DYNAMICAL BEHAVIORS OF SNOW PARTICLES IN THE SALTATION LAYER*

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Abstract: A photographic technique was developed to analyze dynamical behaviors of saltating particles in blowing snow. Each photograph taken with this technique can give information of trajectories of flying snow particles as well as their velocities and accelerations at each height. The analyses have shown that horizontal drag the surrounding air flow exerts on saltating particles is of Stokes type and the drag coefficient C_D can be represented as $C_D=N/Re$ where Re is the Reynolds number and N is numerical constant ranging from 0.6 to 9.

As for vertical motions a substantial downward force was found to act on a snow particle at the time of both its ascent and descent; Ascending snow particles did not reach the maximum height $v_0^2/2g$ where v_0 and g are respectively the initial vertical velocity and the acceleration of gravity, and the maximum heights measured were smaller than those calculated by taking account of drag due to the surrounding air.

1. Introduction

When a wind blowing over a snow surface is sufficiently strong, snow particles begin to be picked up and transported along the surface in a series of successive short trajectories. Each trajectory is a flying path of a snow particle ejected from the surface, which at impact may bounce or kick up other particles. This type of transport is known as *saltation* in a research field of sand grain movements (BAGNOLD, 1941). The saltation layer is a thin lower part of air flow on the snow surface, in which particles are transported by wind mostly in a mode of saltation.

Many photographs of trajectories of saltating particles have been taken in sand storms (BAGNOLD, 1941; CHEPIL, 1945) and blowing snow (OURA *et al.*, 1967; KOBAYASHI, 1972), but in these studies stress was put only on the form of the trajectories and dynamical behaviors of particles and their interactions with the surrounding flow were not investigated in detail.

We have designed a simple device which can take photographs of motions of particles in blowing snow; each photograph contains trajectories with time marks

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of saltating snow particles, so that it can give much information of trajectories as well as velocities and accelerations at each height.

2. Experiments

2.1. Apparatus

Trajectories of particles saltating near the snow surface were taken in photographs under the illumination with time marks. The schematic view of the lighting system is shown in Fig. 1. The beam of light from a slide projector (A) was passed through a slit set in a slide mount. The screen of light was intercepted periodically by a rotating transparent plexiglas disk (C) having dark radial stripes. Two types of disks were prepared; one with 18 stripes and the other with 36 stripes. Stripes were put in such a way that their widths were equal to the distances between. The disks were rotated with a synchronous motor (B) at a rate of 25 Hz or 50 Hz; we could get various time marks with intervals in a range from 1×10^{-4} s to 5×10^{-3} s.

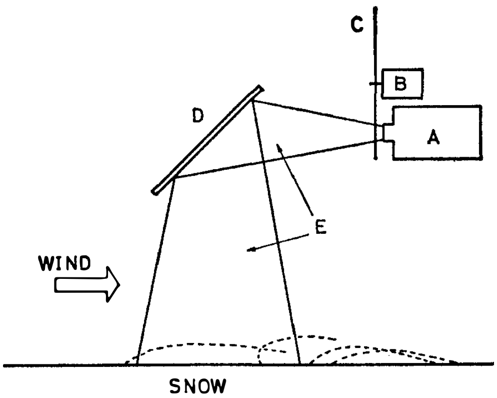

Fig. 1. Schematic diagram of the lighting system. A: slide projector, B: synchronous motor, C: disk with slits, D: mirror, E: screened light.

The screen of light with time marks was thrown on the test snow-surface perpendicularly from above by using a mirror (D). The length of the illuminated snow surface was about 20 cm along the wind direction and its width was about 1 cm at largest, which was necessary to get bright photographs. Photographs of saltating snow particles were taken by means of a 35-mm camera with a zooming lens (Nikon Micro-Nikkor 55 mm f3.5) and a high-sensitivity film (Kodak Tri-Xpan). Time of film development was sometimes lengthened to 32 minutes, which corresponded to ASA 6400.

The present method has merits that may not be attained by laborious high-speed motion-pictures or stroboscopic photography. It can easily provide not only trajectories but also positions, velocities and accelerations of saltating particles at each time.

2.2. Cold wind tunnel

Blowing snow was produced in a cold wind tunnel, whose schematic view is shown in Fig. 2. The working length of the wind tunnel is 8.0 m and its cross section is 50 cm $\times$ 50 cm. The underlying snow was prepared from preserved snow and sieved by meshes; mean radius of snow particles was 100 μm. The thickness of the snow was 2.5 cm and its surface was prepared as even and smooth as possible.

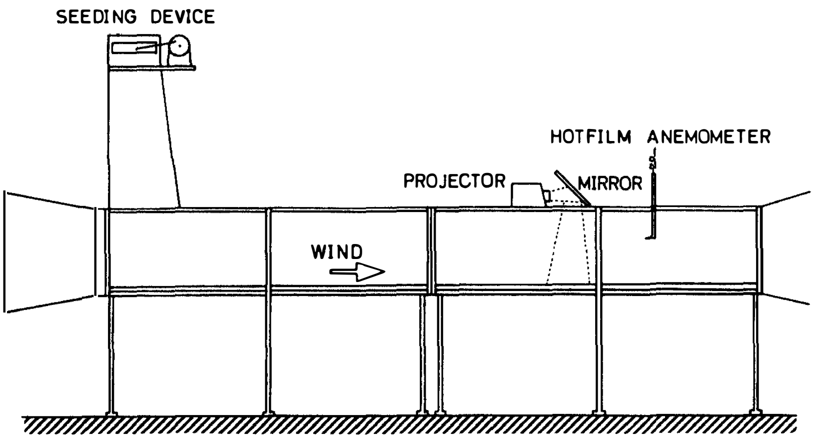

Fig. 2. Schematic diagram of the wind tunnel.

To initiate blowing snow seeding was necessary as already discussed in some detail by MAENO *et al.* (1979). The seeding device consisted of a motor and two meshes, which set snow blocks in a reciprocating motion to produce many tiny snow particles with mean radius of 100 μm. The seed snow particles were supplied far windwards only to trigger the outset of snow drift.

The temperature of the wind tunnel could be varied between 0°C and −30°C, but the experiment of drifting snow was conducted mostly at −9°C.

2.3. Wind velocity

Wind velocity was measured with a hot-film type anemometer and a Pitot tube. The sensors could be moved vertically in an arbitrary speed by the use of a synchronous motor and gears. Positions of the sensors and the wind velocity were recorded automatically with an x-y recorder. It was found that a turbulent boundary layer of about 10 cm thickness was steadily formed on a snow surface.

3. Results

Figure 3 shows trajectories of snow particles on a flat snow surface; more photographs on snow surfaces and steps are given in ARAOKA and MAENO (1981). Mean

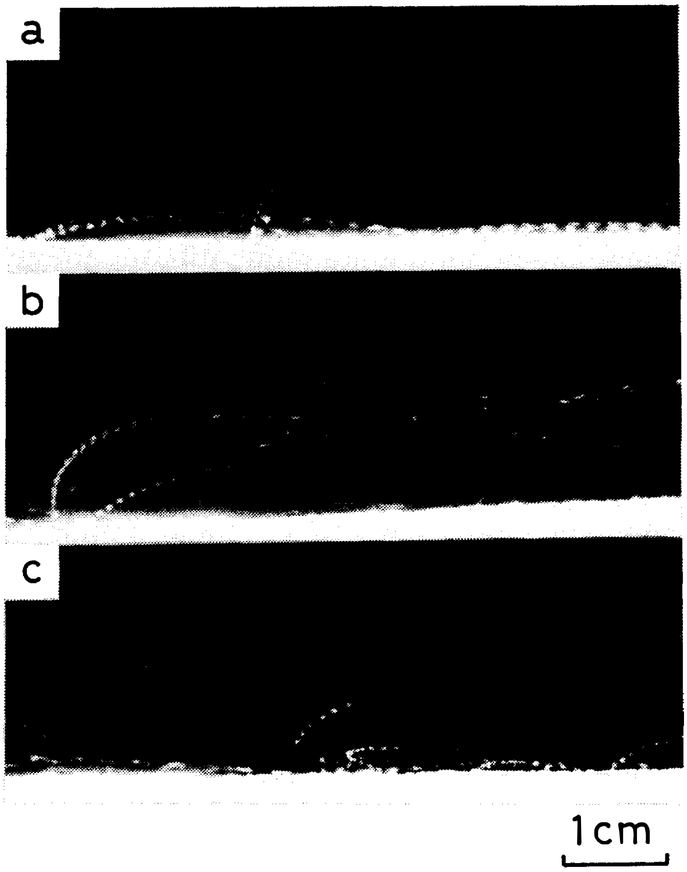

Fig. 3. Trajectories of saltating particles over a flat snow surface. Time intervals between bright marks on each trajectory correspond to 1.1×10^{-3} s.

wind velocity at the middle height of the wind tunnel (25 cm above the snow surface) is 5.0 m/s and the direction of the particle movement is from the left to the right. Cessations in each trajectory indicate time marks; distances between them correspond to the time interval of 1.1×10^{-3} s in this case.

Various trajectories of saltating snow particles are recognized as well as creep and suspension; Compared with low trajectories with small lift-off angles (a), particles having high trajectories (b, c) with large lift-off angles interact more effectively with the general wind. Sometimes the particles which jumped up windwards were even observed.

3.1. *Analyses of particle motion*

In analyzing the motion of snow particles the frame of reference is defined by taking x-axis along the mean flow and y-axis perpendicular to the snow surface with the origin on the snow surface. Velocities and accelerations of saltating snow particles were obtained from loci as shown in Fig. 3; positions of particles were represented by a mid point between two spots. Errors involved in the velocity and acceleration estimate were 10% and 20% respectively.

3.2. Horizontal velocity and acceleration

Figure 4 shows horizontal velocities (u) of snow particles at each position. The mean wind velocity was 5.0 m/s at the height of 25 cm, and its vertical profile is shown with a solid line. Broken lines linking the data indicate a trajectory belonging to a same particle. White and black circles mean that the snow particle is ascending and descending respectively.

The horizontal velocity of an ascending snow particle increases and approaches to the wind velocity at each height. It is shown that particles are increasingly accelerated when they are lifted off from the snow surface. On the other hand, velocities of descending particles are larger than wind speeds at each height, so that they are decelerated, but the deceleration is not so large; most of descending particles maintain their large horizontal velocities and collide with the snow surface to cause ejection of new particles.

The horizontal acceleration of snow particle (a_x) is given in Fig. 5. Although the

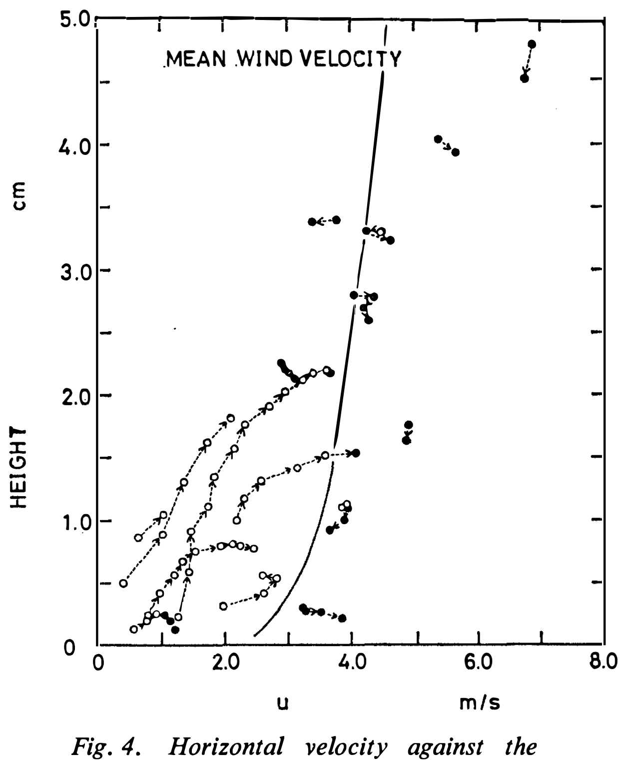

Fig. 4. Horizontal velocity against the height. White and black circles indicate ascending and descending particles respectively.

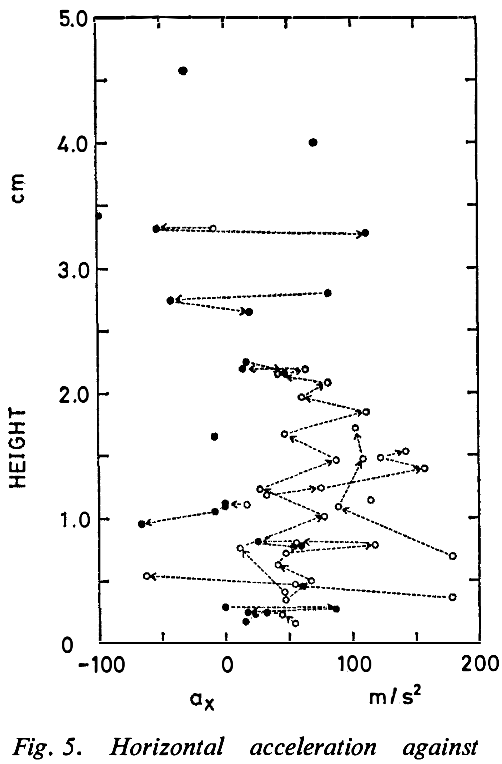

Fig. 5. Horizontal acceleration against the height. The meaning of white and black circles is the same as in Fig. 4.

result is complicated and irregular influence of turbulent wind can be recognized, it is obvious that the magnitude of acceleration and deceleration is rather large; acceleration sometimes mounts to about 200 m/s^2.

3.3. Vertical velocity and acceleration

The vertical velocity (v) of snow particles was obtained in the same way as the horizontal velocity. The result is shown in Fig. 6 with the same notations as before. The vertical velocity decreases when a particle ascends. Dotted lines show trajectories of an ascending particle expected in vacuum under the gravity. It was noted that snow particles did not reach the height $v_0^2/2g$ where v_0 is the initial vertical velocity and g the acceleration of gravity (Table 1). The drag force due to the surrounding air is not sufficient to explain the difference as will be discussed in more detail in Section 4.

This tendency is also recognized in the vertical accelerations (a_y) shown in Fig. 7. Positive values of a_y mean the increase in absolute values of the vertical velocity. Absolute magnitudes of observed a_y are larger than 9.8 m/s^2, that is the expected acceleration in vacuum under the gravity.

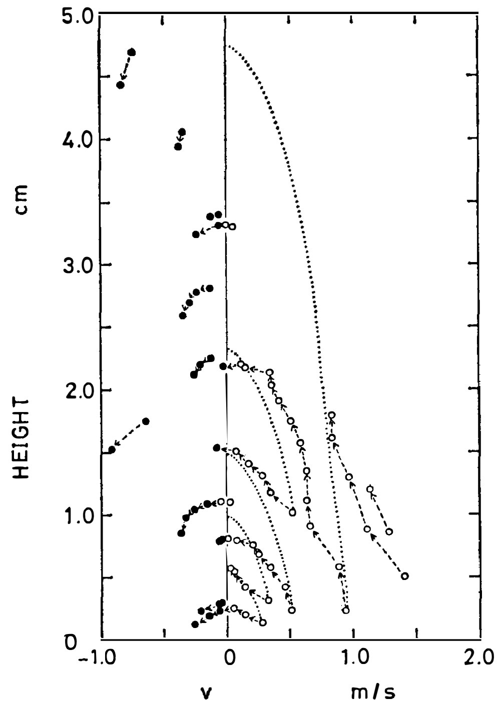

Fig. 6. Vertical velocity against the height. The meaning of white and black circles is the same as in Fig. 4.

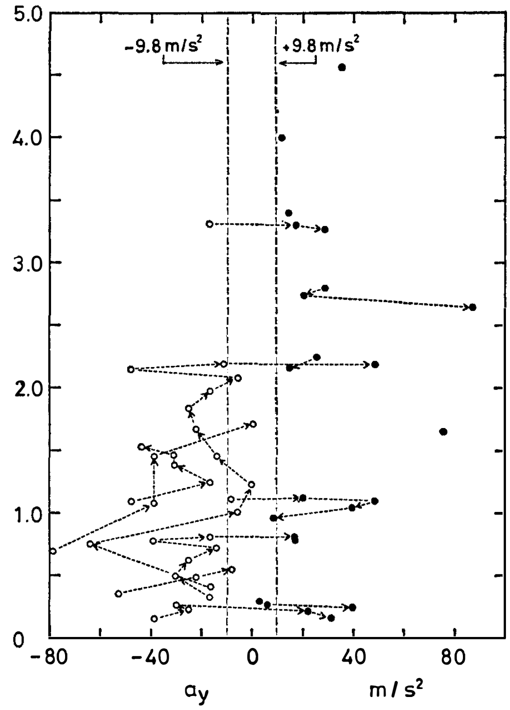

Fig. 7. Vertical acceleration against the height. The meaning of white and black circles is the same as in Fig. 4.

3.4. *Lift-off and incidence angles and velocities*

Lift-off angles (θ_0) and velocities (u_0, v_0) and incidence angles (θ_1) and velocities (u_1, v_1) of saltating particles on a snow surface were estimated from photographs and are shown in Figs. 8, 9 and 10. The mean wind velocity was 5.0 m/s at the height of

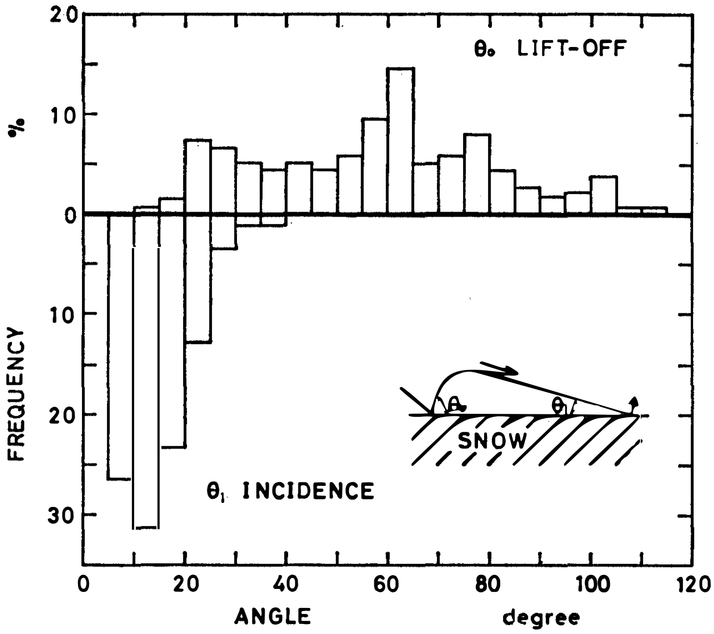

Fig. 8. Frequency histograms of lift-off (θ_0) and incidence (θ_1) angles. The numbers of measured particles (n) are n=137 (θ_0) and n=86 (θ_1).

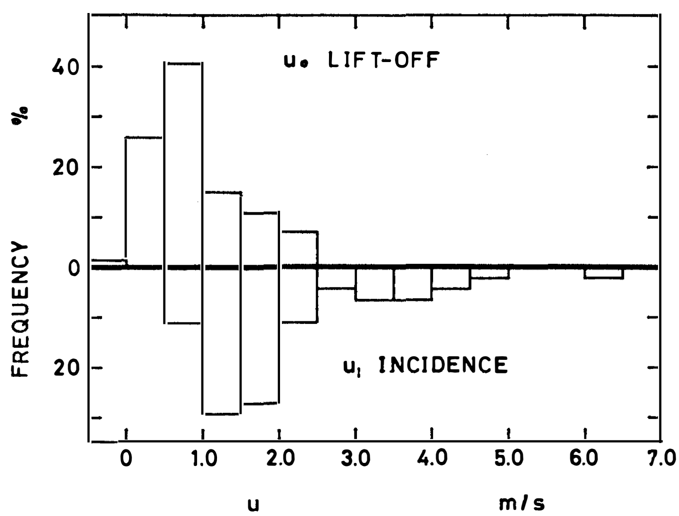

Fig. 9. Frequency histograms of horizontal lift-off (u_0) and incidence (u_1) velocities. n=74 (u_0) and n=45 (u_1).

25 cm. Though the incident angles (θ_1) are concentrated in a relatively narrow region 0°–40°, the lift-off angles (θ_0) cover a wider range of 10°–120°; it was even observed that some snow particles lift off windwards as noted in the photograph (Fig. 3). Possible irregularities on the snow surface might cause such abnormal particle motions.

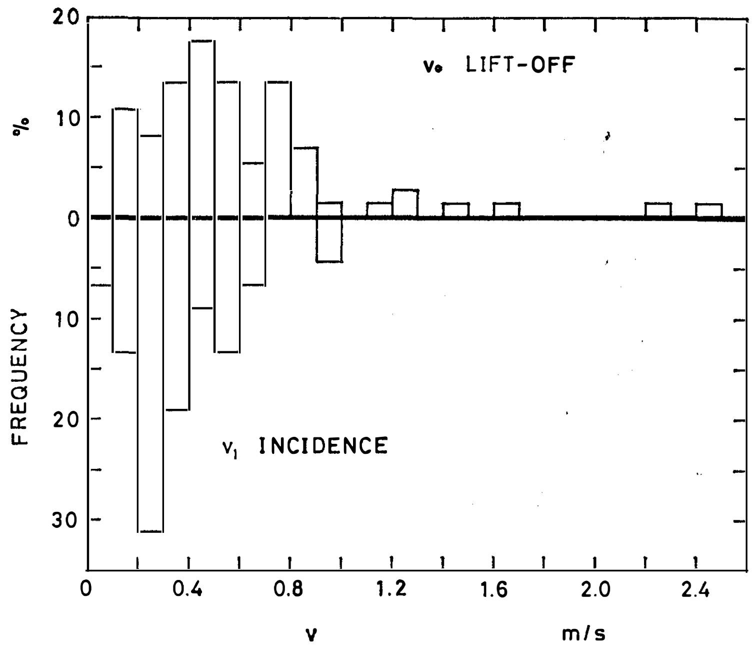

Fig. 10. Frequency histograms of vertical lift-off (v_0) *and incidence* (v_1) *velocities. n=74* (v_0) *and n=45* (v_1).

It is clearly shown in Fig. 9 that the average horizontal incidence velocity (u_1) is substantially larger than that of lift-off (u_0). This result can be explained by the net transport of horizontal momentum from the general air flow to the snow surface. Similar downward transport of vertical momentum can be imagined but its existence does not seem obvious in the histograms of v_0 and v_1 (Fig. 10). Rather, v_0 seems to be comparable in magnitude with v_1, or even larger, which is possibly related with the complex structure of wind in the saltation layer.

4. Discussion and Conclusion

Dynamical behaviors of snow particles in the saltation layer were analyzed from trajectories with time marks taken on photographs with a special technique developed in this study. The merit of the technique is that velocities and accelerations of saltating particles can be estimated at each time on an individual trajectory. It was found that the horizontal velocities of ascending particles are accelerated until the relative velocities between the particles and the wind vanish; the velocities of descending particles are mostly larger than the wind velocity and are decelerated. The result is that the motion of snow particles makes the wind velocity profile uniform, that is to decrease the shear near the snow surface by slowing down the upper parts of wind which move faster and by speeding up the lower parts which move more slowly (MAENO *et al.,* 1979). This explanation is supported by the result that u_1 is larger than u_0 and θ_1 is smaller than θ_0.

The nature of drag acting on saltating snow particles can be examined from the horizontal accelerations and velocities. The drag coefficient (C_D) of a spherical snow particle of radius r_p is defined as (BIRD *et al.,* 1960),

$$C_D=\frac{2a_x m_p}{A_p\rho(u-u_p)^2}=\frac{8a_x r_p \rho_p}{3\rho(u-u_p)^2}\,, \tag{1}$$

where m_p and A_p are the mass and the cross sectional area of a snow particle respectively. a_x is the acceleration and the quantity $(u-u_p)$ is the relative velocity between the snow particle and the surrounding air flow. ρ and ρ_p are the densities of air and ice respectively. C_D is a dimensionless function of Reynolds number (Re), where Re is given by $Re=2\rho r_p(u-u_p)/\eta$, where η is the viscosity coefficient of air. Results of the analyses are given in Fig. 11, in which C_D for horizontal motion is plotted against Re. In the analyses the velocity of the surrounding air flow was taken as the mean wind velocity measured with a Pitot tube, and the radii of snow particles were put to be $r_p=100\ \mu$m.

It is known that at small Reynolds numbers ($Re\sim 0.1$), the flow is Stokes flow and the drag coefficient is written as

$$C_D=N/Re\,, \tag{2}$$

where $N=24$. Observed data in Fig. 11 show that the drag acting on saltating snow particles is of Stokes type and the constant N ranges from 0.6 to 9. The range of N is considered to originate from the assumption that the average snow particles are spheres of 100 μm radius.

It was mentioned in Subsection 3.3 that ascending snow particles did not reach the height $v_0^2/2g$, and a substantial downward force was suggested to act on the particles. If the drag coefficient of a spherical snow particle in a vertical motion is also given by eq. (2) in a similar way as the horizontal motion, the maximum height ($h_{\max}$) the particle can reach in a vertically motionless air is expressed as (MAENO, 1981):

$$h_{\max}=\frac{1}{g\gamma}\left\{v_0-\frac{1}{\gamma}\ln(1+\gamma v_0)\right\}\,. \tag{3}$$

Here

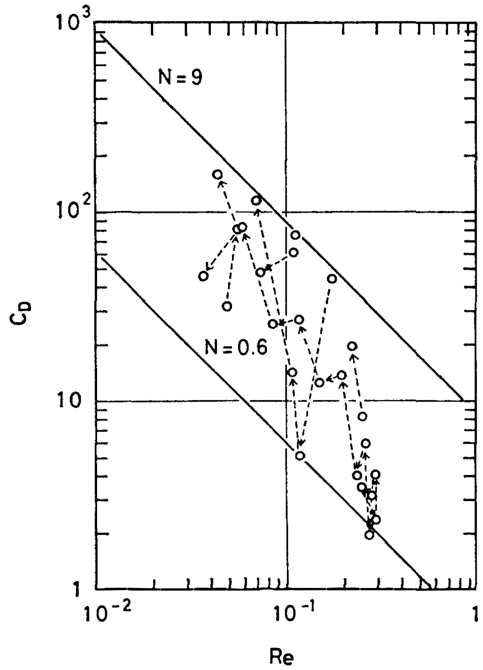

Fig. 11. Relation between C_D and Re. N is a numerical defined in eq. (2).

$$\gamma = \frac{3N\eta}{16 g r_p^2 \rho_p}, \tag{4}$$

where ρ_p is the density of ice. When γ is negligibly small, *e.g.* in a vacuum, h_{max} in eq. (3) approaches infinitely to $v_0^2/2g$.

Maximum heights were calculated for a spherical snow particle of mean radius 100 μm and various initial velocities, and are given in Table 1. The result implies that some unknown downward force is acting on snow particles in the saltation layer in addition to the drag. WHITE and SCHULZ (1977) reported the existence of a substantial upward Magnus force due to spinning which makes the maximum height of

Table 1. Initial vertical velocities and maximum heights of ascending snow particles.

Initial vertical velocity (v_0)	Maximum height measured	Maximum height in vacuum ($v_0^2/2g$)	Maximum height calculated from eq. (3)	
			N=9	N=0.6
28 cm/s	0.10 cm	0.40 cm	0.38 cm	0.40 cm
33	0.49	0.56	0.52	0.55
50	0.84	1.28	1.16	1.27
51	0.52	1.33	1.20	1.32
94	1.93	4.51	3.77	4.45

glass spheres in air even larger than $v_0^2/2g$. However, such a force was not prominent in our experiment. Although snow particles were observed to rotate when they travel over the snow surface (ARAOKA and MAENO, 1981), the spinning rate was not so large as expected by WHITE and SCHULZ. The Magnus force due to spinning is expected to work only at the moment when particles leave the snow surface, as suggested by GRISHIN (1979). Our result agrees with that of BAGNOLD (1936). He reports that the maximum heights of sand grains in air were always smaller than $v_0^2/2g$ (eq. (4) in his paper).

Acknowledgments

The authors express their thanks to Prof. T. ISHIDA and other members of Meteorology Section, the Institute of Low Temperature Science, Hokkaido University for their valuable comments and supports, and to Mrs. Y. UEMATSU for typewriting the manuscripts. This work was partly supported by the Special Grant in Aid for Scientific Research, from the Ministry of Education, Science and Culture, Japan.

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(Received April 6, 1981)