PARTICLE SIZE DEPENDENCE OF HORIZONTAL SNOW MASS FLUX IN DRIFTING SNOW

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ABSTRACT: For understanding the drifting snow structure on saltating particles with particle size distribution over the loose surface, wind tunnel experiments were carried out at friction velocities, u_*, 0.15, 0.23, 0.30, 0.39 ms^{-1} (reference wind speeds of 4, 6, 8, 10 ms^{-1}). The air temperature was kept at -15 ℃ to avoid rapid sintering between snow particles. Disintegrated particles of natural compact snow, an arithmetical mean of which was 0.36 mm, were used. The number flux of drifting snow particles was measured with a snow particle counter at the leeward end at five heights of 16, 21, 31, 41 and 61 mm above the snow surface. The horizontal snow mass flux of each particle diameter, q_d, decreased exponentially with increasing height, and could be described as $q_d=A_d\exp(-B_dz)$, where z is the height, A_d is the horizontal snow mass flux of each particle diameter at the surface (z = 0), and B_d is the gradient of flux decay of each particle diameter. The reciprocal of B_d is a measure of saltation height at each particle diameter. The obtained results are as follows:

(1) A_d increased with increase in particle diameter and friction velocity in general. The dependence on friction velocity varied with particle diameter, that is A_d increased with friction velocity at larger particles, but at smaller particles A_d was independent of friction velocity due to random turbulence effects.

(2) A dimensionless parameter of each particle diameter, λ_d, was introduced as $\lambda_d \equiv B_d/(u_*^2/2g)^{-1}$, where g is the acceleration due to gravity, and $(u_*^2/2g)$ is the scaling height. λ_d was independent of friction velocity at larger particles, and approached a constant value 0.1~0.3 ($\lambda_d \cong 0.2$) characterizing the saltation height. This indicates that we can estimate a universal height ($\cong 5(u_*^2/2g)$) at which the horizontal mass flux virtually diminishes in a saltation layer.

(3) The total snow transport rate, Q_d, was calculated at each particle diameter by integrating q_d from the surface to the infinity. The dimensionless total snow transport rate of each particle diameter, $Q_d g \rho_a^{-1} u_*^{-3}$, where ρ_a is the density of air, varied with increasing particle diameter, and was found to increase more rapidly than the theoretical estimates by Bagnold (1941) and Owen (1964).

KEYWORDS: Drifting snow, Wind tunnel, Saltation, Mass flux.

1. INTRODUCTION

When wind velocity over a loose surface, which is a source of particles, increases gradually, the particles rise from the surface. The aeolian transport of particles, such as drifting snow, becomes more active with increasing wind velocity. Although the total snow transport rate has been measured as a function of wind velocity, there is a large variation in the estimated snow transport rates, probably due to snow properties and differences in particle collection efficiency of their instruments, most of which captured particles directly. Then, a snow particle counter, which individually counts the number flux of snow particles in drifting snow without capturing them directly, has been developed by Schmidt (1977) and Kimura and Sato (1988), and was verified in the field and in the wind tunnel (Sato and Kimura, 1993; Sugiura *et al.*, 1999). Sugiura *et al.* (1998) gave some examples of the use of a snow particle counter, and experimentally confirmed that the total snow transport rate in saltation mechanism increased with the 3-power of friction velocity suggested by Bagnold (1941) theoretically.

Although a great deal of effort including the above has been made on the total snow transport rate, our knowledge on the fundamental particle motion process of drifting snow is not enough to

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understand the structure of drifting snow, the development of drifting snow and other features of drifting snow movement. The fundamental particle motion process, especially splash process, has been recently brought to light by Kosugi *et al.* (1995), Sugiura *et al.* (1997), Sugiura (1999) and Sugiura & Maeno (2000). Sato *et al.* (In press) observed the saltation layer structure in the wind tunnel under conditions of wind speed, snow temperature and hardness of snow cover. It is now necessary to study the fundamental particle motion process of drifting snow as functions of not only wind velocity but also snow properties.

The purpose of this work is to investigate the fundamental particle motion process of drifting snow focused on snow particle diameter. To study the saltation process transporting drifting snow particles, wind tunnel experiments were carried out and the number flux of drifting snow particles was measured using a snow particle counter that enabled us to make size dependence analyses.

2. APPARATUS AND PROCEDURES

A wind tunnel in which drifting snow experiments were carried out is of a return-flow type, a working length 8.0 m, and a cross-sectional area 0.5 m×0.5 m, as shown in Figure 1.

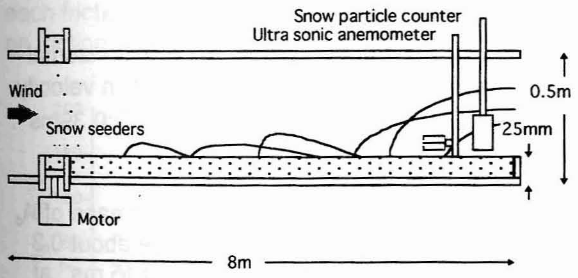

Figure 1: Schematic diagram of the wind tunnel.

The entire wind tunnel was located in a large cold room maintained at -15 ℃. Natural snow blocks in the fields were stored in a cold room at -15 ℃ for about one year, and were disintegrated into individual particles which were scattered on the tunnel floor. A snow cover of 25 mm in thickness was made as smoothly as possible on the tunnel floor. The particle size distribution of the used snow was obtained from image analysis with photographs, and was with an average diameter and standard deviation of 0.36 mm and 0.14 mm, respectively.

Wind velocities were measured with an ultrasonic anemometer set near the snow surface. Friction velocities estimated by the eddy correlation method were u_*=0.15, 0.23, 0.30 and 0.39 ms^{-1} for the reference wind velocities at 250 mm above the snow surface of 4.0, 6.0, 8.0 and 10.0 ms^{-1}, respectively.

Steady drifting snow was produced by seeding a small number of snow particles from the bottom at the windward end. At a friction velocity of 0.15ms^{-1}, however, it was also necessary to supply snow particles not only from the bottom but also from the top.

The number flux of drifting snow particles was measured with a snow particle counter of an optical sensor (SPC-S7, Niigata Electric Co.) set at the leeward end at five heights of 16, 21, 31, 41 and 61mm above the snow surface. The range of particle size used for the following analyses was between 37 and 641 μm.

3. EXPERIMENTAL RESULTS

3.1 <u>Size dependence of horizontal mass flux</u>

Assuming that snow particles are spherical, the horizontal snow mass flux, q, is calculated as

$$q=\sum q_{d}=\sum q'_{d}\frac{4}{3}\pi\left(\frac{d}{2}\right)^{3}\rho_{p}, \qquad (1)$$

where q_d is the horizontal snow mass flux for the particle diameter of d, q'_d is the number flux of the drifting snow particle, and ρ_p is the density of the drifting snow particle assumed to be 917 kgm^{-3}.

The obtained vertical profiles of the horizontal snow mass flux are shown in Figure 2.

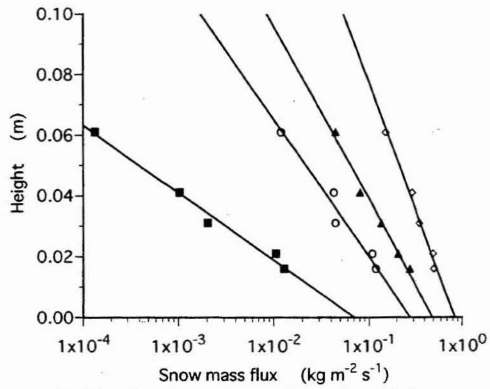

Figure 2: Vertical profiles of horizontal snow mass flux. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

Since it was found that q decreased exponentially with increasing height, q can be described as

$$q = A\exp(-Bz), \tag{2}$$

where z is the height, and A and B are the constants. A is the horizontal snow mass flux at the surface (z = 0). B is the gradient of flux decay, and the reciprocal of B is the scaling height. The exponential decay of the horizontal snow mass flux agrees with a considerable number of studies on the aeolian transport of particles.

The horizontal snow mass flux was decomposed into fluxes of each particle diameter according to the SPC diameter distribution, and these are shown in Figure 3.

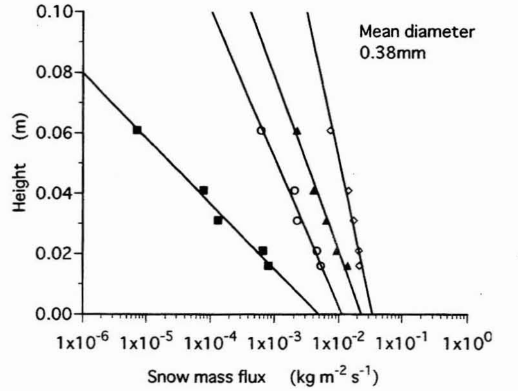

Figure 3: One example of vertical profiles of horizontal snow mass flux of each particle diameter. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

Since it also decreased exponentially with increasing height, it could be described by an equation similar to Equation (2):

$$q_d = A_d \exp(-B_d z), \tag{3}$$

where the subscript d means the particle diameter. A_d and B_d were determined by applying the horizontal mass flux profile of each particle diameter to Equation (3), and are functions of the number, speed and particle diameter of drifting snow particles.

First, it is important to note that the constant A, that is the horizontal mass flux at z = 0, increased with friction velocity, as shown in Figure 4, and A_d increased with diameter in any friction velocities (Figure 5).

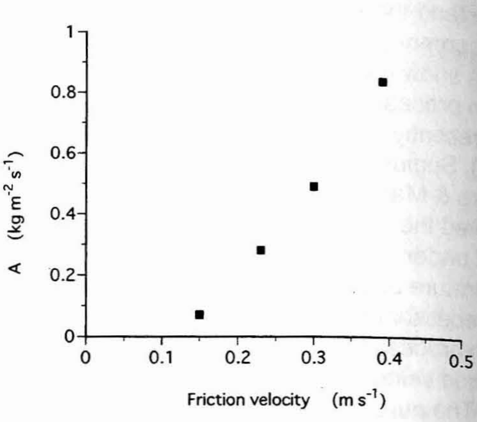

Figure 4: Horizontal snow mass flux at the surface versus friction velocity.

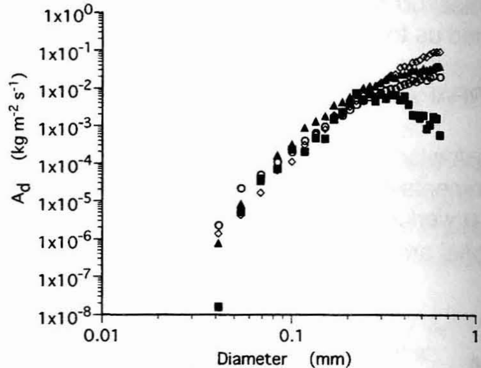

Figure 5: Particle size dependence of horizontal snow mass flux at the surface. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

At a friction velocity of 0.15 ms^{-1}, a decrease of A_d was noted at particle diameters above about 0.3 mm. Except for a friction velocity of 0.15 ms^{-1} at particle diameters above about 0.3 mm, it seems that the dependence of A_d on friction velocity varied; A_d increased with friction velocity at larger particles, but A_d was independent of friction velocity at smaller particles. Therefore, although A, which is the horizontal mass flux at the surface, increases with friction velocity, it is found that the larger particles contribute an increase in the horizontal snow mass flux at the surface especially.

Secondly, it is important to note that the constant B, that is the gradient of flux decay, depends on friction velocity, that is, decreased with increasing friction velocity, as shown in Figure 6.

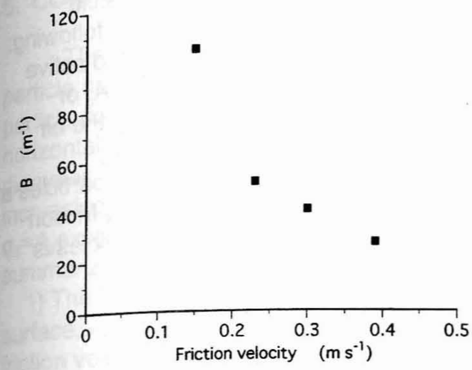

Figure 6: The gradient of flux decay versus friction velocity.

A dimensionless parameter of each particle diameter, λ_d, which is normalized with the approximate vertical scaling height, $(u_*^2/2g)$, where g is the acceleration due to gravity, can be introduced as

$$\lambda_d \equiv \frac{B_d}{\left(\frac{u_*^2}{2g}\right)^{-1}}. \quad (4)$$

Figure 7 shows that the relation between the constants (B_d and λ_d) and the particle diameter at each friction velocity, and that B_d depends not only on friction velocity but also on particle diameter.

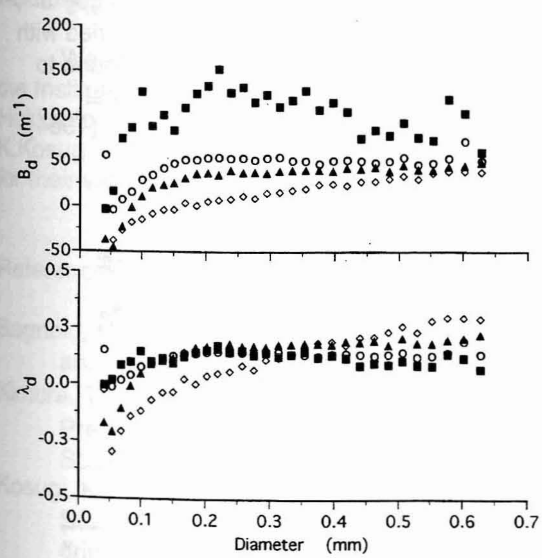

Figure 7: Particle size dependence of B_d and λ_d. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

Thus, the decrease of B with increasing friction velocity can be explained as the contribution of smaller particles. What the values of B_d and λ_d are smaller or negative means that the horizontal snow mass flux remains constant or even increases with height. This may indicate that the horizontal velocity or the concentration of smaller snow particles increases with height. That is, smaller particles are affected by the wind, and are transported by suspension mechanism. On the other hands, λ_d seems to be independent of friction velocity at larger particles. It is especially noteworthy that λ_d approaches a constant and universal value 0.1~0.3 ($\lambda_d \cong 0.2$) at larger particles, which are transported by saltation mechanism. This indicates that saltating particles can reach a higher place from the surface with increasing friction velocity. We can obtain the characteristic height ($\cong 5(u_*^2/2g)$) at which the horizontal mass flux virtually diminishes in a saltation layer.

3.2 Size dependence of total transport rate

The total snow transport rate of each particle diameter, Q_d, was calculated by integrating the horizontal snow mass flux of each particle diameter,

$$Q_d = \int_0^\infty q_d dz = \frac{A_d}{B_d}. \quad (5)$$

In general, the total snow transport rate of each particle diameter increased with particle diameter and friction velocity, except for a friction velocity of 0.15 ms^{-1} and a few points of smaller particles at other friction velocities (Figure 8). It is found that the larger particles especially contribute an increase in the total snow transport rate.

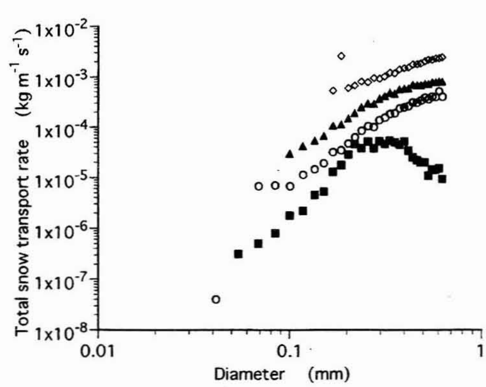

Figure 8: Particle size dependence of total snow transport rate. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

4. DISCUSSIONS

4.1 Horizontal mass flux

At a friction velocity of 0.15 ms^{-1}, a decrease of A_d was noted at particle diameters above about 0.3 mm. This can be explained by threshold conditions as follows: According to Bagnold's (1941) analysis for sand particles, the fluid and impact threshold friction velocities can be expressed as

$$u_{*t} = C\sqrt{\frac{(\rho_p - \rho_f)gd}{\rho_f}}, \qquad (6)$$

where u_{*t} is the threshold friction velocity, C is the constant, ρ_p and ρ_f are the densities of the particles and the fluid, respectively, and d is the diameter of particles. C is defined as 0.1 in case of the fluid threshold, or 0.08 in case of the impact threshold. When the particle friction Reynolds number, u_*d/ν, where ν is the kinematic viscosity of the air, is less than 3.5, the surface approaches the aerodynamically smooth and Equation (6) does not apply to this case. Figure 9 shows the calculated threshold friction velocities applied to ice particles. Since fluid and impact threshold friction velocities for particles larger than 0.3 mm are nearly equal to or larger than 0.15 ms^{-1}, it is reasonable to assume that the horizontal snow mass flux of each particle diameter at the surface decreases at a friction velocity of 0.15 ms^{-1}. Therefore, it seems reasonable to suppose that the total transport rate also decreases at a friction velocity of 0.15 ms^{-1} due to the decrease of A_d.

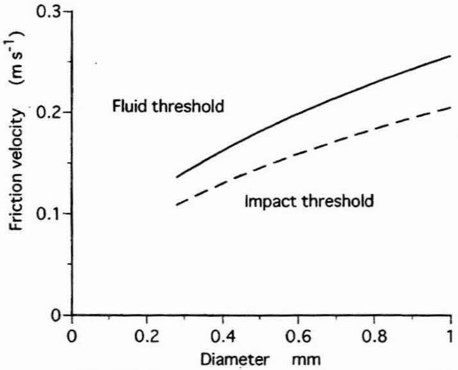

Figure 9: Fluid and impact threshold friction velocities of ice particles.

It was shown that at smaller particles A_d was independent of friction velocity (Figures 5). These smaller particles are transported by suspension mechanism, as stated above, and possible explanations for the results may be the following: Since the air stream is mixed well due to active particle motion near the loose surface, A_d of smaller particles effectively affected by the air stream is independent of friction velocity. Furthermore, since a source of smaller particles at the surface may be less with increasing friction velocity, it seems that A_d of smaller particles is independent of friction velocity.

4.2 Total transport rate

It has been reported that the total transport rate increases with friction velocity, and the dependence of the total transport rate on friction velocity has been the subject of controversy. Sugiura *et al.* (1998) analyzed the total transport rate at different snow particle diameters, and suggested that the suspended particles led to an increase in the exponent of friction velocity and that the exponent (= 3) predicted by Bagnold's theory in saltation was verified experimentally.

Based on dimensional analyses, Bagnold (1941) introduced the dimensionless express of the total transport rate using the 3-power of friction velocity, $Q_d g \rho_a^{-1} u_*^{-3}$, where ρ_a is the density of air. Bagnold (1941) expressed that $Q_d g \rho_a^{-1} u_*^{-3}$ is in proportion to the square root of particle diameter. On the other hands, Owen (1964) noted that $Q_d g \rho_a^{-1} u_*^{-3}$ is in proportion to the 3/4-power of particle diameter for large particles. Figure 10 shows the dimensionless parameter, $Q_d g \rho_a^{-1} u_*^{-3}$, against particle diameter. $Q_d g \rho_a^{-1} u_*^{-3}$ varied with increasing particle diameter, and was found to increase more rapidly than the theoretical estimates by Bagnold (1941) and Owen (1964).

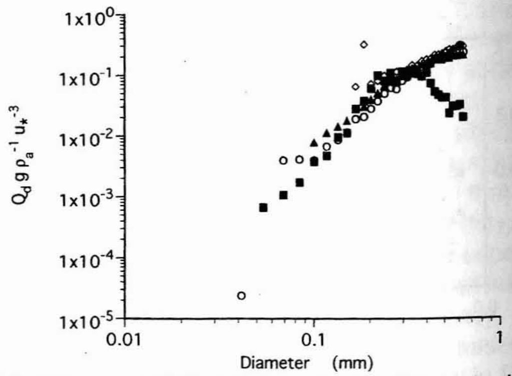

Figure 10: Relationship between dimensionless parameter and particle diameter. ■:Friction velocity of 0.15ms^{-1}; ○:0.23ms^{-1}; ▲:0.30ms^{-1}; ◇:0.39ms^{-1}.

5. CONCLUSIONS

The number flux profiles of each snow particle diameter was measured with a snow particle counter of an optical sensor. The horizontal snow mass flux of each particle diameter, q_d, decreased exponentially with increasing height, and could be described as $q_d=A_d\exp(-B_d z)$. The obtained results are summarized as follows:

1) The horizontal snow mass flux at the snow surface, A_d, increased with particle diameter and friction velocity in general. The dependence of A_d on friction velocity varied with particle diameter, that is A_d increased with friction velocity at larger particles, but at smaller particles A_d was independent of friction velocity due to random turbulence effects.

2) A dimensionless parameter of each particle diameter, λ_d, which was normalized with the scaling height, was introduced as $\lambda_d \equiv B_d/(u_*^2/2g)^{-1}$. λ_d was independent of friction velocity at larger particles, and approached a constant value 0.1~0.3 ($\lambda_d \cong 0.2$) characterizing the saltation height.

3) The dimensionless total snow transport rate of each particle diameter, $Q_d g \rho_a^{-1} u_*^{-3}$, varied with increase in particle diameter, and was found to increase more rapidly than the theoretical estimates by Bagnold (1941) and Owen (1964).

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