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Article

Positive degree-day factors for ice ablation on four glaciers in the Nepalese Himalayas and Qinghai-Tibetan Plateau

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Abstract

Positive degree-day factors for ice ablation on Yala Glacier, central Nepal, Xiao Dongkemadi Glacier and July 1st Glacier in the Qinghai-Tibetan Plateau, west China, are calculated during a summer season of 1996, 1993 and 2002, respectively, and compared with the degree-day factors calculated on Glacier AX010, east Nepal during a summer season of 1978. The degree-day factors for summer ice ablation at two altitudes 5120 m and 5270 m a.s.l. on Yala Glacier range from 8.0 to 10.5 mm d^{-1} $°C^{-1}$. In the case of Xiao Dongkemadi Glacier, the factors range from 13.3 (at 5425 m) to 14.2 mm d^{-1} $°C^{-1}$ (at 5475 m) and on July 1st Glacier, the factors at altitudes from 4305 m to 4619 m a.s.l. range from 5.5 to 8.8 mm d^{-1} $°C^{-1}$. Larger degree-day factors are found on glaciers situated at higher altitude. The results of the individual glaciers also indicate that the degree-day factor for ice at higher altitude is larger than at the lower altitude, which is mainly due to ablation attributed to absorbed global radiation at the high altitude where the positive degree-day sum is low due to low summer air temperature.

1. Introduction

The most important energy source for glacier ablation in the Himalayas is radiation. Many studies have shown that net radiation is the dominant energy source for ablation. 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; Kayastha, 2001).

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. This is because the factors determining the melt process are correlated with temperature or in other words, the air temperature contains the information of a major energy source. For example, in the net radiation, the incoming longwave radiation is important component of incoming heat source for melt at surface, which transfer information of air temperature to surface (Ohmura, 2001). He found that under clear sky, about 60% of the atmospheric emission is derived from within the first 100 m and 90% from the first 1 km of the atmosphere. When the sky is overcast with the cloud bottom within the first 1 km, more than 90% originates within this layer between the surface and the bottom of the cloud.

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 (1995a) used the degree-day concept under Greenland conditions, modified 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) and Johannesson *et al.* (1995) used the degree-day method for estimating melt rates on different 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), simplified models for estimating glacier ablation under 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).

The ablation area of many glaciers in the Himalayas is covered with 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. Kayastha *et al.* (2000b) studied the practical prediction of ice melting beneath various thickness of debris layer on Khumbu Glacier, Nepal, using a degree-day factor. Degree-day factors for ablation under various debris thickness were found and a practical relationship between debris properties and degree-day factor was established for estimating ablation under a debris layer. The data required to predict ice ablation under a debris layer are degree-day factor for ice ablation, air temperature and relation between degree-day factor and thermal properties of debris layer.

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. In this regard, simple degree-day method is used to estimate basin discharge from two glacierized basins in the Langtang Valley (Kayastha *et al.*, 2003) and the results are in good agreement with observed values. To use the degree-day method, the degree-day factor is a key parameter. Generally, the factors for snow and ice ablations are different; the factor for ice ablation is larger than for snow ablation due to the lower ice albedo (Braithwaite, 1995a). Glacier ablation mainly occurs in the ablation area on ice surface rather than snow surface. And the degree-day factor for ice ablation is also an important parameter to estimate ice melting under a debris layer (Kayastha *et al.*, 2000b). Therefore, the main purpose of the present paper is to find out applicable degree-day factors for ice on debris-free glaciers. The factors on Yala Glacier, central Nepal, Xiao Dongkemadi and July 1st Glaciers, west China, are obtained and compared with Glacier AX010, east Nepal (Kayastha *et al.*, 2000a) to study the spatial variation of degree-day factor and its causes.

2. Studied glaciers and data

Locations of studied four glaciers are shown in Fig. 1.

2.1. *Yala Glacier, central Nepal*

Yala Glacier in Langtang Valley is one of the most investigated glaciers in the Nepalese Himalayas. The highest and lowest altitudes are 5749 m and 5094 m a.s.l., respectively, and the area of the glacier is 2.5 km^2.

Data collected during the glaciological and meteorological observations on Yala Glacier from June to September in 1996 (Fujita *et al.*, 1998) are used in the present study. The observed mean air temperature was 1.6 °C at 5350 m a.s.l. and total precipitation was 753 mm at the glacier camp (5110 m a.s.l.) during the above period. Among eight stakes installed and maintained at different altitudes to obtain the mass balance of the glacier during the monsoon season in 1996, only data at two stakes at the lower part of the glacier (5120 m and 5270 m a.s.l.) are used to analyse ice melt in this study. However, the small amount of snowfall brought by summer monsoon is also included in the ice melt amount (Table 1). Very low ice melt

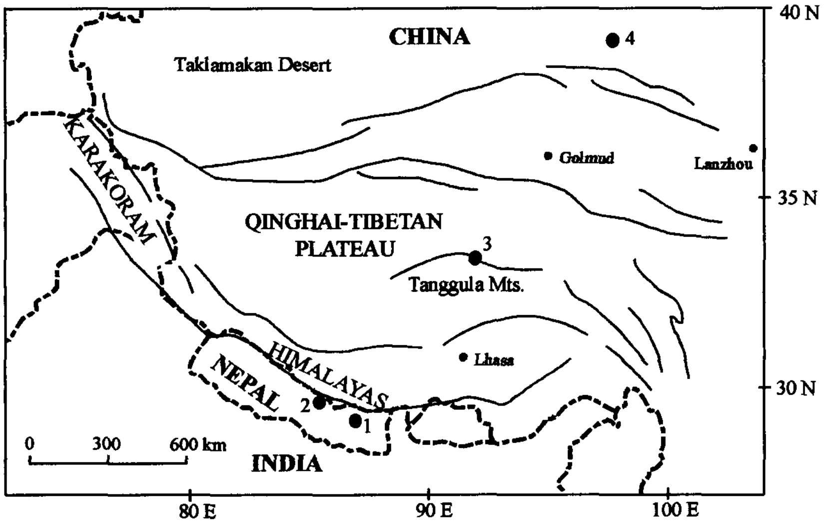

Fig. 1. Location map of study area. The numbers 1, 2, 3 and 4 represent Glacier AX010, Yala Glacier, Xiao Dongkemadi Glacier and July 1st Glacier, respectively.

occurred at stakes at higher altitude.

The total amount of ablation is calculated as a sum of ablation estimated from ice surface lowering and the melting of solid precipitation (snow). The amount of solid precipitation is calculated using the relation between probability of solid precipitation and air temperature obtained by Ageta *et al.* (1980) on Glacier AX010. The precipitation observed at the glacier camp is assumed the same at the two stakes of present study. It is assumed that all snowfall during the period was melted out at the end. Air temperature was recorded in a data logger at altitude 5350 m a.s.l., and its daily mean values are used for PDD. The lapse rate of 5.5 °C km^{-1} (Fujita *et al.*, 1997) is used to derive the temperature at lower elevations.

Table 1. Calculated monthly degree-day factors (k) for ice and related parameters on a) Yala Glacier, b) Xiao Dongkemadi Glacier and c) July 1st Glacier. Values in parentheses show the ice and snow ablations, respectively, on Yala and July 1st Glaciers. Seasonal values of ablation and PDD are cumulative totals; the seasonal degree-day factors are calculated from these totals.

a) Yala Glacier

i) Stake at 5120 m a.s.l.

Months	Ablation (mm w.e.)	PDD (°C d)	k (mm d^{-1} °C^{-1})
June	768 (731+37)	76.5	10.0
July	897 (844+53)	104.7	8.6
August	711 (557+154)	117.4	6.1
September	493 (435+58)	61.3	8.0
Seasonal	2869 (2567+302)	359.9	8.0

ii) Stake at 5270 m a.s.l.

June	518 (468+50)	57.4	9.0
July	901 (816+85)	80.3	11.2
August*	298 (94+204)*	93.0*	3.2*
September	462 (400+62)	42.2	10.9
Seasonal	1881 (1684+197)	179.9	10.5

* omitted in Fig. 2 and in calculation for seasonal values.

b) Xiao Dongkemadi Glacier

i) Stake at 5425 m a.s.l.

Months	Ablation (mm w.e.)	PDD (°C d)	k (mm d^{-1} °C^{-1})
July	661	47.8	13.8
August	657	51.0	12.9
Seasonal	1318	98.8	13.3

ii) Stake at 5475 m a.s.l.

July	535	38.7	13.8
August	611	42.2	14.5
Seasonal	1146	80.9	14.2

c) July 1st Glacier

i) Stake at 4305 m a.s.l.

Months	Ablation (mm w.e.)	PDD (°C d)	k (mm d^{-1} °C^{-1})
July	919 (873+46)	151.8	6.1
August	662 (630+32)	134.0	4.9
Seasonal**	1945 (1809+136)	353.8	5.5

ii) Stake at 4483 m a.s.l.

July	1005 (918+87)	107.0	9.4
August	552 (495+57)	92.7	6.0
Seasonal**	1849 (1620+229)	255.7	7.2

iii) Stake at 4619 m a.s.l.

July	683 (531+152)	73.7	9.3
August	589 (522+67)	63.1	9.3
Seasonal**	1473 (1152+321)	167.2	8.8

* * these seasonal values are cumulative totals from 15 or 16 June to 4 Sept. 2002.

2.2. *Xiao Dongkemadi Glacier, west China*

Xiao Dongkemadi Glacier lies in the middle of the Tanggula Mountains (33°N, 92°E), central Qinghai-Tibetan Plateau, west China. The highest and lowest elevations of the glacier in 1993 were 5926 m and 5380 m a.s.l., respectively, the length was 2.8 km, and the area was 1.77 km^2. The glacier surface faces south to southwest with a gentle slope.

Measured air temperature and simulated ice ablation by a mass balance model (Fujita and Ageta, 2000) in July and August 1993 are used in this study. Degree-day factors for ice are calculated at altitudes of 5425 m and 5475 m a.s.l., where surface composition was dominantly ice during the study period. The observed mean air temperature was -0.1 °C at 5600 m a.s.l. and total precipitation was 339.5 mm at the glacier camp (5500 m a.s.l.) during the period. The mass balance model by Fujita and Ageta (2000) calculates glacier ablation using an energy balance at the glacier surface incorporating the process of water refreezing. The results of the model verification showed that the model was indeed representative of the surface conditions, heat balance, heat conduction in the glacier, mass balance and refreezing process at different glacier altitudes.

2.3. *July 1st Glacier, west China*

July 1st Glacier is a north-facing glacier, located on Qilian Mountains in the Qinghai-Tibetan Plateau, west China (39°15' N, 97°45' E). Meteorological, hydrological and glaciological observations were carried out by a joint research team of Japanese and Chinese scientists on this glacier from mid June to early September in 2002. The highest and lowest elevations on the glacier measured by GPS are 5088 and 4295 m a.s.l., respectively. The length along the centreline in 1985 was 3.8 km, and the area was 2.98 km^2 (Liu *et al.*, 1985). The altitude of the meteorological observation site was 4291 m a.s.l., where meteorological data were collected from 11 June to 4 September 2002. The observed mean air temperature was 4.4 °C and total precipitation 250 mm at the meteorological observation site during the observation period.

Among the 28 stakes established on the glacier to monitor the glacier mass balance, ablation at only three stakes at altitudes of 4305 m, 4483 m and 4619 m a.s.l. are considered in the present study. Snowmelt was dominated above the altitude 4619 m a.s.l. Air temperature was also measured at the altitude 4619 m a.s.l., and lapse rate of air temperature between the meteorological observation station and at 4619 m a.s.l. was 8.1 °C km^{-1}. This lapse rate is used to get the air temperature at higher altitudes than the meteorological observation station. Almost all snowfall at three stakes during the observation period was melted out at the end. The total amount of ablation is calculated same as on Yala Glacier. The density of ice is assumed to be 900 kg m^{-3} and that of snow existed at the beginning of observation, based on measurements, is 450 kg m^{-3}. The threshold daily mean air temperature between snowfall and rainfall is assumed to be 3.7 °C based on the results obtained at the meteorological station on Yang Long He Glacier, Qilian Mountains, China (Ding and Kang, 1985). Altitudinal dependence of precipitation is neglected due to lack of data.

2.4. *Glacier AX010, east Nepal*

Glacier AX010 lies at the southern front of the Nepalese Himalayas in Shorong Himal. 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 was 4958 m a.s.l., where meteorological data were recorded. The observed mean air temperature was 2.7 °C and total precipitation 1236 mm at the meteorological observation site on Glacier AX010 from June to August 1978. Measured air temperature and ice ablation simulated by a glacier mass balance model (Kayastha *et al.*, 1999) are used in this study.

3. Degree-day factors

By definition, degree-day factor, k is calculated as a ratio of total ablation during a certain period to the PDD in the same period (k = total ablation / PDD). In general, the effectiveness of degree-day factor depends on the degree of consistency of ablation and air temperature. Therefore, cumulative monthly ablation versus PDD on Yala, Xiao Dongkemadi and July 1st Glaciers are plotted in Fig. 2. The data in June contains only 15 or 16 days and the data of 4 days in

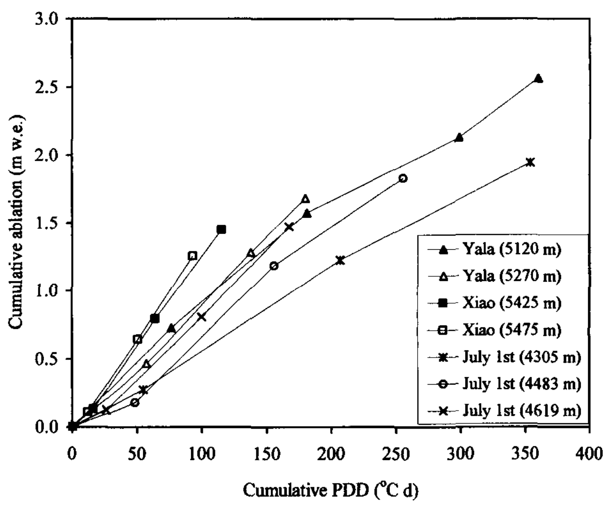

Fig. 2. Cumulative monthly ablation versus cumulative monthly PDD on Yala, Xiao Dongkemadi and July 1st Glaciers at different altitudes. Data in June on Xiao Dongkemadi Glacier when snow ablation was dominant is included in this figure.

September is included in August on July 1st Glacier. Although the lines are not perfectly straight, there is a high degree of consistency between ablation and air temperature on these glaciers. The degree-day factors for monthly and seasonal ablations are obtained from total ablation and PDD during the concerned period. However, at an altitude of 5270 m a.s.l. on Yala Glacier, only three months (June, July and September) total values are used for seasonal ablation as well as monthly ablation due to mostly snowmelt occurrence in August.

3.1. Yala, Xiao Dongkemadi and July 1st Glaciers

Calculated degree-day factors with other related parameters on Yala, Xiao Dongkemadi and July 1st Glaciers are shown in Table 1. Monthly and seasonal degree-day factors on Yala Glacier range from 6.1 to 11.2 and from 8.0 to 10.5 mm d^{-1} °C^{-1}, respectively; those on Xiao Dongkemadi Glacier from 12.9 to 14.5 and from 13.3 to 14.2 mm d^{-1} °C^{-1}, respectively. Similarly, monthly and seasonal degree-day factors on July 1st Glacier range from 4.9 to 9.4 and from 5.5 to 8.8 mm d^{-1} °C^{-1}, respectively. Averaged seasonal degree-day factors for ice at different altitudes on Yala, Xiao Dongkemadi and July 1st Glaciers are 9.3, 13.8 and 7.2 mm d^{-1} °C^{-1}, respectively. The monthly degree-day factors for ice at different altitudes of Yala, Xiao Dongkemadi and July 1st Glaciers are plotted in Fig. 3. In general, the degree-day factor at higher altitude is larger than at lower altitude. Ablation around 0 °C (with small PDD) is mainly attributed to the absorbed global radiation, which has dominant effect on having a large degree-day factor at higher altitudes than at lower altitudes, called "the low temperature effect" (Braithwaite, 1995a).

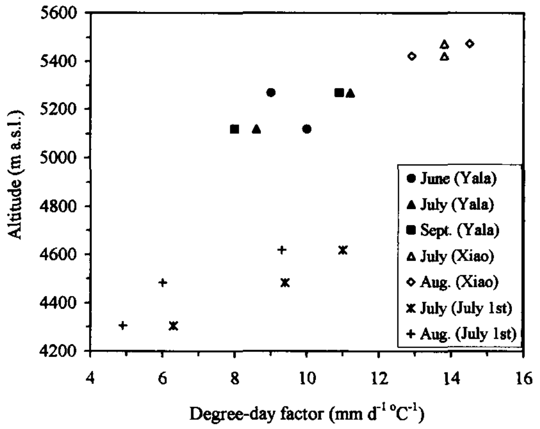

Fig. 3. Altitude versus monthly degree-day factors for ice on Yala, Xiao Dongkemadi and July 1st Glaciers in 1996, 1993 and 2002, respectively.

3.2. Glacier AX010

Monthly (June, July and August) and seasonal (June to August) degree-day factors were calculated at seven points from L10 (4956 m a.s.l.) to U30 (5245 m a.s.l.) on Glacier AX010 in 1978 (Fig. 10 in Kayastha *et al.*, 2000a). The degree-day factors for July and August were relatively small and change little with respect to altitude compared for June. Since the summer monsoon activity is strong and cloud 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 was reduced due to decrease of incoming global radiation. However, the degree-day factors were large in June due to ablation by large amount of absorbed global radiation (Kayastha *et al.*, 2000a). 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}. Averaged degree-day factors at seven points for seasonal ablation on Glacier AX010 was 9.3 mm d^{-1} °C^{-1}. The calculated average degree-day factor for ice from L10 to L100 (5145 m a.s.l.) was 8.7 mm d^{-1} °C^{-1}, during the ice ablation period from June to August 1978 (Fig. 2 in Kayastha *et al.*, 2000a).

4. Comparison of degree-day factors

Calculated seasonal degree-day factors for ice on Glacier AX010, Yala, Xiao Dongkemadi and July 1st Glaciers are plotted in Fig. 4. In general, the degree-day factor for ice increases as altitude increases and this trend holds within a glacier as well as in comparison between two or more glaciers of different regions. During the main ablation period/zone with high PDD values on Glacier AX010, degree-day factors for ice showed relatively similar values at different altitudes.

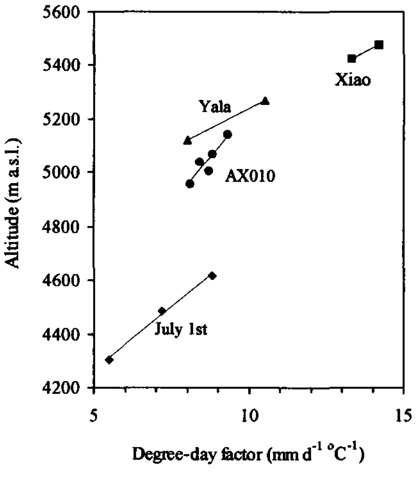

Fig. 4. Altitude versus seasonal degree-day factors for ice on Glacier AX010, Yala, Xiao Dongkemadi and July 1st Glaciers. Solid lines represent regression lines.

Degree-day factors for snow and ice at various locations as tabulated in Braithwaite and Zhang (2000) and Kayastha *et al.* (2000a) are shown with the results of present study in Table 2. Although very large degree-day factors for ice were reported in Greenland ice sheet and Spitsbergen, the degree-day factors on

Table 2. Degree-day factors at various locations. Units are mm d^{-1} °C^{-1}

Ice	Snow	Glacier/location
9.3		Yala Glacier, central Nepal
13.8		Xiao Dongkemadi Glacier, west China
7.2		July 1st Glacier, west China
8.7	7.9	AX010, east Nepal**
8.3	3.7	Q. sermia, W-Greenland*
8.1	2.9	Nordbogletscher, W-Greenland*
5.9 - 9.8		North Greenland*
18.6		EGIG Camp IV, Greenland*
13.8		Spitsbergen*
20.1-22.2		GIMEX profile, W-Greenland*
8.3-9.4		Greisgletscher, Switzerland*
5.0-7.0		Swiss glaciers*
6.9-7.1		Patagonia, Argentina*
6.3		Store Supphellebre*
5.4		Gr. Aletschgletscher*
5.5±2.3		Glaciers in Norway*
6.3±1.0		Arctic Canada*
6.0	3.0	Franz Josef Glacier*
7.7	5.7	Satujokull, Iceland*
6.4	4.4	Nigardsbreen, Norway*
6.2	3.8	Glacier de Sarennes, France*
6.0	4.5	Alfotbreen, Norway*
5.5	3.5	Hellstugubreen, Norway*

*from Braithwaite and Zhang (2000), Table 4.
**from Kayastha *et al.* (2000a), Table 3.

Glacier AX010, Yala and Xiao Dongkemadi Glaciers are relatively larger than many other glaciers in Table 2. Braithwaite (1995a) also 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. The similarity between the degree-day factors in the present study and in some parts of the Greenland ice sheet (Braithwaite, 1995a) is, however, against Braithwaite (1995b) in which the author pointed out that sensible heat flux in the Himalayas and Qinghai-Tibetan Plateau would be nearly half (small k) at same air temperature compared to Greenland ice sheet due to the lower density of air in the high altitudes. This may contribute to inter-regional variations in degree-day factors. Surprisingly, no difference in degree-day factors or the large degree-day factor in the Himalayas and Qinghai-Tibetan Plateau, may be due to ablation attributed to absorbed global radiation at high altitude (lower air temperature), because considerable amount of net shortwave radiation was found even at and around 0 °C air temperature on Glacier AX010 (Fig. 6 in Kayastha *et al.*, 2000a).

5. Variation of positive degree-day factor with respect to summer mean air temperature

Variation of degree-day factor with respect to mean air temperature is studied in order to know how the degree-day factor changes with respect to mean air temperature. It helps to assess the degree-day factor in different climatic region and scenario.

Figure 5 is obtained by plotting the degree-day factors for seasonal ice ablations on Yala, Xiao Dongkemadi and July 1st Glaciers (Table 1) and the factor during ice ablation period on Glacier AX010 (Fig. 2 in Kayastha *et al.*, 2000a) versus mean air temperature. The variation of degree-day factors with respect to mean air temperature is very similar on all four glaciers regardless of being situated at three different geographical locations, namely the Nepalese Himalayas, central Qinghai-Tibetan Plateau, and northern periphery of the Qinghai-Tibetan Plateau. The large degree-day factors are found only at lower air temperature as stated in Braithwaite (1995a).

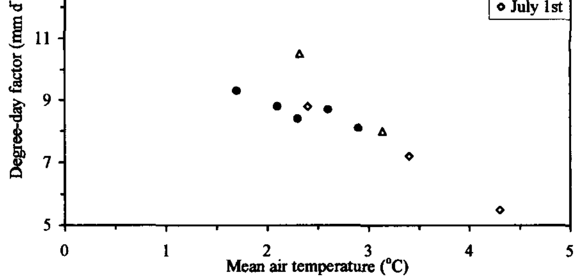

Fig. 5. Seasonal degree-day factor for ice versus mean air temperature on Glacier AX010, Yala, Xiao Dongkemadi and July 1st glaciers.

6. Concluding remarks

The monthly degree-day factors for ice at two altitudes 5120 m and 5270 m a.s.l. on Yala Glacier range from 6.1 to 11.2 mm d^{-1} °C^{-1}. In the case of Xiao Dongkemadi Glacier, the factors range from 12.9 (at 5425 m) to 14.5 mm d^{-1} °C^{-1} (at 5475 m) and on July 1st Glacier the factors at altitudes from 4305 m to 4619 m a.s.l. range from 4.9 to 9.4 mm d^{-1} °C^{-1} mm d^{-1} °C^{-1} showing the larger values at the higher altitudes on all glaciers. The seasonal degree-day factor averaged at different altitudes on July 1st Glacier is 7.2 mm d^{-1} °C^{-1}, both on Yala Glacier and Glacier AX010 is 9.3 and on Xiao Dongkemadi, it is 13.8 mm d^{-1} °C^{-1}. The large degree-day factor at higher altitude is mainly due to ablation attributed to absorbed global radiation at the high altitude where the PDD is low due to low summer air temperature.

In general, degree-day factor varies seasonally as well as with altitude depending on air temperature, radiation, and other climatic and surface conditions of the glacier. Therefore, for the accurate estimation of glacier ablation, it is necessary to obtain the degree-day factors for proper periods and zones.

It would be useful to find out degree-day factor for snow/ice ablation in different Himalayan regions so that one can estimate contribution of glacier melt using a degree-day method while calculating total discharge from a glacierized basin. This is because water resources of ungauged glacierized Himalayan basins are now increasingly being used for small hydropower plant construction due to economic activities in such area. The present research has produced useful results for ablation on debris-free ice but, because the ablation area of large glaciers in the Himalayas are typically covered with debris layers, it would be interesting to extend the simple degree-day method to calculate ice ablation under debris layers.

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