once particles had accumulated there, they would be soon blown up to the air because of strong wind around the surface. Around the three-dimensional fence, snowdrift potential was low just behind but high elsewhere. The higher probability region extended along two arcs from the borders of the fence to the downstream. These

snowdrifts would be an obstacle for drivers if the road runs just downstream of the fence.

A similar situation to the three-dimensional fence experiment can be found in the break fence for the intersection. Rather than a single-sample estimate for snowdrift, the summary of ensemble simulation is probably useful to consider the risk of the snowdrift.

Toward more accurate simulation of snowdrifts, other processes of snow motion and accumulation must be included. For example, resuspension of snow particles from the surface is an important process in drifting snow. In the present model, this process was implicitly included in the prohibition of snow accumulation on the surface with strong wind. However, we did not consider the trajectories of resuspended snow particles and redeposition of them. These processes were indicated as aerodynamic entrainment, rebound and splash (Shao and Li 1999; Ammi et al. 2009). Moreover, the initial condition of the snow surface should be prescribed, because snow particles on the surface are drifted when friction velocity exceeded the threshold velocity.

This paper was limited to the experiment without any interactions between snow and wind. Snow particles and wind flow may exchange their momentum with each other. This possibly modifies the trajectory of snow particles (Figs. 8b, 12), so that they fall short in the windward of a fence. Moreover, there is an interaction between snow surface and wind flow. The snow accumulation changes the bottom boundary condition

436 in the CFD calculation. Since the snow particles generally accumulate in the weak wind
437 speed place in the windward of the three-dimensional fence (Fig. 8a), one easily guesses
438 that the snow surface in the windward is asymptotic to a streamline that crosses the top
439 of the fence. We can promptly implement this interaction process only to combine CFD
440 and snow particle modules, but this remains as the future work.

441

442

Abbreviations

CFD: Computational fluid dynamics; LBM: Lattice Boltzmann method; LES: large-eddy simulation; RANS: Reynolds averaged Navier-Stokes (RANS); SGS: sub-grid scale

Declarations

Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

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Authors' contributions

ST proposed the topic, conceived and designed the study, developed the main source code of the snowdrift model, analyzed the results, and wrote out the manuscript. MI helped in development of the snowdrift model, interpretation of the results, and writing the manuscript, TO made the artificial inflow turbulent and helped in development of the

snowdrift model. All authors discussed the results and read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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659

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661 Figures

662

663 Fig. 1. Schematics of the particle velocity vector $\mathbf{c}_i$ in the D3Q19 configuration of the

664 Lattice Boltzmann model.

665

(a)

(b)

(c)

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667 Fig. 2 Schematic diagram of the calculation domain and initial wind vectors, in the

668 experiment with (a) no fence, (b) a two-dimensional fence, and (c) a three-dimensional

669 fence.

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673 Fig. 3 Vertical profiles of (a) snow concentration and (b) snow volume flux of the initial

674 condition on the western boundary plane of the snow particle module.

675

Fig. 4 Vertical profile of six components of normalized Reynolds stress with the square of friction velocity at the center of the y-axis. The grey dotted line indicates the target value.

Fig. 5 (a) Time series of wind speed for the no-fence experiment at the center of the calculation domain from 0 s to 24 s. (b) The vertical wind speed profile for no fence experiment at $(x,y,t)=(3.5 \text{ m}, 2.5 \text{ m}, 24 \text{ s})$.

Fig. 6 Snowdrift profile for the no-fence experiment on the cross-section along $y = 2.5$ m.

Fig. 7 Wind vector around the two-dimensional fence on the cross-section along $y = 2.5$ m (a) at 8 s and (b) 24 s. The solid line at $x = 0$ shows the two-dimensional fence.

Fig. 8 (a) Snowdrift profile around the two-dimensional fence on the cross-section along $y = 2.5$ m. (b) Trajectories of snow particles at the center of the y -axis around the two-dimensional fence driven by the wind flow data segment starting at 20 s. The initial height of the particle is (circle marks) 0.35 m, (triangle) 0.4 m, and (square) 1.25 m. The plot of marks is every 0.2 s. The position of the fence is shown by a solid line.

Fig. 9 Wind vector around the three-dimensional on the cross-section along $y = 2.5$ m at (a) 8 s and (b) 24 s. The position of the fences shown by a solid line.

Fig. 10 Wind vector around the three-dimensional fence on the horizontal plane at $z = 0.5$ m at (a) 8 s and (b) 24 s. The position of the fences shown by a solid line.

Fig. 11 (a) Snowdrift height around the three-dimensional fence (b) on the cross-section along $y = 2.5$ m and (c) on the cross-section along $x = 2.5$ (m). The position of the fence is shown by a solid line.

Fig. 12 Trajectories of snow particles around the three-dimensional fence driven by the wind flow data segment starting at 20 s. (a) The initial height of the particle is (circle marks) 0.3 m, (triangle) 0.4 m, and (square) 1.25 m at the center of the y-axis. (b) The initial position of the particle is (cross marks) 1.5 m, (diamond marks) 2.5 m at the 0.1 m height. The plot of marks is every 0.2 s. The position of the fence is shown by a solid line.

Fig. 13 Snowdrift potential (a) around no fence, (b) around the two-dimensional fence, and (c) around the three-dimensional fence. The position of the fence is shown by a solid line.

Figures

Figure 1

Schematics of the particle velocity vector c_i in the D3Q19 configuration of the Lattice Boltzmann model.

(a)

(b)

(c)

Figure 2

Schematic diagram of the calculation domain and initial wind vectors, in the experiment with (a) no fence, (b) a two-dimensional fence, and (c) a three-dimensional fence.

Figure 3

Vertical profiles of (a) snow concentration and (b) snow volume flux of the initial condition on the western boundary plane of the snow particle module.

Figure 4

Vertical profile of six components of normalized Reynolds stress with the square of friction velocity at the center of the y-axis. The grey dotted line indicates the target value.

Figure 5

(a) Time series of wind speed for the no-fence experiment at the center of the calculation domain from 0 s to 24 s. (b) The vertical wind speed profile for no fence experiment at $(x,y,t)=(3.5\text{ m}, 2.5\text{ m}, 24\text{ s})$.

Figure 6

Snowdrift profile for the no-fence experiment on the cross-section along $y = 2.5$ m.

Figure 7

Wind vector around the two-dimensional fence on the cross-section along $y = 2.5 \text{ m}$ (a) at 8 s and (b) 24 s . The solid line at $x = 0$ shows the two-dimensional fence.

Figure 8

(a) Snowdrift profile around the two-dimensional fence on the cross-section along $y = 2.5$ m. (b) Trajectories of snow particles at the center of the y -axis around the two-dimensional fence driven by the wind flow data segment starting at 20 s. The initial height of the particle is (circle marks) 0.35 m, (triangle) 0.4 m, and (square) 1.25 m. The plot of marks is every 0.2 s. The position of the fence is shown by a solid line.

Figure 9

Wind vector around the three-dimensional on the cross-section along $y = 2.5$ m at (a) 8 s and (b) 24 s. The position of the fences shown by a solid line.

Figure 10

Wind vector around the three-dimensional fence on the horizontal plane at $z = 0.5 \text{ m}$ at (a) 8 s and (b) 24 s. The position of the fences shown by a solid line.

Figure 11

(a) Snowdrift height around the three-dimensional fence (b) on the cross-section along $y = 2.5$ m and (c) on the cross-section along $x = 2.5$ (m). The position of the fence is shown by a solid line.

Figure 12

Trajectories of snow particles around the three-dimensional fence driven by the wind flow data segment starting at 20 s. (a) The initial height of the particle is (circle marks) 0.3 m, (triangle) 0.4 m, and (square) 1.25 m at the center of the y -axis. (b) The initial position of the particle is (cross marks) 1.5 m, (diamond marks) 2.5 m at the 0.1 m height. The plot of marks is every 0.2 s. The position of the fence is shown by a solid line.

Figure 13

Snowdrift potential (a) around no fence, (b) around the two-dimensional fence, and (c) around the three-dimensional fence. The position of the fence is shown by a solid line.