Influence of a fine debris layer on the melting of snow and ice on a Himalayan glacier

PRATAP SINGH, NARESH KUMAR, K. S. RAMASASTRI & YATVEER SINGH
National Institute of Hydrology, Roorkee 247667, Uttar Pradesh, India
e-mail: pratap@cc.nih.ernet.in

Abstract The effect of a thin layer of fine debris on the melting of snow and ice was investigated over Dokriani Glacier at an altitude of about 4000 m in the Garhwal Himalayas (31°49–31 52 N, 78 47–78 51 E). Such investigations were made during summer 1995, 1997 and 1998. The average melt rate with respect to unit temperature or degree-day factor for clean and dusted snow was computed to be 5.8 and 6.4 mm °C^{-1} day^{-1}, whereas for clean ice and debris-covered ice the value of this factor was 7.3 and 8.0 mm °C^{-1} day^{-1}, respectively. Melt rate of clean ice was about 1.26 times greater than that for clean snow under similar weather conditions. The effect of debris layer on the melt rate of snow was more prominent than that for ice. The presence of debris on the ice increased the melt rate by about 8.5%, whereas for snow it increased by about 11.6%. Information on such factors is useful for runoff modelling of glacierized drainage basins.

INTRODUCTION

An appreciable quantity of the flow of Himalayan rivers is derived from the snow and glacier melt runoff (Singh *et al.*, 1995; Singh *et al.*, 1997). One of the most common characteristics of Himalayan and Trans-Himalayan glaciers is the presence of debris covering a large portion of their ablation zone (Fujii & Higuchi, 1977; Nakawo & Young, 1982; Singh & Ramasastri, 1999). Østrem (1959) and Fujii & Higuchi (1977) found that ablation is accelerated under a thin layer of debris and retarded under a thick layer. Nakawo *et al.* (1993) attempted to estimate the melt rate of a debris-covered area of glaciers using satellite data. Mattson *et al.* (1993) reported direct ablation measurements by drilling wooden stakes into a glacier at different locations with different depths of debris cover. They found a large increase in ablation with debris cover thickness increasing from 0 to 10 mm followed by a reduction in ablation with debris-cover thickness increasing beyond 10 mm. They observed that 30-mm thickness of debris cover as a critical thickness indicating that at thickness greater than 30 mm ablation is suppressed compared with that expected from debris-free ice. Rana *et al.* (1996) measured ablation under debris thickness varying from 0 to 130 mm in the Nepal Himalayas. Similar to other findings, they also found that ablation increased as debris thickness increased up to a certain thickness and then decreased as debris thickness increased further. The maximum ablation was observed for a debris thickness of 26 mm. Evaluation of snowmelt and icemelt under debris cover is important for runoff modelling of glacierized drainage basins.

The quantity of meltwater produced depends on the prevailing weather conditions and the physical characteristics of surface. The degree-day factor representing the meltrate from snow and ice with respect to unit temperature is the most important parameter because of its practical importance in estimating ablation using temperature data. This parameter is used to convert degree-days to snowmelt or icemelt expressed in units of depth of water. In most mountainous basins, only temperature data are available in high altitude regions. However, most stations are located along the valley bottoms. Temperature data at higher elevations can be easily extrapolated using data from the stations located at lower altitudes. In the Himalayan region almost all snowmelt and glacier-melt studies are carried out using this temperature index approach. The first application of degree-day approach was made by Finsterwalder & Schunk (1887) in the Alps. Since then, this approach has been used all over the world for the estimation of snowmelt and icemelt runoff. The melt rate or degree-day factor can be determined from:

$$D = M/(T_a - T_0)$$

where M = depth of meltwater (mm day^{-1}), T_a = mean air temperature (°C); T_0 = base temperature (usually, 0°C); and D = degree-day factor (mm °C^{-1} day^{-1}). It is possible to compute the degree-day factor at a point by measuring temperature and meltwater from the snow or ice block. The number of degree-days for one day is obtained by averaging positive air temperatures.

In spite of the importance of degree-day factors for snow and ice for computation of melting from snow- and ice-covered areas, only limited studies have been carried out to determine these factors in the Himalayan region (Singh & Kumar, 1996). No study has been carried out to estimate degree-day factor for ice. In the present study degree-day factors for both snow and ice, including the effect of a thin debris layer on these factors, are determined at the Dokriani Glacier located in Garhwal Himalayas in India. A large portion of the ablation area of this glacier is covered by debris which varies in thickness from a few millimetres to a few metres.

MELTING FROM CLEAN AND DUSTED SNOW AND ICE

The dusting or blackening of snow and ice surfaces by any dark material tends to a reduction in the albedo. This results in higher absorption of solar radiation which, in turn, leads to accelerated melt and higher meltwater yield. Few studies pertain to increased melting of a snowpack due to dusting (Avsiuk, 1953, 1962; Kotlyakov & Dolgushin, 1972; Singh & Kumar, 1996). A review of the values of degree-day factors reported by various investigators for clean snow varied between 3.0 and 5.7 mm °C^{-1} day^{-1}, whereas for clean ice it varied between 5 and 7.7 mm °C^{-1} day^{-1} (Braithwaite, 1995).

EXPERIMENTS ON DOKRIANI GLACIER

In the present study, two pairs of snow and ice blocks (each 30 cm × 30 cm × 30 cm) were extracted from the glacier snowpack and ice body at an altitude of about 4000 m without disturbing their structure. The density of the snow and ice was measured and found to be 600 and 900 kg m^{-3}, respectively. Each block was wrapped in a plastic sheet, except for their top, and replaced in the snowpack, so that the top was at the same level as the surrounding area. One of the pairs of snow and ice blocks was kept clean while the other was covered with a 2-mm layer of fine debris naturally available on the glacier surface. The major source of such fine debris deposited over different parts of the glacier is landslides, rockslides from the surrounding valley walls and the reworking of old moraines. The density of the fine debris used in the present study was observed to be about 1800 kg m^{-3} and thus the weight of debris over unit area is computed to be about 0.36 gm cm^{-2}. The plastic sheet prevented any infiltration, percolation or lateral movement of the meltwater from the surrounding snowpack.

Observations were made continuously for 24 h on the days of the experiments. Experiments were carried out under fair weather conditions. All the study plots were adjacent to each other so that melting from each block may take place under similar weather conditions. Temperature was observed only at 15-min intervals at 2-m height above the snow surface at a single location in the centre of each plot. These were then averaged for each hour. For all study plots the surface temperature was 0°C because of the snow surface.

The meltwater from each block was collected in separate buckets at a frequency of 1 h and the volume was measured using standard beakers. On 5, 6 June 1995 only snow blocks were studied, while on 29 May 1997 and 24, 25 June and 22 July 1998 both snow and ice blocks were studied. Runoff from the study blocks along with observed air temperature are shown in Fig. 1(a)–(f). Computed degree-day factors for clean and debris-covered snow and ice are given in Table 1.

RESULTS AND DISCUSSIONS

The degree-day factor for the clean snow and debris-covered snow was determined to be 5.8 and 6.4 mm °C^{-1} day^{-1}, respectively, whereas for the clean ice and dusted ice it was observed to be 7.3 and 8.0 mm °C^{-1} day^{-1}. A comparison of degree-day factors for clean snow and ice with the values reported in the literature (for clean snow 3.0–5.7 mm °C^{-1} day^{-1} and for clean ice 5.0–7.7 mm °C^{-1} day^{-1}) at different locations worldwide shows that degree-day factors computed for the Himalayan glacier both for clean snow and ice are close to the upper range of the reported values. These large values are explained by large solar radiation in the low latitude area. Takahashi *et al.* (1981) and Sato *et al.* (1984) examined the dependency of sensible heat, latent heat and longwave radiation on temperature and showed that degree-day factor increases with absorbed shortwave radiation. According to this estimation, the degree-day factor would be large due to large shortwave radiation in the low latitude area. Because diurnal variation in snowmelt factor is controlled by the distribution of temperature, therefore, time of maximum value of the hourly melt factor also follows the time of maximum temperature. Usually, maximum value of the hourly snowmelt and icemelt factors occurred at about 12:00–13:00 h for both clean and dusted blocks. The average maximum hourly snowmelt factor for clean and dusted snow was 0.74 and 0.85 mm °C^{-1} h^{-1}, respectively. For clean and dusted ice, the average maximum hourly icemelt factor was 0.92 and 1.11 mm °C^{-1} h^{-1}.

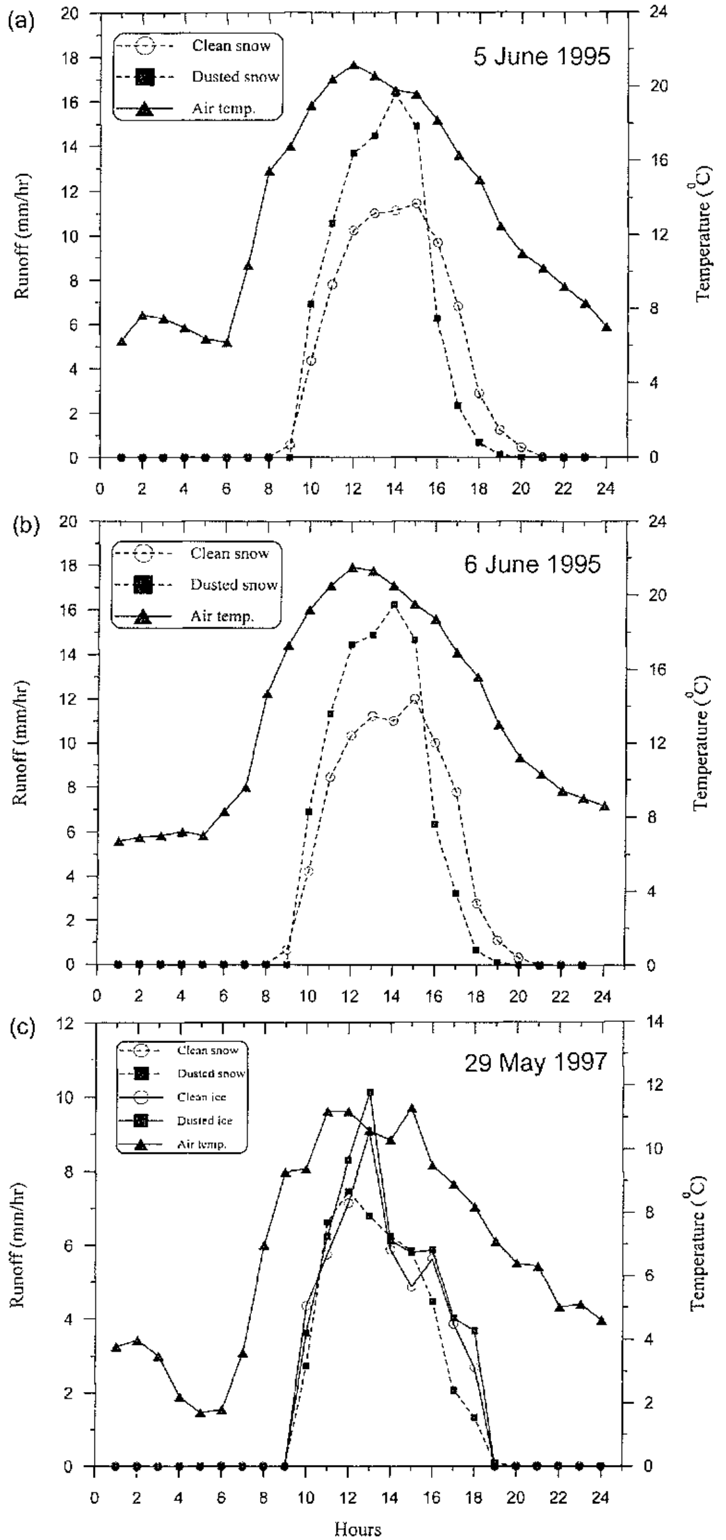

Fig. 1 Melt runoff from clean and dusted snow blocks along with air temperature.

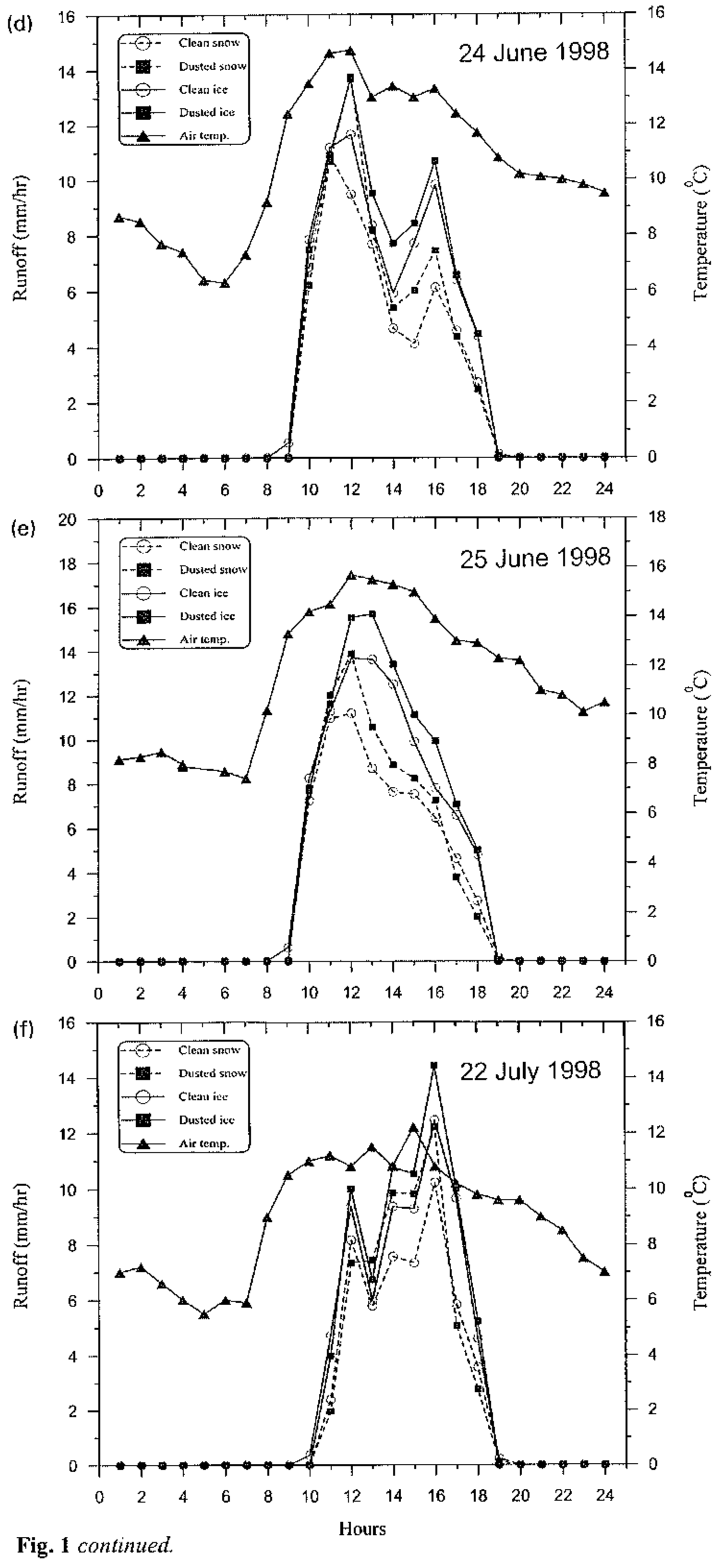

Fig. 1 *continued.*

Table 1 Degree-day factors for clean and dusted snow and ice (mm °C^{-1} day^{-1}). Daily average temperature was obtained from the mean of hourly (0000–2400 h) temperature data. The degree-day factor of clean ice was larger than that of clean snow and it was increased by the existence of debris cover.

Date	Degree-day factor for snow:			Degree-day factor for ice:		
	Clean snow	Debris-covered snow	Increase due to debris layer (%)	Clean ice	Debris-covered ice	Increase due to debris layer (%)
5 June 1995	5.9	6.6	11.9	-	-	-
6 June 1995	6.0	6.7	11.7	-	-	-
29 May 1997	5.8	6.4	10.3	7.3	7.9	8.2
24 June 1998	5.4	6.1	13.0	7.0	7.5	7.1
25 June 1998	5.8	6.4	10.3	7.7	8.4	9.1
22 July 1998	5.7	6.4	12.3	7.4	8.1	9.5
Average	5.8	6.4	11.6	7.3	8.0	8.5

Our observations indicate that the degree-day factor for ice is higher than the degree-day factor for snow. On an average, degree-day factor for ice was about 26% higher than that for snow. Such an increase in the degree-day factor for ice is possible because the lower albedo of the ice results in a greater absorbed radiation at the ice surface compared with a snow surface (Sato *et al.*, 1984).

The introduction of a debris layer on the ice increased the degree-day factor by about 8.5%, whereas for snow it was increased by 11.6% due to presence of debris. Generally a thin debris layer promotes ablation and causes a large degree-day factor, while a thick debris layer suppresses ablation and yields a small degree-day factor. In the present study a 2-mm-thick debris layer is a thin layer which therefore increased the ablation. The reason why its influence was larger on snow than ice was that the albedo change was larger on snow because the original albedo of snow was higher than that of ice. The degree-day factors established in the present study through field investigations can be used for the estimation of melting from snow- and ice-covered areas using only temperature and snow/ice covered area information.

Acknowledgement The authors are grateful to the Department of Science and Technology, Government of India, for providing funds to carry out the study.

REFERENCES

Avsiuk, G. A. (1953) Artificial augmentation of snow and ice melting of mountain glaciers. In: *Proc. Inst. Geogr., Acad. Nauk SSSR* **56**. Moscow.

Avsiuk, G. A. (1962) *Artificial Augmentation of Melting of Mountain Glaciers to Increase the Runoff of Rivers in Soviet Central Asia.* Acad. Nauk Series, Geography, no. 5, Moscow.

Braithwaite, R. J. (1995) Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling. *J. Glaciol.* **41**, 153–160.

Finsterwalder, S. & Schunk, H. (1887) Der Suldenferner. *Z. Deutsch. Österreich. Alpenvereins* **18**, 72–89.

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

Kotlyakov, V. M. & Dolgushin, L. D. (1972) Possibility of artificial augmentation of melting by surface dusting of glaciers (results of Soviet investigations). In: *Role of Snow and Ice in Hydrology* (Proc. Banff Symp., September 1972), vol. 2, 1421–1426. IAHS Publ. no. 107.

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

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

Østrem, G. (1959) Ice melting under a thin layer of moraine and existence of ice cores in moraine ridges. *Geogr. Ann.* **41**, 686–694.

Rana, B., Nakawo, M., Ageta, Y. & Seko, K. (1996) Glacier ablation under debris cover: field observations on Lirung Glacier, Nepal Himalayas. In: *Proc. International Conference on Ecohydrology of High Mountain Areas* (24–28 March, Kathmandu), 393–403. International Centre for Integerated Mountain Development, Kathmandu, Nepal.

Sato, A., Takahasi, S., Naruse, R. & Wakahama, G. (1984) Ablation and heat balance of the Yukikabe snow patch in the Daisetsu mountains, Hokkaido, Japan. *Ann. Glaciol.* **5**, 122–126.

Takahashi, S., Sato, A. & Naruse, R. (1981) A study of heat balance on Yukikabe snow patch in the Daisetsu mountains. *J. Japan. Soc. Snow Ice (Seppyo)* **43**, 147–154.

Singh, P. & Kumar, N. (1996) Determination of snowmelt factor in the Himalayan region. *Hydrol. Sci. J.* **41**(3), 301–310.

Singh, P. & Ramasastri, K. S. (1999) *Temporal Distribution of Dokriani Glacier Melt Runoff and its Relationship with Meteorological Parameters*. Project Report, National Institute of Hydrology, Roorkee, India.

Singh, P., Jain, S. K. & Kumar, N. (1997) Snow and glacier melt runoff contribution in the Chenab River at Akhnoor. *Mountain Res. Develop.* **17**, 49–56.

Singh P., Ramasastri, K. S., Singh, U. K., Gergan, J. T. & Dobhal, D. P. (1995) Hydrological characteristics of the Dokriani Glacier in the Garhwal Himalayas. *Hydrol. Sci. J.* **40**(2), 243–257.