FRACTURE AND ACCUMULATION CONDITIONS OF SNOWFLAKES ON THE SNOW SURFACE

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ABSTRACT: Snowflakes colliding with the snow surface break under strong wind conditions and their fragments are blown off, which leads to the development of drifting snow. If the fragments accumulate, the density of deposited snow becomes greater than that of new snow under calm conditions. Experiments on the fracture and accumulation processes of snowflakes were carried out in a cold wind tunnel and their observations in the field were performed as well.

Experimental results using artificial snowflakes are roughly as follows: Snowflakes do not break if U_1<2m/s, where U_1 is the wind speed at 1m height. If U_1>5m/s, they are completely decomposed into snow crystals. Snowflakes accumulate if U_1<3m/s and are blown off if U_1>4-5m/s. Those values of wind speed slightly vary with the hardness of snow surface. The critical wind speed U_1=4-5m/s for accumulation is close to the impact threshold of drifting snow. Within a range of wind speed, 2<U_1<3m/s, snowflakes partly break and accumulate at the collision point.

Observational results of the collision of natural snowflakes almost agreed with the experimental results. These findings can be utilized in a drifting snow model to describe the snowfall explicitly and will be useful in understanding the wind speed dependence of new snow density.

KEYWORDS: snowflake, fracture, accumulation, drifting snow, snowfall

1. INTRODUCTION

If snowfall is accompanied by strong wind, snowflakes break when they collide with the snow surface. Their fragments become drifting snow particles if they are small enough to be blown off by wind. Therefore snowfall can enhance drifting snow. Drifting snow often occurs with snowfall, and Kojima (1969) showed that snowflakes were actually decomposed into snow crystals. If such fragments accumulate, the density of deposited snow becomes large, which sometimes leads to the 'wind packed snow'.

Kobayashi (1984) took account of snowfall in the diffusion equation of snow particles and derived analytically the vertical distribution of mass concentration that consists of both drifting snow particles and snowflakes. Some numerical models (e.g. Uematsu *et al*.,1991; Liston and Sturm, 1998; Gauer, 2001) considered snowfall, where the physical processes related to snowflakes such as collision with the snow surface were not well described.

The collision of snowflakes with the snow surface has not been investigated in detail, though it has been recognized. In this study, experiments of the collision of a snowflake were carried out in the laboratory, and the results were compared with field observations from a viewpoint that this phenomenon is important for drifting snow development and wind packing of snow.

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2. METHODS

2.1 Laboratory experiment

Snowfall was simulated in the wind tunnel installed in a cold room of the Cryospheric Environment Simulator (CES), where air temperature was kept -7^{o}C. The test section of the wind tunnel is 14m long and is 1m in both width and height. Detailed description of the wind tunnel can be referred to Sato *et al*. (2001). Two kinds of snow surfaces, soft and hard, were prepared in the wind tunnel. The artificial snow, which was produced in the CES and consisted of

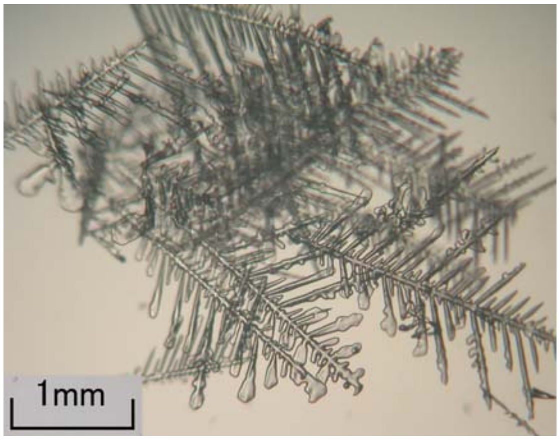

Fig.1: Microscopic picture of the artificial snow used in the experiment.

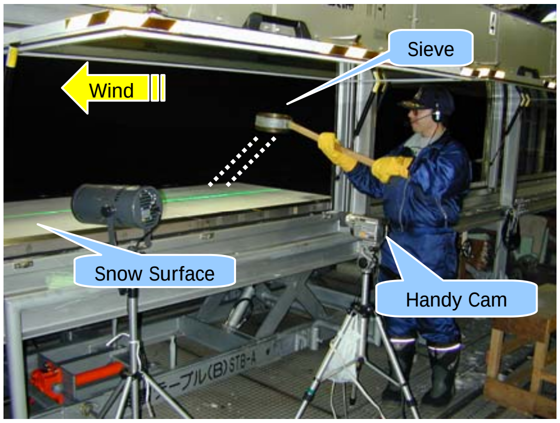

Fig.2: Arrangement of the collision experiment in the cold wind tunnel.

dendritic crystals (Fig.1), was used to make the soft snow surface. The snow was slightly compressed and its density was about 150kg/m^3. The hard snow surface was made with disintegrated settled snow and water was sprayed over the surface.

The artificial snow that had not suffered metamorphism was put into a sieve. The sieve was held at a height of about 0.6m from the snow surface and then an impact was given to the sieve by hitting it (Fig.2). Two sieves with mesh sizes of 7mm and 20mm were used to make small and large snowflakes, respectively. Several snowflakes, which were aggregates of dendritic crystals, fell while being blown away by wind and finally collided with the snow surface.

The set value of wind speed, U_{set}, was changed from 0 to 7m/s, which is almost the same as the wind speed around the center of the wind tunnel. The motion of a snowflake, illuminated by a laser light sheet that flashed with a cycle of 500Hz, was recorded with a handy cam. The behavior of a snowflake at the collision was recorded with a handy cam or a high speed video camera (250frame/s).

2.2 Field observation

Observations of natural snowflakes were carried out in February, 2004 at Shinjo, Japan. The collision was recorded with a handy cam in the nighttime to obtain a clear image of collision with illumination. Wind speed was simultaneously measured with an ultra-sonic anemometer at a height of about 1m from the snow surface, which can measure three components of turbulent wind up to 10Hz. Horizontal components of the wind were sampled at a rate of 5Hz. One second averaged horizontal wind speed was calculated from the components and used in the analysis. Air temperature at z=1.5m was -0.1 to -1.4^{o}C.

3. ANALYSIS

Still images were made from the handy cam image taken in the wind tunnel, and the horizontal and vertical velocities of a snowflake were obtained by digitizing its dotted trajectory recorded.

Replaying the video image of the collision experiment, degrees of fracture and accumulation of snowflakes were judged by eyes and classified into 5 levels. The results of classification are designated as the fracture rate, F, and the accumulation rate, A, respectively. Criteria for the classification are summarized in Table 1. Strictly, snowflakes break without wind due to compressive impact force at the collision. However, such fracture would be a common phenomenon regardless of wind speed. The change of a snowflake into fragments or snow crystals, which is an important process for the development of drifting snow, would be due to the shear force working at the snow surface when a snowflake collides. Therefore, the deformation or the fracture in the vertical direction was ignored in this study.

From the video image of the collision of natural snowflakes in the field, the fracture and accumulation rates were determined by eyes according to the criteria in Table 2. It

Table 1: Criteria of the fracture rate and the accumulation rate (for experiment).

	Definition
Fracture Rate, F	
0	snowflake does not break
0.5	snowflake beaks into a few fragments
1	snowflake is completely decomposed into snow crystals
Accumulation Rate, A	
0	snowflake or its fragments are accumulated at the collision point
0.5	fragments accumulate near the collision point
1	fragments (or decomposed snow crystals) are blown off to leeward

should be noted that the natural snowflakes did not break into a few fragments under moderate wind conditions, but they appeared to be distorted by shear force. This may be because the natural snowflakes were not tight aggregations of snow crystals compared to the artificial snowflakes. Moreover, the shape of composing snow crystal might not be so complicated as that of artificial snow. Those are the reasons why another criteria, Table 2, were applied for the natural snowflakes observed in the field. The intermediate values for *F* and *A* were not estimated in the case of observations.

Table 2: Criteria of the fracture rate and the accumulation rate (for observation).

	Definition
Fracture Rate, F	
0	snowflake does not break
0.5	snowflake distorts but is not completely decomposed into snow crystals
1	snowflake is completely decomposed into snow crystals
Accumulation Rate, A	
0	snowflake accumulates at the collision point
0.5	distorted snowflake (or decomposed snow crystals) accumulates near the collision point
1	decomposed snow crystals are blown off to leeward

4. RESULTS

4.1 Impact velocity of snowflake

Figure 3 shows the vertical distribution of the horizontal velocity of a falling snowflake, V_h, together with the wind speed in the wind tunnel, U, where both are normalized with U_{set}. Approaching the snow surface, V_h/U_{set} tends to depart from U/U_{set}. This represents that snowflakes did not perfectly follow the wind during fall. The difference between large and small snowflakes is not remarkable and the following expression for the horizontal impact velocity, V_{ih}, is obtained by extrapolating the relationship to z=0:

$$V_{ih} = 0.8U_{set} \quad (1)$$

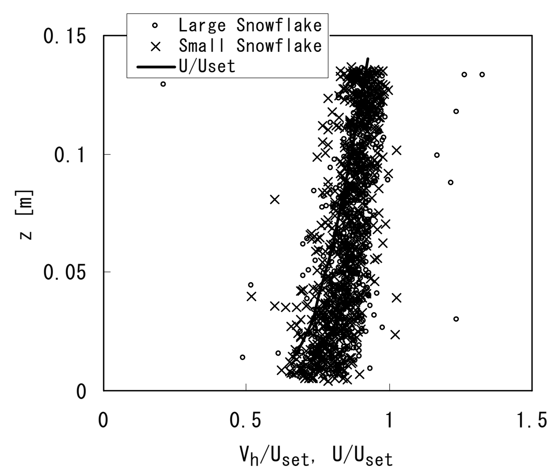

Fig.3: Vertical distribution of the horizontal velocity, V_h, of a snowflake and the wind speed, U, in the wind tunnel. Both are normalized with U_{set}.

The vertical (falling) velocity of a snowflake, V_v, is plotted in Fig. 4 against the height from the snow surface, where V_v of

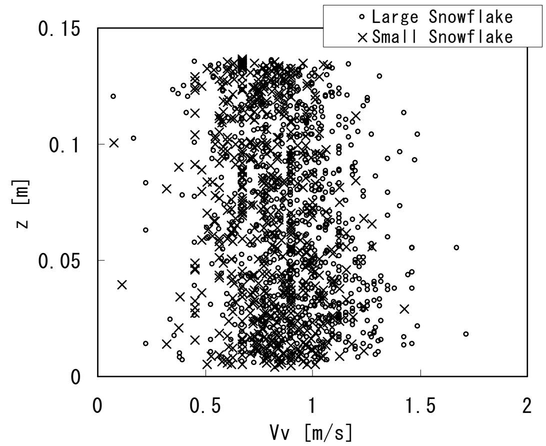

Fig.4: Vertical distribution of the vertical (falling) velocity, V_v, of a snowflake.

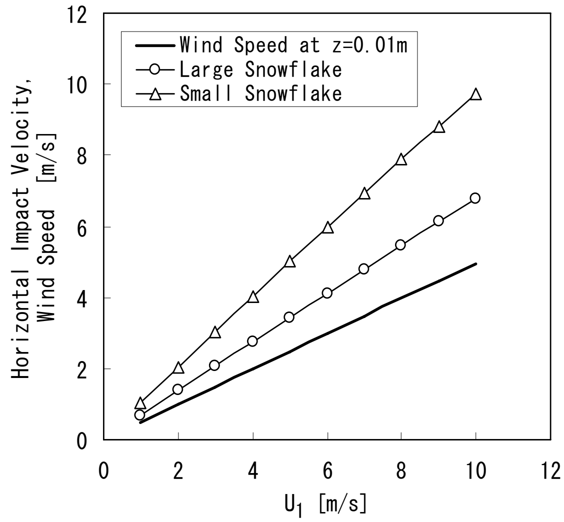

Fig.5: Numerically derived relationship between the horizontal impact velocity of a snowflake and the wind speed at *z*=1m. The wind speed at z=0.01m is also shown.

large snowflakes is somewhat greater than that of small snowflakes. The vertical velocity does not depend on U_{set} and slightly increases as snowflakes approach the snow surface during fall. A similar extrapolation yields V_{iv}=0.8m/s for small snowflakes and V_{iv}=1.0m/s for large snowflakes, where V_{iv} is the vertical impact velocity. Those values obtained in the experiments are slightly smaller than those of natural snowflakes measured in the field (Ishizaka, 1995).

4.2 Fracture rate and accumulation rate

Here the wind speed dependences of the fracture and accumulation rates will be shown based on the experiment. For practical application, the relationship between each rate and wind speed in the field instead of U_{set} would be more useful. In this study, the wind speed at 1m height, U_1, is used as a representative value. The conversion from U_{set} to U_1 will be described in the following:

Two different variables are considered for fracture and accumulation of snowflakes. The horizontal impact velocity of a snowflake is important for its fracture at the snow surface. On the other hand, the wind speed near the snow surface is important for the accumulation of a snowflake, its fragments and snow crystals if the snowflake is smashed. This is because the accumulation is a reciprocal of the snow transport by wind.

Firstly, the case of fracture is considered. In order to obtain the horizontal impact velocity of a natural snowflake, which will be used in the conversion, the equation of snowflake motion was solved numerically. In the calculation, a small and a large snowflake, whose sizes were 7mm and 20mm, respectively, were considered and their vertical speed was assumed to be constant, 1m/s. The mass, cross section, and drag coefficient of a snowflake were assumed based on the measurements by Ishizaka (1995). The vertical distribution of wind speed was expressed by the log-law assuming that the roughness length, z_0, was 10^{-4}m. The horizontal velocity of a snowflake was assumed to coincide with the wind speed at *z*=20m. Since the change of wind speed during the fall of snowflakes is remarkable at lower height, this assumption would be appropriate. The relationship between the horizontal impact velocity, V_{ih}, and U_1 was obtained, which is shown in Fig. 5. This can give the relationship between U_{set} and U_1 through the value of V_{ih} together with Eq.(1). Since the maximum size of natural snowflakes on the video image taken in the field was about 10mm or less, the following relationship for a small snowflake was used in parameterizing the fracture rate:

$$U_1 = 0.8U_{set} \quad (2)$$

Secondly, the case of accumulation is considered. The accumulation would be characterized by the friction velocity, u_*, which is a velocity scale of turbulent wind near the ground surface. The experimental equation,

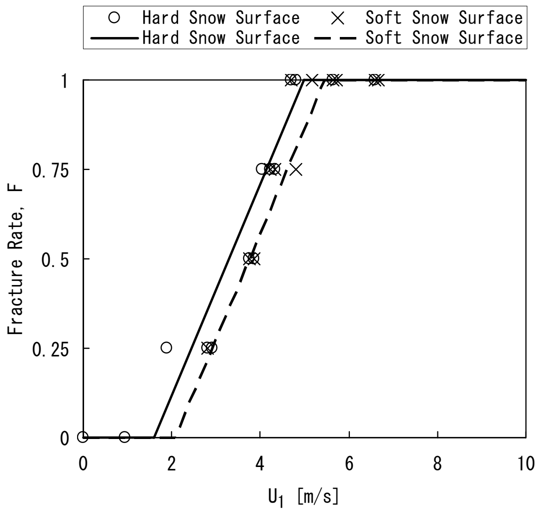

Fig.6: Relationship between the fracture rate, F, and the wind speed at z=1m, U_1, based on the experiment.

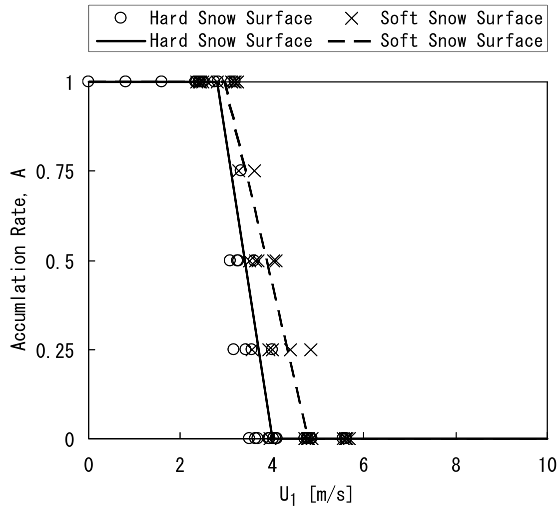

Fig.7: Same as Fig. 6 except for the accumulation rate, A.

u_* =0.041U_{set}, had already been obtained over the snow surface in the wind tunnel. In the field, the log-law of wind speed yields U_1=23u_* where z_0=10^{-4}m was assumed. Both equations give the following relationship in parameterizing the accumulation rate:

$$U_1 = 0.94U_{set} \quad (3)$$

The fracture rate, F, is plotted against U_1 in Fig.6. The snowflake does not break at the wind speed lower than about 2m/s, and it is completely decomposed into snow crystals at the wind speed higher than about 5m/s. Between these two wind speeds, F is a linear function of wind speed. The fracture of a snowflake requires slightly higher wind over the soft snow surface compared to the hard snow surface, which may be attributed to greater absorption of the kinetic energy of a colliding snowflake with the soft snow surface than with the hard snow surface.

The accumulation rate, A, is plotted against U_1 in Fig.7. The functional form of A is roughly complementary to that of F for both soft and hard snow surfaces. The wind speed at which A begins to decrease from 1 is about 3m/s regardless of the hardness of snow surface, which is higher than the wind speed at which F begins to increase from 0. The wind speed at which A attains 0 is about 5m/s for the soft snow surface, which is almost the same as that at which F attains 1, while it is about 4m/s for the hard snow surface. The wind speed above which a snowflake does not accumulate is almost the same as the impact threshold for drifting snow.

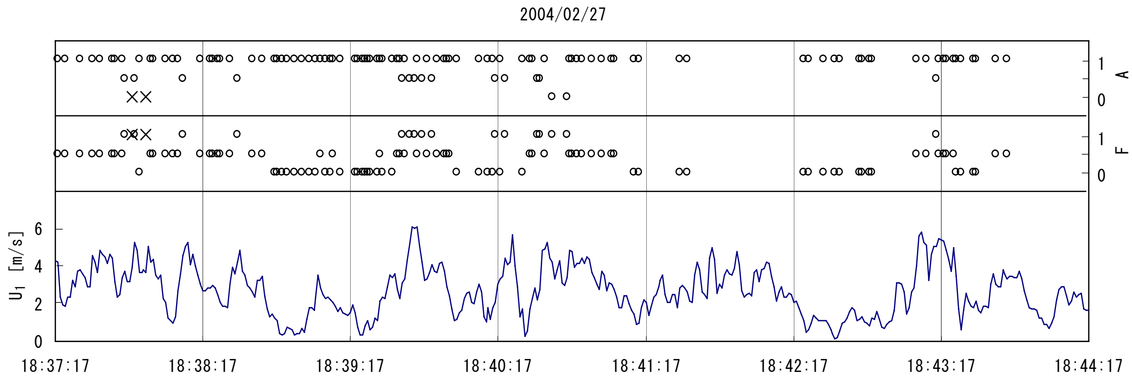

Fig.8: Observed time series of the fracture rate, F, and the accumulation rate, A, (circle) and the wind speed at z=1m, U_1. Cross denotes that both snowfall and drifting snow were observed.

Figures 6 and 7 indicate that there is a wind speed range, 2m/s to 3m/s, where a snowflake is not blown off though it breaks to some extent. In other words, snowfall does not contribute to drifting snow and the new snow density would increase due to the fracture of snowflakes within this wind speed range.

4.3 Comparison with field observation

An example of the time series of fracture and accumulation rates is shown in Fig.8 together with the wind speed, U_1. Each circle corresponds to a collision of one snowflake and a cross denotes that both snowfall and intermittent drifting snow were observed.

The relationship between F and U_1 is shown in Fig. 9 and that between A and U_1 is shown in Fig. 10. The scatter of the plots are caused not only by the uncertainty of synchronization between the video image and the wind speed record but also, probably, by the variety of natural snowflakes such as degree of snow crystal aggregation, shape of composing snow crystal, degree of riming and so on. The observed relationships agree in average with the experimental results indicated by lines in both figures.

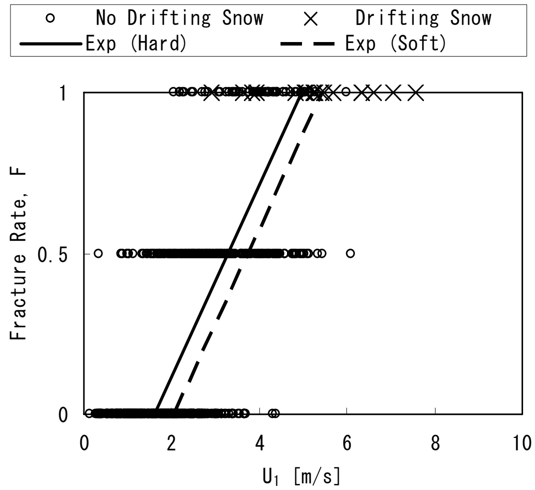

Fig.9: Relationship between the fracture rate, F, and the wind speed at z=1m, U_1, based on the observation. Cross denotes that drifting snow was observed during snowfall and the lines correspond to the experimental results shown in Fig. 6.

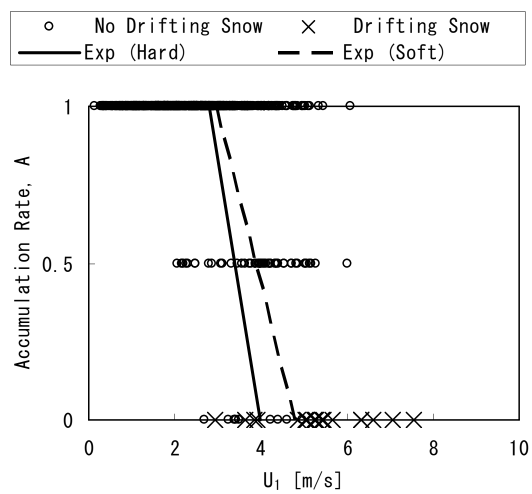

Fig.10: Same as Fig. 9 except for the accumulation rate, A. The lines correspond to the experimental results shown in Fig. 7.

5. DISCUSSION

Snow frequently accumulates during drifting snow with snowfall and strong wind. This seems to contradict the experimental results that snow does not accumulate at the wind speed, U_1, greater than 4-5m/s. These two inconsistent facts, however, can be well explained as follows by introducing a concept of saturation for drifting snow, that is, a state where drifting snow has maximum mass transport corresponding to the wind speed: The experimental condition in the wind tunnel that no drifting snow particles came to the point of collision from windward was a special one selected from among a variety of natural conditions. The fragments of a snowflake, when they are actually decomposed into snow crystals, can easily change to drifting snow particles and can be transported leeward since the drifting snow around the collision point is not saturated. And the accumulation rate can be zero under such condition. In the field, however, decomposed snow particles cannot be added to drifting snow if the drifting snow is saturated, and they accumulate at that time. The same holds if the wind weakens, because the saturation value of drifting mass transport is a decreasing function of wind speed. This phenomenon was sometimes observed during the present field observation (Fig. 8).

One of the natural phenomena similar to that in the wind tunnel is the snow accumulation on a flat roof. Although snow accumulates on a flat roof at the same rate as on a horizontal plain if it is calm, the accumulation on a flat roof is suppressed on a windy day. This is partly because snowflakes cannot accumulate on a roof under strong wind condition. The drifting snow that occurs on a roof is difficult to attain saturation because of a short fetch distance, which is preferable to reduce snow accumulation. This is a similar situation as that in the wind tunnel experiment. Abe *et al*. (2004) reported that the ratio of the water equivalent of the daily snow accumulation on a flat roof to that on a plain decreased with wind speed and it became zero at about 3 to 4m/s, where the wind speed was measured at the height of 1.5m above the roof and air temperature ranged from 0 to -6^{o}C. This critical wind speed corresponds well to that shown in Fig. 7.

The fracture and accumulation rates revealed in this study can be incorporated into a model of drifting snow if it describes explicitly the snowflake behaviors such as motion in wind and collision with the snow surface. An example is shown by Sato *et al*. (2004), where the drifting snow development along a fetch was simulated with a model that took the accumulation rate into account.

The wind speed, U_1=4-5m/s, above which snowflakes cannot accumulate, is fortunately close to the impact threshold of drifting snow. This fact provides another simple treatment of snowfall in a drifting snow model. Namely, the mass of snowflakes can be assumed to change to the mass of drifting snow particles immediately after snowflakes touch the snow surface. This approach does not require the equations of motion or mass conservations of snowflakes.

In the present study, the behavior of a snowflake at the collision was focused. If the impact speed of a snowflake is close to that of drifting snow particles which collide with the snow surface, the snowflake would be able to eject snow particles composing the snow surface. The mass budget of snow cover was not measured in this study and such phenomenon should be investigated in the future.

From the daily observed new snow density by Izumi (1989), the increasing tendency of the density with wind speed was found within a range from 3 to 9m/s. Kajikawa (1989) also reported that new snow density, measured every 6 hours, slightly increased with wind speed up to 5m/s. These observational results seem to reflect the wind speed dependence of the fracture rate experimentally determined.

6. CONCLUSIONS

From the wind tunnel experiments on the collision of artificial snowflakes with the snow surface, the relationships between fracture and accumulation of snowflakes and wind speed were clarified The results were expressed using wind speed in the field for practical use. Snowflakes do not break when the wind speed at 1m height, U_1, is less than about 2m/s and are completely decomposed into snow crystals when *U*1 is greater than about 5m/s. They accumulate at the point of collision when U_1 is less than about 3m/s and are blown off when U_1 is greater than 4-5m/s. Those critical wind speeds for fracture and accumulation slightly depend on the hardness of snow surface.

Through the field observations of the collision of natural snowflakes, the wind speed dependences of both fracture and accumulation were confirmed to agree with the corresponding experimental results.

In order to quantify the degrees of fracture and accumulation, a fracture rate and an accumulation rate were introduced. The relationships between these rates and U_1 can be utilized in a drifting snow model that incorporates snowfall, and will be useful in understanding the wind speed dependence of new snow density.

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