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Development of saltation layer of drifting snow

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ABSTRACT. The saltation length of aeolian snow particles and a new parameter, the ejection factor, which expresses the degree of erosion due to drifting snow, were obtained as functions of friction velocity by means of wind-tunnel experiments for semi-hard snow cover. The saturated-snowdrift transport rate was also obtained experimentally as a function of friction velocity. Based on these characteristics and the parameter, the development of the saltation layer of drifting snow along the fetch was simulated under various conditions such as snow hardness, wind speed and snowfall intensity. The main results are as follows. The developing distance denoting the distance required for the saltation layer to attain saturation, X_{sat}, is determined by saltation length, ejection factor and saturated-snowdrift transport rate, all of which depend on wind speed. It is also affected by the magnitude of snowdrift transport rate at the starting point and by the intensity of snowfall if it exists. The dependence of X_{sat} on wind speed is not simple in the case of semi-hard snow cover: X_{sat} increases with wind speed under weak to moderate wind conditions and then decreases under moderate to strong wind conditions. It is sensitive to snow hardness: it is about one order longer on hard snow cover than on semi-hard snow cover. Snowfall reduces not only the value of X_{sat} but also its dependence on snow hardness.

INTRODUCTION

Snow disasters are caused by drifting snow, which forms snowdrifts and reduces visibility on roads as well as forming snow cornices on mountain ridges. It also affects the hydrological cycle on various scales through the redistribution of snow, which is an important process in high-latitude snowy regions and in Antarctica. Many studies of drifting snow, made both in the field and in the laboratory, emphasise its dependence on wind speed. Drifting snow, however, depends on other factors, such as snow-cover conditions, including hardness, cohesive force and snow type. For example, Schmidt (1980) theoretically derived the threshold impact velocity of an aeolian snow particle as a function of the ratio of bond radius to sphere radius of the particles composing snow cover. A relationship between threshold friction velocity or drag force and snow properties was shown by Kobayashi (1979) and Kind (1981). An observational study by Takeuchi (1980) revealed that the vertical structure of drifting snow varies according to the type of snow cover. Recent wind-tunnel experiments on the saltation layer of drifting snow have revealed that its vertical structure changes with snow hardness (Sato and others, 2001), which may be ascribed to the conditions of the splash process at the snow surface. Sato and Higashiura (2003) also found in the field that the properties of the saltation layer change with snow hardness. These findings suggest that drifting snow may develop along the fetch, in accordance with observations of drifting snow by Kobayashi (1972) and Takeuchi (1980).

In this study, saltation-layer characteristics were measured in a wind tunnel, and a parameter that expresses the degree of erosion was proposed. The development of a saltation layer along the fetch was simulated based on these saltation-layer characteristics and the parameter.

WIND-TUNNEL EXPERIMENTS

Method and analysis

Drifting snow was generated in a cold wind tunnel. Measurements of mass-flux profile and observations of snow surface change were carried out. The compacted snow was broken up and sieved onto the floor of the test section, and the surface was made flat. Three kinds of snow cover, loose, semi-hard and hard, were prepared for the experiments, with mean hardness of 23, 47 and 65 kPa, respectively. The loose snow cover corresponded to that just after sieving, the semi-hard snow cover to moderately sintered snow, and the hard snow cover to highly sintered snow. The snow temperature was about −15°C. A snow seeder was installed near the upwind end, supplying snow particles into the airflow to trigger the bounding motion of snow particles. Details of the wind tunnel are shown in Sato and others (2001).

The mass-flux profile was measured using a snow particle counter (SPC) located about 11 m downwind from the snow seeder and on the center line of the wind tunnel. The SPC was fixed on a traverse device and moved from $z = 2$ cm to $z = 30$ cm, stopping at each of ten heights for 5 s. The snowdrift transport rate, Q, was obtained from

$$Q = \int_0^2 q\,\mathrm{d}z + \int_2^{30} q\,\mathrm{d}z\,, \qquad (1)$$

where q is the horizontal mass flux. The theoretical expression for the mass-flux profile by Kawamura (1948) was fitted to the measured profile, and the surface mass flux was obtained regressively (Sato and others, 2001). This surface value was used to calculate the first term on the righthand side of Equation (1). The second term on the righthand side was calculated from the measured mass-flux values. Since the mass flux decreases markedly with increasing height, as

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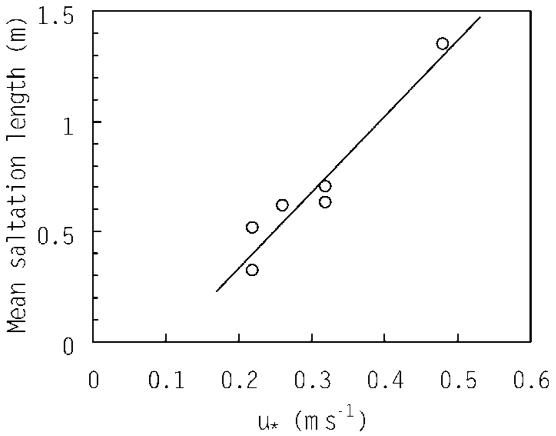

Fig. 1. Relationship between mean saltation length on semi-hard snow cover and friction velocity. The regression line, Equation (3), is also shown.

shown in Sato and others (2001, fig. 2), Equation (1) approximates the total snowdrift transport rate.

Drifting snow is in a state of equilibrium if the numbers of impacted and ejected snow particles are the same. This means that the equilibrium state is governed by the splash process at the snow surface. On the other hand, the airflow cannot carry an infinite number of aeolian snow particles. The situation where the airflow involves the maximum number of snow particles at a certain wind speed is called saturation, which is controlled by the wind field near the snow surface. If the drifting snow does not change along the fetch, the drifting snow is in an equilibrium state and/or saturated. In some literature, this is called a stationary state or a steady state.

In the case of loose snow cover, part of the surface was eroded and the rest was covered with accumulated snow between the snow seeder and the point of SPC measurement. This suggests that the drifting snow was almost saturated. In the case of hard snow cover, erosion was prevented by the strong bonding of snow particles, nor did accumulation occur. Therefore, the drifting snow was considered to be in an equilibrium state but not saturated. In the case of semi-hard snow cover, only erosion occurred and the drifting snow developed along the fetch by incorporating newly ejected snow particles. Thus, the drifting snow was neither in an equilibrium state nor saturated.

Here, a virtual group of snow particles representing actual bounding snow particles is introduced. It bounds on the snow surface and its saltation length is denoted by L. If the snow cover is not hard, the mass of the virtual group of snow particles will increase during every impact as it erodes the snow surface. The rate of mass increase at an impact is expressed by the ejection factor, f_{E}, in this study. After the virtual group of snow particles impacts n times while it travels a distance, X, from the starting point, the snowdrift transport rate is given by

$$Q = f_{\mathrm{E}}{}^{n} Q_0 \,, \tag{2}$$

where $N = X/L$ and Q_0 is the snowdrift transport rate at the starting point, which corresponds to the mass supplied by the snow seeder. As shown by Kobayashi (1972), the mean saltation length can be estimated using a box-type drift gauge.

Results of experiments

The mean saltation length on semi-hard snow cover is plotted against the friction velocity, u_*, in Figure 1. The saltation length is longer on hard snow cover and shorter on loose snow cover compared to that on semi-hard snow cover, which is shown in Kosugi and others (in press, fig. 9), where their wind speed U can be converted to u_* by multiplying 0.04. The mean saltation length was substituted for L and their regression line was obtained as

$$L = 3.45 u_* - 0.36 \,. \tag{3}$$

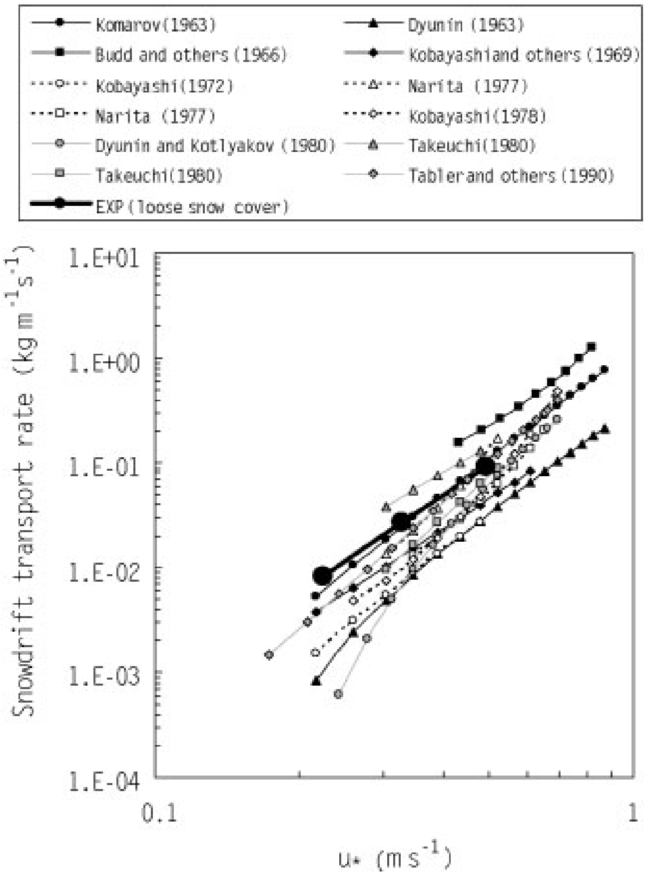

Fig. 2. Relationship between snowdrift transport rate and friction velocity. The three large solid circles are the measurements on loose snow cover, each of which is a mean of several measurements. Relationships obtained in the field by previous researchers are also shown.

The snowdrift transport rate measured on loose snow cover is shown in Figure 2 together with the values observed in the field by previous researchers. Although the observed values were originally expressed as functions of wind speed, friction velocity is used as a parameter in Figure 2, which was converted assuming the log-law of wind profile with a roughness length, z_0, of 10^{-4} m except that $z_0 = 2.5 \times 10^{-4}$ m was used for Budd and others (1966). Since the measurements are close to the uppermost values in the field, they can be regarded as the saturated-snowdrift transport rate, Q_{sat}, which is expressed as a function of friction velocity by

$$Q_{\mathrm{sat}} = 0.84 {u_*}^{3.1} \,. \tag{4}$$

From the experiments on semi-hard snow cover, the ejection factor was obtained using Equations (1–3). Results are shown in Figure 3. The ejection factor is slightly larger than unity for friction velocities of less than about 0.3 m s^{-1}, and it increases with increasing friction velocity.

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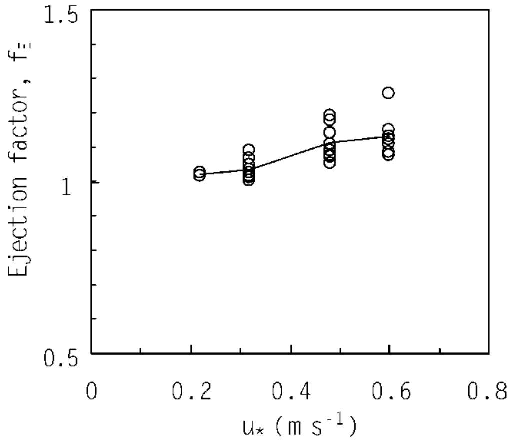

Fig. 3. Relationship between ejection factor and friction velocity for semi-hard snow. Mean values are connected by a solid line.

SIMULATION

Method

The development of a saltation layer along the fetch can be simulated by taking the ejection factor into account. Two kinds of snow cover, semi-hard and hard, were considered. Sublimation of aeolian snow particles during travel was neglected, which corresponds to low-temperature and/or high-humidity conditions. For a given wind speed at $z = 10\,\mathrm{m}$, U_{10}, the corresponding friction velocity was obtained assuming the log-law of wind profile and $z_0 = 10^{-4}\,\mathrm{m}$. The U_{10} value was specified as 5.5, 8 and 12 m s^{-1} for semi-hard snow cover and 12 ms^{-1} for hard snow cover. In the case of semi-hard snow cover, the saltation length, L, was calculated using Equation (3), and the ejection factor, f_E, was given from Figure 3. For hard snow cover, $L = 2.0\,\mathrm{m}$ (Kosugi and others, in press) and $f_\mathrm{E} = 1.02$ were used. The fetch distance, X, was calculated from $X = nL$, where n is the frequency of impact. Since various disturbances can trigger drifting snow, it is difficult to specify the snowdrift transport rate at the starting point. In this study, the snowdrift transport rate at $X = L$, the first landing point, was assumed to be given by

$$Q_1 = \frac{FL}{3600}\,, \tag{5}$$

where F is the snowfall intensity (water equivalent). Equation (5) means that the virtual group of snow particles arriving at $X = L$ results from snowfall alone. If the drifting snow without snowfall is considered, the snowfall intensity is set to be zero for $X > L$, and the snowdrift transport rate after n-times impact, Q_n, can be written as

$$Q_n = f_\mathrm{E} Q_{n-1} \ (n \geq 2)\,. \tag{6}$$

If the drifting snow is accompanied by snowfall, Q_n can be written as

$$Q_n = f_\mathrm{E} Q_{n-1} + \frac{FL}{3600} \ (n \geq 2)\,, \tag{7}$$

where the second term represents the contribution of snowfall to drifting snow. The drifting snow will become saturated as the virtual group of snow particles repeats impact. The saturated-snowdrift transport rate, Q_sat, was substituted for Q_n if the calculated value exceeded Q_sat.

Results of simulation

Figure 4 shows the change of snowdrift transport rate along the fetch for the drifting snow without snowfall. The snowdrift transport rate increases with the fetch distance and attains a saturated value. If the snowdrift transport rate at the starting point is large, namely F is large, the distance required to attain saturation is short. Hereafter this distance is designated as the developing distance, X_sat. The developing distance is determined by saltation length, ejection factor and saturated-snowdrift transport rate, all of which depend on wind speed. In the case of semi-hard snow cover, X_sat increases as U_{10} increases from 5.5 m s^{-1} to 8 m s^{-1}, and then decreases as U_{10} increases to 12 m s^{-1}. In the former range of U_{10}, the wind-speed dependence of X_sat is substantially determined by both the increase in saturated-snowdrift transport rate and the increase in saltation length because the ejection factor is almost constant. In the latter range of U_{10}, however, the effect of increase in the ejection factor with increasing wind speed surpasses other effects. Within the range of U_{10} considered, X_sat is 100–200 m at $F = 0.01\,\mathrm{mm\,h^{-1}}$ and 50–100 m at $F = 1\,\mathrm{mm\,h^{-1}}$. Compared with semi-hard snow cover, X_sat on hard snow cover is about one order longer due to its smaller ejection factor and longer saltation length. X_sat is about 1000 m for $F = 0.01\,\mathrm{mm\,h^{-1}}$ and 500 m for $F = 1\,\mathrm{mm\,h^{-1}}$.

Figure 5 is the same as Figure 4 except that the drifting snow is accompanied by snowfall. Since the snowfall is incorporated into aeolian snow particles during travel, X_sat

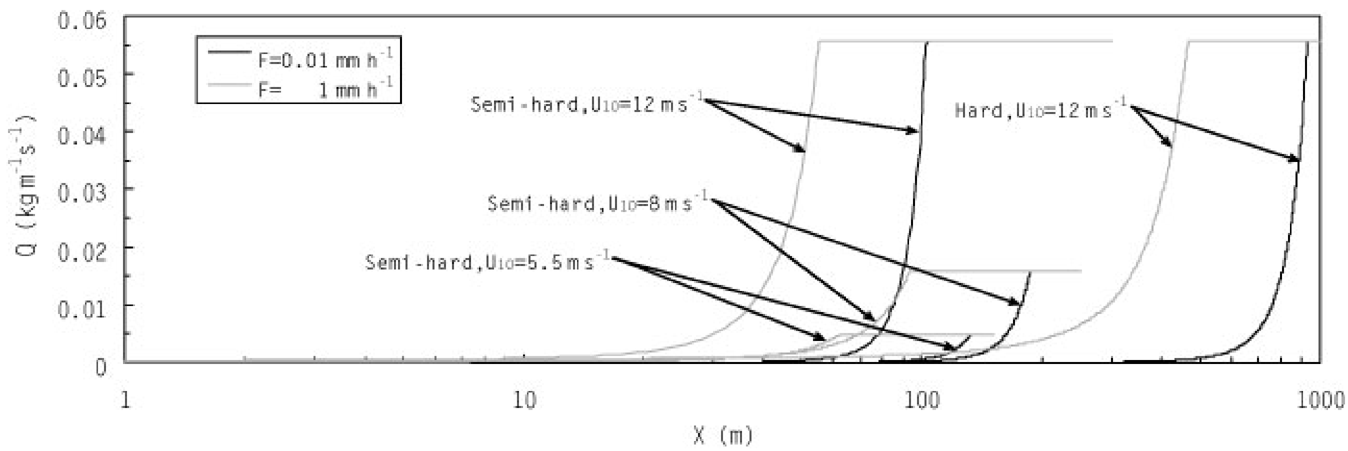

Fig. 4. Change of snowdrift transport rate with fetch distance for drifting snow without snowfall.

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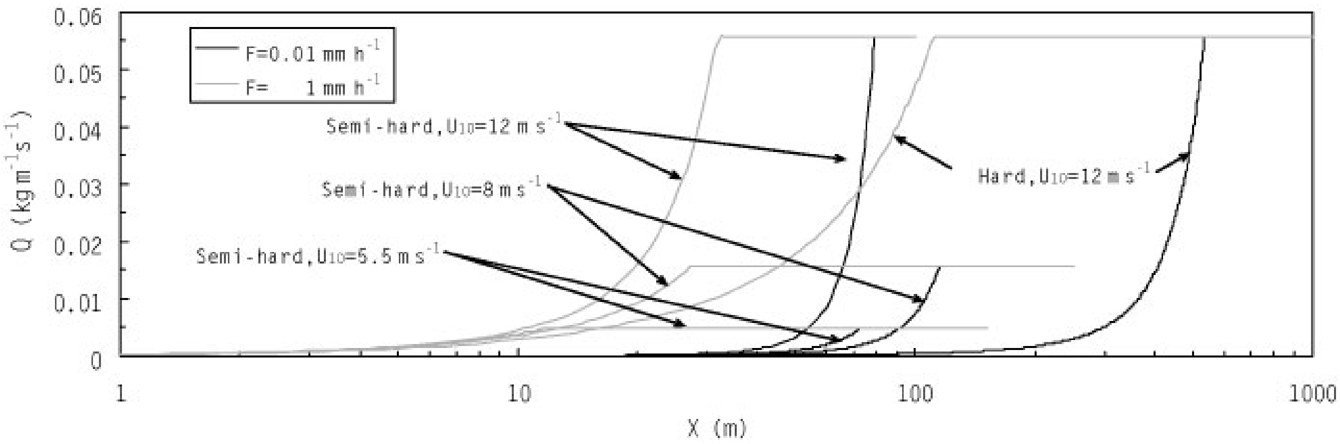

Fig. 5. Change of snowdrift transport rate with fetch distance for drifting snow accompanied by snowfall.

is shorter compared to the drifting snow without snowfall. The dependence of $X_{\rm sat}$ on wind speed at $F = 0.01$ mm h^{-1} is similar to that for the drifting snow without snowfall. The difference in $X_{\rm sat}$ between two types of snow cover is qualitatively the same. However, the hardness dependence of $X_{\rm sat}$ is not so distinct as that for drifting snow without snowfall. This is particularly marked when snowfall intensity is high.

Kobayashi (1972) reported that $X_{\rm sat}$ was 30–60 m under wind-speed conditions of 5–13 m s^{-1}. Takeuchi (1980) observed that $X_{\rm sat}$ was 150–300 m for a wind speed of 5–8 m s^{-1}. Although precise comparison is difficult because there is insufficient knowledge of the snow and meteorological conditions at the time, their values are within a range of the simulated developing distance on semi-hard snow cover. The simulated snowdrift transport rate increases rapidly as it approaches the saturated value, in contrast to the gentle increase observed in the field. Aeolian snow particles absorb the momentum of the airflow, causing the wind speed to decrease, especially when the drifting snow approaches the saturated state. Since the present simulation does not consider this effect, the resultant behavior near $X = X_{\rm sat}$ might be somewhat different from the actual one.

CONCLUDING REMARKS

The bounding motion of aeolian snow particles near the snow surface is affected by snow hardness as well as wind speed. The relationship between the saltation length on semi-hard snow cover and wind speed was obtained experimentally. The degree of erosion was expressed by a new parameter, which was termed the ejection factor, and its dependence on wind speed was obtained for semi-hard snow cover. Based on these results, the development of the saltation layer of drifting snow along the fetch was simulated. The distance required to attain saturation was found to depend on snow hardness, wind speed and snowfall intensity.

The scatter in the relationships between snowdrift transport rate and wind speed that were obtained in the past may be partly ascribed to the fact that the observations were made on snow covers with varying hardness and/or at different stages of drifting-snow development. Field observations of drifting snow, including measurements of snow conditions such as hardness and fetch distance together with snowfall intensity, will be needed to verify the present simulations.

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