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Degree–day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas

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Abstract

In the present study, degree–day factors for snow and ice were determined over Dokriani Glacier located in the Garhwal Himalayas. The field experiments were made at an altitude of about 4000 m. Effect of a thin fine dust layer on both degree–day factors was also examined. Average values of degree–day factor for clean and dusted snow were computed to be 5.7 and 6.4 mm $°C^{-1}$ day^{-1}, respectively, whereas for clean ice and dusted ice the value of this factor was found 7.4 and 8.0 mm $°C^{-1}$ day^{-1}. The degree–day factor for clean ice was about 30% higher than that for clean snow. The presence of dust increased the degree–day factor for snow by about 12%, whereas for ice this factor was increased by about 9%. These observations suggest that the effect of dust on degree–day factor for snow is more pronounced than that for ice. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Degree–day factor; Effect of dust; Melt runoff

1. Introduction

The runoff derived from snow and glaciers contribute significantly to the annual flows of Himalayan rivers (Singh et al., 1995; Singh et al., 1997; Singh and Kumar, 1997a,b). A major portion of melt runoff arrives during the summer period, i.e. June to September. In order to forecast the melt runoff from a glacierized basin, understanding of energy balance components is needed because melting results due to many different processes of heat transfer to the snow and ice surfaces. Estimation of snow and ice melt runoff using the energy balance approach is relatively complex and much climatic data is needed as input such as radiation, cloudiness, wind speed etc. Availability of climatic data required for the snow and glacier melt runoff modelling using energy balance approach, is very poor in the Himalayas. Therefore, certain simplifying assumptions are used in practical computations of snow and ice melt. A temperature index or the degree–day approach is generally considered to be a good model of the heat transfer processes associated with the melting of snow and ice because a temperature index approach often gives melt estimates comparable to those determined from a detailed evaluation of the various components in the energy balance (US Army Corps of Engineers, 1971; Anderson, 1973). Moreover, air temperatures are generally most readily available data in high altitude regions. For these reasons, temperature index is the most widely used method for snow and ice melt computations. The first application of a degree–day approach

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was made by Finsterwalder and Schunk (1887) in the Alps and since then this approach has been used all over the world for the estimation of snow and ice melt runoff. The temperature index method requires the knowledge of melt factors for snow and ice. In the Himalayan region, almost all the hydrological studies related to snow and glacier melt runoff are carried out using a temperature index approach.

Almost all the glaciers in the Himalayan and Karakoram region are covered with dust and debris in their ablation area (Moribayashi and Higuchi, 1977; Fujii and Higuchi, 1977; Nakawo, 1979; Fushimi et al., 1980; Nakawo et al., 1986; Singh and Kumar, 1996). In some cases, ablation area of the glacier is so extensively covered by debris material that clean ice is not visible. These debris and dust material are derived largely from the surroundings to the glacier surface through the disintegration of exposed rock faces and rockfall, debris avalanches, and failure of lateral moraines. There is a wide variation in the thickness of dust and debris in space over the glacier. An assessment of ablation rate under a dust and debris cover is needed for studies of glacier mass balance, glacier dynamics, and artificial ablation control for engineering and hydrological applications. Therefore, studies related with the influence of dust and debris become imperative for such glaciers because the melting of a glacier is influenced largely by the presence of dust or debris on the glacier body. The dust layer over the snow or ice surface reduces the albedo markedly causing more absorption of solar radiation to the surface, which in turn influences the melt rate. In the presence of a dust layer over the surface, the energy is transferred to the snow surface through the dust medium. A very thin debris cover accelerates the melting due to an increase in absorption of solar radiation and onward transmission of the energy to snow or ice surface without much delay. In the case of thick layer of dust on the snow surface, most of the energy is absorbed/stored in the dust layer itself resulting in little or no transfer of heat to the snow surface. In this way, energy reaching to the snow/ice surface is substantially decreased by the presence of a thick layer of dust and melting is reduced considerably.

For computation of melting from snow and ice covered areas, degree–day factor for clean and dusted snow in the Himalayan region were reported by Singh and Kumar (1996). No information was available on degree–day factor for ice for any Himalayan basin. The investigations reported in this paper deal with both snow and ice degree–day factors at the same glacier including the effect of dust on these factors. The experiments for the reported findings in this paper were made during summer 1997 and 1998. However, degree–day factors for clean snow and dusted snow were reported by Singh and Kumar (1996), but it was considered pertinent to include estimation of degree–day factor for snow also through present series of experiments so that a comparison of snow and ice melt factors can be made using the data obtained from the experiments conducted under similar weather conditions at same time and same place.

2. Methodology

The degree–day method used to compute the depth of snow or ice melt is expressed as:

For snow,

$$M = D_{\mathrm{sf}}(T_{\mathrm{a}} - T_0) \tag{1}$$

For ice,

$$M = D_{\mathrm{if}}(T_{\mathrm{a}} - T_0) \tag{2}$$

where M is the depth of melt water (mm/unit time); T_{a}, the mean air temperature (°C) at 2 m above the snow/ice surface (screen level); T_0, the base temperature (usually, 0°C); and D_{sf}, the snow melt factor (mm/(°C unit time)); D_{if}, the ice melt factor (mm/(°C unit time)). When the unit time is one day, then melt factor is termed as degree–day factor (mm $°\mathrm{C}^{-1}$ day^{-1}). The degree–day factor is used to convert the degree–days to snowmelt or ice melt expressed in depth of water. The value of degree–day factor varies with the melt period because of changes in the snow properties, which influence the melting process. It is expected that degree–day factor for ice has a little variation during a season as compared to snow because the ice properties do not change very significantly in a season. It is possible to compute the degree–day factor at specific location by measuring temperature and melt water runoff from the snow or ice block. The number of degree–days for one day is obtained by averaging positive air temperatures.

Table 1
Degree–day factors for snow and ice as reported by various investigators

Degree–day factor for snow (mm °C^{-1} day^{-1})	Degree–day factor for ice (mm °C^{-1} day^{-1})	References
–	5.0–7.0	Kasser (1959)
4.0–8.0	–	Yoshida (1962)
–	13.8	Schytt (1964)
–	6.3	Orheim (1970)
3.0–5.0	8.0	Borovikova et al. (1972)
1.3–3.7	–	Anderson (1973)
5.40	–	Lang et al. (1977)
–	5.5 ± 2.3	Braithwaite (1977)
5.0	8.0	Abal'yan et al. (1980)
–	6.3 ± 1.0	Braithwaite (1981)
2.5	7.2	Braithwaite and Olesen (1988)
3.0	6.0	Woo and Fitzharris (1992)
5.6	7.7	Jóhannesson et al. (1995)
4.4	6.4	Jóhannesson et al. (1995)
4.5	6.0	Laumann and Reeh (1993)
4.0	5.5	Laumann and Reeh (1993)
3.5	5.5	Laumann and Reeh (1993)
–	8.0	Braithwaite (1995)
5.9	–	Singh and Kumar (1996)

3. Review of degree–day factors for snow and ice

The degree–day factors for snow and ice reported by various investigators are given in Table 1. As such there is a broad agreement in degree–day factors for ice except for a high value of 13.8 mm °C^{-1} day^{-1} found in Spitsbergen by Schytt (1964). As expected, in all the cases, degree–day factor for snow is lower than that of ice. For the Himalayan region, Singh et al. (1995) carried out studies to estimate 6 h snow melt factor using the isolated snow blocks. Singh and Kumar (1996) determined the degree–day factor for snow through field investigations and also studied the effect of a thin dust layer on this factor. An average value of degree–day factor for clean and dusted snow was reported to be 5.9 and 6.6 mm °C^{-1} day^{-1}. Studies related to degree–day factor for clean ice or dusted ice are not available for the Himalayan basins.

No data is available on degree–day factor either on dusted snow or dusted ice. Dusting or blackening of snow or ice surface brings down its albedo. It results in higher absorption of solar radiation leading to increase in the melt rate and higher melt water yield. The increase in the melt depends on the radiation absorbing property of the dusting material. There are several materials like charcoal powder, boiler ash, wood ash and common salt etc. which are used in such studies. Application of such methods include to prolong the growing season for agriculture, to clear the mountain passes and air runways earlier than normal, removal of ice dams on rivers, and increase runoff of melt water from glaciers for irrigation purposes is also possible by this method. Singh and Kumar (1996) reported that there are only few studies available in literature wherein the effect of blackening material on the melt rate and degree–day factor has been investigated. In brief, Avsiuk (1953, 1962) indicated that by dusting the whole area of glacier at the beginning of ablation period, the annual river runoff from mountains of Soviet Central Asia could be increased by 50–55%. He also found that most efficient melting occurs when the input of coal dust was between 5–10 g/m^2. It was reported that melting in comparison with dust free surface increases 3–4 times for young firn and snow, 1.5–3 times for old firn and 30% for ice. Kotlyakov and Dolgushin (1972) used mixture of crushed coal, slag and sand to study the melting behaviour of snow and found that best results were achieved by dusting at the rates of 300–350 g/m^2 with crushed coal and slag or 400 g/m^2 with sand and coal mixture. It is to be noted that there is a marked difference in the quantity of dusting material used for maximum melting from snow by different investigators.

4. Study area and field experiments

To obtain more reliable and accurate information on degree–day factors for snow and ice, snow and ice blocks of specific dimensions were prepared from the existing snow and ice in the field. Melting from these blocks was monitored after resetting them into the snowpack. All the experiments reported in this paper were carried out at an altitude of about 4000 m on the Dokriani Glacier located in the Garhwal Himalayas. The location of study area is shown in Fig. 1. Fair weather prevailed during the experiments and no precipitation was observed on the days of experiments. The experimental set up included sawing the snow and ice blocks and monitoring of their melt runoff with dust and without dust separately. The experiment site was in the lower part of the glacier and it was few hundred metres up from the snout of glacier.

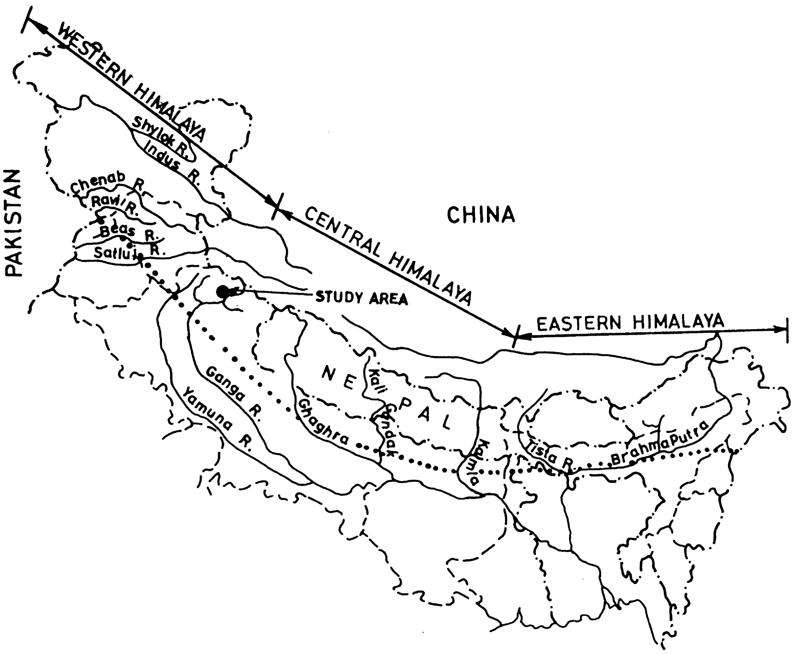


Fig. 1. Location of the study area.

4.1. Preparation of clean and dusted snow and ice blocks

In order to determine degree–day factors, snow and ice blocks were extracted from the snowpack available over the glacier and from the exposed ice body in the ablation area of the glacier. The size of the extracted blocks was slightly larger, but they were trimmed to bring them in required dimensions of $30 \times 30 \times 30\ \mathrm{cm}^3$ The natural structure of the study blocks was not disturbed in the process of extraction and shaping of the block. The densities of the snow and ice used in the study were 600 and 880 $\mathrm{kg\ m}^{-3}$, respectively. The snow was compact enough at this density and it was easy to extract a snow block of the required dimension from the snowpack. But the extraction of the ice block from the glacier ice body was difficult because of the high density and hardness of ice. The snow block and ice block were properly wrapped in the plastic sheet separately from all the sides, except upper one, and again fitted in the snowpack. The location of snow block was very close to the ice block. The upper surface level of the snow and ice blocks was kept same as that of snowpack in which these study blocks were inserted for monitoring. All the boundaries of blocks were intact with snowpack and plastic sheet around all sides ensured that melt runoff only from the snow or ice block under study was collected in the bucket. This set of blocks was treated as clean snow and ice blocks because no dust was used on the surface of these blocks. It is worth mentioning that if these blocks are not inserted into the snowpack, i.e. are monitored in open, all the five exposed surfaces of the blocks will receive the heat, whereas under natural conditions the heat is received only by the upper surface of the snow or ice body. Thus, in the fully exposed scenario, melting from the blocks would be higher than the natural melting because of the additional heat received by the other exposed surface.

To study the effect of dusting on melting behaviour of snow and ice, and therefore on degree–day factor for snow and ice, another set of snow and ice blocks was extracted and placed in the snowpack following the above described process. After setting of these blocks into snowpack, the natural dust was spread over these ice blocks to form a dust layer of about 2 mm thickness. The size and density of the snow and ice blocks used for studying the effect of dusting on snow and ice melt factors were similar to the clean snow and ice blocks, except the upper surface of these blocks which was covered by an uniform 2 mm thick layer of the natural fine dust. It is to be pointed out that instead of using any other dark material to blacken the surface, the use of natural dust available at that altitude on the glacier was preferred because this material affects the melt rate in reality. This dust consisted of mainly moraines and debris powder having mostly coarse particles. No treatment was given to dust in terms of changing the size of the particles. However, the depth of the dust varied from place to place over the glacier, but for this experiment a uniform depth of 2 mm thickness was considered simply because this depth was found at several locations.

After setting up the experiment, only upper surface of snow and ice blocks were exposed to the radiation. There was no loss of melt water in the form of infiltration or percolation from these blocks because of underneath plastic sheet. The clean and dusted snow and ice blocks were adjacent to each other so that melting from these blocks occur under same weather conditions and their melt rate can be compared.

4.2. Observation of melt runoff and temperature

To get a better representation of temperature within each hour, air temperature was observed at every 15 min interval at 2 m height above the snow surface and was used to compute the average temperature for each hour. The melt water draining out as runoff from each block was collected in separate buckets and measured at hourly time interval. To minimize the evaporation losses from the collected volume of water, the melt water was measured immediately after the collection. The time interval and period of observations for the air temperature and melt water were kept exactly the same for all types of snow and ice blocks.

4.3. Period and duration of experiments

The experiments were conducted on 29 May, 1997, and on 24 June, 25 June and 22 July, 1998. All the experiments described above were carried out for a period of 1 day. It was preferred to set up a new experiment every day in the late evening when melting was completely ceased and observations were started from 0000 to 2400 hours. Study of the same blocks for the next day was not continued because the objective of the experiment was to study the effect of uniform dust layer on degree–day factor for snow and ice and to compare the results for each day. It was noticed that if experiment was extended beyond 24 h period, a part of the dust spread over the snow surface percolates into the snow block with the melt water leaving a non-uniform dust layer over the snow block. Moreover, due to the increase in the melt rate, the dusted snow block sinks relatively faster and surface level of both blocks is changed with reference to the snowpack. Under these circumstances, dusted snow and ice blocks are not exposed to solar radiation like the clean blocks. In the case of the ice block, a part of the dust was removed from the ice surface with the melt water because of the impermeability of ice.

5. Results and discussion

5.1. Diurnal variation in the melt runoff from snow and ice blocks

Diurnal variations in runoff generated from clean and dusted snow and ice blocks for different dates are demonstrated in Fig. 2a–d. Hourly distribution of air temperature observed 2 m above the snow surface is also illustrated along with the runoff. It is observed that during all the time of experiment, air temperature was above 0°C. The rise and fall in the runoff observed from the study blocks is governed by the magnitude of temperature above these blocks. The trend of runoff distribution observed from all clean and dusted blocks indicates that it starts rising between 0900 and 1000 hours and, usually, attains its peak value at about 1200–1300 hours. After that it starts reducing and reaches to zero by about 1900–2000 hours. For both snow and ice blocks, diurnal variation in the melt runoff showed that except in the beginning of melt, almost all the time runoff from the dusted blocks was higher than the respective clean blocks. As such diurnal variation of both snow and ice melt factors followed the similar pattern. The total volume of runoff observed from ice block was higher than the snow because of higher melt rate of ice under the same weather conditions. The diurnal

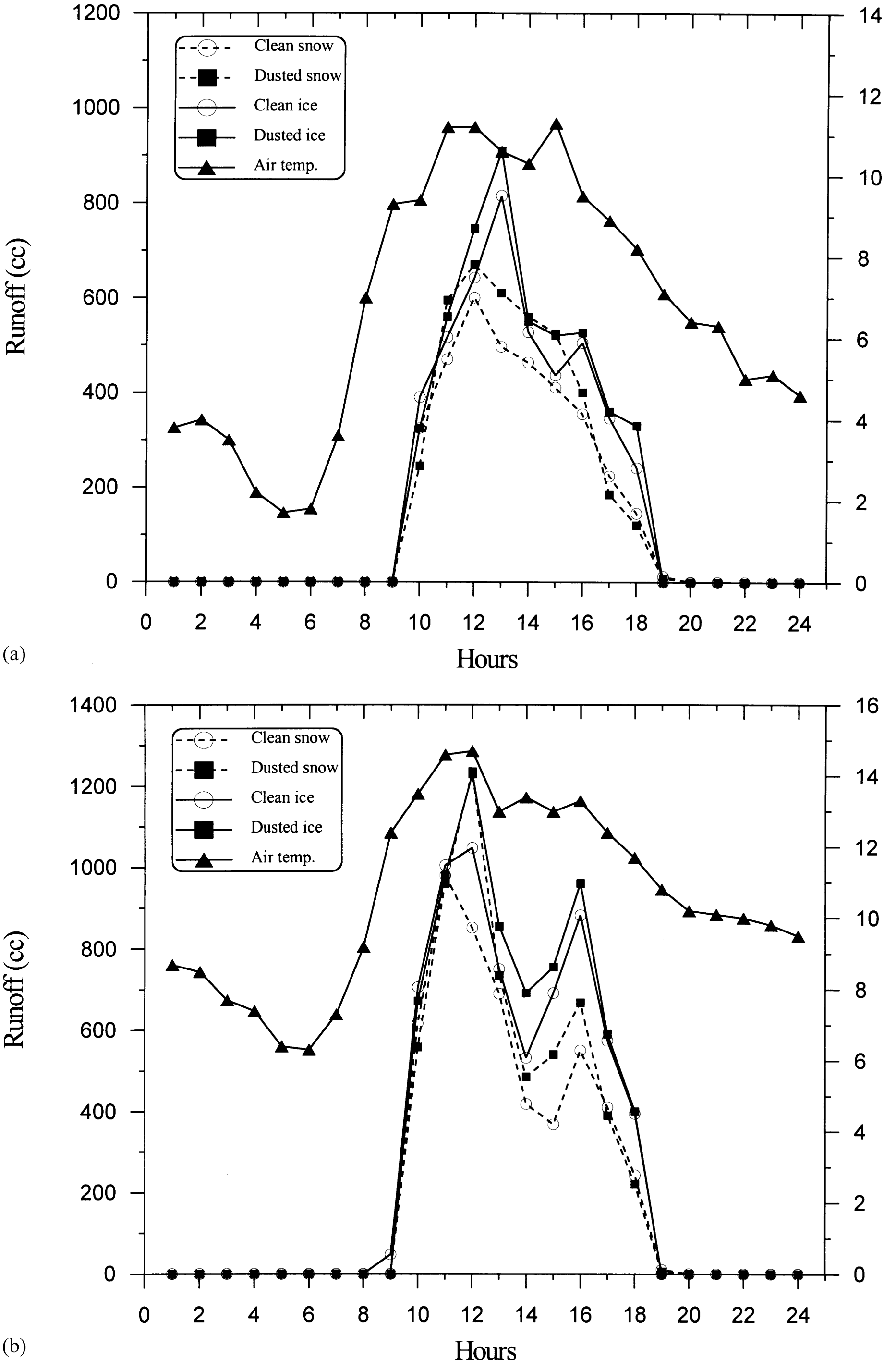
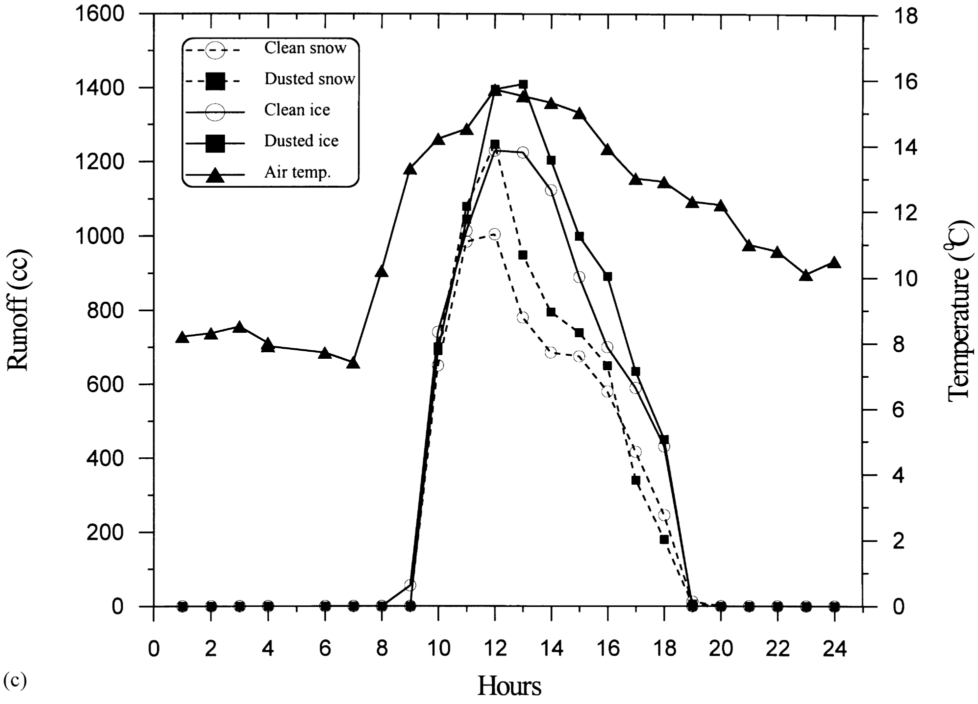
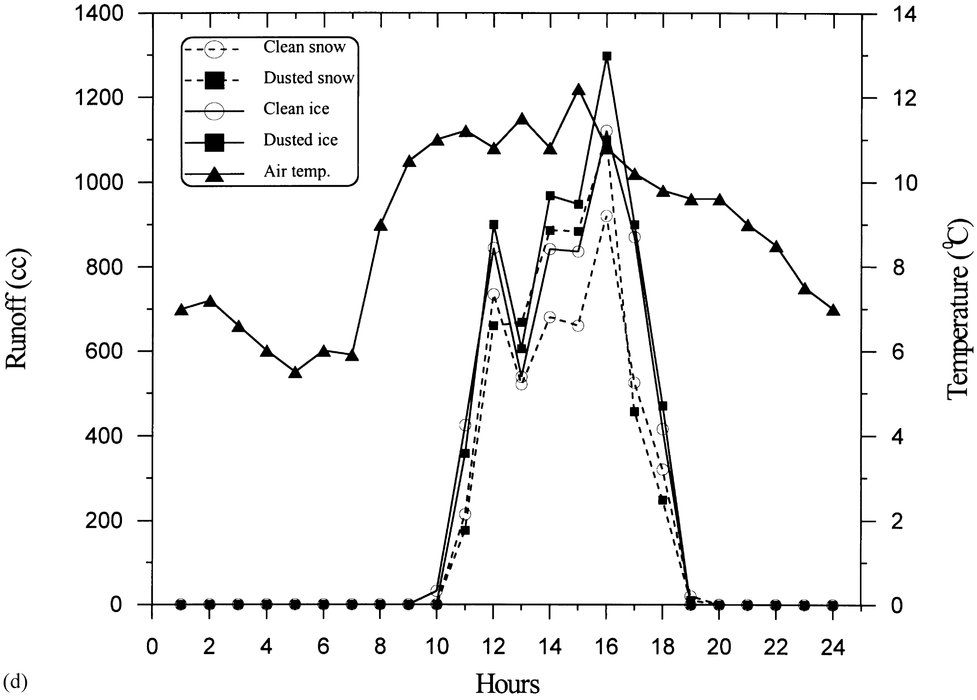


Fig. 2. (a) Melt runoff from clean and dusted snow and ice blocks blocks along with air temperature observed on 29.5.97. (b) Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 24.6.98. (c) Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 25.6.98.(d) Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 22.7.98.



(c)



(d)

Fig. 2. (*continued*)

Table 2
Degree–day factors for the clean and dusted snow and ice for different years using daily average temperature as a mean of hourly (0000–2400 hours) temperature data. Increase in degree–day factors for snow and ice due to dusting of snow and ice is also indicated

Date	Degree–day factor for snow, D_{sf} (mm °C^{-1} day^{-1})			Degree–day factor for ice, D_{if} (mm °C^{-1} day^{-1})		
	Clean snow	Dusted snow	Increase due to dusting (%)	Clean ice	Dusted ice	Increase due to dusting (%)
29.5.1997	5.8	6.4	10.3	7.3	7.9	8.2
24.6.1998	5.4	6.1	13.0	7.0	7.5	7.1
25.6.1998	5.8	6.5	12.1	7.7	8.4	9.1
22.7.1998	5.7	6.4	12.3	7.4	8.1	9.4
Average	5.7	6.4	11.9	7.4	8.0	8.5

variation in the snow and ice melt runoff for both clean and dusted snow and ice blocks can be explained on the basis of change of albedo or energy absorbed by the melting surface. Albedo varies with the angle of incidence of radiation and also depends on the features of the energy receiving surface. A higher value of albedo on the same surface is associated with larger angle of incidence. In the case of snow and ice, however, this variation may also be partially due to changes in the concentration of liquid water on the surface. For example, when melt rate is at a maximum, the higher concentration of the liquid water in the top layers of the snow and ice decreases the albedo and increases the melt rate.

Distribution of runoff indicates that the melt runoff from a clean or dusted ice block follows a sharp rise and recession as compared to the clean or dusted snow block. Runoff from the dusted blocks, whether it was snow block or ice block, was observed late than the respective clean block. The exact delay period could not be ascertained from the present investigations because discharge observation interval was one hour and delay period was also about in the same range. In fact, to determine the actual delay period on the plot scale, discharge observations at shorter time intervals are needed.

5.2. Degree–day factors

The values of degree–day factors for clean and dusted snow and ice have been calculated for different years and are given in Table 2. In order to obtain these factors, mean daily air temperature and total runoff observed during 24 h are used. Daily average temperature is computed using hourly (0000–2400 hours) temperature data, whereas the total runoff is obtained by adding the hourly runoff data. Based on the data obtained in two different years under fine weather conditions, degree–day factor for clean snow varied from 5.4 to 5.8 mm °C^{-1} day^{-1}, whereas for dusted snow it varied from 6.1 to 6.5 mm °C^{-1} day^{-1}. The average value of degree–day factor for clean and dusted snow was computed to be 5.7 and 6.4 mm °C^{-1} day^{-1}, respectively. Increase in degree–day factor for snow was computed for each day and it was found that on average this factor was increased by about 12% due to normal dusting of 2 mm uniform thickness (Table 2). It is to be pointed out that an increase in the degree–day factor for snow due to dust layer of same thickness was reported in the same range (11.4%) by Singh and Kumar (1996). In all the cases, degree–day factor for a dusted snow block was found higher than for the clean snow block.

The degree–day factor for clean ice was determined in the range from 7.0 to 7.7 mm °C^{-1} day^{-1}, whereas for dusted ice it ranged from 7.5 to 8.4 mm °C^{-1} day^{-1}. The average value of degree–day factor for clean ice is 7.4 mm °C^{-1} day^{-1}, whereas for dusted ice it was 8.0 mm °C^{-1} day^{-1}. Like the degree–day factor for dusted snow, the value of degree–day factor for dusted ice is also higher as compared to the clean ice block. On average degree–day factor for dusted ice was about 8.5% higher than for the clean ice (Table 2). However magnitude of the increase in melting depends on the type and depth of the dusting material. A comparison of degree–day factors for clean snow and clean ice indicates that on average the degree–day factor for ice was about 30% higher than that for snow. Such increase in the degree–day factor for ice is possible because of lower albedo of ice and the

Table 3
Computed degree–day factors for the clean and dusted snow and ice using daily average temperature as a mean of daily maximum and minimum temperatures

Date	Clean snow (mm °C^{-1} day^{-1})	Dusted snow (mm °C^{-1} day^{-1})	Clean ice (mm °C^{-1} day^{-1})	Dusted ice (mm °C^{-1} day^{-1})
29.5.1997	6.0	6.7	7.6	8.3
24.6.1998	5.4	6.1	7.0	7.6
25.6.1998	5.8	6.4	7.7	8.4
22.7.1998	5.8	6.4	7.4	8.1
Average	5.8	6.4	7.4	8.1

resulting higher absorption of energy which is used to melt the ice.

These results indicate that the effect of dust on degree–day factor for snow is more prominent than the degree–day factor for ice. The variation in the degree–day factor due to dust for a particular surface depends on the degree of variation in the heat absorbing and transmitting properties of surface due to dusting. For snow, a higher increase in degree–day factor is possible due to relatively large variation in albedo of snow because of the availability of dust on its surface. In the case of ice, the variation in albedo will be less because albedo of ice is already lower. Secondly, the impermeable nature of the ice surface also helps in reducing the influence of dust on the degree–day factor of ice. In the case of ice surface which is impermeable, a part of the dust available on the ice surface is removed away from the surface along with the melt water because melt water travels as overland flow over the ice surface. Whereas in the case of snow, dust particles persist for longer time on the snow surface because of its porous characteristics. The dust particles are sunk into the snow surface and more rough surface features are produced. These are known as the radiation brush and decrease the albedo of surface, which in turn increases the melt from snow.

Daily maximum and minimum temperatures are the most readily available data for the high altitude basins. Therefore, following Singh and Kumar (1996), an attempt has been made to compute degree–day factors for both clean and dusted snow and ice blocks using average temperature of the day as a mean of the daily maximum and minimum temperatures. These values were compared with the snow and ice degree–day factors derived from the average temperature of a day computed on the mean of the 24 h values of temperature data. Results are shown in Table 3. It is observed that the variation in degree–day factors was less than 2% when these factors were calculated taking average temperature of the day as the mean of the daily maximum and minimum temperatures. Thus, on the basis of this marginal change in degree–day factors for snow and ice, it can be concluded that average temperature of a day as a mean of daily maximum and minimum temperatures, can be used in the snow melt and ice melt runoff calculations when hourly data are not available. This type of situation is very common in the Himalayan basins.

The degree–day factors obtained for the clean snow and ice were compared with the earlier reported values, as given Table 1. A comparison of the degree–day factor for the clean snow and ice with the reported values of degree–day factor suggest that the values determined through the present investigations lie in the range suggested by Jóhannesson et al. (1995). The values of degree–day factors for snow and ice in the present study are slightly higher than the values reported by other investigators. Degree–day factors for dusted snow and ice could not be compared because data from other investigators was not available.

Degree–day factors are used for computing melt with temperatures extrapolated usually from the meteorological stations located at lower elevations in the vicinity of glacier to higher elevations of the glacier basin using temperature lapse rate. Meteorological parameters and their distribution in a basin are influenced by the presence of glacier in a basin. During the summer period, glaciers cool the air blowing above them. This cooling effect is most pronounced for air close to glacier surface. The difference between the temperature over the glacier surface and that over the non-glacier surface at the same altitude is called the "temperature leap (Δt)". The glacier cooling effect reduces and gradually vanishes in high elevation areas where the air temperature is below zero. The cooling effect of glaciers in the glacier-adjacent territories occurs due to winds. The degree of cooling effect can be estimated by the difference in the air temperature between a glacier and ice-free surfaces at the same altitude. The temperature measurements presented in this paper were obtained near the glacier margin where the glacier cooling effect is not expected to be large. The degree–day factors derived here should therefore be applicable in studies where the temperature records from meteorological stations on ice free land near the glacier are used. Khodakov (1975) has proposed an empirical formula to estimate the cooling effect of the glacier.

6. Conclusions

Degree–day factors for snow and ice were determined at an altitude of about 4000 m over Dokriani Glacier in the Garhwal Himalayan region. These factors were obtained through the field experiments during the summer 1997 and 1998 in which melt water runoff from a known surface area of snow and ice blocks was monitored. The influence of a natural fine dust layer of 2 mm thickness was studied on both snow and ice degree–day factors. The average degree–day factor for clean snow and dusted snow was computed to be 5.7 and 6.4 mm $°C^{-1}$ day^{-1}, respectively, whereas for the clean ice and dusted ice this factor was found 7.4 and 8.0 mm $°C^{-1}$ day^{-1}, respectively. The presence of dust on the ice increased the degree–day factor by about 9%, whereas for snow it increased by about 12%. Results indicate that the effect of dust on degree–day factor for snow was more pronounced than that for ice. It is found that degree–day factor for clean ice is 30% greater than that for clean snow. No significant change in the degree–day factors for snow and ice, with dust or without dust, was found when mean of daily maximum and minimum temperatures was used in calculations, instead of average of 24 h temperature values. It confirms that the average temperature of the day computed as mean of maximum and minimum temperatures is equally good approach for using in both the snow melt and glacier melt runoff calculations when hourly data are not available. It is suggested that such studies should be extended to study seasonal variation in the degree–day factors under different conditions in the Himalayan region.

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