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Article

Positive degree-day factors for ablation on glaciers in the Nepalese Himalayas: case study on Glacier AX010 in Shorong Himal, Nepal

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Abstract

The relationships among ablation, air temperature, and radiation are studied using a glacier mass-balance model on Glacier AX010 in the Nepalese Himalayas during the 1978 summer season (June to August). Positive degree-day factors for snow and ice ablations are calculated and their variations with respect to time and space are analysed. Calculated average positive degree-day factors for snow and ice ablation on Glacier AX010 are 7.9 and 8.7 mm d^{-1} $°C^{-1}$, respectively during a period from June to August 1978. Calculated monthly degree-day factors for July and August are smaller than those for June because of summer monsoon activity with large cloud amount in July and August which reduces incoming shortwave radiation, the main heat source of ablation. The large degree-day factors in June are mainly due to ablation by large net shortwave radiation. The present study indicates that the degree-day factor for snow ablation at higher altitude is larger than at the lower altitude, which is mainly due to ablation by net shortwave radiation at the low temperature.

1. Introduction

The important energy sources for glacier ablation are radiation, sensible heat, and latent heat. Their relative importance depends on climatic, topographic and surface condition of location, time of year, and time of day. Many studies have shown that radiation energy is the dominant energy source for ablation. The net radiation constitutes more than half of the total energy supply in 24 out of the 32 studies in different areas listed by Paterson (1969) although his figures are somewhat influenced by errors and differences in definition. The net radiation contributes more than 80 % of the total energy supply for ablation in the Nepalese Himalayas (Ohata and Higuchi, 1980; Kayastha *et al.*, 1999).

Air temperature is an important meteorological element for explaining variations in ablation and mass balance of a glacier. In particular, the melting of snow or ice during any particular period is assumed to be proportional to the sum of daily mean temperatures above the melting point during that period and the sum is called the positive degree-day sum (*PDD*). The factor linking ablation to this temperature sum is the positive degree-day factor. The degree-day factor involves a simplification of complex processes that are properly described by the energy balance of the glacier surface and overlaying atmospheric boundary layer. In general, the degree-day factor can not apply to daily ablation rates. However, it can give acceptable results when applied over longer periods of time. This is because the factors determining the melt process are correlated with temperature. The degree-day concept was applied in glaciology for the first time by Finsterwalder and Schunk (1887) in the Alps and has been used since by many authors. Braithwaite and Olesen (1985, 1989) and Braithwaite (1995) used the degree-day concept under Greenland conditions, modified the concept by Reeh (1991) to calculate melting over the whole Greenland ice sheet, and used in ice-dynamics modelling by Huybrechts *et al.* (1991) and Letreguilly *et al.* (1991). Similarly, Laumann and Reeh (1993) used the degree-day model developed for parameterizing melt rates on the Greenland ice sheet and on glaciers in southern Norway, and Johannesson *et al.* (1995) applied a degree-day glacier mass-balance model to three glaciers in Iceland, Norway and Greenland.

Several models and empirical relations have been proposed to calculate glacier ablation in the Nepalese Himalayas, for example, empirical relations to calculate glacier ablation by Ageta and Higuchi (1984), degree-hour factors for ablation on Yala Glacier by Motoyama and Yamada (1989), simplified model for estimating glacier ablation under a debris layer by Nakawo and Takahashi (1982), and Rana *et al.* (1997), and energy balance modelling for glacier mass balance on Glacier AX010 by Kayastha *et al.* (1999). According to Kayastha *et al.* (1999), the albedo of snow or ice and radiation processes, such as the effects of screening by surrounding mountain walls, areal variations in the multiple reflection between clouds and the glacier surface, and thin snow covers which alter the surface albedo, have a strong influence on the ablation.

Although the net radiation energy is generally the major source of ablation energy, there are useful correlations between ablation and air temperature, which are very convenient to apply on glaciers in remote areas where detailed observations are scarce. Therefore, the main purpose of the present paper is to study the relationship between ablation and air temperature on Glacier AX010 as a case study in the Nepalese Himalayas and to find out applicable positive degree-day factors to calculate glacier ablation. Variations of the calculated degree-day factors are also to be analysed with respect to time and space on Glacier AX010.

2. Studied glacier and data

Glaciological and meteorological observations were carried out on Glacier AX010 intensively during the summer monsoon season in 1978 by the Japan-Nepal Joint Glaciological Expedition in Nepal (GEN). Since necessary data and glacier mass balance model (Kayastha *et al.*, 1999) for the analyses are available, this glacier is chosen for the present study.

Glacier AX010 lies at the southern front of the Nepalese Himalayas in Shorong Himal (Fig. 1). It extends from west to east-southeast. The highest and lowest elevations on the glacier in 1978 were 5360 and 4950 m a.s.l., respectively, the length along the centreline was 1.7 km, and the area was 0.57 km^2. The glacier ends at a pond. The altitude of the meteorological observation site near the base camp, BC, was 4958 m a.s.l., where meteorological data were recorded. The data used in the present study comprise (1) daily meteorological data collected during that intensive observation period, and (2) daily energy balance components (net shortwave and longwave radiation fluxes, sensible and latent heat fluxes and heat conduction), and ablation rates calculated from the glacier mass-balance model (Kayastha *et al.*, 1999) for the particular period.

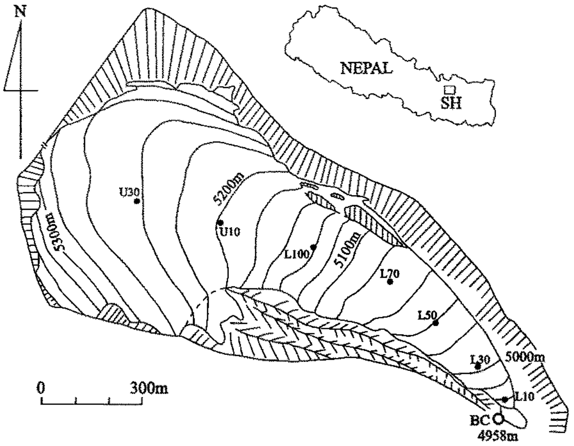

Fig. 1. Map of Glacier AX010 in Shorong Himal, Nepal and locations of BC and seven observation points (L10 to U30). The box labelled SH in the inset shows the location of the Shorong area.

The average air temperature, relative humidity and wind speed were found to be 2.3 °C, 88 %, 1.5 m s^{-1}, respectively and total precipitation was 1453 mm at the meteorological observation site (4958 m a.s.l.) during the observation period, which lasted from 25 May to 25 September 1978.

A lapse rate of 0.6 °C/100 m as in Ageta *et al.* (1980) and Kayastha *et al.* (1999) is used for estimating the air temperature at higher altitudes. Global radiation was measured near L50 from 14 June to 29 June for a heat balance study (Ohata and Higuchi, 1980). Since the global radiation measured near L50 is more representative for the whole glacier than that at the meteorological observation site, an experimental relation between the above two sites is applied for the whole period in order to adjust for areal variation due to surrounding topography in global radiation for respective points. Other meteorological elements for the entire glacier are assumed to be the same as those at the meteorological observation site.

3. Glacier mass-balance model

The glacier mass-balance model by Kayastha *et al.* (1999) calculates hourly ablation and mass balance using six meteorological variables (air temperature, global radiation, relative humidity, wind speed, cloud amount, and precipitation amount) and surface charateristics (surface albedo, roughness length, snow/ice density). The main features considered newly in this model were: I) distinction of snow into three different types namely, new, old and dirty snow; II) the effect of thin new snow layer above ice or dirty snow on surface albedo; III) topographic effects on shortwave and longwave radiation; and IV) a relationship between air temperature and relative humidity in order to distinguish between snow and rain for precipitation events.

The basic energy balance equation employed was:

$$Q_M = K_* + L_* + Q_S + Q_L + Q_G \qquad (1)$$

where Q_M is the energy used for melting of snow/ice, K_* is the net shortwave radiation flux, L_* is the net longwave radiation flux, Q_S is the sensible heat flux, Q_L is the latent heat flux, Q_G is the heat conduction at the glacier surface. Heat transport by precipitation was assumed to be negligible. Incoming energy at the glacier surface was taken as positive and outgoing as negative. Details of this model and its application to Glacier AX010 were described in Kayastha *et al.* (1999).

Three types of snow namely, new snow, old snow and dirty snow were considered in the model, but they are collectively termed as snow in the present study for simplicity. Glacier surface was covered by snow at all points at the beginning of the model calculation and the surface conditions were changed with time depending on the initial snow thickness and altitudes of the specific points on the glacier. The days when the glacier surface is covered with few centimetres and more of snow and without snow (glacier ice occasionally with traces of snow) during the observation period are termed as snowsurface period and icesurface period, respectively, in the present study (Fig. 2). Glacier surface at U10 and U30 was always covered with snow; ice surface was exposed at points L10 to L100. At the lowest point, L10, the surface changed from snow to ice later than at upper points since drifted snow due to strong west winds in winter was deposited and the ablation was reduced due to screening effect of solar radiation by the high mountain wall. The glacier surface was turned from ice into snow earlier at the higher altitude than the lower altitude. The entire glacier surface was covered with snow on 23 August, which lasted for several days at L10 and L30.

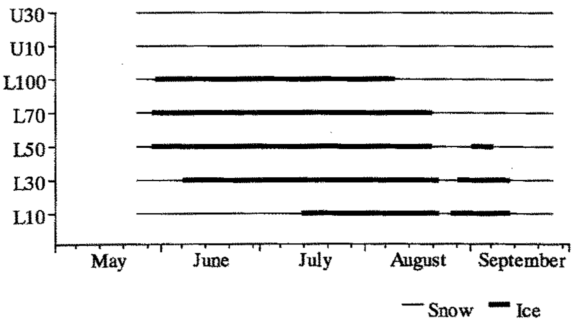

Fig. 2. Surface composition at seven points (L10 to U30, Fig. 1) from May to September 1978.

The model calculates the energy to be used for melting of snow/ice, Q_M every hour according to equation (1) using hourly meteorological data and surface parameters at seven points on the glacier. Hourly mass balance is then calculated as an algebraic sum of ablation and snowfall amount in that hour, if any, and finally the daily mass balance amounts are obtained by summing hourly values.

Calculated energy balance components at points L10, L50, and U30 on Glacier AX010 (Fig. 1) from 25 May to 25 September 1978 are summarised in Table 1. Net radiation flux is the main energy source of ablation, which contributes 86 % in average of the total energy income at the three points on the glacier surface. The contribution of the net radiation is larger at the upper point (U30) than at the lower point (L10). Sensible and latent heat fluxes have much less contribution for ablation compared to the net radiation flux. Calculated and observed mass balance for each half

Table 1. Calculated total values of energy balance components (W m^{-2}) at three points on Glacier AX010 for the period from 25 May to 25 September 1978 (after Kayastha *et al.*, 1999).

Components	L10	L50	U30
Net radiation	7973	6861	5067
Sensible heat	961	991	486
Latent heat	473	374	−52
Heat conduction	−275	−353	−120
Ablation energy	9132	7873	5381
Net radiation/ablation energy	0.87	0.87	0.94

month at points L10, L50 and U30 were compared and the correlation coefficient was found 0.77. Calculated and observed area-averaged mass balances of the glacier during the 1978 summer season (10 June-24 September) showed good agreement, namely -0.44 m (w.e.) and -0.46 m (w.e.), respectively. Since the model results are in good agreement with the observed values, it is used to calculate degree-day factor for ablation during the summer three months (June, July and August) on Glacier AX010 in the present study.

4. The correlation between ablation and radiation

To know the relation between the main heat income and ablation, calculated daily ablation rate is plotted against daily mean global radiation at L10 from June to August 1978 in Fig. 3. There is nearly no correlation between the ablation and global radiation (r=0.19 with sample size 92). One of the main reasons for such a very weak correlation is that global radiation is negatively correlated with longwave radiation balance because it increases with increasing cloudiness whilst the global radiation decreases (Braithwaite and Olesen, 1985). Albedo variations also weaken the correlation between global radiation and ablation.

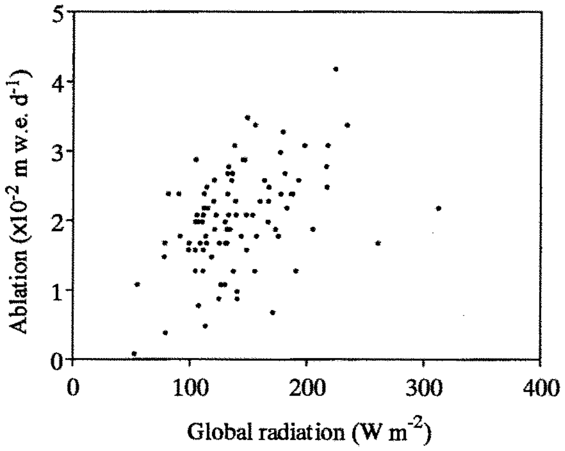

Fig. 3. Daily ablation rate versus daily mean global radiation at L10 from June to August 1978.

On the other hand, there is a strong correlation between the daily ablation rate and the shortwave radiation absorbed by the surface (r=0.84 and 0.81 at L10 and U30, respectively with sample size 92) as shown in Fig. 4. The proportionality factor linking ablation to absorbed shortwave radiation averaged at L10 and U30 on this glacier is 0.22 mm/W m^{-2}. This value is more than two times greater than the value obtained by Braithwaite and Olesen (1985) on two outlet glaciers, Quamanassup sermia and Nordboglectsher (0.09 mm/W m^{-2}) in the Greenland ice sheet. The main reason for such a large proportionality factor may be due to the net radiation, which contributes about 90 % of ablation energy on Glacier AX010 (Table 1) while only about 60 % on the two outlet glaciers in the Greenland ice sheet.

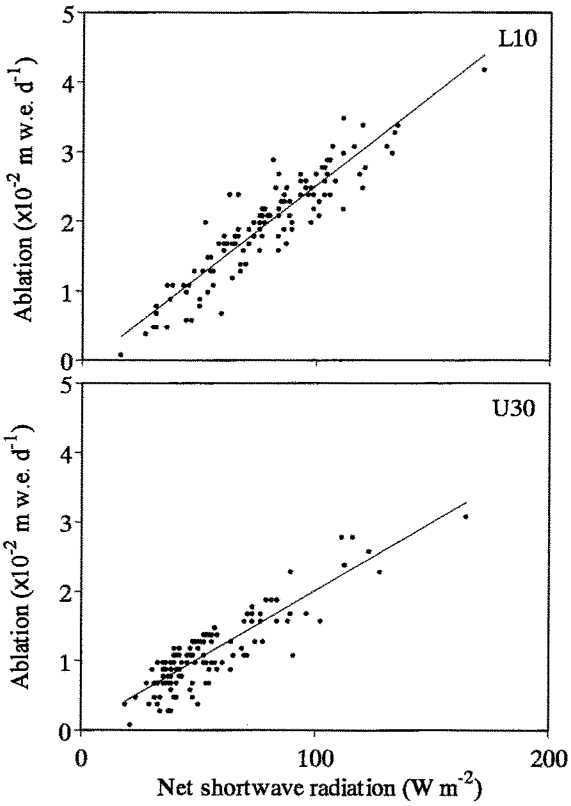

Fig. 4. Daily ablation rate versus daily mean net radiation at L10 and U30 from June to August 1978. The thin line represents the regression line.

Daily mean air temperature versus daily mean net shortwave radiation is plotted in Fig. 5 (L10) and Fig. 6 (U30). Considerable amount of net shortwave radiation is found at low air temperature during snow surface period on many days at U30 but only a few days at L10 (Fig. 6). Since net shortwave radiation is one of the main energy sources for ablation, the net shortwave radiation found at these points is used for ablation. This confirms that glacier ablation occurs

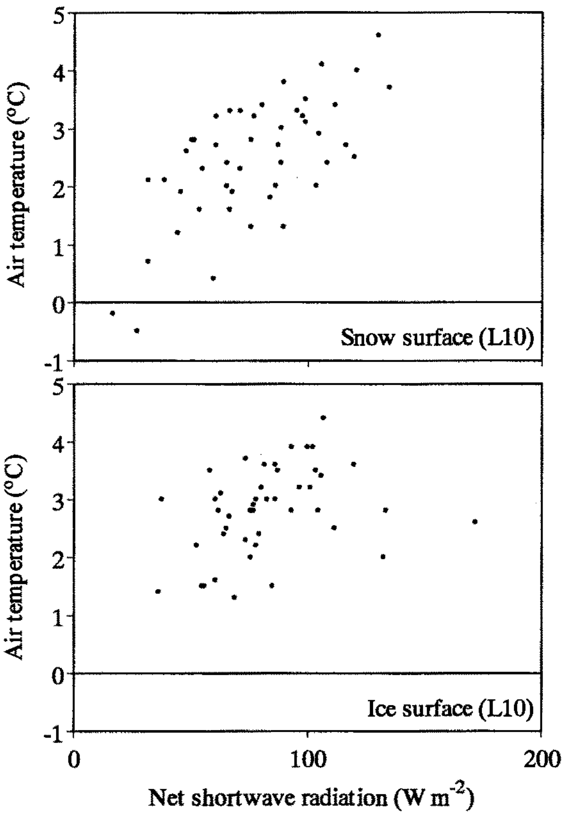

Fig. 5. Daily mean air temperature versus daily mean net shortwave radiation at L10 during snow surface period (47 days) and ice surface period (45 days) from June to August 1978.

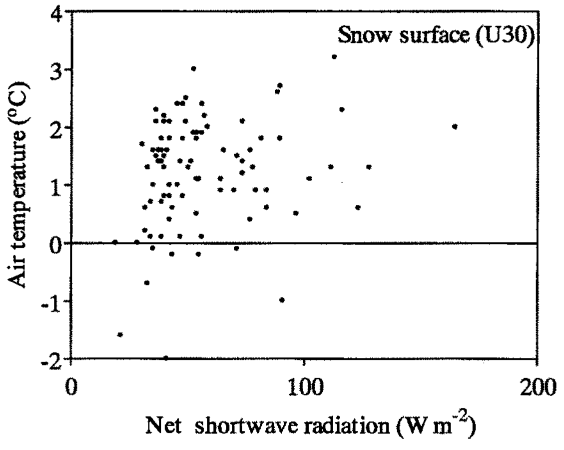

Fig. 6. Daily mean air temperature versus daily mean net shortwave radiation at U30 from June to August 1978. Ice surface did not appear at U30.

even around 0°C due to large net shortwave radiation. Air temperature during the ice surface period was always higher than 1°C at L10 (Fig. 5).

5. The correlation between ablation and air temperature

Daily ablation rate calculated from the model is plotted against daily mean air temperature at L10 and U30 from June to August 1978 in Fig. 7. There is a weak correlation between daily ablation and temperature (r=0.38 and 0.15 at L10 and U30, respectively with sample size 92) in Fig. 7, showing the higher correlation at L10 than at U30. However, the correlation between monthly mean daily ablation and monthly mean air temperature is high as shown in Fig. 8 (r=0.50 for 7 points in 3 months with sample size 21). It indicates that the factor linking between ablation and temperature is useful for relatively long period.

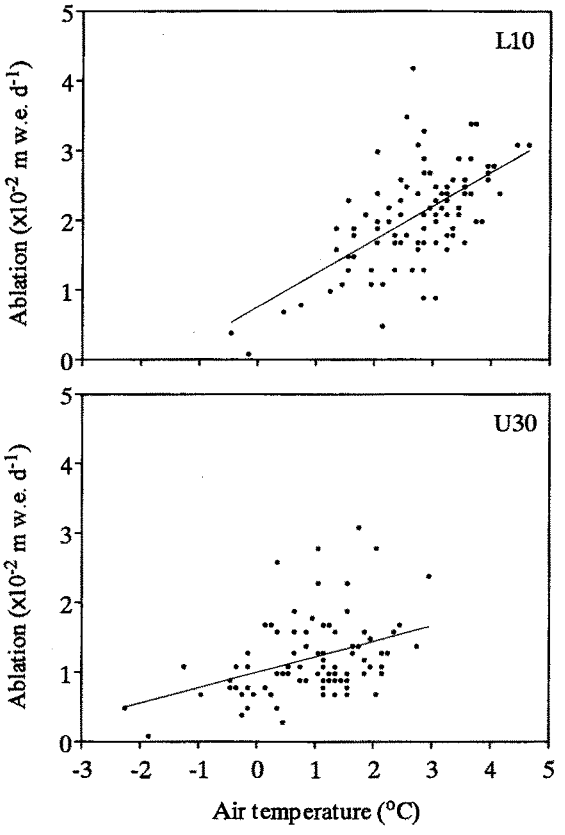

Fig. 7. Daily ablation rate versus daily mean air temperature at L10 and U30 from June to August 1978. The thin line represents the regression line.

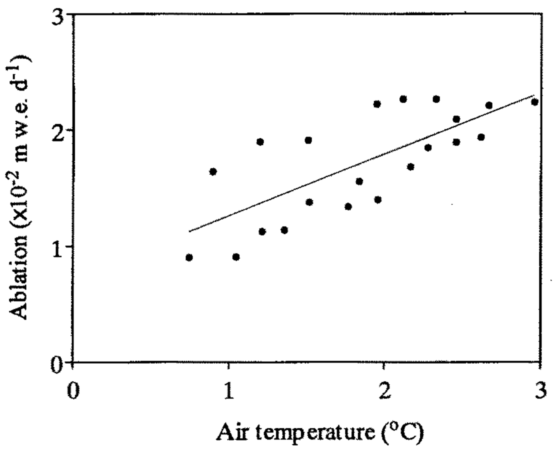

Fig. 8. Monthly mean daily ablation rate (June, July and August) versus monthly mean air temperature at seven points (L10 to U30). The thin line represents the regression line.

Figure 9 shows double-mass curves of cumulative ablation versus cumulative *PDD* at seven points (L10 to U30) based on ablation during the period from June to August 1978 calculated for each half month from energy balance model. Although the curves are not perfect straight, there is a high degree of consistency between ablation and temperature.

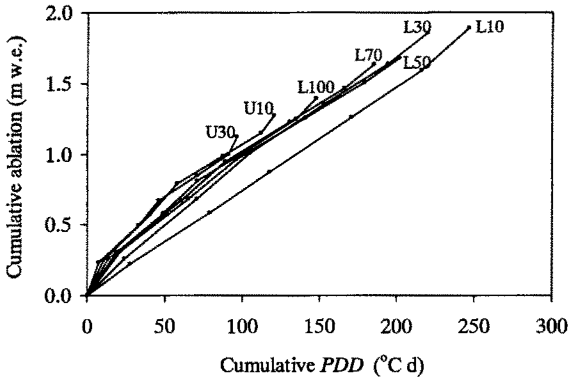

Fig. 9. Cumulative ablation versus cumulative *PDD* at seven points (L10 to U30) from June to August 1978.

6. Positive degree-day factors

Positive degree-day factor for ablation is based on the claimed relations between the air temperature and ablation (Fig. 8), and between *PDD* and ablation (Fig. 9). Positive degree-day factor, k is calculated as:

$$k = \frac{\sum a}{PDD} \tag{2}$$

where $\sum a$ is total ablation during a certain period same as the period for *PDD*. Although data are available for 25 days in September, positive degree-day factor is not calculated for September because there were only few days with positive air temperature at higher altitudes.

Monthly (June, July, and August) and seasonal (June to August) degree-day factors are calculated at seven points (L10 to U30) on Glacier AX010. Altitudinal distributions of these values are shown in Fig. 10, and monthly degree-day factor versus monthly mean air temperature at each point is shown in Fig. 11. These figures show that the degree-day factors for July and August are relatively small and change little with respect to altitude and air temperature compared for June.

Degree-day factors are large at high altitude in all cases in Fig. 10. The seasonal average degree-day factor increases with respect to altitude and its value ranges from 7.7 to 11.6 mm d^{-1} °C^{-1}. As mentioned in Section 4 (Fig. 5 and 6), the ablation around 0°C due to net shortwave radiation increases at high altitude with low temperature (low *PDD*). Ablation around 0°C due to net shortwave radiation has dominant effect

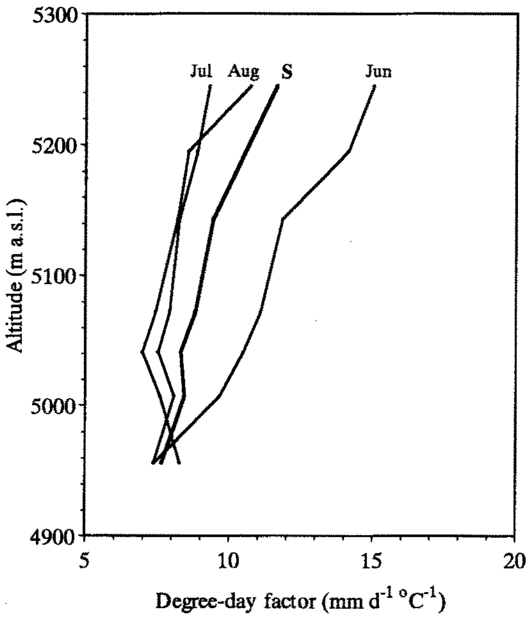

Fig. 10. Altitude versus monthly and seasonal (S: June -August) positive degree-day factors.

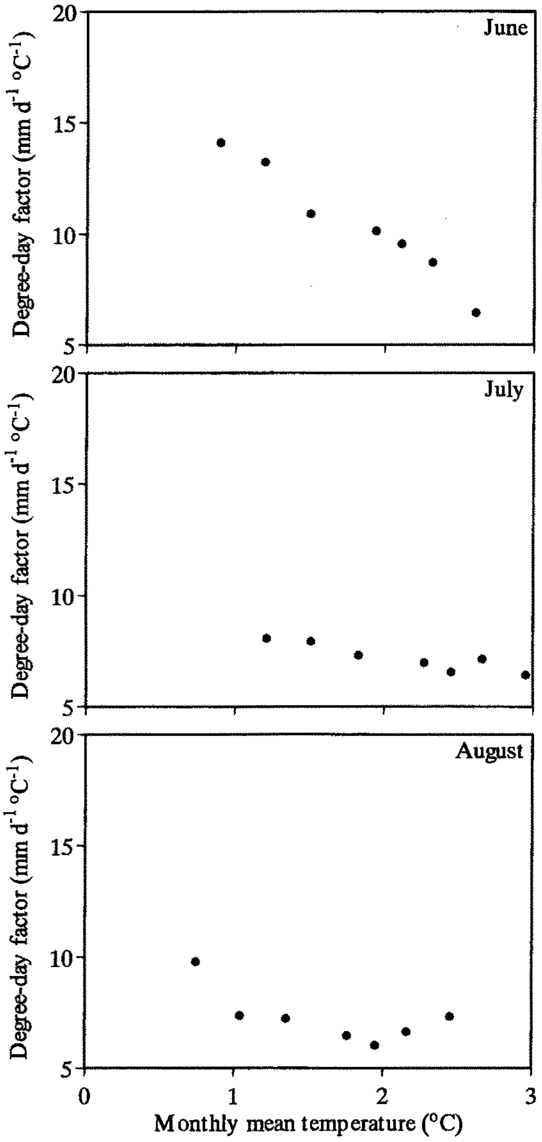

Fig. 11. Monthly degree-day factor versus monthly mean air temperature at seven points on Glacier AX010 in June, July and August 1978.

on having a large degree-day factor at higher altitudes than at lower altitudes.

In the previous studies for Greenland ice sheet (Braithwaite, 1995; Braithwaite and Olesen, 1989), large values of degree-day factor are obtained in case of low surface albedo (generally, ice albedo<snow albedo) due to larger ablation at the similar *PDD*, and in case of low air temperature due to low *PDD*, under the large contribution of net shortwave radiation to ablation. In the present study, the former case and the latter case are called "the low albedo effect" and "the low temperature effect," respectively for the large degree-day factors.

Positive degree-day factors for snow and ice ablation are calculated using the corresponding total values of positive daily mean air temperature and daily ablation during the snow and ice surface periods (Fig. 2), respectively. The positive degree-day factors for seasonal ablation and snow ablation at seven points (L10 to U30), and ice ablation at five points (L10 to L100) are shown in Table 2. Averaged positive degree-day factors at seven points for seasonal ablation on Glacier AX010 is 9.3 mm d^{-1} °C^{-1}. In general, snowmelt has a smaller positive degree-day factor than the ice melt at the same altitude. Degree-day factor increases largely with increase of altitude (decrease of air temperature) for snow ablation than ice ablation. During 92 days from June to August 1978, the maximum degree-day factor for snow ablation is 11.6 mm d^{-1} °C^{-1} at U30 (5245 m). Such large degree-day factor is mainly due to ablation at low temperature by radiation at higher altitude because of "the low temperature effect" (Fig. 6).

Table 2. Calculated positive degree-day factors (k: mm d^{-1} °C^{-1}) for seasonal ablation, snow and ice ablation on Glacier AX010 during the period from June to August 1978.

Points	Altitude (m a.s.l.)	*k* for seasonal ablation	*k* for snow ablation	*k* for ice ablation
L10	4956	7.7	7.3	8.1
L30	5007	8.5	5.9	8.7
L50	5041	8.3	7.3	8.4
L70	5072	8.8	8.7	8.8
L100	5143	9.4	10.2	9.3
U10	5195	10.6	10.6	---
U30	5245	11.6	11.6	---

7. Discussion

The degree-day factors for July and August are relatively small in comparison with those for June as shown in Figs. 10 and 11. Variations of 5 days running mean of daily mean net shortwave radiation (average of L10, L50 and U30), daily mean air temperature at the meteorological observation site and daily ablation at L50 are shown in Fig. 12. The net shortwave radiation fairly decreased in July and August, and the correlation of variations between air temperature and ablation was well during these months (Fig. 12). Since the summer monsoon activity is strong and cloud

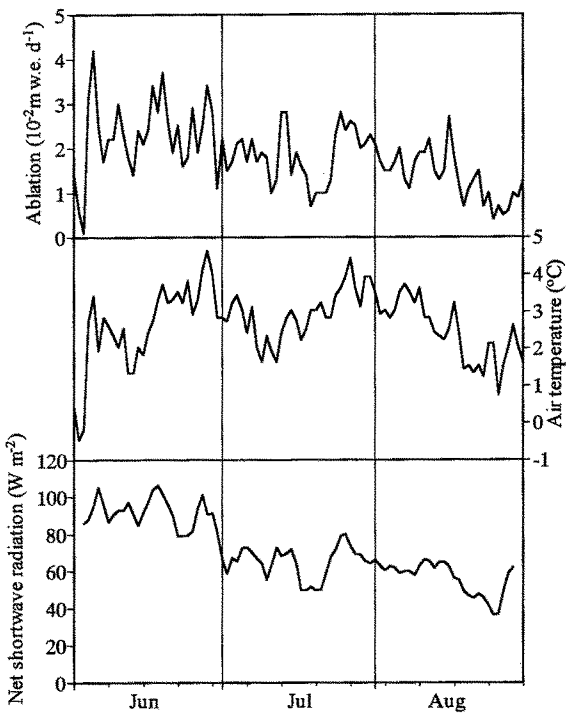

Fig. 12. Variations of 5 days running mean of daily mean net shortwave radiation averaged from L10, L50 and U30, daily mean air temperature at meteorological observation site (4958 m a.s.l.) and daily ablation at L50 from June to August 1978.

amount increases in July and August (monthly averaged cloud amount in tenths in daytime: June 8.7, July 9.7, and August 9.6), glacier ablation is reduced due to decrease of incoming shortwave radiation. Therefore, the degree-day factors during these months become small, while the degree-day factors are large in June due to ablation by large amount of net shortwave radiation.

Positive degree-day factors for ice and snow ablation on various glaciers as tabulated in Braithwaite (1995) are shown with the result of the present study in Table 3. The degree-day factors for snow and ice ablation on Glacier AX010 in Table 3 are the simple average values obtained from the degree-day factors at five points (L10 to L100) as tabulated in Table 2. The degree-day factor for ice ablation on Glacier AX010 is slightly larger than those found on other glaciers, excluding Spitsbergen, and the degree-day factor for snow ablation is very large; in some cases about two times larger than the one found on other glaciers. If the degree-day factor for snow ablation is calculated as a simple average obtained from the degree-day factors at seven points (L10 to U30), it becomes 8.8 mm d^{-1} °C^{-1} more than the degree-day factor for ice.

Table 3. Positive degree-day factors for ice and snow ablation on glaciers. Units are mm d^{-1} °C^{-1}

Ice	Snow	Glacier/location
8.7	7.9	AX010, East Nepal
5.0-7.0		Swiss glaciers*
13.8		Spitsbergen*
6.3		Store Supphellebre*
5.4		Gr. Aletschgletscher*
5.5±2.3		Norway*
6.3±1.0		Arctic Canada*
6.0	3.0	Franz Josef Glacier*
7.7	5.7	Satujokull*
6.4	4.4	Nigardsbreen*
6.0	4.5	Alfotbreen*
5.5	4.0	Nigardsbreen*
5.5	3.5	Hellstugubreen*

*from Braithwaite (1995), Table 2.

Braithwaite and Olesen (1993) found various degree-day factors for ice on Qamanarssup sermia (790 m a.s.l.) in the Greenland for different seasons: 9.4 for September-May, 7.5 for June-August and 7.9 mm d^{-1} °C^{-1} for the whole year. There is a broad agreement in degree-day factors for ice ablation on Quamanarssup sermia and Glacier AX010. Very large degree-day factors for ice ablation were also reported in Spitsbergen (Table 3) and in the Greenland ice sheet, *i.e.* 22.2 and 20.1 mm d^{-1} °C^{-1} for GIMEX profile (Bintanja *et al.*, 1990; van de Wal, 1992), and 18.6 mm d^{-1} °C^{-1} for EGIG Camp IV (Ambach, 1963); Braithwaite (1995) mentioned that large positive degree-day factors only occur with lower positive degree-days (lower temperatures) and there is no sign of large values at high temperatures. In case of Glacier AX010 also, the larger degree-day factors than other glaciers are mainly attributed to the low summer temperature around the glacier in the high Himalayas (Figs. 5 and 6). There is no information about the shortwave radiation on the above past studies and hence the radiation data of Glacier AX010 could not be compared with the past studies.

Although the degree-day factor for snow is smaller than that for ice ablation generally (Tables 2 and 3) due to "the low albedo effect," the degree-day factor for snow ablation on this glacier is found larger than for ice ablation at high altitude (L100) in Table 2. Since ice surface is exposed during warm period under high *PDD* condition (Fig. 5), the degree-day factor for ice has a possibility to be smaller than that for snow. Such condition characterised ablation condition of Glacier AX010, due to "the low temperature effect" for large degree-day factor as seen in the result at L100. In such case, "the low temperature effect" is predominant over "the low albedo effect." So, there is a possibility of very large degree-day factors or it is impossible to use degree-day factor to calculate snow and ice ablation in low air temperature period. In such cases, it may be necessary to fix a boundary of negative air temperature (critical temperature) when calculating a degree-day factor or to introduce another type of a factor, which relates with both air temperature and solar radiation for low temperature period, since negative air temperature periods prevails at the beginning and end of the melting season.

There is obviously a relation between ablation and positive degree-days but degree-day factors vary seasonally as well as with altitude depending on air temperature, radiation, and other climatic conditions and surface condition of the glacier. Therefore, for the accurate estimation of glacier ablation, it is required to obtain the degree-day factors for proper periods and zones.

8. Conclusion

The correlation between ablation and air temperature (monthly) is strong and hence degree-day factors for snow and ice ablation are calculated. The seasonal degree-day factors for ablation on Glacier AX010 are large at high altitudes with low temperature, in a range of 7.7 mm d^{-1} °C^{-1}at L10 (4956 m a.s.l.) and 11.6 mm d^{-1} °C^{-1} at U30 (5245 m a.s.l.). Averaged positive degree-day factors for seasonal (June, July and August) ablation on Glacier AX010 is 9.3 mm d^{-1} °C^{-1}. Calculated monthly degree-day factors for July and August are smaller than for June because of summer monsoon activity with large cloud amount, which reduces incoming shortwave radiation, the main heat source of ablation. The large degree-day factors in June are due to ablation by large net shortwave radiation. On Glacier AX010, the degree-day factor for snow ablation is larger than those on other glaciers, and even larger than for ice ablation in some case (L100), since "the low temperature effect" is predominant on this glacier.

As noted, the degree-day method is better suited for longer duration and depends on climatic condition of a glacier. It would be good to have observational data of several years from glaciers in different regions in the Nepalese Himalayas to discuss on the degree-day factor. Further study on degree-day factor will be carried out with available data from different glaciers soon. In addition, because many glaciers in the Himalayas are typically covered with a debris layer and very complicated to calculate ice ablation under the debris layer using a surface energy balance model, it would be interesting to use such a simple degree-day method to calculate ice ablation under the debris layer. It would be a great help in the field of glacier hydrology if degree-day factor can be used to calculate ice ablation under the debris layer as on debris-free glaciers.

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