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Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas

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Abstract Ablation of natural ice under a dust cover was investigated at Lirung Glacier, Nepal Himalayas. Total ablation of a relatively flat ice surface was increased to a maximum of about 4 to 5 fold when the initial dust concentration increased from 0 to 0.112 kg m^{-2}. Ablation decreased from the maximum rate when the dust concentration exceeded 0.112 kg m^{-2}. The most effective dust concentration (0.112 kg m^{-2}) for ice ablation did not depend on weather conditions, and was larger by a factor of 1.4 compared to that for snow (0.08 kg m^{-2}) found in previous research. With the initial application of dust concentration in the range 0–0.112 kg m^{-2}, the ice surface albedo was reduced to values of 0.15–0.22 that were substantially lower than the albedo of the bare ice (average 0.39). Dust particles on melting ice were usually washed away depending on the surface slope and the amount of meltwater. Migration of locally-applied dust particles on the melting surface caused an evolution of the spatial pattern of albedo that spreads the albedo reduction to adjacent cleaner ice surfaces. During our observations the influence of dust on ice melting was relatively large on a cliff compared to a flat surface.

INTRODUCTION

The presence of surface debris consisting of dust, silts, sands, gravel, cobbles and boulders is a common feature of Himalayan glaciers. Moribayashi & Higuchi (1977) classified Himalayan glaciers into two categories: (a) clean type (C type) without rock debris and (b) debris-covered type (D type) covered with rock debris. However, contrary to their name, C type glaciers are not truly clean but are actually covered with fine dust (Kohshima *et al.*, 1993). The dust concentration at the surface is particularly visible during the summer season when significant melting of the glaciers takes place. Although the Lirung Glacier is a typical example of the D type glacier with heavy debris cover, there are still many ice cliffs that are usually covered with a thin layer of scattered particles (hereafter referred to as TS dust). Ablation at such cliffs in D type glaciers plays a very important role in the total ablation (Inoue & Yoshida, 1980). Examples of TS dust on cliffs are shown in Fig. 1 for two different slopes and orientations. For

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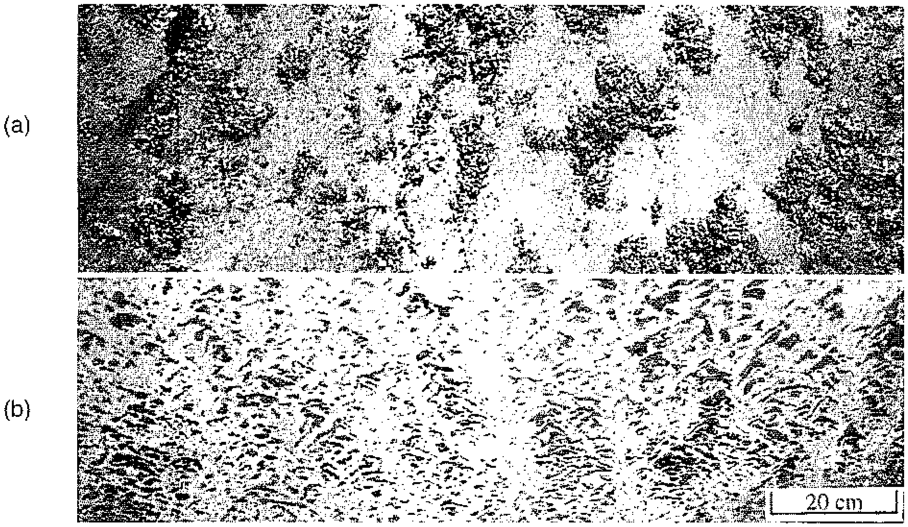

Fig. 1 Two different ice cliffs at Lirung Glacier (30 May 1996). (a) Mean slope: 45°; orientation: southeast. (b) Mean slope: 60°; orientation: Northwest.

Lirung Glacier the average melting rate is 10 times larger at ice cliffs than on the less steep debris-covered area (Private communication; A. Sakai, December 1999). This result indicates that TS dust is important for ablation even on D type glaciers.

The melting of the Himalayan glaciers is dominated by the radiation balance at the surface. In particular, the surface albedo affects the absorption of solar radiation (Ohata & Higuchi, 1980). For a TS dust covered surface, the effect on albedo is more important than insulation by the debris. According to Warren & Wiscombe (1980), ice is very weakly absorptive in the visible region of solar radiation, and even a trace amount of dust can strongly reduce the albedo of an ice surface.

Unlike a heavy debris cover (e.g. cobble or boulder size), TS dust of relatively fine particles (e.g. dust or silt) has a tendency to redistribute on melting snow or ice surfaces causing the effect on albedo to be dynamic and complicated (Adhikary *et al.*, 1997). Consequently in order to understand the full effect of dust, it is essential to monitor the albedo in space and time. Adhikary *et al.* (1997) showed that the albedo of melting snow surfaces with distributed dust, increases with time due to gradual aggregation of dust particles. However, the behaviour of dust on a melting ice surface could be different from that of the snow. Observations have consistently shown that the ablation rate of the underlying snow or ice can be accelerated if the debris thickness is relatively thin (order of a few centimetres) (e.g. Østrem, 1959; Fujii, 1977; Nakawo & Young, 1981). However, studies on TS dust-covered surfaces have received considerably less attention than heavily debris-covered surfaces, particularly because of uncertainties about redistribution of the particles. Experimental data on TS dust layers are crucial for realistic modelling studies, for which it is important to consider albedo as a spatial and temporal variable influenced by melting and dependent on slope orientation and magnitude.

In this study we report experimental data illuminating the behaviour of dust particles on melting ice and the consequent quantitative changes in albedo and melting rate. Two dissimilar surface types, one relatively flat and one on a slope, are examined to investigate the effect of gravity driven flow of meltwater on the particles.

EXPERIMENTAL PROCEDURES

Field experiments were carried out during daytime (11:00–14:00 NST) on 28, 29 and 30 May 1996 at Lirung Glacier, Langtang region, Nepal Himalayas, as a part of the GEN project (Nakawo *et al.*, 1997). The weather conditions during each set of the experiments are summarized in Table 1.

Table 1 A summary of major meteorological parameters for the 3-h period of each set of experiments evaluated from recorded 5-min mean values.

Parameter	28 May:			29 May:			30 May:		
	min.	mean	max.	min.	mean	max.	min.	mean	max.
Air temperature (°C)	10.7	15.7	17.8	9.4	12.3	14.6	13.0	13.9	15.2
Incoming solar radiation (W m^{-2})	43.8	184.4	825.4	272.7	684.8	1093.3	717.7	829.0	985.6
Relative humidity (%)	30.7	45.5	64.1	41.1	50.8	62.6	38.6	46.0	54.4
Wind speed (m s^{-1})	5.4	6.2	7.5	5.1	5.9	6.9	5.1	6.1	7.3
Average cloud cover (in tenths)		9/10			8/10			7/10	

Experiment on a relatively flat surface

On the 28 and 29 May a 5 m × 2 m plot at elevation 4400 m a.s.l. (Site F, Fig. 2) was cleaned free of debris and smoothed with a shovel. Remaining scattered dust or sand was removed with water. The flatness of the surface was verified with the help of a spirit level. Each day the prepared bare ice surface was manually dusted using a known dust material (black soil containing a large amount of organic matter, albedo 0.08 and 0.06 for dry and wet conditions respectively, particle size $0.35 \geq \phi > 0.15$ mm, bulk density 450 kg m^{-3}) on seven sub-plots P1 to P7 (25 cm × 25 cm) with varying concentrations (Table 2). Besides the seven dusted plots, an approximate area of 40 cm × 40 cm of the prepared ice surface about 1 m away from the nearest dusted plot was monitored as an undusted reference plot (P8). Measurements of albedo and surface lowering (ablation)

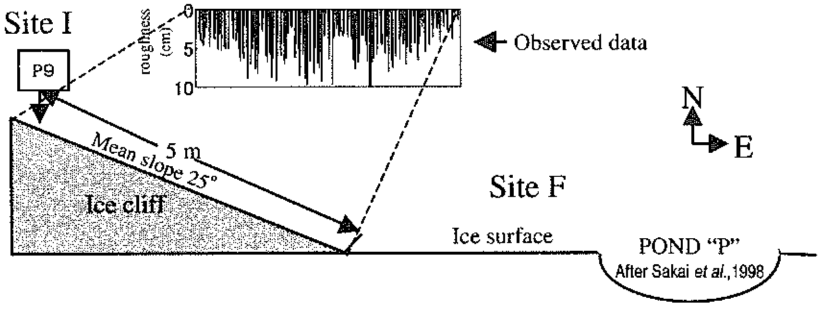

Fig. 2 A schematic drawing showing the experimental setting, where Sites I and F refer to the ice cliff and the relatively flat surface respectively. The observed roughness (expressed by the amplitude of the surface undulation) of the ice cliff surface prepared for the experiment is also shown. P9 is the dusted plot.

Table 2 Comparative statistics between initial and final conditions of dust concentrations, surface albedos, and ablation.

Initial dust concentration ($kg\ m^{-2}$) (11:00)		Initial thickness (mm)	Initial albedo (11:00):		Final dust concentration ($kg\ m^{-2}$) (14:00):		Final albedo (14:00):		Total (3 h) ablation (cm, ice):	
			28 May	29 May	28 May	29 May	28 May	29 May	28 May	29 May
P1	0.056	0.13	0.16	0.22	0.050	0.047	0.24	0.28	0.85	1.18
P2	0.080	0.18	0.16	0.21	0.067	0.062	0.19	0.27	1.32	1.69
P3	0.112	0.25	0.15	0.17	0.092	0.088	0.17	0.18	1.45	1.86
P4	0.160	0.36	0.15	0.14	0.136	0.130	0.17	0.15	1.12	1.45
P5	0.224	0.50	0.13	0.13	0.201	0.188	0.15	0.15	0.60	1.04
P6	0.448	1.00	0.11	0.11	0.413	0.402	0.14	0.11	0.33	0.75
P7	0.896	2.00	0.10	0.11	0.842	0.808	0.11	0.09	0.24	0.58
P8	Bare ice	-	0.38	0.39	-	-	0.37	0.40	0.28	0.51

on each plot were made. The instrumentation and the methods of observation employed for all sets of experiments are the same as those described in Adhikary *et al.* (1997).

Experiment on an ice cliff

On the 30 May an ice cliff with an average surface gradient of 25° sloping towards the east, length 15 m and width 5 m was chosen for the experiment. Existing scattered debris on the lower portion of the cliff (~6 m) was removed as described for the flat surface. The average surface roughness (expressed here as the amplitude of the surface undulation) on the lower portion of the cliff along three longitudinal profiles was of the order of several centimetres, which was larger than that of the natural bare surface (Site I, Fig. 2). A trench was dug immediately above the debris cleared portion of the cliff, so that the experimental area would not be affected by water or debris flow from the upper portion (~9 m) of the cliff. An area approximately 25 cm × 25 cm on the uppermost part of the cleared portion of the cliff was artificially contaminated with 3.5 g (or 0.056 $kg\ m^{-2}$) dust (P9). Also, an area approximate 40 cm × 40 cm with the same slope as the cleared section of the cliff (i.e. 25°), was isolated as a reference, undusted surface (P10) by digging another trench.

Quantitative measurements of dust flow on melting surfaces

Since dust particles on melting ice surfaces are often transported by meltwater, we measured the net dust loss from each dusted plot during the experiments. The average slope of P1, P2 and P3 were also measured by an inclinometer at the end of the experiments on 28 and 29 May. They were small (approximately 0.2° southward in all the cases). It was not practical to measure the slope of the remaining plots due to the soft surface of the dust layer. At the end of each experiment, the remaining dust from each area of the plot was drawn off together with the underlying ice samples to a depth of about 1 cm. The ice was melted and filtered through Millipore filters with a pore size of 0.45 μm in order to measure the dust content. Next, ice samples were collected at the lower zone of the cliff down from P9. The method of sampling and measuring the dust inclusion was the same as for the flat surfaces.

RESULTS AND DISCUSSION

Ablation observations

Figure 3(a) and Table 2 show ablation (3 h total) on 28 and 29 May for different initial dust concentrations. The thickness for each concentration was calculated based on given mass and observed bulk density assuming that the dust material was distributed

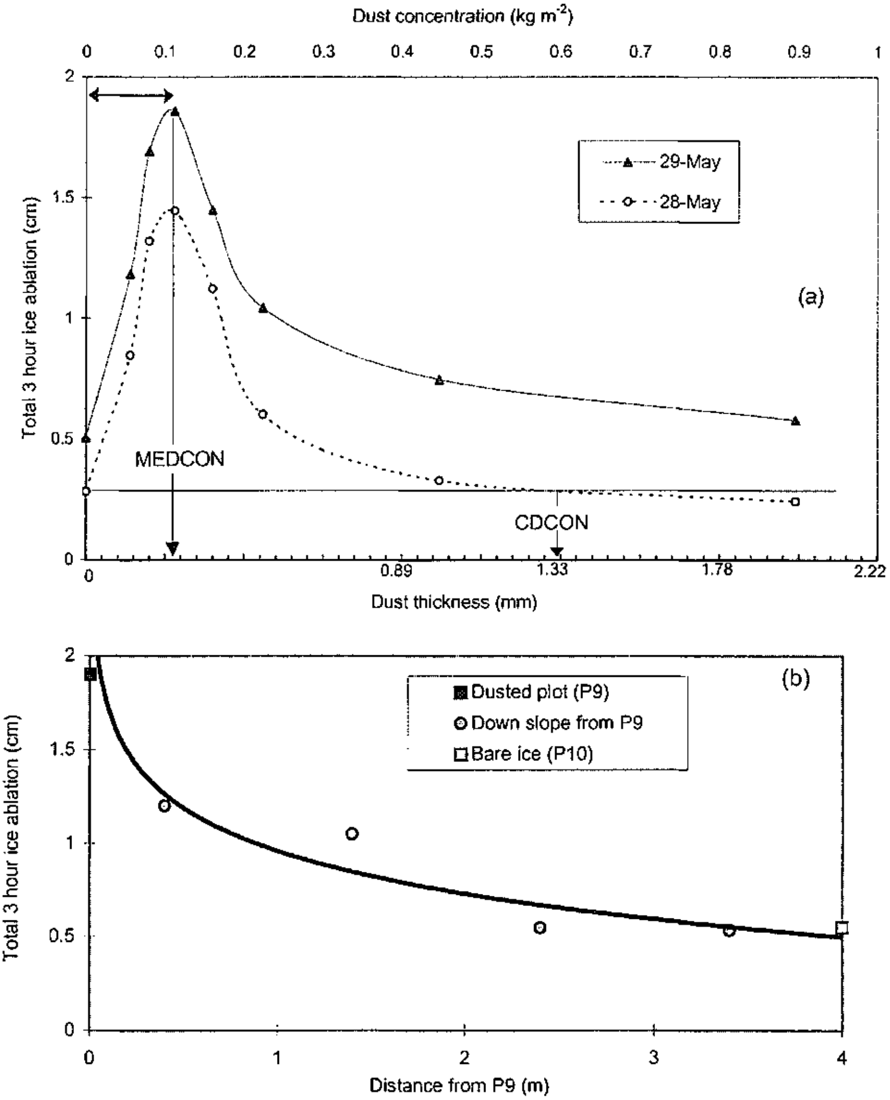

Fig. 3 (a) Relationship between dust concentration (or dust layer thickness) and the total ice ablation during the experimental periods. MEDCON and CDCON stand for most effective dust concentration and critical dust concentration respectively. The horizontal bar with double arrows shows the range of dust concentration of special interest. (b) Total ablation on the ice cliff for P9, P10, and various points down-slope from P9. The exponential curve is the best fit to the observed data.

uniformly. Total ice ablation increased with increasing dust concentration (thickness) from 0 to 0.112 kg m^{-2}. There was a decreasing trend for concentrations larger than 0.112 kg m^{-2} (0.25 mm). The critical dust concentration, beyond which the ablation was smaller than for clean (bare) glacier ice was approximately 0.6 kg m^{-2} (1.33 mm) on 28 May. Total ablation was generally larger on 29 than on 28 May. It was larger under the most densely dusted surface (0.896 kg m^{-2}) than for bare ice. The most effective dust concentration (hereafter abbreviated as MEDCON) for the ablation was the same (0.112 kg m^{-2}) on both days. The total ablation under the MEDCON on 28 (1.45 cm) and 29 (1.86 cm) May was about 5 and 4 times larger than for bare ice. These results are qualitatively similar to those observed by previous researchers since Østrem (1959) did his pioneering work.

Adhikary *et al.* (1997) found 0.08 kg m^{-2} MEDCON for snow ablation. Although the physical properties of the dust used by Adhikary *et al.* (1997) that used in the present experiment are very similar, a larger initial concentration by a factor of 1.4 is required for maximum ablation for ice compared to snow. This difference suggests that similar dust material work differently on snow and ice surfaces. Dust particles on a melting ice surface are vulnerable to transport by meltwater and migrate as the melt progresses. Consequently the spatial pattern of melting changes with time due to the alteration of the rate of solar energy absorption caused by the redistribution of dust particles. A short horizontal line with double arrows in Fig. 3(a) illustrates the range of concentration 0 to MEDCON of special interest for the following discussion.

Figure 3(b) shows the results for differential ice ablation on the experimental ice cliff on 30 May. During the observation period the total amount of ice ablation measured on P9 was 1.9 cm compared to 0.5 cm on P10. The meltwater from the cliff did not accumulate on the surface but flowed down the steep slope (25°). Some of the dust particles were observed to be sliding down the cliff moving along with the meltwater. The scattered bold dots on Fig. 3(b) indicate our ablation measurements along the moving path of the particles on a longitudinal profile down-slope from P9. The data show that total ice ablation decreased as the distance from P9 increases. The trend is approximately exponential.

In spite of the equal initial dust concentration (0.056 kg m^{-2}), total ablation on P9 (1.9 cm) was about 2 times greater than on P1 (1 cm, average from 28 and 29 May). Ablation rates on P9 (cliff) and P1 (flat surface) relative to respective bare ice were about 4 and 2.5 times greater respectively (see Table 2 and Fig. 3(b)). Other than the difference in absolute values of ablation, which depend on the prevailing weather conditions and exposure angle to the sun, ablation under a dust cover relative to bare ice was greater on the sloping cliff surface than on the flat surfaces. Reasons for the difference in ablation between the cliff and the flat surfaces may be that:

- each dust particle absorbs more solar radiation on the sloping cliff surface because the radiation intensity on a slope is higher than on a flat surface;
- each moving particle leaves a track of surface disturbance that absorbs solar radiation.

The former can be explained in terms of the effect of dust on albedo that leads to greater ablation on a cliff than on a flat surface. For Lirung Glacier, sloping surfaces, in particular those facing east generally receive greater solar radiation (Sakai *et al.*, 1998). Our experimental cliff was facing the east which might have exposed it to greater solar radiation during the early part of the experiment when the sky was relatively clear. Dust particles on the cliff were more scattered than on the flat surfaces, so that the shadow of one particle on an adjacent particle was insignificant. This situation allows each particle to absorb maximum radiation.

The latter relates to the action of each individual particle moving on the ice surface. Dust particles on a sloping cliff surface are more dynamic than on a flat surface due to the gravity driven flow of meltwater. As pointed out by Kotlyakov & Dolgushin (1972), dust particles not only absorb the solar energy and release it for melting, but also form pits in the ice surface where they are placed that collect meltwater. Such surface morphology leads to an additional decrease of surface albedo and increase in melting. The additional decrease in albedo is caused by trapping of a certain amount of the incident total solar radiation due to multiple reflection inside the pit and absorption in the water. However, if a particle is in a pit, its effectiveness for absorbing radiation will decrease. Formation of such pits by a particle would be greater on the cliff than on a flat ice surface since the gravity-driven flow of meltwater would usually displace a particle from a pit, allowing the particle to form successive pits on its way down the surface. However, the preceding pits do not last long as the melt progresses. The principle difference of surface morphology between the cliff and the flat surface caused by the actions of individual particles may account for the relatively large ablation on the cliff compared to the flat surface during our observations.

Albedo observations

Table 2 shows albedos of dusted surfaces on 28 and 29 May at the beginning and end of each experiment. The data indicate that the albedo of the ice surfaces covered with dust decreased with increasing concentration and approached the albedo of dust itself when the underlying surface was fully covered by the dust. A comparison of the albedos at the beginning and end indicates that the albedo increased dramatically with time particularly on more lightly dusted surfaces. This shows that the albedo of the TS dust-covered surface is variable with time during conditions of melt.

Figure 4 shows the time variation of albedo on dirty and clean areas of the ice cliff. Albedo was measured at 10-min intervals. With the initial application of dust, the albedo of the cliff surface dropped from 0.45 (bare ice) to 0.22 (P9), then increased monotonically with time until reaching a value of about 0.36. After that there were small variations around a mean of 0.36. Observations at areas below P9 show that the albedo decreased over time at a slow rate broken by frequent small fluctuations. The lowering of albedos at locations close to P9 was particularly evident. The albedo of P10, however, remained nearly constant.

Behaviour of dust on melting surfaces

Figure 5(a) shows the amount of dust lost from the flat dusted surfaces during the melting of the ice surface on 28 and 29 May. The data indicate that dust loss increased sharply with increasing initial concentration up to the MEDCON, which resembles the rising portions of the ablation curves (Fig. 3(a)). Unlike a snow surface, which is generally porous, an ice surface is usually relatively impermeable. Thus, meltwater remains on the surface instead of percolating into the ice. However, for a sloping surface, meltwater flows down the slope and gravitational force coupled with water-layer lubrication enhance the rate of dust loss. Although absolute values of dust loss are high for the high initial concentrations, the trend of increasing loss declines beyond the MEDCON. Visual observation in the field showed that the high absolute values were due to the considerable erosion from the edges of the higher dust concentration plots. Although the correlation coefficient for both the curves ((i) and (ii) in Fig. 5(a)) is high (above 0.90), there are significant errors above the MEDCON. Contrary to the snow surface, where the aggregation of dust particles was clearly observed (Adhikary *et al.*, 1997), the aggregation of dust particles was not evident on the flat melting ice surfaces. Lack of aggregation was probably due to the short duration of the experiments and impermeability of the ice surface, which favours the export of the particles out of the plot together with the local meltwater derived from intense melting. However, clumps of particles forming interesting patterns that were seen on frozen cliffs (Fig. 1) presumably testify the earlier actions of gravity driven channels of meltwater.

Figure 5(b) shows the distribution of dust concentrations on the ice cliff at the beginning and the end of the experiment. The lowermost portion of the cliff was initially dirtier than the upper part. The figure also shows the dust concentration increase (final minus initial) due to P9 upslope on the cliff. The concentration increase decreased toward the lower part of the cliff with down-slope distance from P9. The result gives direct verification that the dust particles moving downward with meltwater caused the decrease in surface albedo shown in Fig. 4.

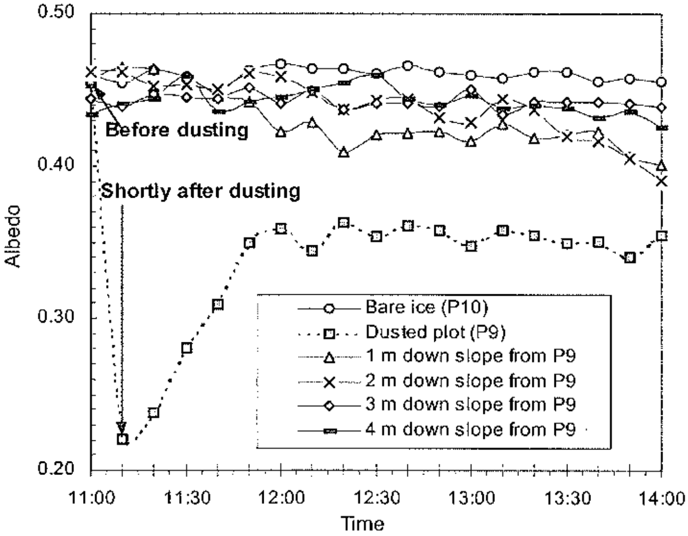

Fig. 4 Albedo changes on a melting ice cliff with different dust concentrations. The dust was distributed shortly after 11:00 (30 May).

The experimental results presented in this paper are basically restricted to a few short periods on TS dust-covered surfaces that indeed constitute the most difficult range of debris concentration for estimation of ablation underneath. Most of the

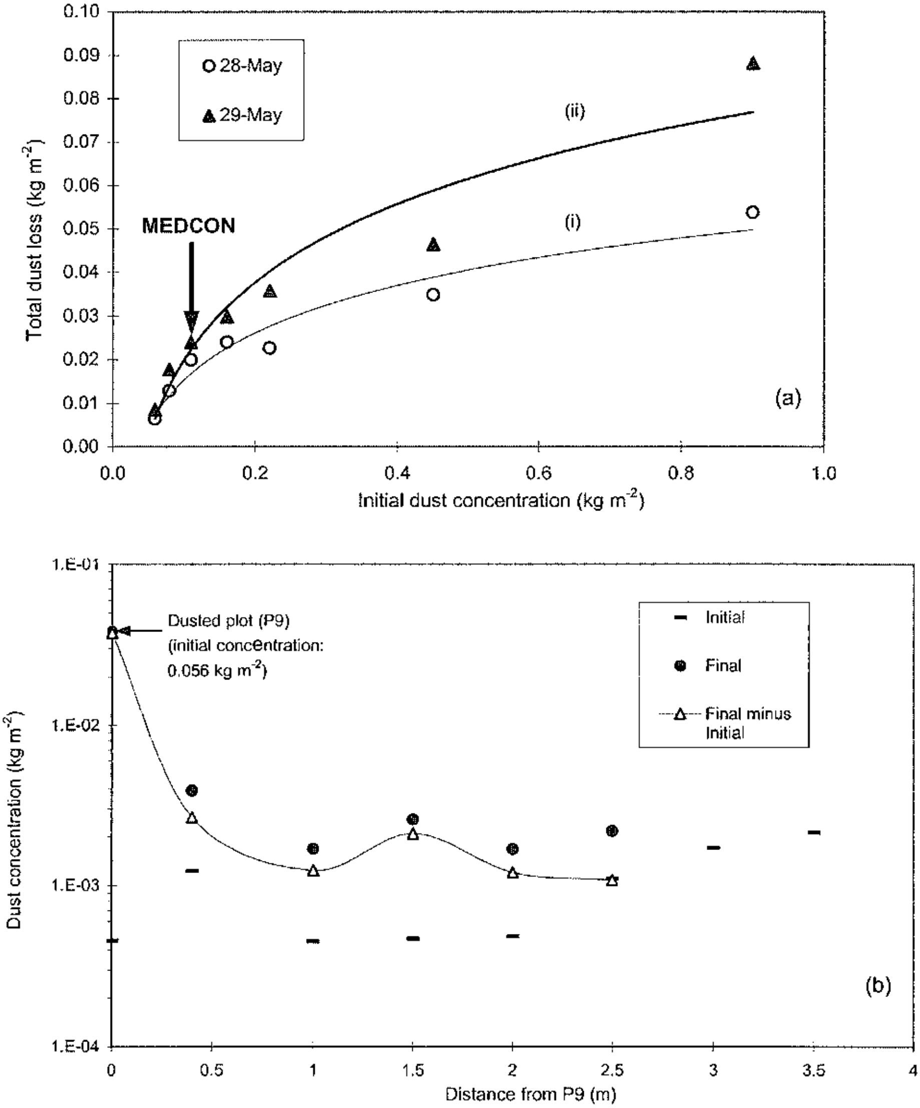

Fig. 5 (a) Dust loss from dusted surfaces due to horizontal migration of particles with meltwater. Curves (i) and (ii) are the best fits to the data for 28 and 29 May respectively. MEDCON is the most effective dust concentration for ice ablation. (b) Dust concentration on the ice cliff at the beginning (initial) and end (final) of the experiment.

previous studies found maximum ice ablation under a debris layer (MEDCON) a few centimetres thick, while our results show that maximum ice ablation can be attained under a very thin dust layer (0.25 mm or 0.112 kg m^{-2}). This striking difference of MEDCON may indicate the effect of the size of particles upon glacier ice melting. The uniqueness of our study lies in the examination of glacier ice ablation under fine particles covering a wide range in albedo. Even in remote areas, for example the Himalayas, glacier surfaces have been found to be contaminated by atmospherically derived fine particles (aerosol). The presence of such dust can lower glacier surface albedo significantly, with an increase in ablation. Moreover, such fine particles can be easily moved by surface meltwater thereby reducing albedo on adjacent cleaner ice surfaces. The total consequences on the glacier surface melting would be even higher as a result of redistribution of particles that changes surface morphology as noted earlier. Our study suggested that for a TS dust covered glacier surface, the behaviour of the particles must be considered an important factor in modelling surface melting. We believe that the present study will support realistic modelling work, but, further studies on TS dust layers are necessary.

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