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Evaporation and percolation effect on melting at debris-covered Lirung Glacier, Nepal Himalayas, 1996

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Abstract

Heat flux with rain has not been taken into account in estimating melt amounts of debris-covered ice, although there was a lot of rain during the melting season in the Nepal Himalayas. Some of the rain falling on the debris-covered glacier will evaporate, and the rest will percolate through the debris layer and will supply heat to melt the ice beneath it. Evaporation amounts during a melting season from 15 July to 29 August in 1996 were measured using a lysimeter on a debris-covered area of Lirung Glacier, Nepal Himalayas. Observational results indicated that 25% of the total rainfall evaporated at that debris-covered glacier. The heat flux with percolated water has no effect on the heat needed to melt ice under the debris, although percolated water accounts for as much as 75% of the total rain amount.

1. Introduction

Glaciers in the Nepal Himalayas are categorized by their surface conditions into debris-free and debris-covered glaciers (Moribayashi and Higuchi, 1977). Large valley glaciers several kilometers in length usually have a debris-covered ablation area, and occupy more than half of the glacialized areas in the Himalayas (Fujii and Higuchi, 1977).

The melt rate of debris-covered ice has been studied by many researchers (*i.e.* Østrem, 1959; Fujii, 1977; Mattson *et al.*, 1993; Khan, 1989). Estimating the melt amount of such ice has been done by using thermal resistance (Nakawo and Takahashi, 1982; Nakawo and Young, 1981; 1982); Rana *et al.* (1997) applied the above method to estimate melt amount the debris-covered glacier in the Nepal Himalaya. In the previous studies, however, no allowance was made for evaporation at the surface of the debris, even though there is heavy rainfall during the summer melting season in the Nepal Himalayas.

Heat balance at the debris-covered glacier surface has been calculated from meteorological data by Mattson and Gardner (1989). They estimated latent heat to melt the debris-covered ice using the surface temperature and humidity, but they did not measure the actual evaporation rate at a debris-covered glacier. Moreover, they assumed that water percolating through the debris layer made no contribution to the heat for melting ice covered with debris. Actually, rain plays two roles in melting such ice. One is latent heat for evaporation. Evaporation amounts should be large, when it has rained and the surface has remained wet. Latent heat flux accompanying evaporation will decrease the melting of ice under the debris layer by taking away heat from the debris surface, whereas heat flux accompanying percolated water will increase the melt amount.

The other is heat flux with percolation. Some rain will percolate down to the debris layer. The daily average surface temperature of debris reached 20 ℃ during the monsoon season (Fujita *et al.*, 1997). Therefore, percolated water would be warmed by the debris layer and would carry the heat from the debris surface downward to promote ice melting. Since there have been no observations of either evaporation or percolation amounts at a debris-covered glacier, those two factors are evaluated in this paper. Moreover, evaporation and percolation at a non-glacier area were also observed in the same way as at the debris-covered area, in order to compare evaporation and percolation with those on the debris-covered glacier.

2. Location and observations

Observations were carried out on the Lirung Glacier, which is located near Kyangjin Kharka in the Langtang Valley in the Nepal Himalayas 60 km north of Kathmandu, the capital city of Nepal. The Lirung Glacier is covered with debris in the ablation area. Figure 1 shows a schematic map of the Lirung Basin. Average debris thickness was about 90 cm, which was

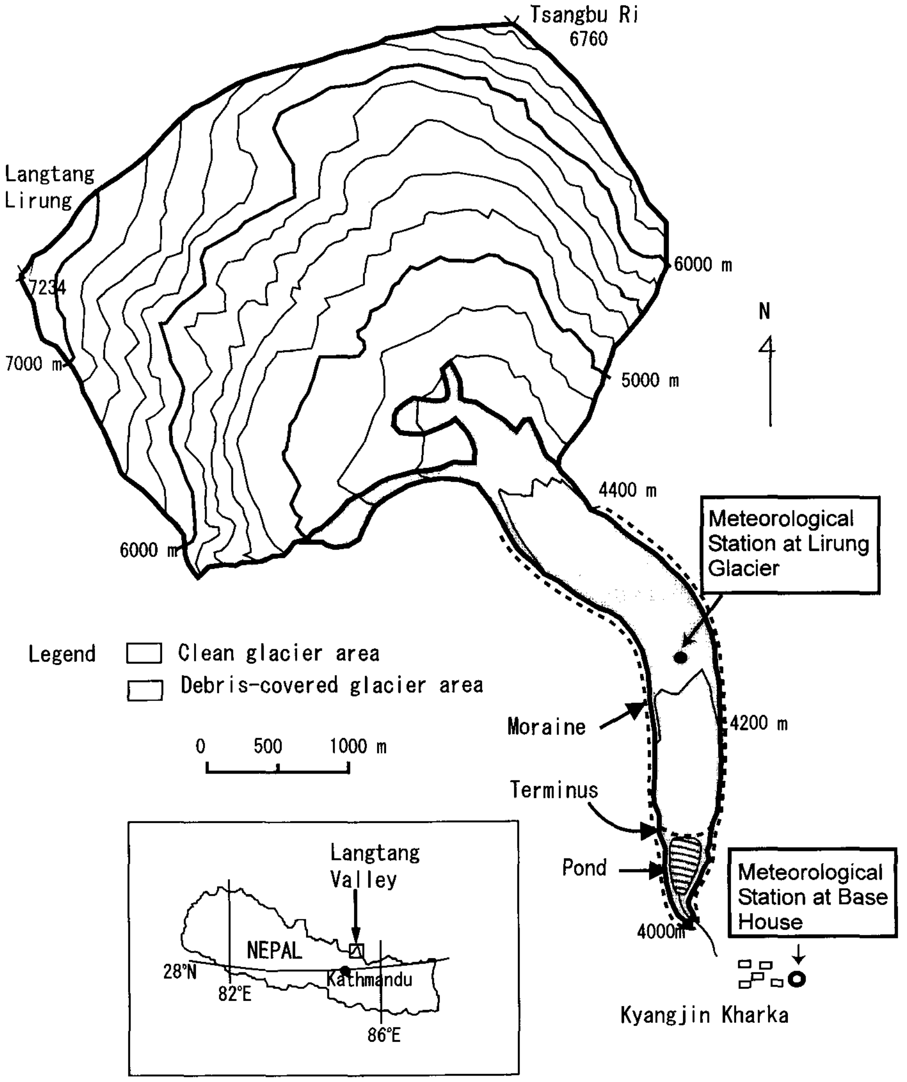

Fig. 1. Schematic map of Nepal and the Lirung Glacier.

observed at the edge of the ice cliff.

Two meteorological stations were established, one on the Lirung Glacier and another at the base house (Fig. 1) from May to October 1996, including the monsoon season. Surface conditions at the base house consisted of soil and grasses. Altitudes of the meteorological stations on the Lirung Glacier and at the base house were 4190m a.s.l. (Fujita *et al.*, 1997). and 3880m a.s.l. (Fujita *et al.*, 1998) respectively. Air temperature, humidity, wind speed, ground surface temperature, downward solar radiation, upward solar radiation, net radiation and precipitation were measured at intervals of 5 minutes at both stations. The details of the observation and preliminary results were described by Fujita *et al.* (1997).

In order to measure the evaporation amount, one lysimeter was set up at the base house from 19 June to 15 October, and the other at the glacier from 19 June to 29 August, 1996. Figure 2 shows a schematic diagram of the lysimeter, which was a plastic cylinder 10 cm in depth and 16.7 cm in diameter. The edge was set to be the same level as the ground surface, as shown in Fig. 2. It was packed with debris or soil to fill gaps.

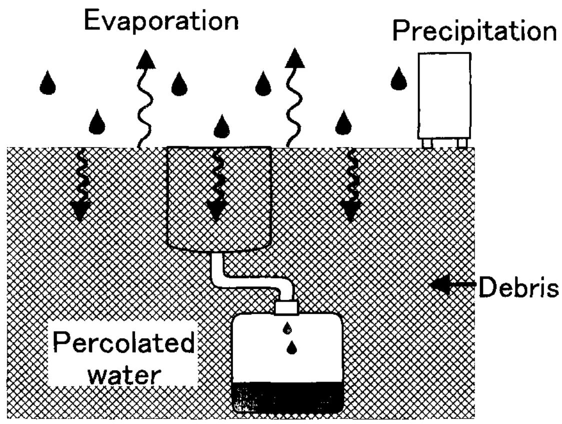

Fig. 2. Cutaway illustration of the lysimeter. Percolated water which does not evaporated descends through the debris layer and flows into a bottle from which it can be measured directly. Precipitation amount was observed by the tipping bucket. Evaporation amount was calculated by subtracting observed percolated water from observed precipitation amount.

Precipitation falls into the lysimeter, some of which will evaporate while some will percolate inside the lysimeter and be collected in a bottle. The percolated water from the bottle is weighed at intervals of 5-10 days. Evaporation (W_e) can be obtained from precipitation (W_r) and percolated water (W_p) by assuming that the water content in the lysimeter is constant, as in the following equation

$$W_e = W_r - W_p. \quad (1)$$

Here the unit is mm s^{-1}. W_p can be measured directly by the lysimeter at intervals of several days. W_r can be obtained by tipping bucket rain gauges at each meteorological station. Most precipitation fell as liquid rain, since air temperature was above 3.0 degrees. There was found to be only a 20% probability of occurrences of solid precipitation by Ageta *et al.* (1980). Precipitation data, therefore, obtained by tipping bucket rain gauges was not corrected because liquid precipitation data was not greatly affected by wind. Evaporated water, therefore, can be evaluated from Eq.(1).

3. Result

Fluctuations in the amounts of evaporation and rain observed at the glacier and at the base house were shown in Figs. 3(a) and 3(b), respectively. Rain data were averaged at each measurement interval of percolated water. Since we have a lysimeter data set including meteorological data for the period from 15 July to 29 August, we will call that "the analyzed period" hereafter.

Averages of the rain, percolation and evaporation data at both sites during the analyzed period were summarized in Table 1. The amount of evaporation was greater than the percolated water amount at the base house, whereas percolated water accounted for more than 70% of total rainfall at the Lirung Glacier.

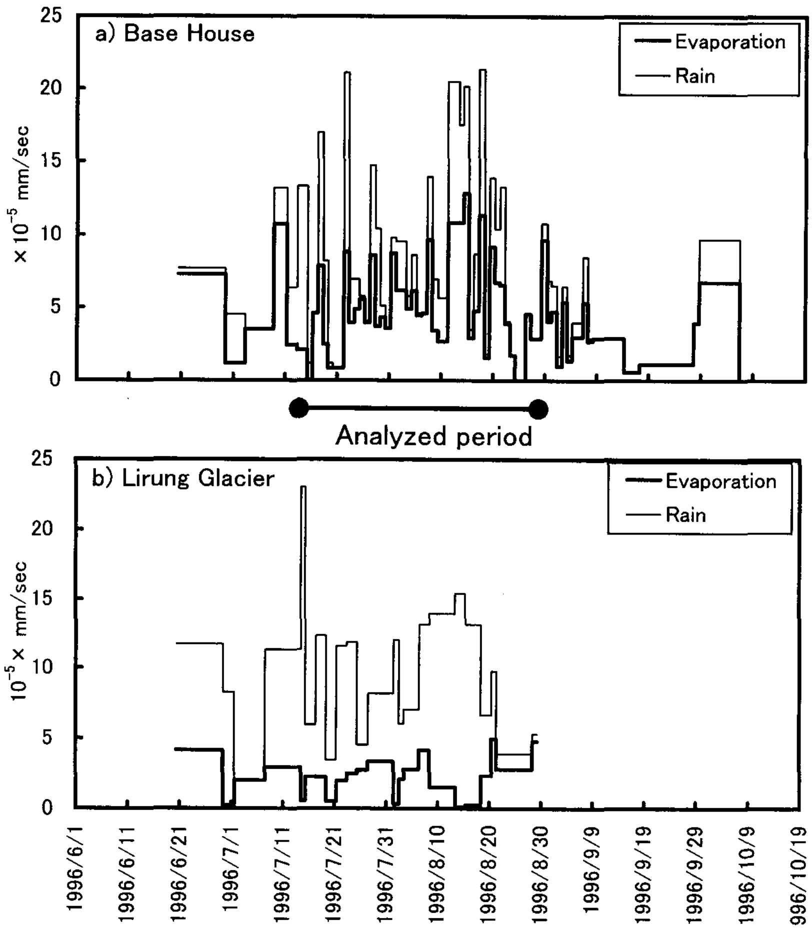

Fig. 3. Fluctuations in evaporation and precipitation a) : at the Lirung Glacier and b) : at the base house.

Table 1. Observed rain, percolation and evaporation data from 15 July to 29 August.

Site	Rain; W_r ($\times 10^{-5}$ mm s^{-1})	Percolation; W_p ($\times 10^{-5}$ mm s^{-1})	Evaporation; W_e ($\times 10^{-5}$ mm s^{-1})
Lirung	9.3 (100%)	7.0 (75%)	2.3 (25%)
Base house	8.8 (100%)	3.6 (41%)	5.2 (59%)

Two factors might account for the difference in evaporation and percolation between the glacier and the base house. The first is the difference in surface conditions. Debris, which contains matter of various sizes like silt, sand, gravel, pebbles and huge boulders, was distributed on the glacier as described for a debris-covered glacier at East Nepal by Fushimi *et al.* (1980) while the base house surface was soil containing organic substance and grass. The soil at base house sometimes contained pebbles, but mostly seemed to consist of sand and silt. Permeability of the debris at the Lirung Glacier would be higher than that at the base house (Terzaghi and Peck, 1967). Therefore, the evaporation rate at the base house would be larger.

The second factor is the difference in temperature between the air and the surface. Table 2 shows average air temperature average surface temperature and the difference between them at both sites during the same period as in Table 1. The difference in air temperature between the two sites was only 1.6 ℃ making the lapse rate of air temperature about 0.51 ℃ per 100 meters, which was a common value (Fujita and Sakai, 2000). However, the difference in the surface temperature between the two sites was as high as 5.5 ℃. This marked difference in surface temperature should be caused by ice under the glacial debris, which cooled the debris surface.

The third factor is the wind speed. Fluctuations of daily wind speed at the Lirung Glacier and the base house were shown in Fig. 4. Wind speed at the base house was always higher than at the Lirung Glacier. Average wind speed at the Lirung Glacier and the base house were 1.1 and 1.4 m s^{-1}, respectively.

Table 2 shows the ratio of difference between air temperature and surface temperature at the base house to that at the Lirung Glacier. The ratio of wind speed is also shown. The ratio of temperature (2.3) was larger than that of wind speed (1.3). Therefore, the temperature difference, in other words, the cool surface temperature at Lirung Glacier, would be one of the main effects of the smaller evaporation at Lirung Glacier than that at the base house.

Table 2. Average air temperature, surface temperature, difference of air temperature and surface temperature and wind speed at Lirung Glacier and the base house from 15 July to 29 August. Ratios of difference of air temperature and surface temperature and wind speed at the Lirung glacier to those at the base house are also shown.

	Air temperature; T_a (℃)	Surface temperature; T_s (℃)	T_a-T_s (℃)	Wind speed (m s^{-1})
At the Lirung Glacier	8.8	11.8	3.0	1.1
At the base house	10.4	17.3	6.9	1.4
Difference in temperature (℃)	1.6	5.5	-	
Temperature of lapse rate (℃ (100 m)$^{-1}$)	0.5	1.8	-	
Ratio of the Lirung Glacier to the base house	-	-	2.3	1.3

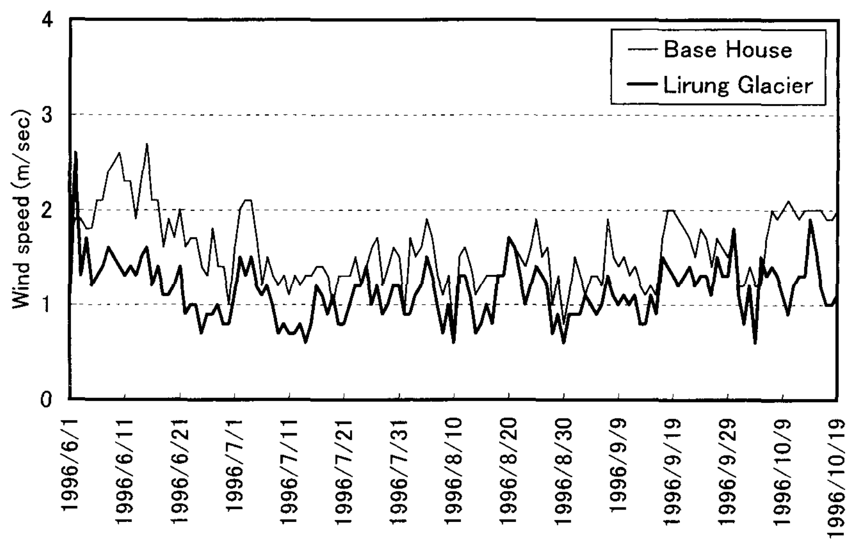

Fig. 4. Fluctuations of daily wind speed at the Lirung Glacier and at the base house.

4. Discussion

Heat balance at the debris surface can be expressed by assuming that the temperature profile in a debris layer is in a steady state and that conduction heat contributes to ice ablation, as in the following.

$$R+H+E+P+G=0, \qquad (2)$$

where R = Net radiation,
H = Sensible heat flux,
E = Latent heat flux,
P = Precipitation heat transfer and
G = Conductive heat transfer from debris surface to ice surface.

All fluxes are in $\mathrm{W\,m^{-2}}$ and are positive if directed towards the debris surface.

There are two heat transfers for melting ice under the debris layer. One is conductive heat from the debris surface, the other is heat advection, involved in percolated rain water. Heat balance at the ice surface under the debris layer can be expressed as follows,

$$P_e-G-M=0, \qquad (3)$$

where P_e= Heat flux with percolated water and
M= Latent heat for melting ice.

Units are in $\mathrm{W\,m^{-2}}$. Heat elements of P_e, $-G$, are positive if they are directed towards the ice surface under the debris. Net radiation was observed at both meteorological stations. The bulk aerodynamic formula for sensible heat can be expressed as follows,

$$H=c_p\rho_a C_H U(T_a-T_s), \qquad (4)$$

where c_p= Specific heat capacity of air ($=1000\ \mathrm{J\,kg^{-1}K^{-1}}$),
ρ_a= Air density ($=0.819\ \mathrm{kg\,m^{-3}}$ at 4000 m a.s.l.),
C_H= Heat transfer coefficient (non-dimensional),
U= Wind speed at 1 m height ($\mathrm{m\,s^{-1}}$),
T_a= Air temperature at 1 m height (℃) and
T_s= Surface temperature of debris (℃).

Naruse *et al.* (1970) have concluded that when height of air temperature and wind speed was 1 m, the sensible heat transfer constant on a snow surface, $\beta(=c_p\rho_a C_H)$, was 4.9 $\mathrm{J\ m^{-3}K^{-1}}$ at Moshiri in Japan, located at 290 m a.s.l. This heat transfer constant was found to work favorably by Nakawo and Young (1981, 1982) as well as by Nakawo and Takahashi (1982) in debris cover investigations on the Peyto Glacier in the Canadian Rocky Mountains. Mattson and Gardner (1989) also applied this constant at debris-covered Rakhiot Glacier in Pakistan. The C_H, therefore, could be estimated as 4.0×10^{-3} (when ρ_a was 1.225 $\mathrm{kg\,m^{-3}}$ at 290 m a.s.l) at 4000 m a.s.l. Correction of C_H depending on the height of the instruments was not considered, since the roughness at measurement site was relatively high (about 10-20 m), and instrument height was probably 1 meter (Air temperature : 1.20 m, Wind speed : 1.55 m).

Latent heat can be calculated from observed data as follows.

$$E=lW_e, \qquad (5)$$

where l= Latent heat for evaporation from the water surface ($=2.50\times10^6\ \mathrm{J\,kg^{-1}}$).

The precipitation heat transfer with precipitation can be calculated as follows by assuming that the precipitation temperature would be the same as the air temperature (Mattson and Gardner, 1989).

$$P=c_w W_r(T_a-T_s), \qquad (6)$$

where c_w= Specific heat of water ($=4.17\times10^3\ \mathrm{J\,kg^{-1}\,K^{-1}}$) and
W_r= Rainfall amount ($\mathrm{mm\,s^{-1}}$).

The conductive heat transfer into debris layer, G, can then be evaluated by Eqs. (2) and (4) to (6).

Heat flux with percolated water was expressed as follows by assuming that the percolated water temperature would be the same as the debris surface temperature.

$$P_e=c_w W_p(T_s-T_i), \qquad (7)$$

where T_i= Temperature of ice melting point (=0 ℃).

The distribution of temperature in the debris layer would be less than the surface debris temperature, in particular during the daytime. Then, the water temperature flowing down to the ice surface would be less than the debris surface temperature. Therefore, the heat flux with percolated water estimated by Eq. (7) would be at a maximum value.

Calculated heat elements in Eqs. (2) and (3) at the Lirung Glacier averaged during the analyzed period are shown in Tables 3 and 4, respectively. The average heat for melting ice during this analyzed period was 47 $\mathrm{W\,m^{-2}}$. Heat flux with percolated water was at most 4 $\mathrm{W\,m^{-2}}$ (4% of the total latent heat for an ice melt), although percolated water accounted for 75% of total rainfall (Table 1). In contrast, latent heat for evaporation was -57 $\mathrm{W\,m^{-2}}$, almost half of the net radiation amount, which was the main heat source for the glacier ice melt. (Rain contribution to cool the glacier as a heat with evaporation was much larger than that of to melt glacier ice as a heat with percolated water.)

Actually, the observed precipitation taken by tipping bucket rain gauges might have been smaller than the actual amount, since tipping buckets could

Table 3. Heat element calculations at Lirung Glacier from 15 July to 29 August.

Heat elements	Net radiation; R	Sensible heat; H	Latent heat; E	Precipitation heat transfer; P	Conductive heat; G
$W m^{-2}$	111	−10	−57	−1	−43

Table 4. Heat elements calculated from meteorological data at Lirung Glacier from 15 July to 29 August.

	Heat flux with Percolation; P_e	Conductive heat flux; $-G$	Heat for ice melt; M $(=P_e - G)$
$W m^{-2}$	4	43	47
(%)	(9)	(91)	(100)

not catch all precipitation that fell down on the tipping bucket because of the wind. This error of rain gauge would provide smaller evaporation than actual amount. Meanwhile, the observed evaporation taken by lysimeter might be larger than the actual evaporation, since the diameter of the lysimeter was relatively small to obtain the actual amount. Those above errors have to be taken into account to evaluate an exact evaporation amount.

5. Summary

Rain was separated into percolation and evaporation by a lysimeter at debris-covered Lirung glacier and at the base house from 15 July to 29 August 1996. 25% of the rainwater evaporated, and 75% was percolated at the debris-covered glacial area. In contrast, evaporated water accounted for 59% of the rainwater at the base house. The soil at the base house showed relatively lower permeability than the debris on the glacier. Moreover, surface temperature of the debris was relatively low because of the ice underneath it. Therefore, the level of evaporated water would be low at the debris area.

Percolated water accounted for 75% of total rainfall at the Lirung Glacier. However, the heat flux with percolated water was only 9% of the total heat for an ice melt. The absolute value of heat from evaporation was much larger than that of the heat flux accompanying percolated water. If the heat flux accompanying evaporation has not been taken into account, melt amounts under the debris will be estimated to be twice as large as they actually are.

Actual evaporation amounts at debris-covered glaciers should vary with the debris thickness and with the type of debris. Evaporation amounts might increase with debris thickness, since surface temperature depends on debris thickness. However, the debris surface would remain wet when the debris thickness was only several cm, since melt water would appear on the debris surface because of capillary action. Evaporation is high when the surface is wet, even though the surface temperature is low.

Thus, it is highly complicated to estimate the evaporation amounts at various debris thicknesses in a debris-covered glacier.

Acknowledgments

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