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Measurements of blowing snow, part II: Mass and number density profiles and saltation height at Franklin Bay, NWT, Canada

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ABSTRACT

Blowing snow is a frequent and significant winter weather event, and there is currently a need for more observations and measurements of blowing snow, especially in arctic and subarctic environments. This paper is the second part in a two part series studying blowing snow in Churchill, Manitoba, and Franklin Bay, NWT. In this part, the development and use of a camera system to measure the relative blowing snow density profile near the snow surface is described. This system has been used, along with standard meteorological instruments and optical particle counters, during a field campaign at Franklin Bay, NWT. A best-fit to the mass density profile in the saltation layer is derived, assuming a half-normal distribution of the vertical ejection velocity of saltating particles. Within the saltation layer, the observed vertical profile of mass density is found to be proportional to the function $\exp(-0.61z/\bar{h})$, where $\bar{h}$ is the average height of the saltating particles. For the range of conditions studied, $\bar{h}$ varies from 1.0 to 10.4 mm, while the extent of the saltation layer varies from 17 to over 85 mm. There is a weak correlation between $\bar{h}$ and the square of friction velocity. There are weak negative correlations between $\bar{h}$ and temperature and relative humidity. No correlation is seen between $\bar{h}$ and the snow age. At greater heights, $z>0.2$ m, the blowing snow density varies according to a power law ($\rho_s \propto z^{-\gamma}$), with a negative exponent $0.5<\gamma<3$. Between these saltation and suspension regions, results suggest that the blowing snow density decreases following a power law with an exponent possibly as high as $\gamma \approx 8$.

1. Introduction

This paper is the second part of a two part series. For an overview of the frequency, impact, and physical processes of blowing and drifting snow, the reader is referred to Gordon and Taylor (2008) (Hereafter GT08). We will use the term blowing snow to refer to aeolian transport of snow particles at all heights without distinction between blowing snow, which is at or above eye level, and drifting snow, which is closer to the ground (as defined in Atmosphere Environment Service, 1977). GT08 presents the results of a camera system which records the number and size of blowing snow particles. This system was used during two blowing snow episodes in Churchill, Manitoba on December 14 and 20, 2006. Blowing snow particles were also collected and digitally imaged in Churchill to study the shapes of the particles. The second camera system, discussed in this paper, records the mass density profile of blowing snow near the surface. This system was used in Franklin Bay, NWT between February and April, 2004, during the Canadian Arctic Shelf Exchange Study (CASES).

The primary mechanism of blowing snow particle motion near the surface is saltation (Pomeroy and Gray, 1990). Saltating particles are those which become dislodged and ejected into the boundary layer, are accelerated by aerodynamic drag forces, and follow a projectile trajectory moving back to the surface under the influence of gravity. Upon impact with the surface, the particle may bounce back into the flow, or its momentum may be transferred to other particles. Snow experiences strong bonding between particles on the surface, which inhibits particle motion. Age and wetness of the snow can increase the strength of these bonds, and hence inhibit the onset of blowing snow (e.g. Clifton et al., 2006). Some saltating particles are lifted by turbulent eddies and carried into the suspension layer. Hence, the saltation layer is effectively a source for the suspension layer, and the amount and intensity of blowing snow depends primarily on the dynamics of saltating particles.

Many blowing snow models, such as PIEKTUK (Déry et al., 1998) and the Prairie Blowing Snow Model, PBSM (Pomeroy et al., 1993), use empirical parameterizations of the mass flux and particle size distribution at the top of the saltation layer as a lower boundary condition for the suspension layer. Hence, the accuracy of these models is limited by knowledge of the saltation layer. To calculate the total sublimation rate of blowing snow, PIEKTUK assumes a constant horizontal blowing snow flux in the saltation layer, which has not been verified with experimental observations. Although measurements of variables within the saltation layer such as mass flux and particle density exist (e.g. Kikuchi, 1981 and Maeno et al., 1985), there

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is now a significant need for more observations, especially in arctic and subarctic environments.

The purpose of this paper is to provide data to improve knowledge of the saltation layer. These data can be used to improve the accuracy of existing models, which may result in increased forecast reliability.

2. Background

The friction velocity is defined as $u_* = \sqrt{\tau_0/\rho_a}$, where τ_0 is the fluid shear stress at the surface and ρ_a is the density of air. Owen (1964), following Bagnold (1941), suggested that the mean initial vertical velocity of saltating particles is proportional to the friction velocity. This suggests that the average saltation height of particles can be calculated as

$$h_s = a u_*^2/2g, \tag{1}$$

where a is a dimensionless constant, and g = 9.81 m s^{-2} is the acceleration of gravity. Based on experimental results of saltating sand, Owen (referenced in Greeley and Iversen, 1985) proposed that a = 1.6. However, the constant a could also be dependent on the ratio of particle-to-air density and the size of the particles and could differ for blowing snow. Assuming that $a \propto \rho_a/\rho_p$, where ρ_p is the density of the particle, the constant a for saltating snow would be approximately 2.6 times greater than a for saltating sand.

In the suspension layer (discussed in GT08), Prandtl (1952) proposed an equilibrium balance between upward transport by turbulent diffusion and downward settling of particles due to gravity. Assuming there is no net influx of particles from the surface and ignoring sublimation, this gives a blowing snow mass density for a given particle radius of

$$\rho_{s,i}(z,r) = \rho_{sr,i}\left(\frac{z}{z_r}\right)^{-\gamma_i}, \tag{2}$$

where $\rho_{sr,i}$ is a reference blowing snow density for a given particle radius at height z_r, $\gamma_i = \omega_{si}/\kappa u_*$, ω_{si} is the average particle settling velocity for a given radius and κ=0.4 is the von Kármán constant. Eq. (2) is sometimes modified (e.g. Budd, 1966) to give

$$\rho_s(z) = \rho_{sr}\left(\frac{z}{z_r}\right)^{-\gamma}, \tag{3}$$

where ρ_{sr} is a reference blowing snow density for all particle sizes at height z_r, and $\gamma = \omega_s/\kappa u_*$, where ω_s is a bulk settling velocity representing all particle sizes.

Kawamura (1948) derives an expression for the horizontal mass flux of saltation snow by assuming that uniformly sized particles are ejected from the surface with velocities that follow a Maxwell distribution. This gives a half-normal distribution for the vertical component of velocity,

$$f_w(w) = \frac{2}{\pi\overline{w}}\exp\left(-\frac{1}{\pi}\frac{w^2}{\overline{w}^2}\right), \text{ with } w>0, \tag{4}$$

where $\overline{w}$ is the average particle ejection velocity. Neglecting air resistance in the vertical direction, the saltation height of a particle relates to the ejection velocity as $h = w^2/2g$. McElwaine et al. (2004) measured the trajectories of saltating particles using digital imaging in a wind tunnel. From these trajectories, they extrapolated the vertical component of the ejection velocities for particles saltating over fresh and compact snow. These data are shown in Fig. 1a and b (derived from figures 4 and 2 respectively, in McElwaine et al., 2004). They note that velocities of w<0.25 m s^{-1} are under-represented in their analysis, due to limitations of the measurement system. The ejection velocity w=0.25 m s^{-1} corresponds to a particle saltation height of h=3.2 mm. As shown in Fig. 1, the data for w>0.25 m s^{-1} show a relatively good fit to the half-normal distribution of Eq. (4).

Following Kawamura, if F_z [kg m^{-2} s^{-1}] is the vertical mass flux of particles at the surface, then the mass of particles per unit area between heights z and z+dz is

$$\rho_s(z)\mathrm{d}z = F_z\int_{w_o}^{\infty} f_w(w)2\mathrm{d}t\mathrm{d}w, \tag{5}$$

since all particles with ejection velocity greater than $w_o = \sqrt{2gz}$ will pass though the space between z and z+dz twice, for a length of time dt on each pass. Energy conservation gives $(\mathrm{d}z/\mathrm{d}t)^2 = w^2 - 2gz$. Since $2gz = w_o^2$, we obtain $\mathrm{d}t = \mathrm{d}z/\sqrt{w^2-w_o^2}$ to substitute into Eq. (5). This gives

$$\rho_s(z) = \frac{4F_z}{\pi\overline{w}}\int_{w_o}^{\infty}\frac{\exp\left(-w^2/\left(\pi\overline{w}^2\right)\right)}{\sqrt{w^2-w_o^2}}\mathrm{d}w, \tag{6}$$

It is noted that this equation does not hold at the surface since at z=0, w_o=0. Letting $f_h(h)$ represent the distribution of particle saltation heights, $f_w(w)\mathrm{d}w = f_h(h)\mathrm{d}h$, which gives

$$f_h(h) = \frac{\sqrt{2g}}{\pi\overline{w}\sqrt{h}}\exp\left(-\frac{2gh}{\pi\overline{w}^2}\right). \tag{7}$$

The average saltation height is defined as

$$\overline{h} = \int_0^{\infty} h f_h(h)\mathrm{d}h = \frac{\pi\overline{w}^2}{4g}. \tag{8}$$

Letting $\zeta = w/w_o$, Eqs. (6) and (8) give

$$\rho_s\left(\frac{z}{\overline{h}}\right) = \frac{2F_z}{\sqrt{\pi g\overline{h}}}\int_1^{\infty}\frac{\exp\left(-\left(z/\overline{h}\right)\left(\zeta^2/2\right)\right)}{\sqrt{\zeta^2-1}}\mathrm{d}\zeta. \tag{9}$$

As there is no analytical solution for this integral, it is solved numerically (see Appendix for details). The solution is shown as a

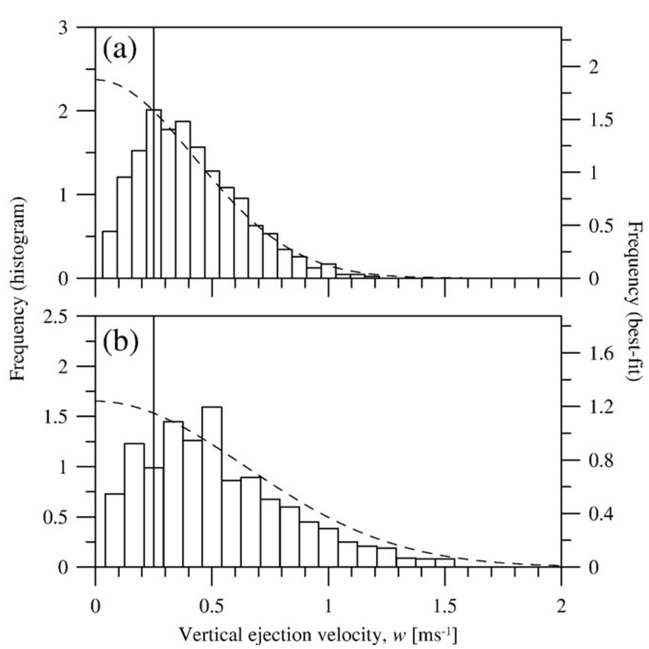

Fig. 1. Distribution of the vertical component of ejection velocity from McElwaine et al. (2004) for fresh (a) and compact (b) snow. The number of particles sampled are 1629 (a) and 1366 (b). Best-fit half-normal distributions are shown (dashed lines), scaled with the right axes, to demonstrate the agreement with the McElwaine et al. results.