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Characteristics of ablation and heat balance in debris-free and debris-covered areas on Khumbu Glacier, Nepal Himalayas, in the pre-monsoon season

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Abstract Ablation and heat balance were measured in debris-covered and debris-free areas of the ablation zone of Khumbu Glacier from 22 May to 1 June 1999. On the debris-free ice, the ablation rates ranged from 1.4 to 4.7 cm day^{-1} and were inversely correlated with the albedo. The contribution of turbulent heat flux to melting was very small, so net radiation accounted for about 98% of the incoming heat. Melting under debris decreased sharply with increasing thickness. Debris with thickness of 10 cm slowed melting to about 40% of that of bare ice with the same low albedo. The primary cause of melt reduction was the insulating effect of the debris. The heat stored in the debris layer during daytime was released to the atmosphere during night-time and warmed the air rather than being conducted downward to melt ice.

INTRODUCTION

Most of the glacier ice in the Nepal Himalayas is covered by debris (Moribayashi, 1974; Moribayashi & Higuchi, 1977; Fujii & Higuchi, 1977). Effects from the debris on ablation processes probably dominate recent glacier changes in the Nepal Himalayas (Nakawo *et al.*, 1997).

Ablation processes were examined by Kraus (1975) and Inoue & Yoshida (1980) on Khumbu and other debris-covered glaciers. Inoue & Yoshida (1980) made heat balance observations at two areas covered with different types of debris on Khumbu Glacier for several days. They reported that solar radiation was the main heat source for ablation and that a thin layer of schistose debris with low albedo enhanced ablation. Nakawo & Young (1982) showed that the surface temperature of the debris layer can be used for estimating the thermal resistance and consequently the ablation under the layer. This model was simplified for its practical use in the field by Nakawo & Takahashi (1982). Moreover Nakawo *et al.* (1993) proposed that a model could be used to estimate the melt rate of a debris-covered glacier by using surface temperature data derived from thermal infrared satellite images. Recently, Sakai *et al.* (1998) showed that the ablation of ice cliffs can contribute significantly to the total ablation in a debris-covered area.

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No simultaneous meteorological observations in both debris-covered and debris-free areas on the same glacier had been made prior to the present study. This paper compares heat balance characteristics on debris-covered and debris-free areas at Khumbu Glacier under the same meteorological conditions. It also examines how the different surface characteristics affect the local micrometeorology.

METHODS

Observation methods

Heat balance observations were carried out near the Everest Base Camp (27°59'N, 86°51'E, 5350 m a.s.l.) on the upper ablation zone of Khumbu Glacier from 22 May to 1 June 1999 just before the monsoon season. Meteorological stations were established both in the debris-free and debris-covered areas (Fig. 1). The two stations were about 200 m apart and at nearly the same altitude. Measurements on the debris-free ice included net radiation, air temperature, relative humidity, wind speed and direction. Solar radiation, air temperature, relative humidity, wind speed and surface temperature of the debris were measured over the 10-cm-thick debris. Observations were made continuously and recorded with portable data loggers. Ablation in the debris-free area was measured once or twice a day at seven stakes. Albedo of the ice surface at each stake was measured at 11:00–12:00 h on sunny days. The ablation rate under various thicknesses of debris (2, 5, 10, 20, 30 and 40 cm) was measured four times (8:00,

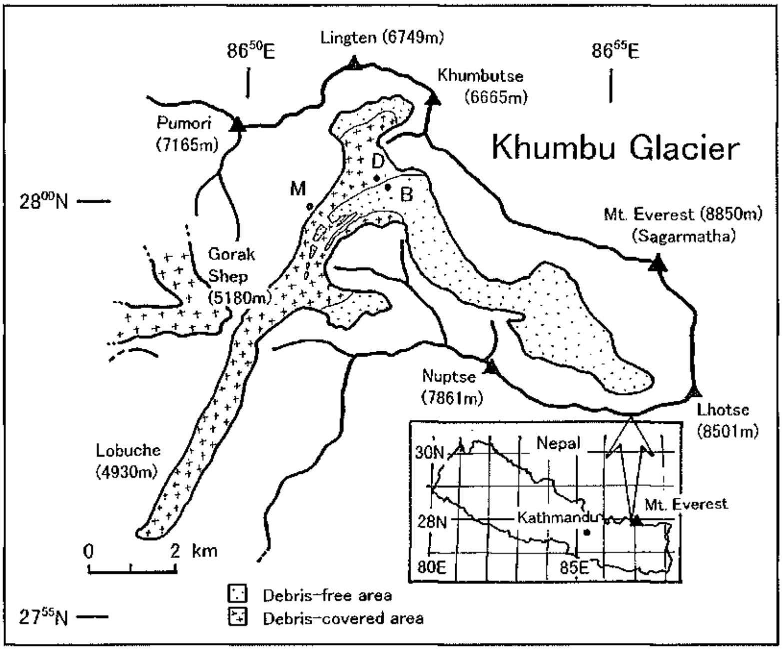

Fig. 1 Map of Khumbu Glacier, Nepal Himalayas and observation sites. B: the observation site on the debris-free ice. D: the observation site in the debris-covered area. M: the observation site on the lateral moraine.

11:00, 14:00 and 17:00 h) a day. The surface temperature and albedo of the debris layers were also measured at those times. Air temperature was measured continuously on the lateral moraine close to the glacier margin (Fig. 1). Details of measurement methods are reported by Kayastha *et al.* (2000) and Takeuchi *et al.* (2001).

Heat balance computations

The heat balance equation at a melting bare ice surface and upper surface of debris can be written as follows:

$$R + S + L + M = 0 \quad \text{(bare ice)}$$

and (1)

$$R + S + L + C = 0 \quad \text{(debris layer)}$$

where positive indicates toward the surface for all components. R is the all-wave net radiation. S is the sensible heat flux. L is the latent heat flux. M is the heat for ice melting. C is the conductive heat flux through debris layer. M and C were calculated as residual of equation (1). R was measured directly by an all-wave net radiometer on the bare ice. On the debris, it was calculated by the radiative balance equation using data for solar radiation, albedo, surface temperature measured on the debris layer and net radiation measured on the bare ice (Takeuchi *et al.*, 2001). It is assumed that heat conduction in the ice is negligible.

The turbulent heat fluxes (S and L) were calculated using a bulk aerodynamic approach following Stull (1988). The formulae are:

$$S = \rho_a C_p D_H (T_z - T_0) \tag{2}$$

and

$$L = \rho_a L_e D_E (0.622/P_a)(e_z - e_0) \tag{3}$$

where ρ_a is the air density; C_p is the specific heat of air at constant pressure; T_z is the air temperature at height z; T_0 is the surface temperature; L_e is the specific latent heat of vaporization of water; P_a is the atmospheric pressure; e_z and e_0 are the vapour pressure at height z and at the surface; D_H is the bulk exchange coefficient for heat. D_E is the bulk exchange coefficient for water vapour. The temperature and vapour pressure at the melting ice surface are taken as 0°C and 6.11 hPa, respectively.

Under neutral conditions, D_H and D_E are assumed to be equal to the momentum exchange coefficient given by:

$$D_0 = k^2 U_z [\ln(z/z_0)]^{-2} \tag{4}$$

k is the von Karman constant (= 0.4); U_z is the wind speed at height z; z_0 is the roughness length for momentum. The values of z were 1.06 m and 1.52 m at debris-free and debris-covered sites, respectively. z_0 was calculated from wind speeds at two heights assuming neutral conditions using the equation:

$$z_0 = \exp[(U_2 \ln z_1 - U_1 \ln z_2)/(U_2 - U_1)] \tag{5}$$

In this measurement, z_1 and z_2 were 0.52 m and 1.52 m, respectively. The value of z_0 for the debris-covered surface was found to be 6.3 mm. This is similar to the value

(3.5 mm) obtained by Inoue & Yoshida (1980). The wind speed profile could not be measured well for the bare ice surface where wind speed was very small. The value of z_0 for the bare ice surface was taken to be the same as for the debris surface. This assumption is reasonable because the bare ice surface was very rough due to differential melting by the strong solar radiation.

The measured ablation amount h_i is related to the heat for melting (M'), by:

$$M' = \rho_i L_i h_i \tag{6}$$

where ρ_i is the density of glacier ice (900 kg m^{-3}) and L_i is the specific latent heat of melting.

RESULTS

Ablation characteristics

Mean daily ablation rate measured with seven stakes and the mean albedo for the seven debris-free sites are shown in Fig. 2. The ablation rates ranged from 1.4 to 4.7 cm day^{-1} and were inversely correlated with the albedo for the reason discussed below.

The mean ablation rate under the debris depended on the thickness of the debris (Kayastha *et al.*, 2000). The highest rate occurred under debris with thickness of about 0.3 cm. For greater thicknesses, the ablation rate decreased with increasing thickness. The thickness at which the ablation rate was the same as for bare ice was about 5 cm.

The cumulative ablation on bare ice (S1 and S4) and under 10 cm of debris are compared in Fig. 3. Values of albedo were 0.44 and 0.21 for the bare ice sites, and 0.21 for the debris layer. The 10-cm debris layer slowed ice melting to about 40% of that of bare ice with the same low albedo (S4). It was also smaller than that of bare ice (S1), which had the highest albedo among the seven measurement sites.

Heat balance characteristics

The heat for ice melting calculated as a residual of the heat balance (M in equation (1)) is compared with that obtained from measured ablation (M' in equation (6)) in Fig. 4. During the first half of the observation period, the values from heat balance are

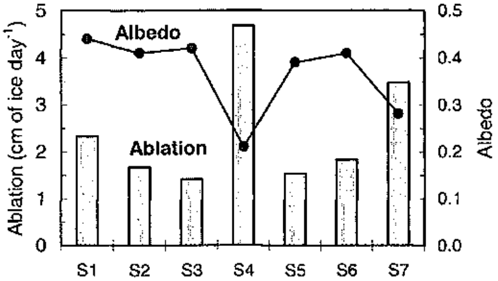

Fig. 2 Mean ablation rates and mean albedo over 10 days at the seven stakes (S1 to S7) on the bare ice.

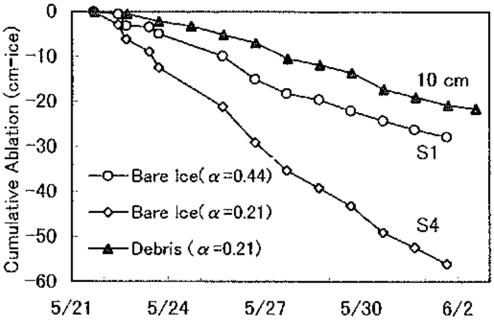

Fig. 3 Cumulative ablation on bare ice and under a 10-cm debris layer during the observation period

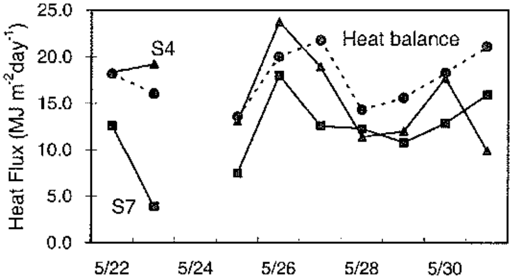

Fig. 4 Comparison of heat for ice melting on bare ice (albedo 0.26) obtained from the heat balance method (dashed) and measurement of ablation at S4 (albedo 0.21) and S7 (albedo 0.28).

between those from melting at S4 and S7. This result is reasonable because the albedo of the meteorological station on bare ice (0.26) was between the albedos at S4 and S7 (0.21 and 0.28, respectively). During the second half of the observation period, the trends agree, but heat for melting calculated from heat balance is slightly larger than that found from ablation. The causes are not well understood at present.

The conductive heat flux *C* was calculated as a residual of equation (1) for a 10-cm thickness of debris. Because the actual vapour pressure of the debris surface was not known, two limiting cases were considered: saturated with maximum latent heat flux and dry with no latent heat flux. These estimates of *C* are compared with the heat for ice melting under the same thickness obtained from measured ablation (Fig. 5). Most of the measured values are between the two limiting cases and this result is considered to be reasonable. Accordingly, the characteristics of the contribution of the heat balance components to ice melting in both debris-free and debris-covered areas can be calculated by the heat balance method.

Mean daily values of the heat balance components on the bare ice and the 10-cm debris layer are compared in Fig. 6. For the debris layer, the maximum latent heat flux is shown. On the bare ice, the sensible and latent heat fluxes were very small because the wind speed was very small (see also Takeuchi *et al.*, 2001), and almost all heat for melting came from net radiation.

The net radiation was similar in value on both surfaces. On the debris cover, increased shortwave absorption due to lower albedo is balanced by higher outgoing longwave radiation from the higher surface temperature (Takeuchi *et al.*, 2001). On the

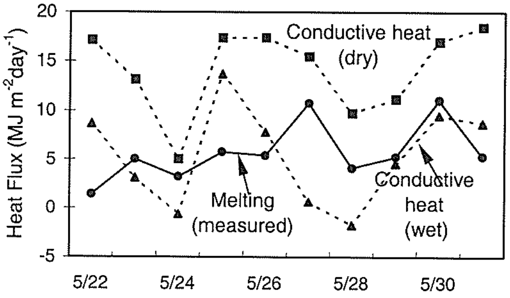

Fig. 5 Comparison of heat for ice melting under the 10-cm debris layer obtained from measurement of ablation and conductive heat flux calculated from the heat balance.

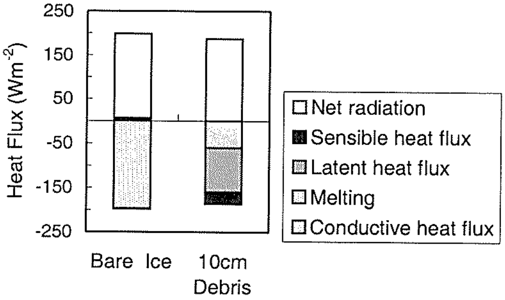

Fig. 6 Comparison of heat balance components on the bare ice and the 10-cm-thick debris layer assuming saturation over the debris.

bare ice, almost all the absorbed energy by net radiation and sensible heat flux was used directly for ice melting. Under the debris layer, the energy source for icemelt was the conductive heat flux through the warmed debris layer. The negative sensible and latent heat fluxes and oscillating storage of heat in the upper part of the debris layer should result in less ablation under the debris layer.

DISCUSSION AND CONCLUSION

The reason that the ablation rate for bare ice is related to albedo can be understood from the heat balance data. Generally, the energy source for the melting of bare ice consists of not only net radiation but also turbulent heat fluxes. On Khumbu Glacier, the contribution of turbulent heat flux to melting was very small, so net radiation accounted for about 98% of the heat income. The mean ablation was largest at S4, where the albedo was lowest, even though the turbulent heat flux was smallest. Since only S4 was on a flat area, the turbulent heat flux may have been smaller than at the other six stakes which were on a ridge on the glacier surface.

The relationships between the debris thickness, the heat for melting and the total incoming heat at the upper surface of the debris during the daytime are shown in Fig. 7. In the calculations, the hourly daytime surface temperature at each debris site was estimated from three-hourly measurements interpolated using the hourly values at the 10-cm site assuming linear relationships. Albedo and surface temperature varied at

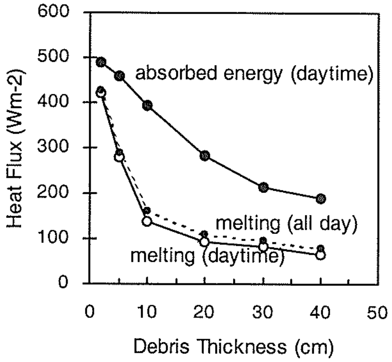

Fig. 7 Relationships between debris thickness and the heat for melting and net absorbed energy by net radiation and sensible heat flux.

the sites, but meteorological variables such as air temperature, wind speed, solar radiation and atmospheric radiation were assumed to be equal at all the sites.

Melting under a debris layer decreased with increasing thickness of debris, as found by many previous workers (e.g. Fujii, 1977; Mattson *et al.*, 1993). One reason is that the absorbed energy was less for larger debris thickness (Fig. 7). At thickness larger than 2 cm, the absorbed solar radiation decreased with increasing debris thickness because the surface of a thicker debris layer was easy to dry and had higher albedo. However, outgoing longwave radiation increased with debris thickness because the surface temperature became higher. Moreover the outgoing sensible heat flux also increased for the same reason. Furthermore, heat stored in the debris layer in the daytime increases with debris thickness. Melting decreased sharply under thin debris (less than 10 cm) but gradually under thick debris, in spite of the absorbed energy decreased linearly. This implied that the insulating effect of the debris had a more significant effect on the smaller melting than the decrease of absorbed energy.

Over the observation period, changes in the heat stored in the debris from day to day integrate approximately to zero. However, there are diurnal variations in the amount of heat stored. It increases in the daytime and decreases at night. Some heat stored in the daytime could be used for melting during the night-time, but the mean night-time ablation rate (the difference between melting in the daytime and all day in

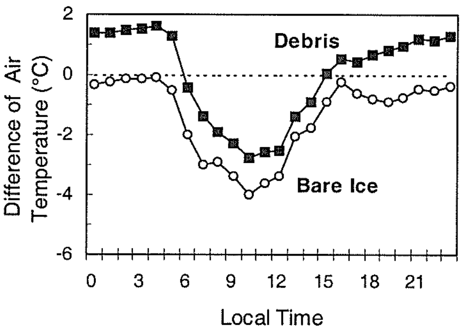

Fig. 8 Mean daily variations of air temperature difference (temperature on the bare ice and the debris minus that on the moraine).

Fig. 7) was very little for any debris thickness. Accordingly, it is likely that most stored heat was used to keep the debris surface temperature higher and was released back to the atmosphere at night.

Diurnal variations of air temperature over the bare ice and the debris layer were compared with those on the lateral moraine, under which there is no glacier ice (Fig. 8). In the daytime, the air temperature over both the bare ice and the debris layer were lower than that on the moraine, but it was higher at night over the debris layer. This night-time warming over the debris was probably caused by the release of heat stored in it during the daytime as described above. Release of stored heat at night by the same process did not happen on the moraine probably because of the thermal characteristics of the moraine surface (e.g. conductivity and capacity). Many glaciers in the Himalayas are considered very vulnerable to the recent global warming (Nakawo *et al.*, 1997). The changes in glacier debris-free and debris-covered areas and changes in debris thickness may affect the local climate through the surface–atmosphere interaction. Differences between the thermal characteristics of supraglacial debris layers and moraine may play a role and need investigation.

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REFERENCES

Fujii, Y. (1977) Field experiment on glacier ablation under a layer of debris cover. *J. Japan. Soc. Snow Ice (Seppyo)* **39**, special issue, 20–21.

Fujii, Y. & Higuchi, K. (1977) Statistical analyses of the forms of the glaciers in the Khumbu Himal. *J. Japan. Soc. Snow Ice (Seppyo)* **39**, special issue, 7–14.

Inoue, J. & Yoshida, M. (1980) Ablation and heat exchange over the Khumbu Glacier. *J. Japan. Soc. Snow Ice (Seppyo)* **41**, special issue, 26–33.

Kayastha, R. B., Takeuchi, Y., Nakawo, M. & Ageta, Y. (2000) Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal, using a positive degree-day factor. In: *Debris-Covered Glaciers* (ed. by M. Nakawo, C. F. Raymond & A. Fountain) (Proc. Seattle Workshop, September 2000). IAHS Publ. no. 264 (this volume).

Kraus, H. (1975) An energy balance model for ablation in mountainous areas. In: *Snow and Ice* (Proc. Moscow Symp., August 1971), 74–82. IAHS Publ. no. 104.

Mattson, L. E., Gardner, J. S. & Young, G. J. (1993) Ablation on debris covered glaciers: an example from the Rakhiot Glacier, Panjab, Himalaya. In: *Snow and Glacier Hydrology* (ed. by G. J. Young) (Proc. Kathmandu Symp., November 1992), 289–296. IAHS Publ. no. 218.

Moribayashi, S. (1974) On the characteristics of Nepal Himalayan Glaciers and their recent variation (in Japanese with English abstract). *J. Japan. Soc. Snow Ice (Seppyo)* **36**, 11–21.

Moribayashi, S. & Higuchi, K. (1977) Characteristics of glaciers in the Khumbu region and their recent variations. *J. Japan. Soc. Snow Ice (Seppyo)* **39**, special issue, 3–6.

Nakawo, M., Fujita, K., Ageta, Y., Shankar, K., Pokhrel, P. A. & Tandong, Y. (1997) Basic studies for assessing the impacts of the global warming on the Himalayan cryosphere, 1994–1996. *Bull. Glacier Res.* **15**, 53–58.

Nakawo, M., Moroboshi, T. & Uehara, S. (1993) Satellite data utilization for estimating ablation of debris covered glaciers. In: *Snow and Glacier Hydrology* (ed. by G. J. Young) (Proc. Kathmandu Symp., November 1992), 75–83. IAHS Publ. no. 218.

Nakawo, M. & Takahashi, S. (1982) A simplified model for estimating glacier ablation under a debris layer. In: *Hydrological Aspects of Alpine and High-Mountain Areas* (ed. by J. W. Glen) (Proc. Exeter Symp., July 1882), 137–145. IAHS Publ. no. 138.

Nakawo, M. & Young, G. J. (1982) Estimate of glacier ablation under a debris layer from surface temperature and meteorological variables. *J. Glaciol.* **28**(98), 29–34.

Sakai, A., Nakawo, M. & Fujita, K. (1998) Melt rate of ice cliffs on the Lirung Glacier, Nepal Himalayas, 1996. *Bull. Glacier Res.* **16**, 57–66.

Stull, R. B. (1988) *An Introduction to Boundary Layer Meteorology*. Kluwer, Dordrecht, The Netherlands.

Takeuchi, Y., Kayastha, R. B., Naito, N., Kadota, T. & Izumi, K. (2001) Comparison of meteorological features in the debris-free and debris-covered areas at the Khumbu Glacier, Nepal Himalayas, in the premonsoon season, 1999. Submitted to: *Bull. Glaciological Res.* **19**.