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Effect of surface dust on snow melt

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Abstract

Snow dusting experiments were performed to study the relationship between dusting amount and ablation rate under different meteorological conditions, the behavior of dust particles on a melting snow surface, and its effects on albedo change and ablation. Results indicated that ablation rate increased with dust amount, from undusted condition in the range of 0 to 0.08 kg/m^2. However, when the amount was beyond 0.08 kg/m^2, the rate of ablation decreased. A maximum ablation rate was found for the dusting amount of 0.08 kg/m^2 in all the experiments. The dusting amount, beyond which the ablation rate is smaller than for undusted snow, increased linearly with the increase of sum of solar radiation input. Dust particles were found to aggregate with time through each experiment. The rate of aggregation was accelerated under conditions of intense solar energy, which inturn, caused the albedo to increase with time. This was particularly evident for lightly dusted snow surfaces. The increase in albedo resulted in a decreased ablation rate.

1. Introduction

Glacier surfaces in the Himalayas are covered with varying amounts and sizes of debris (Watanabe *et al.*, 1980 ; Fushimi *et al.*, 1980 ; Nakawo *et al.*, 1992 ; and Mattson *et al.*, 1992). Himalayan glaciers have been categorized mainly into two types : the clean type glacier (C-type) without a debris cover and the debris-covered type glacier (D-type) (Moribayashi and Higuchi, 1977). The surfaces of D-type glaciers are covered with a wide variety of debris types ranging from big boulders to fine debris. Also, Kohshima *et al.* (1992) suggested that some of the C-type glaciers in the Nepal Himalayas are not truely clean but are actually covered with a biogenic material. This material is known to cause a decrease in albedo of the snow/ice surface and consequently accelerates ablation. Hence, supraglacial debris plays a significant role in glacier mass balance in the Himalayas.

Several researchers have conducted experiments on the relationship between the amount of dust and the ablation rate, and have shown that the rate of ablation was enhanced with a debris cover less than a critical amount while being retarded with an amount larger than that limit (*e.g.* Østrem, 1959 ; Loomis, 1971 ; Fujii, 1977 and Mattson, 1992). The amount of debris on the snow/ice surface beyond which the ablation rate is less than the rate for undusted snow/ice surface is called the "critical amount". According to Nakawo and Takahashi (1982) the critical amount varies depending on prevailing meteorological conditions. They proposed a simple model to predict the ablation of glacier ice under a debris layer, which agreed with field data. However, the model assumed a constant albedo despite the debris amount. They did not take into account for rather small amounts of dust materials where the albedo changes with the dust amount. The quantitative estimation of ablation for less contaminated snow/ice covering a wide range in albedo has not been performed satisfactorily.

In this study, we monitored the change in albedo with different dust amounts and also with different inputs of solar energy to obtain empirical data for a better estimation of the ablation of dusted snow/ice surfaces. Also, a short time after melting begins, the dust particles have a tendency to change their location on the melting snow/ice surface (Zotikov, 1972). So, we made a effort to examine quantitatively the behavior of the particles on the melting snow surface. This paper describes the nature of aggregation of dust particles, and its effects on the albedo and ablation rate.

2. Experiment

A snow surface was artificially dusted with different dust loadings on 25-cm-square snow surface plots on March 21, 23, 24 and 26 and April 11, 1995. Time periods of the experiments were 13:00−17:00, 09:00−16:00, 12:00−16:00, 11:00−17:00 and 09:00−17:00 on March 21, 23, 24, 26 and April 11 respectively. The inconsistency of the duration of each sample day was due to technical difficulties : it was not possible to start the experiments at the same time. The total number of dusted plots were seven in each experiment with dust loadings ranging from 0.06 kg/m^2 to 0.90 kg/m^2 (Fig. 1a). A black soil sieved with meshes of 0.35 mm and 0.15 mm was used for the experiments to have the grain size in the range between the two (*i.e.* $0.35 \geq \Phi > 0.15$ mm.). The dry albedo and the approximate dry bulk density of the soil were 0.08 and 448 kg/m^3 respectively. Since the soil-type which is used for the experiments is used as a fertilizer at the Department of Agriculture, Nagoya University, the soil must have contained organic matters.

The dusting experiments were carried out on a seasonal snow cover with a horizontal surface at 450 m a.s.l. at Saiho (lat. 36°59' N, long. 138°43' E), Niigata Prefecture, Japan. The snow surface albedo and the density of snow were different between different experiment days (Table 1) although the locations of each experiment were close to each other within the horizontal surface of the snow cover.

After preparing the plots, inflexible graduated strings were stretched over the plots between hollow aluminum poles of 1 cm in diameter and 1 m in length each installed at the sides of each plot. The aluminum poles were painted white to reduce the amount of solar radiation absorption on their surfaces (Fig. 1b). Surface lowerings on the dusted plots and on the undusted snow surface were measured every 1 or 2 hours at graduations marked on the strings, with a graduated ruler, at intervals of 1 to 2 cm from one side to the other. Measurements of surface lowering was limited to depressions wider than, or equal to, the ruler's width (1.4 cm). Total ablation was determined by multiplying the average difference in the measured distance from the string to the surface by the snow density on that day, for a given period of time.

The albedo of the dusted and undusted snow surfaces was measured every hour by an albedo meter. It was composed of two photo diodes (one open, and the other shielded) which can instantaneously sense the upward and downward short-wave radiation (Fig. 1c). A short hollow black cylinder was used to shield

Table 1 Consequences from different experimental days.

	Mar 21	Mar 23	Mar 24	Mar 26	Apr 11
Snow albedo (undusted)	0.67	0.60	0.65	0.83	0.57
Snow density (g/cm^3)	0.38	0.39	0.39	0.34	0.42
Effective total ablation under the effective amount of dust (cm, w.e)	2.01	3.32	0.75	1.05	4.06
Effective amount of dust (kg/m^2)	0.08	0.08	0.08	0.08	0.08
Critical amount of dust (kg/m^2)	0.24	0.60	0.10	0.18	0.56
Heat balance components for undusted snow surface (W/m^2)					
Net short-wave radiation, Rns		207.2	110.8	41.1	240.1
Net long-wave radiation, RnL		−66.3	−18.9	−63.2	−49.7
Sensible heat, H		10.0	6.8	3.5	85.5
Latent heat, Lh		1.2	3.3	−1.3	4.0

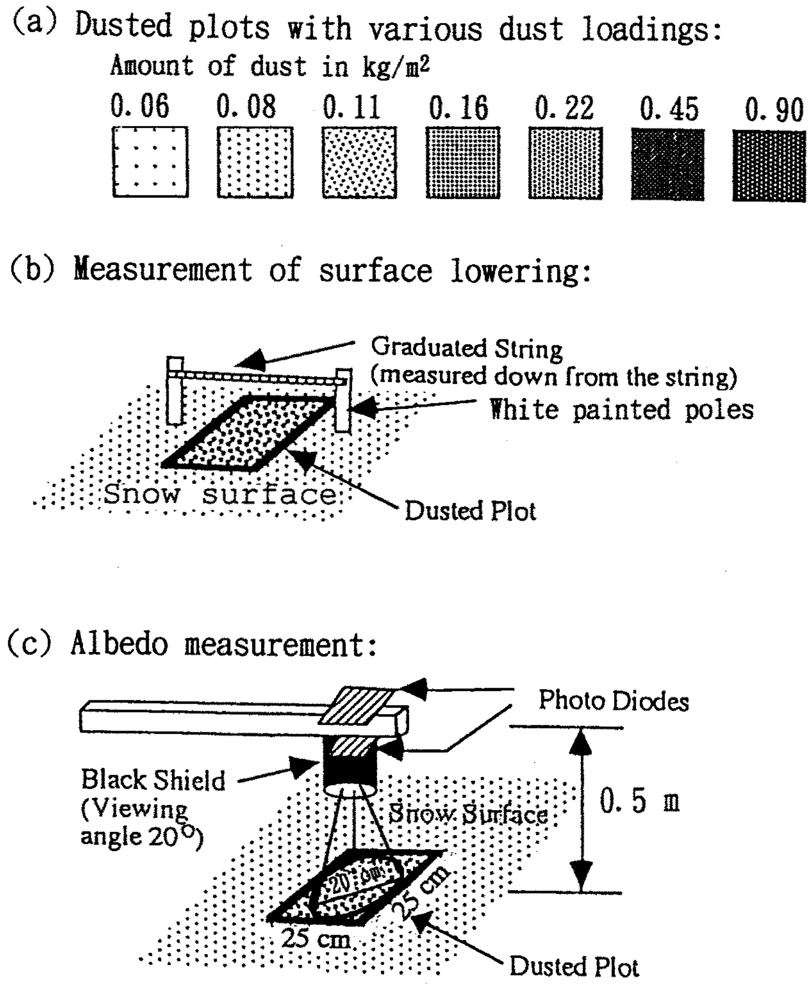

Fig. 1 Schematic diagram of the experimental procedures.

one of the diodes for the measurements of outgoing short-wave radiation only from the plots. The viewing angle of the shielded photo diode was 20° and the height from the surface was about 0.5 m so as to prevent the diode from receiving the radiation outside the plot. The incoming radiation sensor has a 180° cone of acceptance. The diodes (5.8×5.8 mm in size each) were sensitive from visible to near infra-red light (300 nm to 1100 nm in wavelength). Taking into account the difference in the viewing angles of the two diodes, the correction factor of 1.4 was applied, which was obtained by comparing the measured radiation with and without the shield over a wide area of the snow surface. In addition, photographs of every plot were taken at intervals of 1 to 3 hours to investigate the aggregation of soil particles on the dusted plots.

3. Meteorological conditions

Ten-minute averages of meteorological variables such as incoming solar radiation (W/m²), air temperature (°C) and relative humidity (%) were collected from a meteorological station about 50 m away from the experiment site. The instrument for the measurement of incoming solar radiation was EKO (MS-43F), thermocouple type. Air temperature and relative humidity were measured with Hakusan (HS151LS) instrument, being capable of measuring in the range of −50∼80 °C and 0∼100 % respectively. Wind speed was measured manually once an hour by a calibrated anemometer at the experiment site. Fig. 2 shows the meteorological conditions of each experiment day.

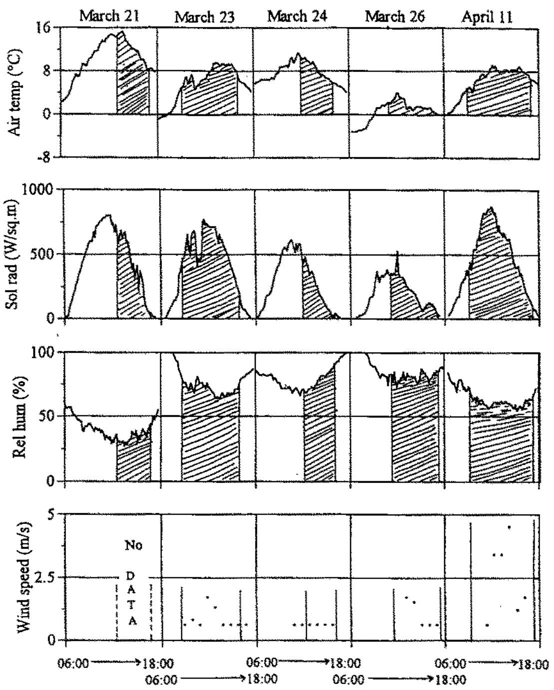

Fig. 2 Meteorological conditions during the experiments. Shadow area indicates the time duration of each experiment.

4. Results and Discussions

4.1 *Ablation*

Characteristics of snow ablation under different amounts of dust is revealed from the experiments and the results were found similar to those obtained by previous researchers (for example ; Østrem, 1956, Loomis, 1970 & Fujii, 1977). Fig. 3 illustrates the total ablation for different dusting amounts of three different experiments as an example. In all cases total ablation increased with the increase of the dusting amount from 0 to 0.08 kg/m^2, followed by a decrease in ablation when the dusting amount went beyond 0.08 kg/m^2. The dusting amount which corresponded with the maximum snow ablation, termed *the most effective amount* in this study, appeared to be a constant, 0.08 kg/m^2 but the *critical amount* of the dusting amount, beyond which the ablation is less than

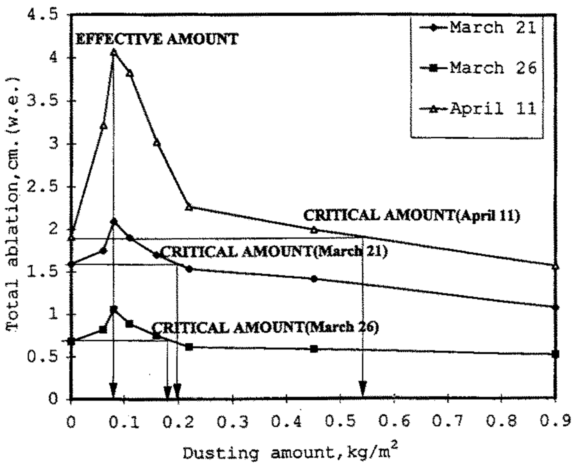

Fig. 3 Relationship between dusting amount and ablation.

the one for undusted snow, was different from day to day (Table 1). This is illustrated more clearly in Fig. 4, where effective as well as critical amounts are plotted against the total incoming solar radiation corresponding to each experiment. The total solar radiation is the sum of the ten-minute averages of the radiation data corresponding to the duration of each experiment. Fig. 4 shows that the most effective ablation occurred at the same dusting amount, 0.08 kg/m^2, but critical amount increases linearly with the increase of solar energy.

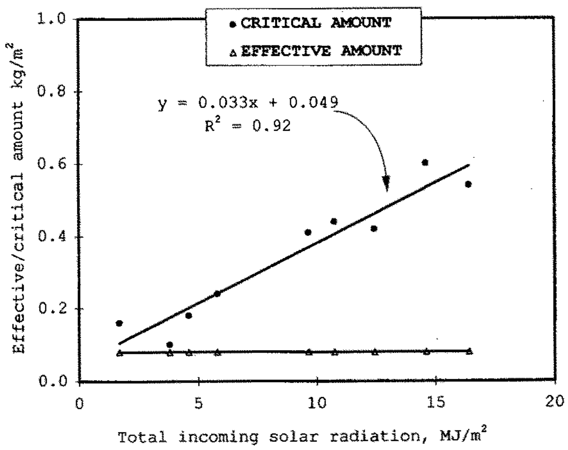

Fig. 4 Relationship of most effective amount and critical amount against the sum of solar radiation. Additional data are plotted for short periods selected from the five runs of the experiments.

Fig. 5 illustrates the total ablation on the undusted snow surface plotted against the total incoming solar radiation. It shows a linear relationship between the total incoming solar radiation and the ablation (correlation coefficient : 0.91). The relation, however, is not linear for the dusted surfaces as shown in Fig. 6. Fig. 6 shows ablation results from different meteorological conditions which shows the ablation

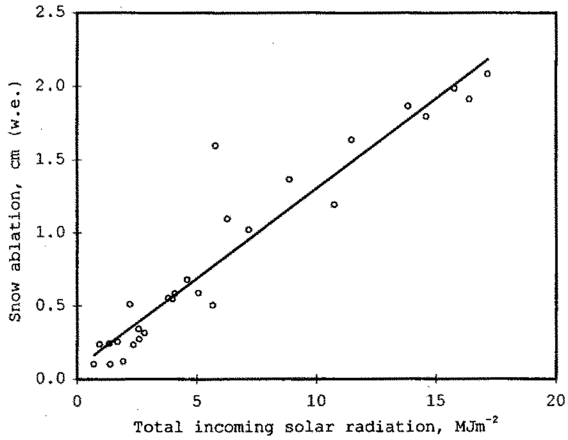

Fig. 5 Relationship between total ablation and total incoming solar radiation for undusted snow surface. The solid line is the linear regression between the ablation and the solar radiation. Additional data are plotted for short periods selected from the five runs of the experiments.

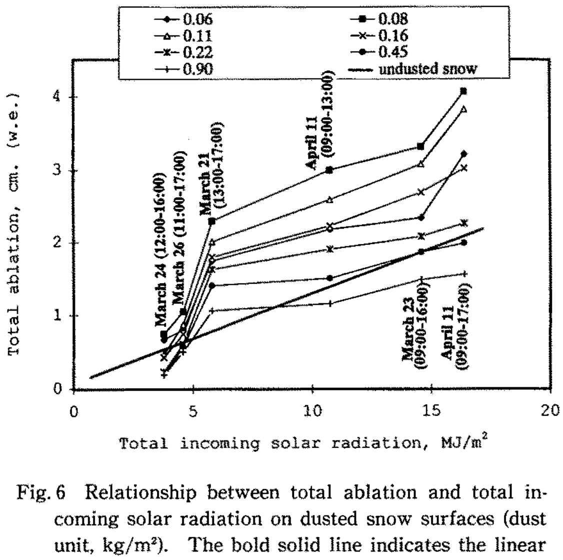

Fig. 6 Relationship between total ablation and total incoming solar radiation on dusted snow surfaces (dust unit, kg/m^2). The bold solid line indicates the linear relation obtained for undusted snow surface (Fig. 5).

rate increasing sharply up to 5.8 MJ/m^2 but the increasing trend at energy levels larger than 5.8 MJ/m^2 is shown to be more gentle compared to that below 5.8 MJ/m^2 on the dusted plots.

Table 1 illustrates the heat balance calculations on undusted snow surfaces during each experiment, showing that the solar radiation is the most dominant energy source among the heat sources. In heat balance calculation, sensible heat, latent heat and net short wave radiation were calculated according to Paterson (1994) and net longwave radiation was calculated according to Oke (1987). Intensity of heat conduction through the dust on and into the snow varies depending on the amount of dust present on the surface. In our experiments, heat storage within the debris layer is considered negligible with the fact of a relatively thin debris cover on the snow. It is considered that the total heat flux increased up to the most effective amount due to the reduction of albedo and then decreased on a higher amount of dust due to thicker dust cover than the effective dust amount. The dusted area with dust amount less than the most effective amount exhibited less ablation due to higher reflectivity caused from partial snow coverage by the dust. Hence, albedo is the dominant factor controlling ablation up to the most effective amount, but the insulation by dust layer is the most dominant factor above the most effective amount. Consequently, maximum ablation occurs when the function changes from the domination of albedo to the domination of the insulation.

The insulation effect is enhanced as it goes to higher dust loadings and reduces the ablation above the most effective amount. The amount of ablation above the critical amount is less compared to undusted snow surfaces due to the insulating effect of the thick dust cover. Dust less than the critical amount absorbs solar radiation more than a dust free surface and transmits energy to the dust/snow interface and accelerates the total ablation. If the available energy is large, the flow of energy to the snow is large and more dust is needed to protect the surface from melting. Due to this fact that critical amount of dust on the snow would varies depending on solar radiation inputs. Our data have proved that the critical amounts increase linearly as the input of energy becomes large (Fig. 4). This result on the critical amount substantiate the prediction by Nakawo and Takahashi (1982) from a modeling study.

4.2 Aggregation and its effect

Fig. 7a shows an example of the aggregation of dust particles on a dusted plot on a melting snow surface with time. It was observed that the particles of soil-dust changed their location shortly after the melting started, having a trend to aggregate at the melting crusts. The aggregation resulted in a decrease of areal fraction of the black part with time on the dusted snow surface. The areal fraction of the black part along one line across each plot was measured from the photographs taken during each experiment. Fig. 7b shows an example of the result of aggregation along a line on a plot. From this figure, it is clear that the dust particles aggregated into small groups with time.

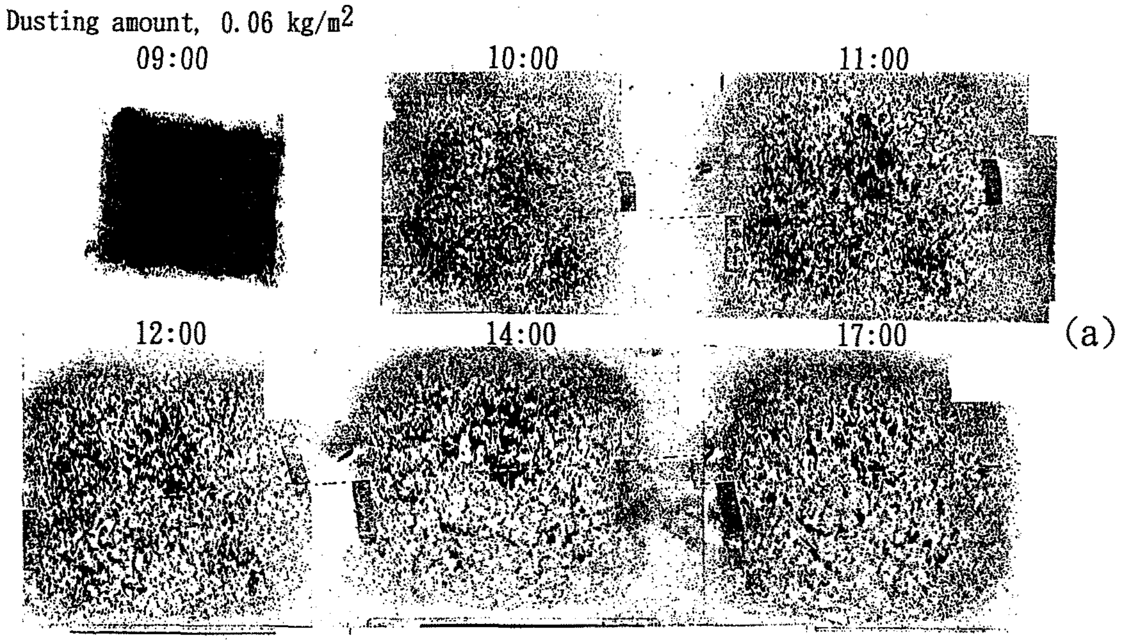

Fig. 7a. An example of the progressive aggregation of dust particles on a melting snow surface (Mar. 23, 1995). The dust was distributed on the snow shortly before 09 : 00, when the size of the area was 25×25 cm².

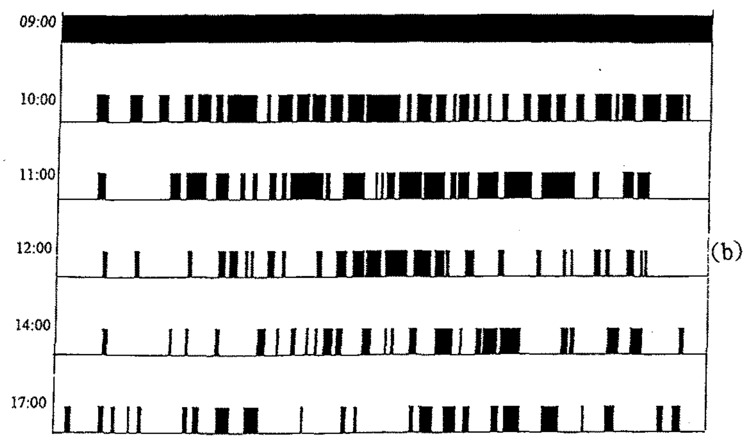

Fig. 7b. Schematic representation for the aggregation along a line across the plot (Fig. 7a.).

Fig. 8 shows the temporal variation of the ratio of black parts (in percentage) with time. The ratio decreased with time in the range of light dusting amounts from 0.06 to 0.45 kg/m², but for the heaviest dusting amount, 0.90 kg/m², the whole area remained covered with dust. In other words, aggregation on the snow surface became intense for light dusting amounts, but aggregation did not occur at a plot with heavy dust. It is evident from the figure that dust particles were highly aggregated on the snow with time only up to a certain limit, and no further aggregation was found beyond that limit. As the particles aggregated with time, the aggregation would proceed with lowering of the snow surface upto the limit. Note the surface lowering is enhanced with the increase of solar energy. After the aggregation limit is reached, the process of aggregation becomes independent of the energy flux when the particles reach their maximum stage.

Fig. 9 shows the changes in the albedo with time. For a plot with the lightest dust amount (0.06 kg/m²), the albedo increased from 11 % to 32 % due to the aggregation of dust particles. It remained relatively stable, however, with the heavy dusting amount (0.90 kg/m²) because of the absence of aggregation. Figure 10a indicates the albedo against the sum of the solar radiation after each plot was prepared, showing linear relations between them caused by aggregation. The slope of albedo change in Fig. 10a is shown against dusting amounts in Fig. 10b. The regression

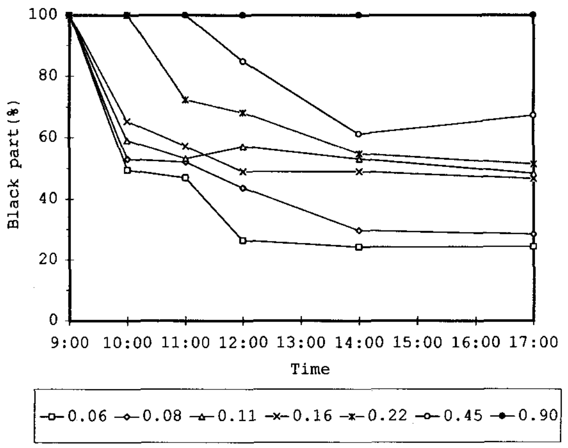

Fig. 8 The temporal change in ratio of the black part on the dusted snow surfaces (Mar. 23, 1995) (dust unit, kg/m²).

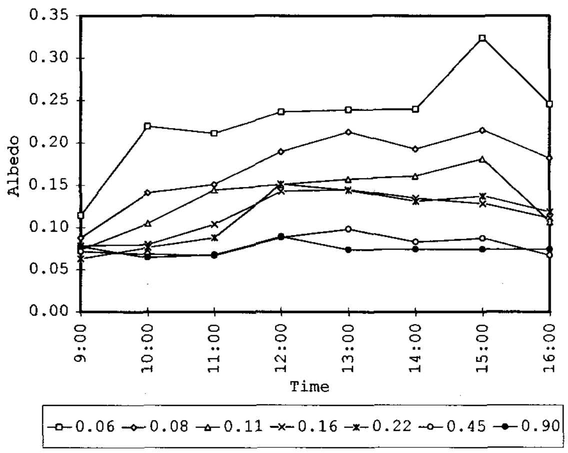

Fig. 9 Albedo change for various dusted snow surfaces (Mar. 23, 1995) (dust unit, kg/m²).

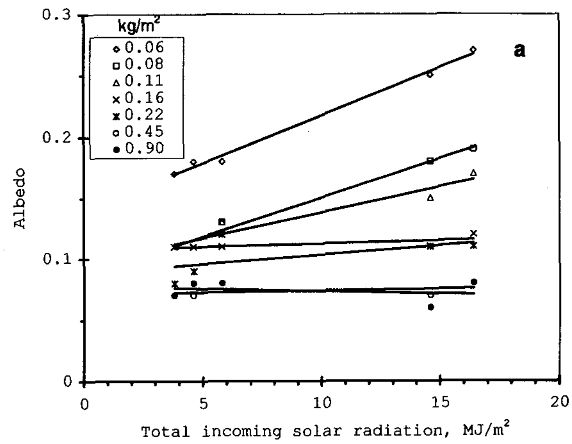

Fig. 10a. Relationship between total incoming solar radiation and albedo on the dusted snow surfaces.

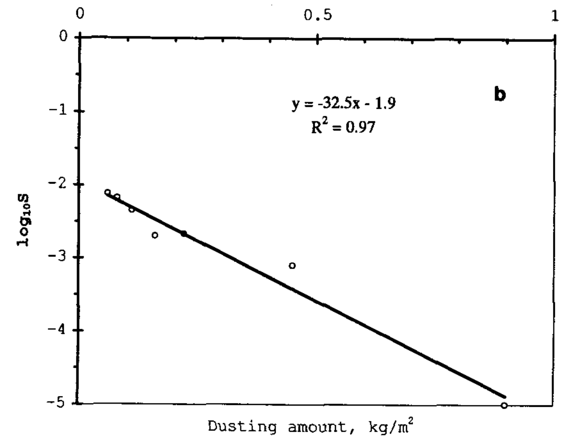

Fig. 10b. The relation between the dusting amount and the gradient of radiation dependence of albedo (Fig. 10a.)

resulted in $S=0.142\times e^{-32.5x}$ (correlation coefficient is -0.97), where S is the slope with the unit of m^2/MJ and x is the dusting amount in kg/m^2.

The aggregation of dust particles caused an increase in albedo compared to the initial stage and the amount of solar radiation absorption on the surfaces was obviously reduced. This confirms that the aggregation became intense at higher energy levels where the total ablation is large, but the ablation trends of dusted snow surfaces were suppressed, as shown in Fig. 6, at the energy levels higher than 5.8 MJ/m^2. Therefore, the aggregation of particles can be a negative feedback for melting.

5. Conclusions

Snow dusting experiments under different meteorological conditions were performed to understand the effect of surface dust on snow melt and to clarify the quantitative behavior of dust particles on melting snow surfaces. Our data have revealed the following principal results :

1. For dusting amounts ranging between 0.06 kg/m^2 and 0.90 kg/m^2, ablation rate was the highest with the dusting amount of 0.08 kg/m^2 (which we termed *the most effective amount*). The effective amount was found constant for varieties of meteorological conditions.
2. The *critical amount*, beyond which the ablation is less than the undusted snow, on the other hand, appeared to increase linearly with the increase of solar energy. This result confirmed the result obtained by Nakawo and Takahashi (1982).
3. Albedo of the dusted snow surfaces increased with time as solar radiation amount increased, in particular for lightly dusted snow surfaces due to gradual aggregation of the dust particles.
4. The aggregated dust particles showed an aggregation limit after the particles reached a maximum aggregated stage. The process of aggregation was found to be independent with time after the limit, suggesting that the aggregation became independent on the sum of the solar energy as well.
5. The rate of aggregation became intense for large solar energy, which caused the albedo to increase for lightly dusted snow surfaces. The increase in albedo resulted in a decreased ablation rate. Therefore, the aggregation of dust particles on a melting snow surface can be a negative feedback for melting.

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