# Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal, using a positive degree-day factor

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**Abstract** Ice ablation on bare ice and under various thickness of debris was measured on Khumbu Glacier from 21 May to 1 June 1999 in order to study how debris affects the relationship between positive degree-day factor and ablation rate. Results for a debris cover ranging in thickness from 0 to 5 cm show that ice ablation is enhanced by a maximum at 0.3 cm. Debris thicker than 5 cm retards ablation. Although meteorological measurements show that the main energy source for ablation is net radiation (about 96% of total energy available for ablation on bare ice) the positive degree-day factor is nevertheless a successful predictor. For ice ablation on bare ice it is 16.9 mm day$^{-1}$ °C$^{-1}$. Under 10- and 40-cm-thick debris layers, the factors are 11.1 and 5.3 mm day$^{-1}$ °C$^{-1}$, respectively. The data required to predict ice ablation under a debris layer are ablation rate on bare ice, ratio of degree-day factor for debris cover to bare ice based on thermal resistance for the critical debris thickness and effective thermal resistance of the debris cover.

## INTRODUCTION

The means to predict ablation on glaciers in the Himalayas is important in order to predict the long-term availability of water resources and assess glacier response to climate change. The use of an energy balance model to calculate ablation on a remote Himalayan glacier is difficult due to limited input data. Furthermore, the ablation areas of many glaciers in the Himalayas are covered by debris. Debris has a strong influence on the surface energy balance and melting of the underlying ice. The thermal conductivity (or thermal resistance) and albedo are the main physical characteristics of a debris layer that control heat conduction to the ice–debris interface. This barrier to heat transfer causes the rate of ablation to decrease with increasing debris thickness once a critical thickness is exceeded (Østrem, 1959; Loomis, 1970; Fujii, 1977; Mattson & Gardner, 1989; Rana *et al.*, 1997). A critical debris thickness is defined as

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the thickness at which the ablation rate for debris-covered glacier ice is the same as for debris-free ice. A simple model by Nakawo & Young (1981) showed that the ablation under a given debris layer can be estimated from meteorological variables when the thermal resistance of the debris layer is known. Nakawo & Takahashi (1982) proposed a model to overcome the difficulty of determining heat flux components from meteorological variables. The model used positive degree-day factor as input data. However, the proposed model needs meteorological data, thermal resistance, radiation and albedo data, which are difficult to determine for a remote glacier.

Many studies have been carried out using positive degree-day factors for glacier ablation on a debris-free ice surface. Kayastha *et al.* (2000) studied the positive degree-day method on debris-free Glacier AX010 in the Nepalese Himalayas and compared their results with other glaciers. Since the positive degree-day method can give a good estimate of ablation on debris free-ice without radiative and turbulent heat flux data, there is good reason to investigate whether it could be effective where there is a debris cover. This paper describes the degree-day factors for ablation under various thickness of debris cover characterized by their thermal resistance on Khumbu Glacier. A practical relationship between degree-day factor and effective thermal resistance is established so that the degree-day factor can be predicted from the thermal resistance of a debris layer. In addition, different energy balance components are calculated using meteorological data to establish their relative importance for ablation. The energy balance method is tested by comparing the calculated and measured values for ice ablation. Variations of ice ablation and positive degree-day factors on different debris-covered glaciers are studied by comparing measured ice ablation and calculated degree-day factors on two other glaciers.

## OBSERVATION SITE AND DATA COLLECTION

Observations were made on the uppermost part of the ablation area of Khumbu Glacier near the Everest Base Camp (5350 m a.s.l.). Ablation measurements were carried out from 21 May to 1 June 1999. Seven plots were prepared ranging from bare ice to debris cover up to 40 cm thick (Fig. 1). The length of each plot ranges from about 0.5 m to 1 m with breath about 0.5 m. The plots were prepared by first removing all the debris and then rearranging the debris with different thickness of 2 cm, 5 cm, 10 cm, 20 cm, 30 cm and 40 cm. The debris consisted of mainly angular, loosely packed wet cobbles up to 3 cm in diameter. The dominant debris lithology was light coloured granitic rocks. A string was tied tightly to two poles that were drilled and frozen solidly into the ice to about 1.5 m depth at the extreme end of the plots. The vertical distance from the string to the bare ice or debris surface was measured at fixed points over each plot four times (08:00, 11:00, 14:00 and 17:00) a day. The change in height with time was taken as a measure of ice ablation. In addition, stake measurements were carried out between 26 May to 1 June 1999 near the plots on a clean ice surface with a thin debris layer (average thickness 0.3 cm) prepared by spreading fine debris onto the bare ice.

The surface temperature and albedo of the bare ice and different debris surfaces were measured at the four observation times using an infrared thermometer and a

**Fig. 1** Experimental site on Khumbu Glacier, Nepal, showing plots of debris thickness ranging from 0 to 40 cm.

photodiode. The albedo measured by the photodiode was calibrated with an albedometer (by Eiko-seiki). The cloud amount and type were also observed at the four observation times. Meteorological variables such as dry and wet bulb temperature, incoming shortwave radiation, wind speed, and surface temperature on a debris thickness of 10 cm were recorded at 10 minute intervals at another plot near the measured plots. The types of instruments used in the field were described in detail in Takeuchi *et al.* (2000).

## METEOROLOGICAL CONDITIONS

The observation period was just before the onset of the monsoon, and weather was dominated by high pressure. There were only two precipitation events, one on 24 May (1.9 mm) and another on 27 May (2.5 mm). The following means for the full observation period were recorded: air temperature 1.5°C, incoming shortwave radiation 310 W $m^{-2}$, relative humidity 91%, wind speed 0.7 m $s^{-1}$, and cloud cover 7/10. The most common cloud type was stratus with a few cases of cumulus. Variations of air temperature, incoming shortwave radiation, wind speed, relative humidity, cloud cover, albedo for bare ice and 10-cm thick debris cover, and surface temperature on a 10-cm thick debris cover are shown in Fig. 2. The hourly values of daytime albedo and cloud cover are obtained by linearly interpolating between measurements at 3-h intervals from 8:00 to 17:00. Similarly, the hourly cloud cover during night-time was obtained by interpolating the data from 17:00 and 8:00 with the addition of 1/10 to take account of climatological information that more precipitation occurs during night-time than daytime in the valleys of the Nepalese Himalayas (Ageta, 1976).

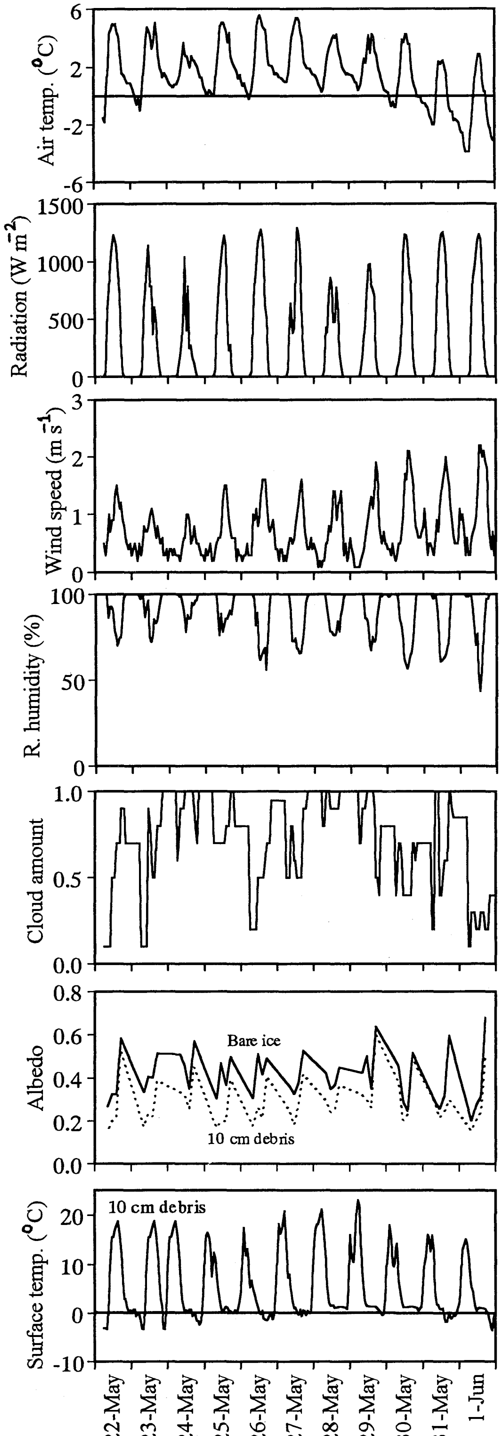


**Fig. 2** Variations of meteorological parameters on Khumbu Glacier during the observation period in 1999.

## POSITIVE DEGREE-DAY FACTOR

The positive degree-day method assumes that the amount of snow or ice melt during any particular period is proportional to the sum of daily mean temperatures above the melting point during that period. This sum is called the positive degree-day sum (*PDD*). The factor linking ablation to *PDD* is the positive degree-day factor ($k$). The factor $k$ involves a simplification of complex processes that are properly described by the energy balance of the glacier surface and overlaying atmospheric boundary layer (Braithwaite, 1995). By definition $k$ is calculated as:

$$k = \frac{\Sigma a}{PDD} \tag{1}$$

where $\Sigma a$ is total ablation during the same period as the period for *PDD*.

## ENERGY BALANCE CALCULATION

The energy balance equation on a melting bare ice surface can be expressed as:

$$Q_M = Q_R + Q_H + Q_E \tag{2}$$

On top of a debris layer it is

$$Q_C = Q_R + Q_H + Q_E \tag{3}$$

where $Q_M$, $Q_C$, $Q_R$, $Q_H$, and $Q_E$ are energy used for ablation on bare ice, conductive heat flux through the debris, net radiation flux, sensible heat flux, and latent heat flux, respectively. All the fluxes are taken to be positive downward.

The net radiation flux is the sum of net shortwave ($K^*$) and longwave radiation ($L^*$) fluxes. The net shortwave radiation flux can be calculated as:

$$K^* = G(1 - \alpha) \tag{4}$$

where $G$ is the global radiation and $\alpha$ is the albedo of the surface.

The longwave radiation emitted from the surface, $L_\uparrow$, can be calculated from the Stephan-Boltzmann law:

$$L_\uparrow = \sigma(T_S + 273K)^4 \tag{5}$$

where $\sigma$ is Stephan-Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$) and $T_S$ is surface temperature (°C).

The downward longwave radiation under clear-sky, $L_\downarrow$, is calculated from the equation by Kuz'min (1961):

$$L_\downarrow = \sigma(T_a + 273)^4 (0.62 + 0.005\sqrt{e_a}) \tag{6}$$

where $T_a$ is air temperature (°C), and $e_a$ is vapour pressure of the air (Pa).

According to Oke (1987), the net longwave radiation under a cloudy sky (mostly stratus cloud) is given by:

$$L^* = (L_\downarrow - L_\uparrow)(1 - 0.96c^2) \tag{7}$$

where $c$ is the cloud amount as a fraction.

The convective energy fluxes $Q_H$ and $Q_E$ are estimated using the bulk aerodynamic method:

$$Q_H = \beta u (T_a - T_s) \quad (8)$$

$$Q_E = \beta u L_e \frac{0.622}{P c_p}(e_a - e_s) \quad (9)$$

where $\beta$ is the bulk transfer coefficient (4.9 J m$^{-3}$ K$^{-1}$, Naruse *et al.*, 1970); $u$ is wind speed (m s$^{-1}$); $L_e$ is the latent heat of evaporation (2.5 × 10$^6$ J kg$^{-1}$); $P$ is atmospheric pressure (hPa); $c_p$ is the specific heat of air at constant pressure (1005 J kg$^{-1}$ °C$^{-1}$); $e_a$ is vapour pressure of the air (hPa); $e_s$ is saturation vapour pressure at the surface (hPa). Since the debris was wet at the beginning and only the top few millimetres of debris ever dried out, it is assumed that the vapour pressure at the debris surface was saturated.

A linear variation of temperature is assumed in the debris layer so that:

$$Q_C = \frac{T_s}{R} \quad (10)$$

where $T_s$ is the debris surface temperature relative to melting (0°C) and $R$ (m$^2$ °C W$^{-1}$) is the effective thermal resistance of the debris layer.

The energy used for ice ablation $Q_M$ or $Q_C$ is calculated from:

$$Q_M \text{ or } Q_C = L_f \rho_i r \quad (11)$$

where $L_f$ is the latent heat of phase change of ice (334 × 10$^3$ J kg$^{-1}$), $\rho_i$ is density of the ice (900 kg m$^{-3}$) and $r$ is ablation rate in ice thickness (m s$^{-1}$).

## RESULTS

### Ice ablation and energy balance

Measured mean daily ablation rates on bare ice and under 10- and 40-cm-thick debris layers during the observation period are about 3.1, 2 and 1 cm day$^{-1}$, respectively

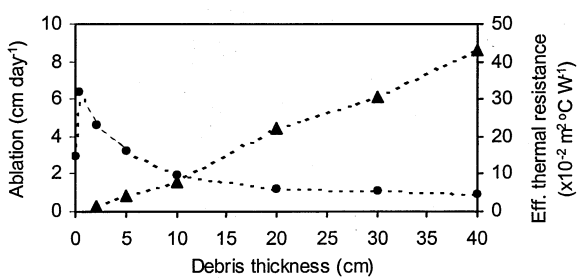


**Fig. 3** Variation of measured mean daily ice ablation (dotted line with solid dots) and calculated thermal resistance (dotted line with solid triangles) with respect to debris thickness.

**Table 1** Measured ice ablation and daily mean air temperature, calculated positive degree-day factors ($k$) and effective thermal resistances ($R$) for different thickness of debris cover.

| Date | Air temp. (°C) | Daily ice ablation (cm) under a debris layer of thickness: 0 cm | 0.3 cm | 2 cm | 5 cm | 10 cm | 20 cm | 30 cm | 40 cm |
|---|---|---|---|---|---|---|---|---|---|
| 21 May | 0.6 | 1.3 | - | 4.5 | 2.4 | 1.5 | 0.6 | 0.7 | 0.6 |
| 22 May | 1.9 | 4.6 | - | 5.4 | 3.6 | 1.4 | 1.0 | 1.9 | 0.7 |
| 23 May | 2.3 | 1.7 | - | 4.2 | 2.7 | 1.8 | 1.6 | 1.6 | 1.2 |
| 24 May | 1.6 | 1.4 | - | 3.4 | 1.2 | 1.2 | 0.8 | 0.8 | 0.5 |
| 25 May | 2.4 | 2.6 | 6.7 | 5.0 | 3.2 | 2.0 | 1.5 | 1.5 | 1.1 |
| 26 May | 2.6 | 4.2 | 8.3 | 6.6 | 4.0 | 2.8 | 1.6 | 1.1 | 1.0 |
| 27 May | 2.6 | 3.9 | 6.3 | 4.7 | 4.3 | 1.9 | 1.6 | 1.3 | 0.9 |
| 28 May | 2.2 | 3.1 | 5.2 | 4.2 | 2.6 | 1.7 | 0.8 | 0.7 | 0.8 |
| 29 May | 1.6 | 2.7 | 5.1 | 4.1 | 4.1 | 3.3 | 1.0 | 0.9 | 1.5 |
| 30 May | 1.0 | 3.4 | 6.5 | 4.7 | 3.9 | 2.0 | 2.8 | 1.1 | 0.9 |
| 31 May | –0.9 | 3.6 | 6.5 | 5.1 | 3.5 | 2.1 | 1.6 | 1.8 | 1.6 |
| 1 June | –1.4 | 2.7 | 6.5 | 4.2 | 2.9 | 1.5 | 0.6 | 0.4 | 0.3 |
| Mean | 1.5 | 3.1 | 6.4 | 4.7 | 3.3 | 2.0 | 1.4 | 1.2 | 1.0 |
| $k$ (mm day$^{-1}$ °C$^{-1}$) | | 16.9 | 37.2 | 26.9 | 18.4 | 11.1 | 7.4 | 6.6 | 5.3 |
| $R$ (×10$^{-2}$ m$^2$ °C W$^{-1}$) | | | | 1.4 | 4.0 | 8.1 | 22.3 | 30.6 | 43.0 |

(Fig. 3 and Table 1). It is found that the largest mean daily ablation rate (6.4 cm day$^{-1}$) during the observation period occurred beneath a debris layer of about 0.3 cm. The ablation rate under a debris cover thicker than about 5 cm is less than that for clean ice. Ablation becomes negligible for a debris thickness greater than about 1 m.

We first examine now how well the energy balance method explains this pattern. The energy balance components are calculated only for bare ice and a 10-cm debris layer, since continuous surface temperature is available only for the 10-cm debris layer. The

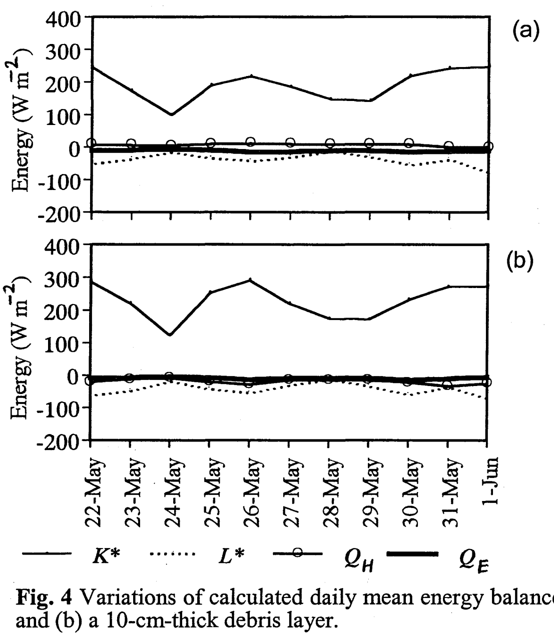


**Fig. 4** Variations of calculated daily mean energy balance components on (a) bare ice and (b) a 10-cm-thick debris layer.

surface temperature of bare ice is assumed to be always 0°C. The variations of energy balance components are shown in Fig. 4. Figure 4 shows that the main energy source is the net shortwave radiation, which contributes about 96% of total energy available for ablation on bare ice and near 100% under the 10-cm debris layer. Sensible heat makes only a little contribution (4%) on bare ice. All energy balance components are negative except shortwave radiation on the 10-cm debris surface mainly due to higher surface temperature and evaporation from the wet debris. The very low values of the net shortwave radiation on 24 May and 28–29 May are due to rainfall and the presence of high cloud cover, respectively.

Figure 5 shows calculated and measured variations of daily ice ablation on bare ice and under the 10-cm debris layer. The calculated ice ablation is always greater than the measured value and the difference is especially large in the case of the 10-cm debris. The overestimated energy on bare ice and the 10-cm debris layer are about 45 W $m^{-2}$ and 80 W $m^{-2}$, respectively, during the observation period. In general, the difference is higher on clear days than cloudy days (e.g. 24, 28 and 29 May). The main cause for this systematic difference may be the parameterization of elements in different energy balance equations. In any case there is uncertainty in the standard application of the energy balance method.

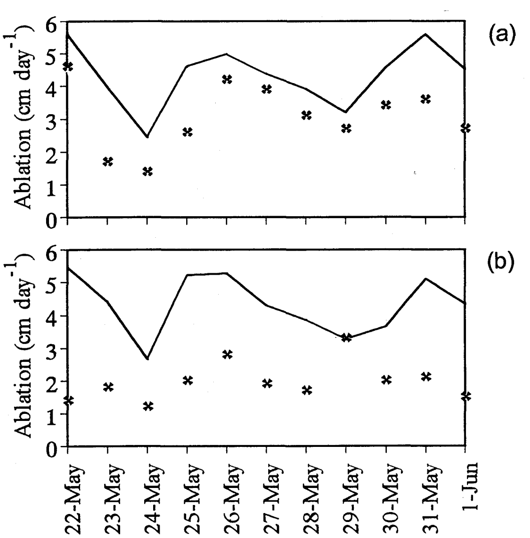


**Fig. 5** Comparison of measured and calculated daily ice ablation (a) on bare ice and (b) under a 10-cm-thick debris layer. Crosses and lines indicate the measured and calculated ice ablation, respectively.

## Thermal resistance and positive degree-day factor

Effective thermal resistances of different debris layers are calculated from the measured ice ablation and surface temperature using equation (10) during daytime (from 06:00 to 18:00), but full day averages are used for the 10-cm debris layer. The effective thermal resistance increases as the debris thickness increases (Fig. 3 and Table 1).

Positive degree-day factors for ablation on bare ice and different thickness of debris cover are calculated from 21 May to 1 June 1999, except for the 0.3-cm-thick debris layer where measurements did not start until 25 May 1999. Since the air temperature is the same in all cases, the calculated positive degree-day factor increases as the ablation increases. Therefore, the positive degree-day factor for ablation is highest at 37.2 mm day$^{-1}$ °C$^{-1}$ for a 0.3-cm-thick debris layer and the lowest at 5.3 mm day$^{-1}$ °C$^{-1}$ for a 40-cm-thick debris layer. The positive degree-day factor for ablation on bare ice is 16.9 mm day$^{-1}$ °C$^{-1}$.

The positive degree-day factor for bare ice $k_b$ is probably controlled by meteorological conditions and the degree-day factor for ice ablation under a debris cover $k_d$ is affected by both the debris properties and the meteorological conditions. Therefore, we seek a relationship between $k_d$ and these two kinds of variables in simplified form given by

$$\frac{k_d}{k_b} = \mathrm{F}\left(\frac{R}{R_c}\right) \qquad (12)$$

This assumes that the meteorological information is expressed entirely in $k_b$ and that the characteristics of the debris are given by the function F. F should depend primarily on the thermal resistance $R$ of the debris. However, to account for effects from debris albedo and possibly other secondary variables, we define F to be a function of $R/R_c$, where $R_c$ is thermal resistance for critical debris thickness. $R_c$ is calculated as the ratio of critical debris thickness to the thermal conductivity of debris cover. In this experiment an average found for thickness 2–40 cm was used. Figure 6 shows the function F as defined by our measurements. This relationship should be transferable to other glaciers with debris with possibly different thermal characteristics. So, if $R/R_c$ is known, $k_d/k_b$ and ice ablation under the debris layer can be estimated.

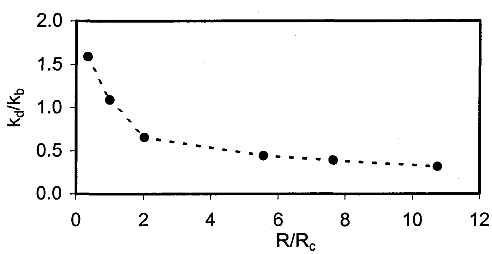


**Fig. 6** Ratio of $k_d$ to $k_b$ ($k_d$: degree-day factor for given debris thickness, $k_b$ degree-day factor for bare ice) *vs* ratio of $R$ to $R_c$ ($R$: effective thermal resistance of debris and $R_c$: thermal resistance for critical debris thickness).

## Comparison of the results with other similar experimental results

The present results are compared with results of similar experiments on two other glaciers in the Himalayas. An experiment on Lirung Glacier (4350 m a.s.l.) showed a maximum ablation rate (4.5 cm day$^{-1}$) for a 2.6-cm-thick debris layer and the critical thickness of about 9 cm (Rana *et al.*, 1997). Maximum ablation (12.1 cm day$^{-1}$) was recorded under a 1-cm-thick debris layer and the critical thickness was about 3 cm on

Rakhiot Glacier at about 3350 m a.s.l. (Mattson & Gardner, 1989). The present and the above-mentioned experiments showed that the ice ablation under a debris layer varies widely from glacier to glacier as well as from one point to another even on the same glacier.

The positive degree-day factors for ablation on bare ice and under the 10-cm-thick debris layer were recalculated for Lirung and Rakhiot Glaciers using the original data, which gave 6.6 and 5.5 mm $day^{-1}$ $°C^{-1}$ on Lirung Glacier and 6.6 and 3.5 mm $day^{-1}$ $°C^{-1}$ on Rakhiot Glacier. The degree-day factors for ablation on bare ice were similar on Lirung and Rakhiot Glaciers, although their observation periods were different. The predicted degree-day factor for ice ablation under the 10-cm-thick debris cover on Rakhiot Glacier was smaller than on Lirung Glacier. In the case of Khumbu Glacier, these values are very large as shown in Table 1 (16.9 and 11.1 mm $day^{-1}$ $°C^{-1}$) due to the smaller *PDD* at higher altitudes compared to the Lirung and Rakhiot Glaciers and a strong contribution of the net radiation to ablation energy.

Very large positive degree-day factors for ablation were also found on Glacier AX010, east Nepal, in June at high altitude (15.6 mm $day^{-1}$ $°C^{-1}$; Kayastha *et al.*, 2000), in Spitsbergen (13.8 mm $day^{-1}$ $°C^{-1}$; Schytt, 1964), and on GIMEX profile (20.1 mm $day^{-1}$ $°C^{-1}$; van de Wal, 1992). Since thermal properties of the debris were not available on the Lirung and Rakhiot Glaciers, the results could not be compared in terms of the ratio of $k_d$ to $k_b$ and $R$ to $R_c$.

According to the present study, the data required to predict ice ablation under a debris layer are ablation rate on bare ice and $k_d/k_b$. The $k_d/k_b$ ratio can be obtained from F defined in Fig. 6 if $R/R_c$ is known. $R_c$ can be measured for different glaciers, and it is likely that $R_c$ will be the same for the same geological environment. Regional estimate of glacier ablation from debris-covered glaciers can be implemented with the aid of remote sensing data giving surface temperature to estimate thermal resistance $R$ of the debris cover (Nakawo *et al.*, 1993). The most important parameter remaining is then the degree-day factor for bare ice $k_b$.

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