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Ablation on Debris Covered Glaciers: an Example from the Rakhiot Glacier, Punjab, Himalaya

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Abstract This paper reports on ablation research carried out on the Rakhiot Glacier, Punjab, Himalaya. Specifically, detailed measurements of ablation rates on debris covered and debris free surfaces allow specification of relationships between ablation and debris cover thickness. Direct ablation measurements indicate a sharp increase in ablation with debris cover thickness increasing from 0.0 to 10 mm followed by a decrease in ablation with debris cover thickness increasing beyond 10 mm. Field observations reveal a critical thickness of 30 mm indicating that at any greater debris thickness ablation is suppressed from that expected on debris-free ice. A comparison with previous research indicates similar hyperbolic trends in the relationship between debris cover thickness and ablation, however, the intensity of these trends differ with global location.

INTRODUCTION

One of the most common characteristics of Himalayan and Trans-Himalayan glaciers is the presence of a debris mantle masking a large portion of their ablation zones. The existence of a debris cover exerts a tremendous influence on the ablation process itself. Østrem (1959) found that when the debris cover was relatively thin, in the order of a few centimetres, the rate of surficial lowering increased when compared to clean surficial ice. However, when the debris cover exceeds a critical thickness, defined by the point at which the ablation rate for debris covered glacier ice is the same as for debris free ice, the ablation rate is retarded. Muller (1968) found large variations in ablation rates between sample sites of equal debris thicknesses for the same period as well as variations at the same site over differing periods. This suggests that debris thickness is only one of several factors which controls the ablation process on debris covered glaciers. The purpose of this paper is to describe differential ablation rates on a debris covered glacier within the Himalaya and to compare and contrast the results with those obtained from similar investigations situated within, as well as outside of, this region.

STUDY SITE

Field work took place on the Rakhiot Glacier of the Nanga Parbat massif, Western Himalayas, Pakistan. The Rakhiot Glacier occupies approximately 45 km^2 of the 102 km^2 basin in which it is situated. The glacier is roughly 13.5 km in length and displays an altitudinal range of over 4500 m. The surficial debris extends along the glacier's lateral margins (at widths up to 800 m) and over the entire terminus area for a distance of 1600 m up-glacier of the snout. There is a tendency for the debris cover to decrease in thickness as one moves from the lateral margin to the central longitudinal axis of the glacier (at which point very little debris-cover exists). Surficial pits indicate that debris thickness may become several metres thick along the margin of the glacier. Direct field observations conducted at the base of the icefall (8 km up-glacier of the terminus) indicate that the major contribution of this debris is through rockfalls and earthslides off the freshly exposed proximal faces of the Pleistocene lateral moraines. These faces have recently been exposed through the down melting of the Rakhiot's surface and, therefore, possess abnormally steep slopes which have not yet stabilized to the changing conditions associated with deglaciation. Hewitt (1988) states that low frequency catastrophic landslide events originating on adjacent valley walls contribute significantly to the debris cover. It was also found that snow and ice avalanches contribute minimally to the supraglacial debris load.

DATA COLLECTION

The ablation monitoring programme was initiated on 22 June 1986 and ended on 8 August. Ten high density wooden stakes were drilled into the glacier at sites which ranged from debris free ice to a debris cover of 400 mm. The stakes were painted white in order to reduce the amount of solar radiation absorption at their surface. Ablation at these locations was measured on a weekly basis and stakes were redrilled every two weeks.

Ablation rates were determined by calculating the difference in the measured distance from the top of the stake to the debris cover surface, over a known period of time. The straight edge method, described by Adams (1966), was employed to measure the distance from the top of the stake to the surface of the debris cover. The surface of the debris cover had to be used as the reference point, rather than the ice surface, based on the fact that any disturbance of the debris cover would disrupt the internal thermal regime thus altering true ablation rates. While debris cover thickness may change through time (thinning due to settling or thickening due to meltout) this value is thought to be slight compared to the effects associated with the weekly disruption of the cover.

The error involved in the above sampling technique is primarily dependent on the structural characteristics and thickness of the debris cover. In the case where the debris cover consists of a mixture of silts, sands and gravels, error values are assumed to be relatively low (±5 mm). However, in the event where the debris cover consists of larger material (cobble to boulder size) the error increases significantly (±20 mm). This is due to the fact that the larger material displays a tendency to shift (settle) in an uneven manner.

Shifting of the debris cover is also a function of ablation which, in turn, is a function of debris thickness. In areas displaying low ablation rates (where the debris cover is thick) shifting rates are low, thus minimizing error in measurements. In areas displaying high ablation rates (where the debris cover is thin) shifting rates are high, thus increasing error in measurements. Error values are maximized in areas where the debris cover is thin and consists of large particles. Error also results from the flow or creep of the debris cover down a slope. For this reason, ablation stakes were located in areas of minimal relief.

In addition to the natural sites, 12 artificial plots, with varying debris thicknesses, were prepared on a relatively flat area of the glacier's surface, in a location with uniform slope and orientation. Each plot was approximately 1.0 m^2. Precautions were taken to maintain a constant depth of debris cover at each site by removing any irregularities in the surface of the ice to be buried. However, as the field season progressed, differential ablation rates between the debris covered ice and that adjacent to it made it very difficult to maintain a constant debris thickness over the entire plot. As a result, plots had to be relocated or reconstructed at least once during the field season. Ablation at these plots was monitored on a daily basis using the same technique described above.

RESULTS

Figure 1 illustrates the 1986 ablation results from the Rakhiot Glacier along with those of previous studies. Past a threshold thickness of approximately 30 mm, ablation rates decreased in comparison to "clean" glacier surfaces on the Rakhiot Glacier. It was found that the greatest mean ablation rate (110 mm day^{-1}) occurred beneath a debris cover of about 10 mm. This occurs because a thin layer of debris, rather than insulating the underlying ice, decreases albedo, thereby increasing absorbed shortwave radiation which in a thin debris cover is quickly transmitted to the debris/ice interface thereby contributing to rapid ablation (Mattson & Gardner, 1991).

Those areas with a mean thickness of less than 10 mm of debris exhibit less ablation due to higher reflectivity caused from partial ice coverage. The field data indicate that the mean daily ablation rate for a clean ice surface is about 70 mm day^{-1}. In locations where the debris cover is thicker than 10 mm, the insulation effect of the debris is greater than the effect produced by the increased absorptivity of the surface. A mean ablation rate of 10 mm day^{-1} was

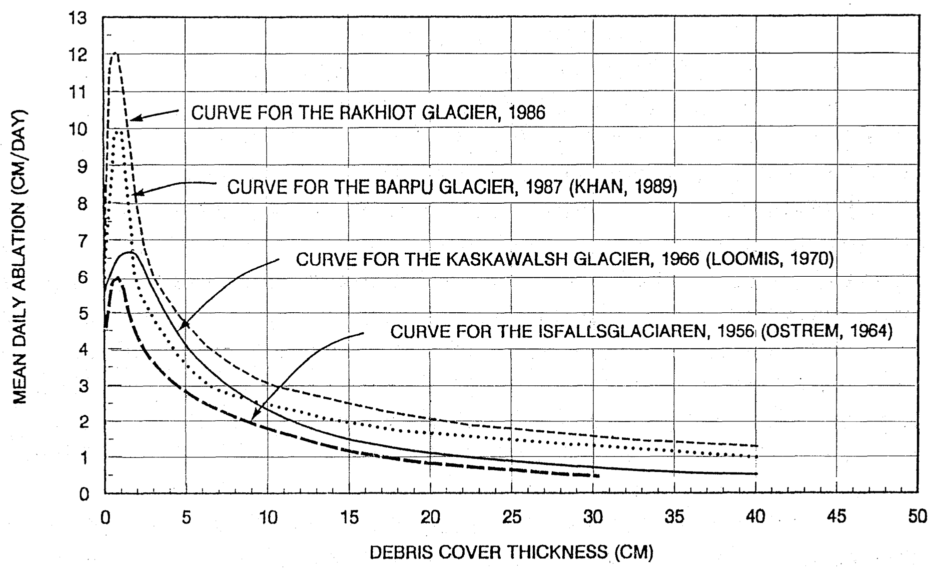

Fig. 1 Relationship between debris cover thickness and ablation.

estimated for ice beneath 400 mm of debris and by extrapolating the curve one will find that ablation will cease to occur past a debris thickness of 1 m.

Table 1 indicates that not only was there a significant difference in mean seasonal ablation rates between sites of varying debris thicknesses but there were also high variations in ablation rates at the same site over time. The trend in variability seems to follow that of ablation. In other words, where mean

Table 1 Ablation data and statistics for the period from 22 June to 8 August 1986.

Site number	Debris thickness (mm)	Mean daily ablation (mm day^{-1})	Max. daily ablation (mm day^{-1})	Min. daily ablation (mm day^{-1})	Range in ablation
01	0	65	90	40	50
02	1	75	100	50	50
03	5	82	120	50	70
04	10	121	220	50	170
05	15	103	160	40	120
06	20	75	130	40	90
07	30	63	80	40	40
08	40	52	80	40	40
09	50	49	70	30	40
10	60	45	70	30	40
11	80	40	60	30	30
12	100	34	50	20	30
13	200	15	10	30	20
14	400	10	10	10	0

seasonal ablation is large, variability will also be large. The differences in ablation rates among and within debris covered sites on the Rakhiot Glacier are explained by Mattson & Gardner (1991) through their energy balance investigations.

Calculation of the degree of correlation in the relationship between overburden thickness and ablation using mean, maximum, minimum, and $\log_{10}$ mean daily ablation, yields Pearson correlation coefficients of -0.74, -0.67, -0.84, and -0.92, respectively. The strongest correlation exists between $\log_{10}$ mean daily ablation and overburden thickness suggesting a non-linear relationship. The correlation is considered to be significant at the 95% confidence level.

Figure 2 is a scatter diagram which shows the relationship between $\log_{10}$ mean daily ablation and overburden thickness. Although there is a high correlation between the rate of ablation and thickness of debris, the predicted regression line is not a perfect fit. There seems to be a tendency for the model to under predict ablation rates in areas containing relatively thin debris covers while over predicting ablation rates in areas containing relatively thick debris

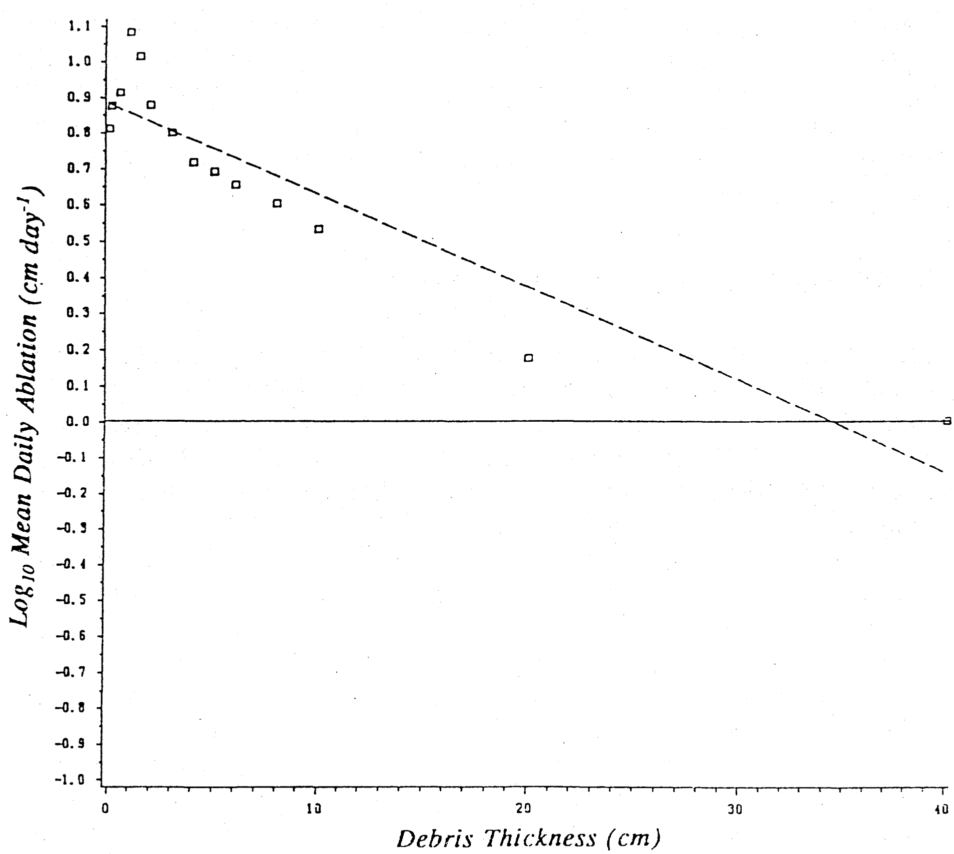

Fig. 2 Scatter diagram relating $\log_{10}$ mean daily ablation and debris cover thickness.

covers. The regression model is: Y = −0.026 X + 0.88. In this case, 85% of the variation in the dependent variable can be accounted for by the model; the standard error is 0.04. The good fit of the model is, in part, due to the fact that slope and aspect of sampling locations were fairly consistent. It is quite likely that the model would not have as good a fit if there were greater variability in slopes and aspects.

In order to illustrate the effect of orientation, four stakes were inserted into ice facets displaying different aspects: North, South, East and West, each covered with a slight dusting of debris. The slope of each facet remained constant at approximately 90° from the horizontal. Results indicate that the greatest mean daily ablation occurred on the West facing facet (77 mm day^{-1}) followed by the East, South and North facing facets at 74, 71, and 52 mm day^{-1}, respectively. These results do not coincide with those obtained by Khan (1989) who found that South facing facets experience the greatest amount of ablation. The reason for this can be explained by the local pattern of daily cloud cover. During the ablation season, when the monsoon was not in effect, most days were characterised by clear skies in the morning and evening and cloud cover between 1100 and 1500 h. The clouds would always form to the South, over Nanga Parbat, and thus, place the entire basin in shade during afternoon hours. As a result, the East and West facing facets received direct solar radiation in the early morning and late afternoon while the South facing facets received only diffuse solar radiation during midday. The North facing facet received the least amount of solar radiation and therefore follows the general trend of having the lowest ablation rate.

COMPARISON WITH PREVIOUS WORK

Results of the ablation programme on the Rakhiot Glacier substantiate previous accounts of glacier melt beneath a debris cover and are in close agreement with those quantitative results presented by Østrem (1959) on the Isfallsglaciaren, Sweden; Loomis (1970) on the Kaskawulsh Glacier, Canada; and Khan (1989) on the Barpu Glacier, Pakistan (Fig. 1). Similarities in results obtained from the four studies include:

(a) all show the same hyperbolic pattern with an initial increase in ablation rates as debris cover thickness increases to a point where the ice is completely covered after which the trend reverses and ablation rates decrease with an increase in debris cover thickness;

(b) all have similar threshold thicknesses which occur in areas with debris cover thicknesses of 30-40 mm; and

(c) all have their greatest mean daily ablation rate occurring beneath a debris cover of 10-20 mm in thickness.

The similarities between the sites can be explained by the fact that the processes responsible for ablation on debris covered glaciers remain the same no matter where the glacier is located.

The main difference in results between the four studies is the intensity of ablation associated with differences in debris cover thickness. Figure 1 indicates that the Rakhiot and Barpu Glaciers experience significantly greater ablation rates under thin debris covers as compared to the Kaskawulsh Glacier and Isfallsglaciaren. The greatest difference between the four sites is where the debris cover is about 10 mm in thickness. At this point mean daily ablation rates are twice as great on the Rakhiot Glacier compared to the Isfallsglaciaren (120 vs. 60 mm day^{-1}, respectively). Beyond the threshold thickness, the differences in ablation intensity between the sites become less. For example, in areas where the debris cover is 300 mm thick, the mean daily ablation rate for the Rakhiot Glacier is about 15 mm day^{-1} while that for Isfallsglaciaren is about 5 mm day^{-1}.

The difference in ablation intensity is, in part, a function of available energy, which is controlled by local meteorological conditions as well as global locality. The Rakhiot and Barpu Glaciers are located in low latitude (35° and 36°, respectively) and high altitude (3200 and 3500 m asl, respectively) areas compared to the Kaskawalsh Glacier and Isfallsglaciaren which are located in relatively high latitude (61° and 68°, respectively) and low altitude (1600 m and 1200 m asl) areas. As a result, the Himalayan sites would be subjected to greater amounts of incident solar radiation which has been proven (Mattson, 1992) to be the main contributor of energy to the surface of debris covered glaciers. It would appear that the importance of global locality is greatest where debris cover thicknesses are non-existent or relatively thin (0.0-40 mm). However, in areas where the debris cover is relatively thick, global locality becomes less important due to the overwhelming influence of the debris cover.

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