Analysis of Climate and Melt-runoff in Dunagiri Glacier of Garhwal Himalaya (India)

Deepak Srivastava · Amit Kumar · Akshaya Verma · Siddharth Swaroop

Abstract The hydrology of high altitude glacierized basin in Himalaya is complex to understand due to high variability in climate and lack of hydro-meteorological data. In this study, analysis of hydrological, glacier ablation and meteorological records have been made for Dunagiri Glacier (~4,200 m) during the melt season (July - September), for the years 1985 and 1987–1989. In the daily cycle of mean diurnal discharge in summer months during 1985–1989, maximum discharge occurred at midnight, and minimum discharge occurred in the morning. Mean daytime and nighttime discharge volume was contributing approximately equal amounts. Such type of analysis will be the basis for designing/developing Run-off-the river type hydroelectric power projects which are heavily dependent on snow and glacier melt in Himalaya. Time series analysis of available hydro-meteorological records have been used to understand governing hydrological processes within the basin and to develop regression model for future development in runoff forecasting using climate data.

Keywords Himalaya · Dunagiri Glacier · Climate · Melt-runoff · Hydropower

1 Introduction

Glaciers in India are restricted to extra-peninsular region i.e. Himalaya within the latitude 27°N to 36°N and longitude 72°E to 96°E. Indian Himalayan Region contains about 9,575 glaciers and other permanent ice bodies covering an area of about 40,000 km^2, with an approximate ice volume of 2,000 km^3 (Raina and Srivastava 2008). Himalayan glaciers are important for generating hydroelectricity, irrigation, drinking water supply and daily needs of over 10 billion people.

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Morphology of a glacier's subglacial drainage system has important implications for understanding glacier dynamics. Changes in subglacial water pressure causes variation in basal motion by sliding and deformation of ice (Iverson et al. 1995; Hubbard and Nienow 1997; Hanson et al. 1998; Fischer and Clarke 2001). Dye tracer techniques (Fountain 1993; Hock and Hooke 1993; Kohler 1995; Nienow et al. 1998) including glacier velocity surveys (Mair et al. 2002) and borehole water level measurements (Fountain 1994; Hubbard et al. 1995; Gordon et al. 1998) have been used to explain seasonal evolution and diurnal variability (Schuler et al. 2004; Werder et al. 2010) of drainage system beneath a number of glaciers, suggesting that subglacial drainage system can be either channelized or distributed. Jansson et al. (2003) identified that glacier storage occurs as ice, snow, and water associated with different time-scales and can affect runoff characteristics in glacierized catchments and downstream river flow regimes.

Furthermore, hydrology based studies i.e. time series analysis of hydro-meteorological data inferred that morphology of the subglacial drainage system, (Hodgkins 2001; Qiao and Shiyin 2009) influences discharge and water chemistry in proglacial stream throughout melt season (Tranter et al. 1993; Arnold et al. 1998). Jobard and Dzikowski (2006) suggested that proglacial discharge is controlled by the geometry of glacial drainage network and by meltwater processes. A few glaciers have been studied to understand morphology of subglacial drainage in Indian Himalaya; however existing results show strong meltwater storage characteristics during ablation season (Hasnain et al. 2001; Singh et al. 2004; Singh et al. 2010). Meltwater storage in a glacier has been classified as long-term storage (ice and snow); intermediate-term storage (seasonal runoff variations); and short-term storage (diurnal storage of meltwater in snow, firn and englacial and subglacial channels). Short-term storage or diurnal storage controls the magnitude of runoff, depending on the dynamics, size, drainage network, seasonal snow cover, ablation and accumulation area of a particular glacier (Jansson et al. 2003; Singh et al. 2010).

Glacier ablation and seasonal snow are main contributors to generate melt runoff from Himalayan glaciers. In order to understand the effects of glacier ablation on melt runoff, it is important to relate ablation to climate. One of the approaches is to correlate ablation with air temperature or degree day factor. Ablation occurs with variable intensity during the ablation season (May–September) and along with multi−annual variations. Relation between ablation and climatic factors depends on the meteorological conditions above the glacier and the physical conditions of ice (Laumann and Reeh 1993; Braithwaite 1995; Johannesson et al. 1995; Hock 1998; Debele et al. 2010) which in turn has lead to many physics based energy balance models and temperature base models (Anderson 1973; Panagoulia, 1991; Sui et al. 2010; Kuchment and Gelfan 1996; Singh et al. 2008) with support of site specific meteorological observations (Singh et al. 2008; Ishikawa et al. 1992; Van de Wal et al. 1992) or synthesis from nearby meteorological stations (Oerlemans 1992, 1993).

Hydrological modeling is challenging in the Himalaya, as the measurements of meteorological variables in mountainous regions are difficult. The most important and persistent problem in hydrology is the areal representativeness of point measurements (Panagoulia 1991). It may be noted that hydrograph separation using conceptual watershed models requires large amount of input data which is necessary to run the model over a medium size snow covered basin with a number of meteorological observatories at different elevations (Panagoulia, 1991), but for small glacier catchments it is difficult to estimate the distribution of snow cover, temperature, radiation etc over the glacier with a network of observations.

Only few studies have been carried out to estimate snow and glacier contributions to annual flows at the gauging sites in large river basins of Himalaya, along with maximum and minimum snow covered area. These results show substantial contribution from snow melt

runoff to the annual stream flows of Himalayan Rivers, which attributes to high water yield from the Himalayan river basins. Estimation of the snow and glacier contribution in the annual runoff of various Himalayan rivers is necessary for the development and efficient management of water resources, which includes flood forecasting, reservoir operation, design of hydraulic structures (Jain et al. 2010).

In this paper we have tried to establish mathematical relationships between climatic variables and discharge, ablation, in order to understand the intricacies of the hydrological system of debris covered Himalayan glaciers. Development of a conceptual empirical model based on significant climatic factors which may forecast ablation and discharge reliably in near future.

2 Location of the Study Area

Dunagiri Glacier (30°33′20″N and 79°53′36″E) is a north facing glacier, situated in Chamoli district of Uttarakhand, India (Fig. 1a and b). Dunagiri Gad (river), a tributary of Dhauliganga River originates from Dunagiri Glacier. Its identification number as per the glacier inventory of Himalaya is IN 5O 132 09 *044* (Kaul 1999). It is a 5.5 km long valley glacier with an area of
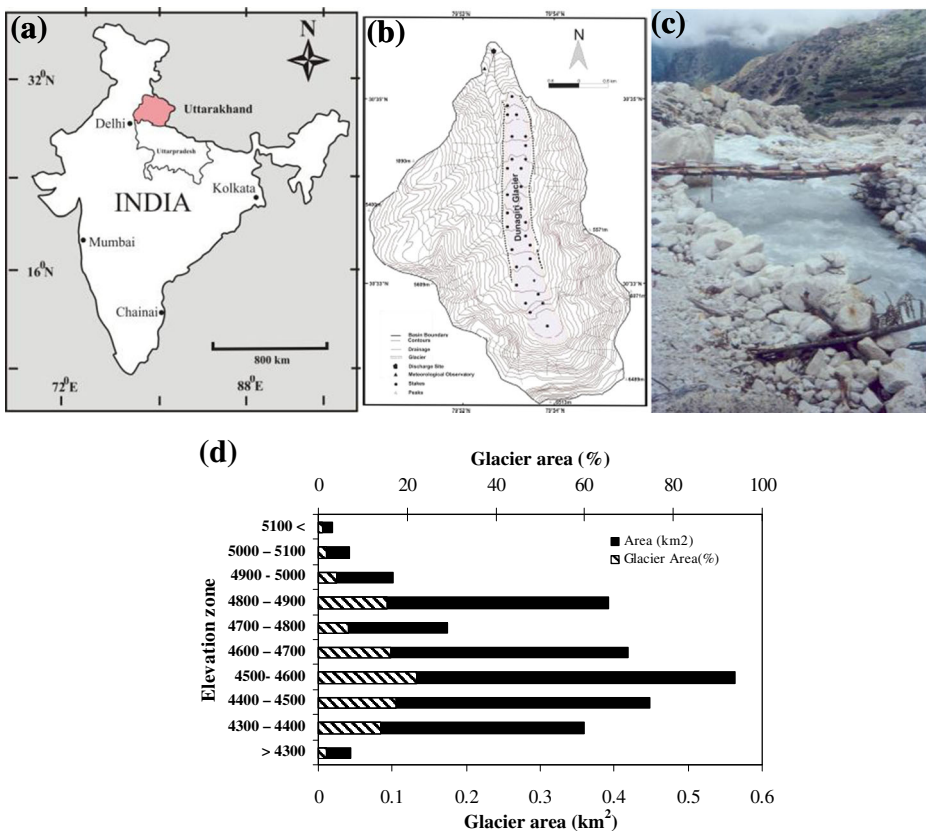

Fig. 1 (**a**) Locations of Uttarakhand and study area and view of Dunagiri Glacier basin (**b**) with networking of stakes, (**c**) upto the gauge site and (**d**) altitudinal distribution of Dunagiri Glacier area in comparison to total area of glacier in different elevation zones

about 17.9 km^2 up to the gauging site (Fig. 1c). The snout of the glacier is at 4,200 m and the head of the glacier at 5,100 m. Hypsometry of the glacier shows that maximum glacierized area (22 %) lies in between the altitude range of 4,500–4,600 m, followed by (17.5 %) in the 4,400–4,500 m (Fig. 1d) (Survey of India Toposheet).

3 Methodology

In mountainous areas the accuracy of measured meteorological variables is less than it is in flat regions. The high slopes and strong wind affect the catch of the true precipitation by the gauges, while harsh conditions cause instruments to malfunction more frequently (Panagoulia 1992), therefore it is foremost requirement to define hydro-meteorolgical processes within a basin, with the availability of continuous consistent discharge and meteorological data. Discharge and meteorological data were collected near the snout of Dunagiri Glacier during the melt season (July- September) for the years 1985 to 1989. The archived data from records of Geological Survey of India consisting of reports, proceedings and raw data have been utilized for detailed analysis. Ice ablation was estimated by measuring the change in glacier ice thickness against ablation stakes placed in holes drilled manually at different altitudes.

3.1 Collection of Glacio-Hydrological and Meteorological Data

A conventional meteorological observatory was established about 2 km downstream of the snout for recording various parameters. The thermometers were kept inside a Stevenson's screen, at a height of 2 m (Srivastava and Swaroop 1987). In order to know the variations in meteorological variables, coefficient of variability was determined. Area velocity method was adopted for measurement of discharge. A discharge monitoring site was established at a stable cross-section over the meltwater stream of Dunagiri Glacier (Fig. 1b). Manual river gauge was placed in the river to read water level and the float readings were repeated at least three times and an average value was adopted for further computations (Srivastava et al. 1988, 2014; Srivastava and Swaroop 1987, 1989; Swaroop and Gautam 1990, 1992). Furthermore, associated errors in data collection particularly during the peak melt period (July and August) are expected in the range of ±5 % as discussed by Singh et al. (2006).

In order to determine the storage characteristics and diurnal variations in discharge, round the clock water level records were taken and have been divided into daytime discharge (09:00–20:00 h) and nighttime discharge (21:00–08:00 h). Further discharge auto-correlations (ACF), cross correlations (CCF) and stepwise multiple regressions between discharge and climatic variables (temperature and rainfall) at various lag intervals have been carried out in order measure the delay in meltwater runoff and to establish mathematical relationship between discharge and temperature, rainfall, which may be useful for prediction of discharge. The lag period with maximum correlation represents the mean time for all meltwaters to pass through the glacier.

For the glacier ablation monitoring, aluminum rods were used as ablation stakes for their durability, and inability to break. Measurements were made from the snout upto the (Equilibrium line Altitude) ELA. A network of stakes was maintained in such a manner so as to represent the entire glacier surface (June to September). During the first year of observations, a total of 29 stakes were fixed on the glacier (Fig. 1c). Considering the width of the glacier, two rows of stakes were found sufficient to represent ablation. Stakes were placed at regular intervals on level surface of bare glacier ice away from the crevasses. However, this could not be strictly adhered to on account of rugged nature of glacier surface,

thick supraglacial morainic mantle and presence of supraglacial water pools (Srivastava and Swaroop 1987, 1989; Srivastava et al. 1988). The measurements of ablation were computed at stakes in reference to the height of stake emerging above the glacier ice surface over a measurement period of 15 days during the ablation seasons (1985–1989).

The ablation for each year is measured in reference to the previous year's summer surface, at the end of the ablation season i.e. 30th September (Østrem G and Brugman 1991). Ablation was converted to water equivalent by taking into account the density of ice to be 0.85 gm/cm^3 as determined by the field measurements (Srivastava and Swaroop 1996).

4 Results and Discussion

4.1 Meteorological Analysis

Meteorological observations are important for hydrological studies as they are the basis with which different hydrological models can be developed. There are very few observatories at high altitudes region of Himalaya (Basistha et al. 2008). The role of complex topography in mountains basin makes the spatial distribution of precipitation and temperature different than the plain areas (Arora et al. 2008). Thus it is essential to generate good, reliable meteorological data. Average daily maximum and minimum temperatures over the ablation season were 15.9 °C and 2.5 °C with an average mean temperature of 9 °C. Diurnal variations in temperature indicate that, generally, maximum temperature is observed between 11:30 h to 14:30 h, while minimum is observed in the early morning hours 06:00 h to 07:00 h.

Monthly variations in temperature over the ablation season is also important and mean monthly maximum temperatures for July to September were 12.1, 13.4 and 11.6 °C respectively, whereas mean monthly minimum temperatures for these months were 7.7, 7.1 and 3.9 °C respectively. Subsequent mean monthly temperatures for these months were 9.9, 10.2 and 7.8 °C respectively (Fig. 4b). Daily values of relative humidity ranged between 26 and 100 %. Mean monthly relative humidity was 89, 87 and 76 % from July to September respectively (Fig. 4d).

Monthly total rainfall for Dunagiri Glacier is shown in Fig. 2a. It is observed that out of the total rainfall in the basin, on an average 71 % of the rainfall occurred during night time. In high altitude regions wind plays an important role in transport of moisture, formation of clouds and occurrence of precipitation as well as melting of glaciers. The daily mean wind speeds for July to September were 4.6, 4.3 and 6.0 km/h, respectively (Fig. 2c) and the average wind speed for the whole season was 5 km/h. Respective maximum, minimum and mean monthly values of meteorological data for each year and months are given in Table 1 (a) and (b). Statistical characteristics of meteorological data provide direct information about their distributions and variability. Figure 2e presents the plot of variability reflected by coefficient of variations during five different ablation seasons (1985–1989) (Table 1 (c)).

4.2 Hydrological Analysis

Discharge estimation at a river site is fundamental for water resource management. However, streamflow gauges and historical records are not always available at remote sites of glacierized basins. Thus, information about the distribution of streamflow from glacierized basin during summer season is not very well understood. To understand characteristics of streamflow, total water yield and distribution of melt runoff with time from a glacierized basin is of practical importance and necessary for water resource managers. Records of daily discharge suggest that, total streamflow recorded during the ablation period (July to September) for 1985, 1987–1989
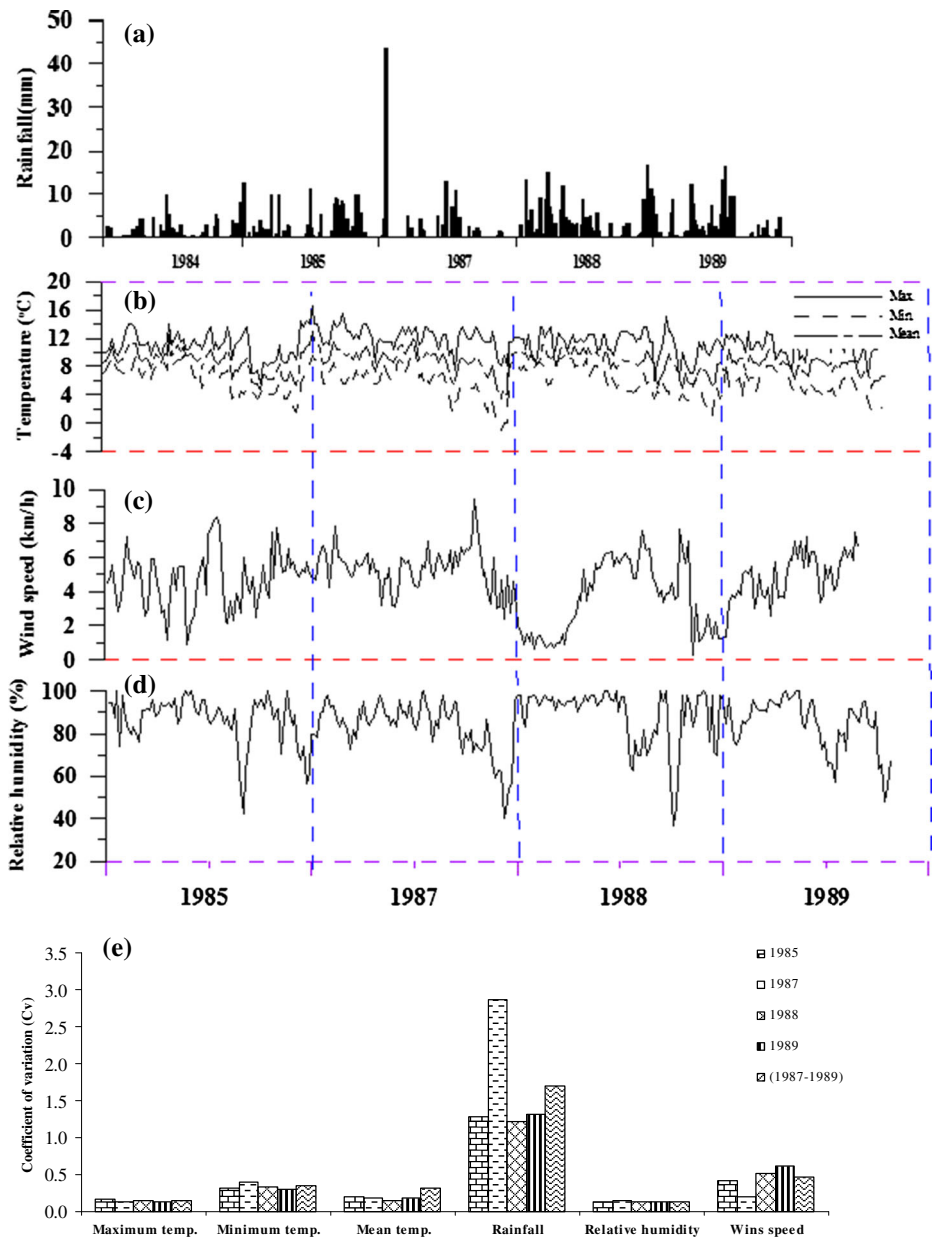
Fig. 2 Daily variations of (**a**) rainfall, (**b**) air temperature, (**c**) wind speed, (**d**) relative humidity and (**e**) variability in meteorological variables reflected by coefficient of variation over Dunagiri Glacier

were 13.0, 16.6, 18.3 and 13.6 million cubic metres (MCM) respectively. Monthly distribution of runoff volume indicates maximum runoff in August (43 %) followed by July (30 %) and September (27 %) during the study period.

Table 1 (a) Mean monthly values of hydro-meteorological data, (b) rainfall, discharge, (c) coefficient of variation observed during 1985–1989 and (d) computed monthly discharge ratio (daytime to nighttime discharge) in comparison with other glaciers in Himalaya during the ablation season

(a)	Temperature (°C)			Relative humidity (%)			Wind speed (km/h)		
	July	Aug.	Sep.	July	Aug.	Sep.	July	Aug.	Sep.
1985									
Max.	14.0	14.0	13.5	100.0	100.0	100.0	7.2	5.9	8.4
Min.	7.0	5.0	1.5	74.0	76.0	42.5	2.9	0.9	2,1
Mean	9.5	9.5	7.1	87.3	91.7	83.0	4.9	3.9	4.7
1987									
Max.	16.5	15.5	13.5	98.0	100.0	98.0	7.7	7.9	9.4
Min.	5.5	5.5	−1.0	56.0	73.0	41.0	4.7	3.1	4.3
Mean	10.4	9.7	7.7	84.0	89.0	75.0	5.5	5.4	5.9
1988									
Max.	13.5	13.5	15.0	98.0	100.0	100.0	6.0	6.3	7.7
Min.	6.5	4.5	1.0	83.0	63.0	37.0	0.9	0.7	0.3
Mean	9.8	9.4	7.4	95.1	91.7	83.1	3.4	2.7	5.1
1989									
Max.	−	13.0	13.5	−	100.0	96.0	−	5.7	7.5
Min.	−	3.5	1.5	−	74.5	48.3	−	1.1	3.4
Mean	−	8.6	7.6	−	90.9	78.4	−	3.2	5.6

(b)	Discharge (Q_i) m³/s			Rainfall (mm)		
	July	Aug.	Sep.	July	Aug.	Sep.
1985						
Max	4.0	3.4	3.5	12.6	11.2	9.7
Min	1.7	1.6	0.7	34.9	58.2	92.4
Mean	2.4	2.1	1.2			
1987						
Max	6.6	4.6	3.6	43.5	13.2	2.6
Min	2.5	1.4	0.8	48.4	68.0	10.7
Mean	4.0	2.8	1.5			
1988						
Max	3.9	3.5	2.1	14.7	11.8	16.6
Min	2.7	1.9	1.5	72.1	93.7	74.4
Mean	3.3	2.6	1.8			
1989						
Max	−	2.2	2.0	−	16.3	9.5
Min	−	1.8	1.5	−	120.5	36.9
Mean	−	2.0	1.8			

(c)	Tx	Tn	Tm	Q_i	Rn	RH	WS
Coefficient of variation (Cv)							
1985	0.17	0.32	0.20	0.44	1.29	0.13	0.41
1987	0.14	0.40	0.18	0.54	2.87	0.15	0.20
1988	0.16	0.34	0.15	0.28	1.21	0.13	0.51
1989	0.14	0.29	0.18	0.07	1.32	0.13	0.62
(1987–1989)	0.15	0.35	0.32	0.40	1.70	0.14	0.47

Table 1 (continued)

(d) Dunagiri Glacier (1985–1989)					
Months	1985	1987	1988	1989	Mean
July	0.48	0.88	0.96	1.00	0.83
August	0.45	0.93	0.91	1.03	0.83
September	0.50	0.94	0.98	1.05	0.87
Gangotri Glacier (2000–2003)					
	2000	2001	2002	2003	Mean
July	1.03	1.06	1.08	1.02	1.05
August	1.02	1.03	1.01	1.01	1.02
September	1.00	0.99	0.98	0.98	0.99
Dokriani Glacier (1996–1998)					
	–	1996	1997	1998	Mean
July	–	0.91	0.90	0.90	0.90
August	–	0.88	0.85	0.79	0.84
September	–	–	0.86	0.83	0.85

[*Tx* Maximum temperature (°C); *Tn* Minimum temperature (°C); *Tm* Mean temperature (°C); Q_i daily discharge (m³/s); *Rn* Rainfall (mm); *RH* Relative humidity (%); *WS* Wind speed (km/h); *Cv* Coefficient of variation]

Average monthly discharge was found to be 2.3, 1.9, 2.4 and 2.7 m³/s for the years 1985, 1987–1989. Respective dates of peak discharge were found in July for the ablation periods of 1987 and 1988, while August was the peak discharge month for the year 1989. Daily and monthly distribution of discharge volumes from Dunagiri Glacier are shown in Fig. 3a-c.

4.2.1 Melt-runoff Delay and Variations in Diurnal Discharge

Hydrological response and melt delaying characteristics of Dunagiri Glacier during the melt season (July to September) shows occurrence of maximum streamflow at night with peak discharge on any particular day being reflected between 22:00 and 02:00 h and minimum discharge during 10:00–14:00 h, which clearly suggests that a major part of the melt water produced during daytime, reaches the snout few hours later. Daily mean daytime and nighttime discharge for different months are shown in Fig. 4a, whereas monthly discharge for the respective periods is presented in Fig. 4b.

Mean monthly distribution of day and night streamflow shows that nighttime discharge is almost same as the daytime discharge throughout the melt season except for the year 1985, where daytime discharge is approximately half of the nighttime discharge. The ratios of daytime discharge to the nighttime discharge with comparison to other glaciers in Garhwal Himalaya are given in Table 1 (d). To understand the relationships between the variation in runoff and delaying characteristics of the glacierized basin, changes in the monthly discharge ratio, i.e. Q_{max}/Q_{min} were calculated over the study period. This meltwater discharge ratio for Dunagiri Glacier varied between 0.45–0.50 (1985) and 0.88–1.05 (1987–1989), indicating a large variation in the runoff during July to September.

Overall impact of rainfall during the period does not disturb the diurnal discharge, as shown in Fig. 5a. Though most of the rainfall occurs in the night time yet it does not cause
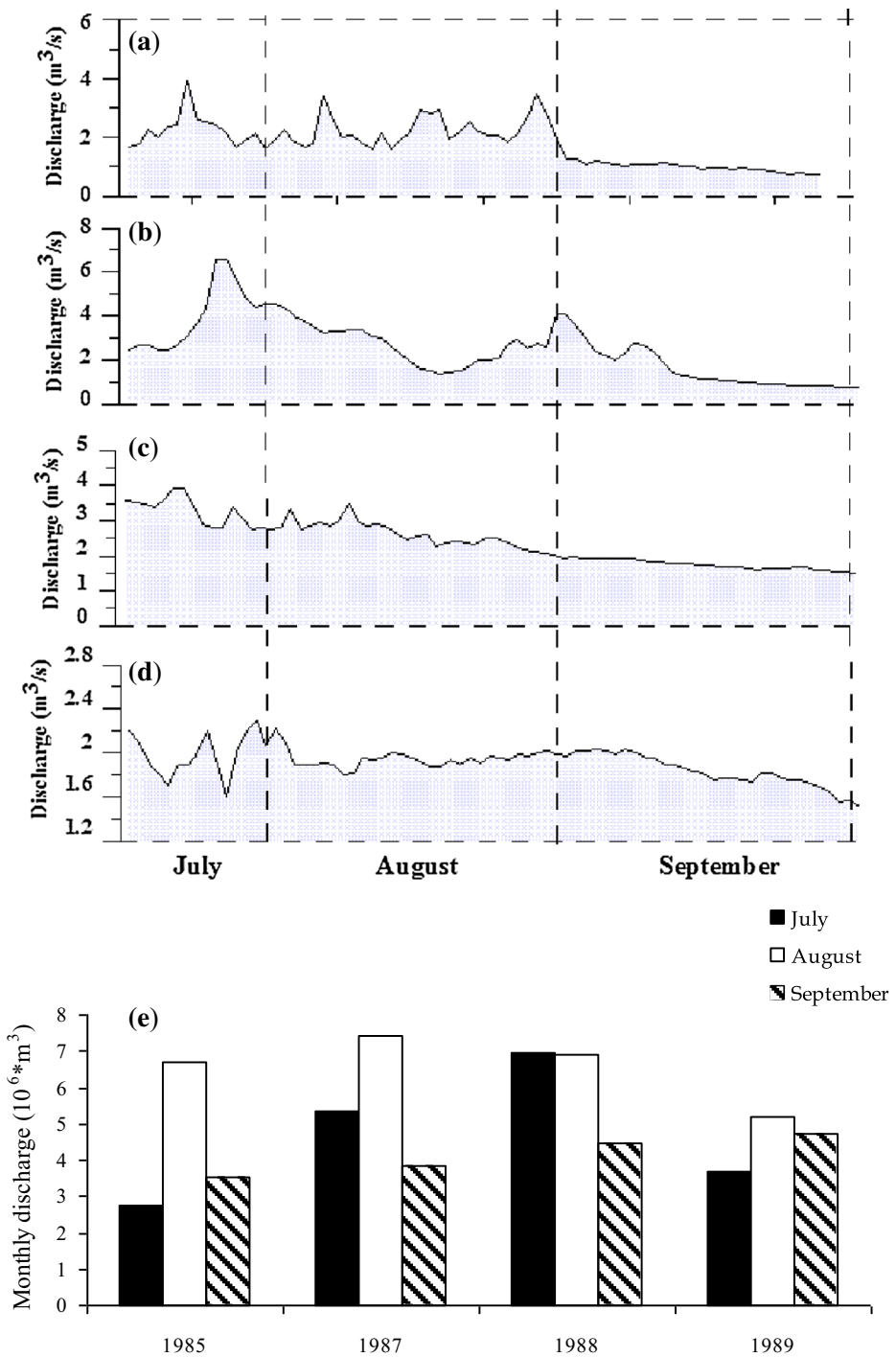
Fig. 3 Distribution of daily discharge (a) 1985, (b) 1987, (c) 1988, (d) 1989 and (e) monthly distribution of discharge volume draining from Dunagiri Glacier
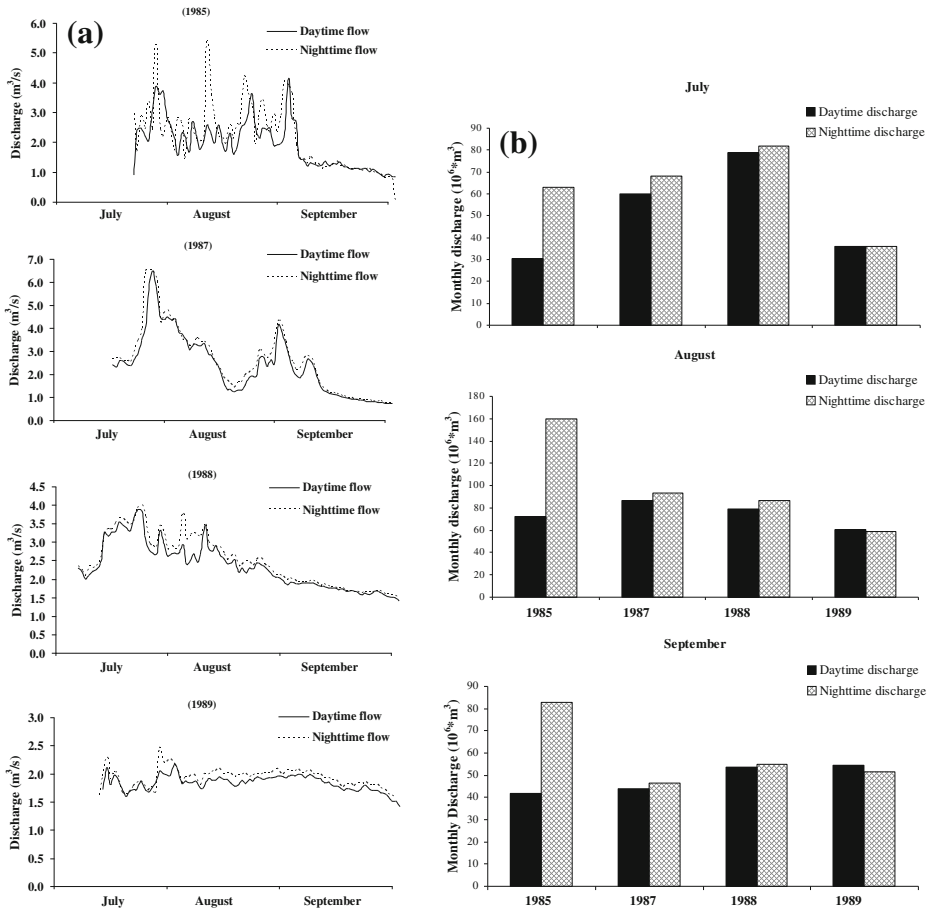
Fig. 4 (a) Day-time and night-time mean discharges (b) monthly day-time and night-time discharge volume observed in the year 1985, 1987 to 1989 near the snout of Dunagiri Glacier

any significant variation in the hydrograph as monthly rainfall is very less as compared to monthly discharge.

Diurnal discharge fluctuations in snow fed streams of Himalaya provide a useful technique for measuring lag time for meltwater to travel from the melting snowpack, where snowmelt typically peaks in the afternoon, to the river gauge, where the daily maximum discharge may arrive a few hours later (Jessica and Dettinger 2005). These melt water holding characteristics of snowpack/glaciers are responsible for delaying the delivery of meltwater generated over the glacier surface to the gauging site. The mean daily discharge on diurnal scale for different months is shown in Fig. 5b. It is observed that the hydrograph starts rising from ablation season, reaches its maximum in July end or early August and then starts reducing. Hydrographs are almost flat during the early and later parts of melt season. In the beginning of melt season, distinct diurnal fluctuation in discharge from glacierized basin may be because of large extent of seasonal snow over the glacier. Under such conditions, runoff can have much delayed response because melt water passes through the snowpack.
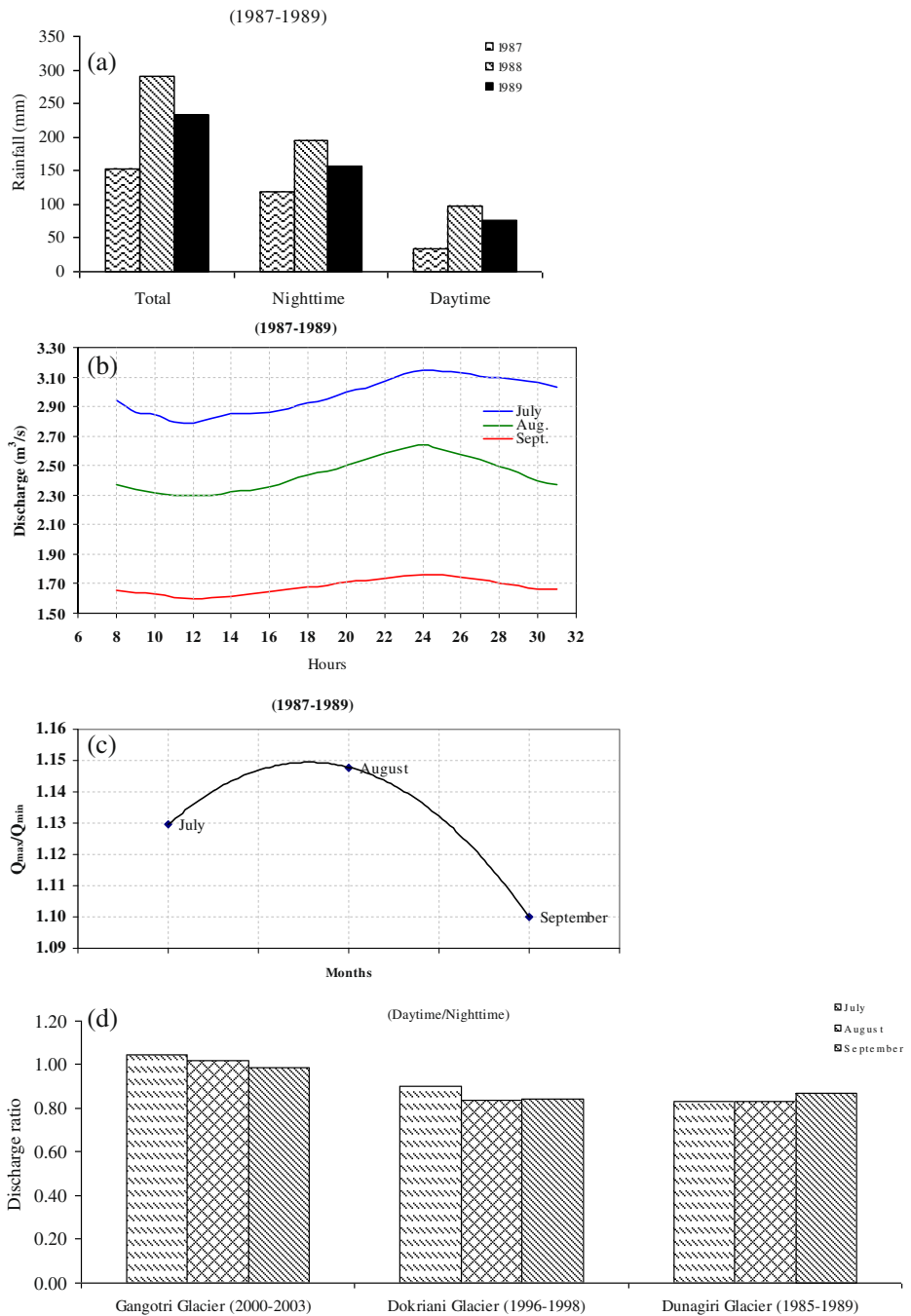
Fig. 5 (a) Distribution of rainfall during nighttime along with (b) variations in mean daily discharge (c) daytime and nighttime discharge ratio during the ablation period for Dunagiri Glacier (1987 – 1989) and (d) its comparison with other glaciers of Garhwal Himalaya (Singh et al. 2004; Singh et al. 2010)

Flatness of the hydrograph represents no significant changes in later part of the season, because lower temperatures reduce the melting in this period. During, July and August intense melting takes place due to availability of higher radiation and greater extent of exposed glacier ice. These results in rapid response of melt runoff producing well distinguished diurnal changes in discharge and drainage system becomes more responsive to diurnal scale.

Hourly discharge pattern shows that maximum discharge was observed during late night (22:00 to 02:00 h) and minimum discharge in the morning (10:00 to 14:00 h). In order to investigate the inter relationship between the variation in runoff and delaying characteristics of the glacierised basin, changes in the discharge ratio, i.e. Q_{max}/Q_{min} were computed over the melt period (Fig. 5c). In Garhwal Himalaya, results are consistent with comparison to glaciers like Gangotri and Dokriani, having different size and different basin area. Due to this the total melt water produced in a day does not drain out as runoff from the snout on the same day. Therefore, short-term melt water delay characteristics result in diurnal variation of discharge from the glacier. Variations in delay characteristics of Gangotri, Dokriani glaciers and the present study of Dunagiri glacier may be attributed to the variation in size, aspect, snow cover and drainage system of these glaciers (Fig. 5d).

4.3 Relationships Between Glacier Discharge and Climate

Discharge ACF for different melt seasons as well as for the combined series of four seasons (1985–1989) is shown in Fig. 6a. A comparison of discharge auto-correlations for different years indicates that discharge auto-correlations are very high for all the years. The sharing of discharge auto-correlation with time-lag for different years shows a drop in autocorrelation with increase in time-lag (Q_{i-1}, Q_{i-2}, $Q_{i-2....}$ Q_{i-n}). It is found that discharge auto-correlation varied from 0.79 to 0.90 for the time-lag of 0–3 days. A high discharge auto-correlation indicates the dominance of storage reservoir in response of runoff from the glacierized basin. The results show that discharge for a particular day is extremely reliant on the previous day's discharge. In the present study Dunagiri Glacier basin has provided higher discharge auto-correlations. Thus, for predicting future scenario discharge from glacierized basins for a particular day, the previous day's discharge becomes a considerable predictor (Singh et al. 1995, 2000, 2010).

The established CCF between discharge and air temperatures with time-lags (T_i, T_{i-1}, T_{i-2}, and $T_{i-3....}T_{n-1}$) have been considered, the plots of discharge-temperature correlation for each ablation season and combined data series are given in Fig. 6b. The analysis shows that discharge is less correlated with temperature for each ablation season. The value of discharge-temperature correlation varied from 0.10 to 0.50 for a time-lag of 0–3 days. The highest correlation between discharge and temperature was obtained with temperature of 0-day time-lag. Weigang et al. (2010), established high correlation ($R^2=0.79$) of discharge and mean temperature for selected clear days between discharge and air temperature at Rongbuk Glacier. Analysis between discharge and temperature were carried out for selected clear days at Dunagiri Glacier with R^2 value of 0.51. Similarly results suggest that discharge is exponentially correlated to ablation with an R^2 value of 0.75, i.e. discharge increases exponentially as the ablation increases (Table 2 (a)).

CCF between discharge and rainfall with time-lags of 0–3 days (R_i, R_{i-1}, R_{i-2}, R_{i-3}) for different ablation seasons were developed. The values of discharge and rain correlations for each ablation season and combined data series are given in plots and presented in Fig. 6c. For the study basin correlation between discharge and rainfall are found poor and highly
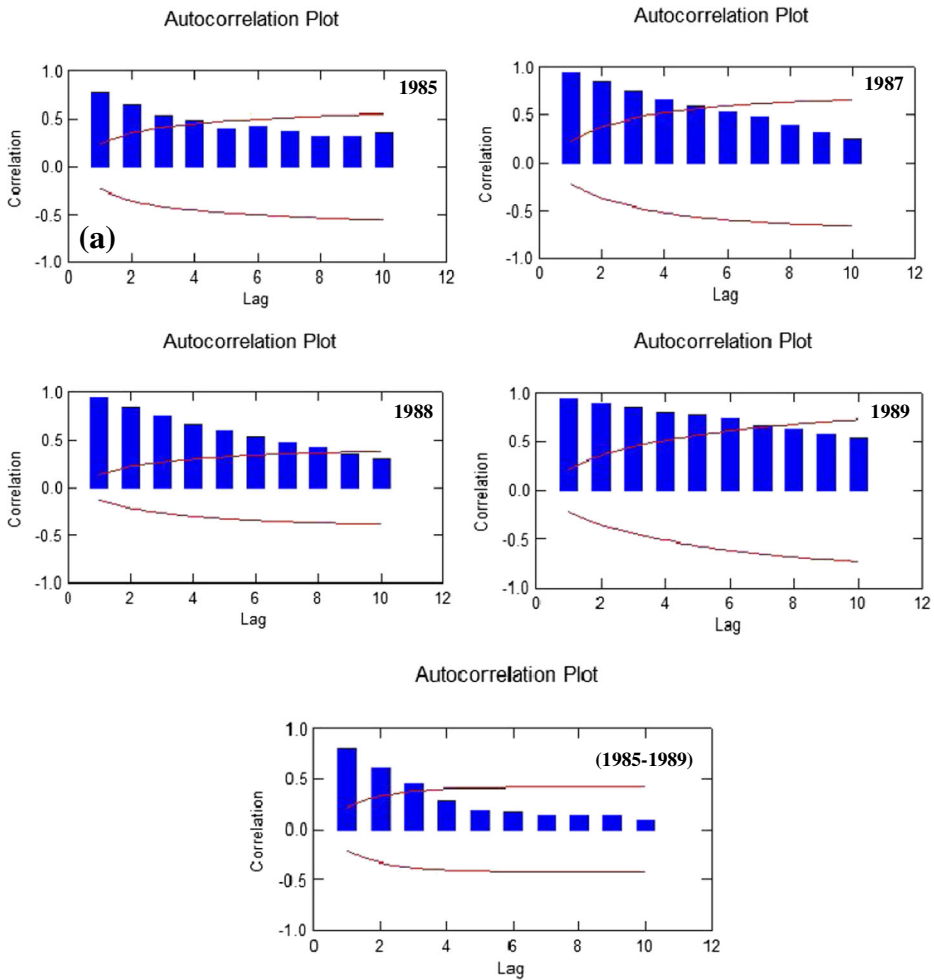
Fig. 6 (a) Autocorrelation (*ACF*) plots of daily discharge (*Q*), (b) Cross-correlation (*CCF*) plots of daily discharge (*Q*) vs. mean temperature (*Tm*) and (c) Cross-correlation (*CCF*) plots of discharge (*Q*) vs. rainfall during the year 1985, 1987, 1988, 1989 and 1987–1989 observed at Dunagiri Glacier

variable for all years. No consistent change in correlation between discharge and rainfall was found with increase in time-lag.

Daily series of observed discharge, temperature and rainfall are used as important variables to represent discharge from the study basin. To understand relationships between discharge and climate, multiple regression equations were developed separately for each melting season (1985–1989) and for the combined series of four melt seasons. Stepwise regression technique has been used to identify important variables that control runoff during melting season. Regression equations were developed considering possible climatic factors, which may significantly influence the runoff.

Multiple regression equations obtained through stepwise regression and corresponding values of correlation for each year and for combined series of all four seasons are given in Table 2 (b). It can be noted that some variables were dropped in the regression equations due to
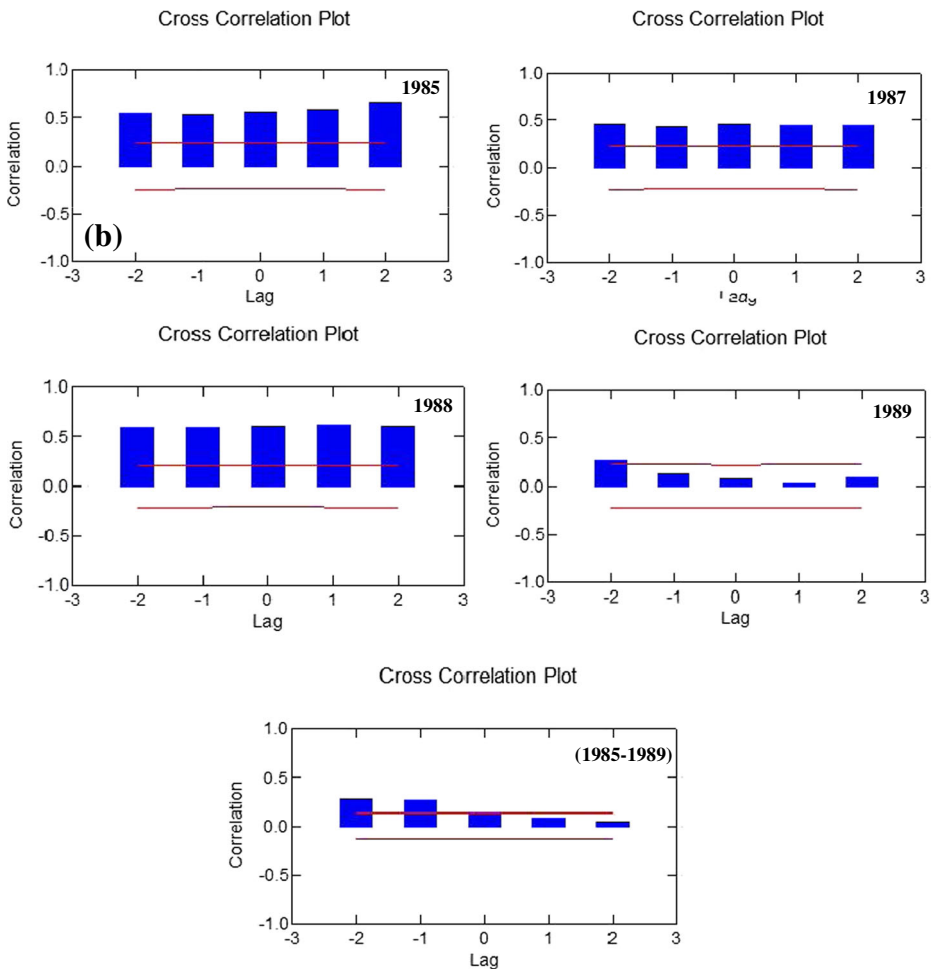
Fig. 6 (continued)

their statistical insignificance determined by stepwise regression model. A high value of R^2 varied between 0.68 and 0.91 for all the four ablation seasons, showing that discharge is well represented by these equations. For the combined series also a very high value of R^2 (0.89) was obtained. The multiple regression models developed will be used to simulate daily streamflow for independent years in future and can be compared with other published records. (Table 2 (c)).

4.4 Glacier Ablation

The process of ablation is an important and preliminary stair to estimate mass balance of any glacier, the magnitude of glacier ablation varies at seasonal scale because of climatic factors. To understand climate dynamics that control ablation under varying thickness of debris is of great interest in Himalayan region. In order to understand the factors affecting the ablation process, correlations and multivariate regression analysis between fortnightly ablation with
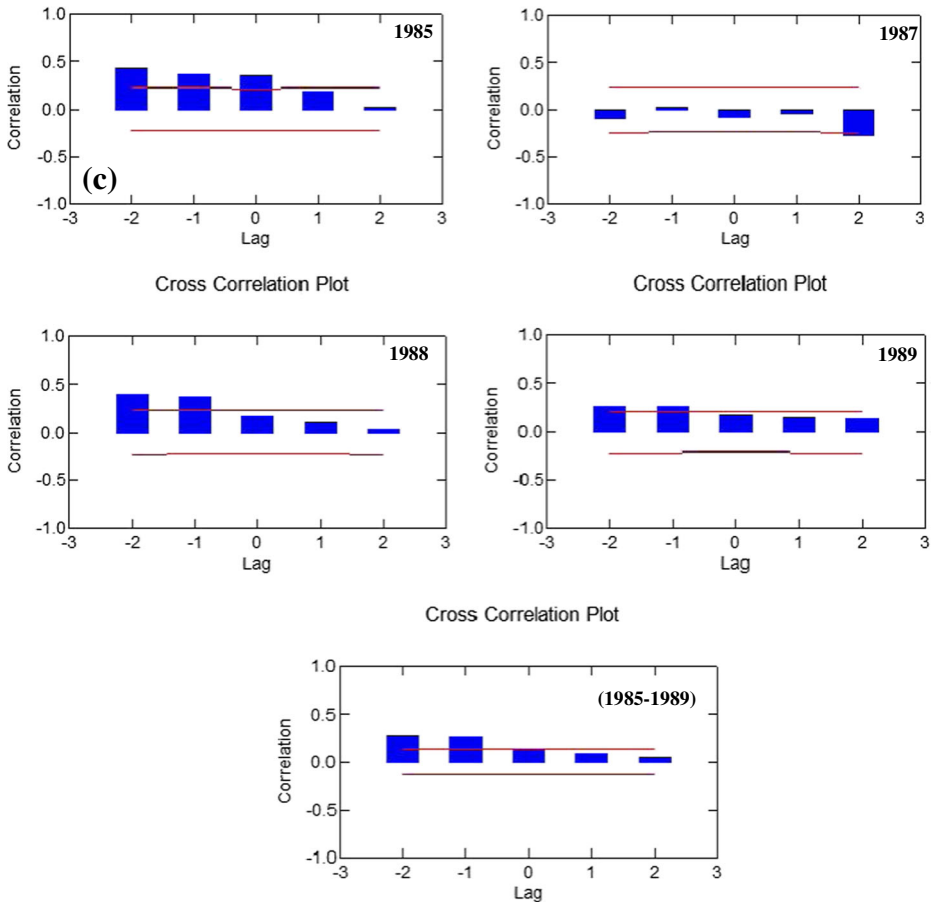
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fortnightly maximum, minimum, mean temperatures; precipitation; relative humidity and wind speed have been carried out.

4.4.1 Fortnightly Ablation

The annual net ablation for the period of 1986–1989 was 2.92, 3.41, 2.89 and 3.04×10^6 m^3 of w.e. respectively, with an average net ablation of 3.07×10^6 m^3 of w.e. (Table 3 (a)). The fortnightly glacier ablation during the summer period in each of the observation year has been computed. The observations were taken for all five fortnight commencing 16th July to 30th September. The average ablation in each of the five successive fortnights commencing 16th July to 30th September for the observation years, has been computed to be 0.91, 0.76, 0.63, 0.50 and 0.27×10^6 m^3 of w.e., respectively (Table 3 (b)). The values with respect to the base value of second fortnight of July, declined by 16.50 %, 30.80 %, 45.10 % and 70.30 %, in each of the four successive fortnights, respectively. Evidently the average ablation registered a sharp decline during the first fortnight of September.

During the observation years, fortnightly ablation in the second fortnight of July, varied from 0.68 to 1.19×10^6 m^3 w.e. In each of the two successive fortnights of

Table 2 (a) Multivariate Regression equations developed in Himalayan Glacier basin using discharge (Q_i) in vs. mean temperature (Tm) and discharge (Q_{15}) vs. ablation (Ab_{15}) (b) regression equations developed for Dunagiri Glacier basin, Garhwal Himalaya and (c) its comparison with other studies in Himalaya

(a) Location		Equation (clear days)	R^2	Reference
Dunagiri Glacier		$Q_i=0.273*e^{(1.81*Tm)}$	0.51	Present Study
Dunagiri Glacier		$Q_{15}=0.06*e^{(1.81*Ab15)}$	0.75	Present Study
Rongbuk Glacier		$Q_i=0.19472*e^{0.26037*(4.7986 + Tm)}$	0.79	Weigang et al. 2010
(b) Years		Equation	R^2	
1985 16th July- 30th September		$Q_i=0.681+0.774*Q_{i-1}-0.065*R_{i-2}$	0.68	
1987 16th July- 30th September		$Q_i=0.187+0.946*Q_{i-1}-0.016*R_{i-2}$	0.90	
1988 16th July- 30th September		$Q_i=0.146+0.967*Q_{i-1}-0.065*R_i$	0.91	
1989 16th July- 30th September		$Q_i=0.332+0.832*Q_{i-1}-0.065*R_{i-2}$	0.70	
(1985–1989) 16th July- 30th September		$Q_i=0.172+1.144*Q_{i-1}-0.188*$ $Q_{i-2} -0.025 *R_i$	0.89	
(c) Basin	Location	Equation	R^2	Reference
Dunagiri Glacier	Garhwal Himalaya	$Q_i=0.172+1.144*Q_{i-1}-0.188*$ $Q_{i-2}-0.025*R_i$	0.89	Present study
Dokriani Glacier	Garhwal Himalaya	$Q_i=-0.671+0.901*Q_{i-1}+0.125*$ $T_i+0.016*R_i$	0.96	(Singh et al. 2000)
Gangotri Glacier	Garhwal Himalaya	$Q_i=7.649+ 0.995*Q_{i-1}+(1.450*T_i) *$ $(1.523T_{i-1}) * (0.701*T_{i-2})+0.22*R_i$	0.94	(Singh et al. 2010)

[Q_i daily mean discharge (m^3/s); Tm daily mean temperature (°C); Q_{15} fortnightly discharge (10^6 m^3 w.e.); Ab_{15} fortnightly ablation (10^6 m^3 w.e); Q_{i-1} = discharge lagged by 1 day (m^3/s); R_i daily rainfall (mm); R_{i-2} rainfall lagged by 2 days (mm), T_i daily mean temperature (°C); T_{i-1} = temperature lagged by 1 day (°C); T_{i-2} temperature lagged by 2 days (°C)]

August, the ablation recorded a variation from 0.72 to 0.79×10^6 m^3 of w.e. and from 0.46 to 0.84×10^6 m^3 of w.e. respectively. The ablation declined further in the following fortnights of September and varied from 0.38 to 0.57×10^6 m^3 of w.e. and 0.10 to 0.37×10^6 m^3 of w.e. respectively.

During the observation period, maximum ablation occurred during the two fortnights constituting the second fortnight of July and first fortnight of august during 1986 while during the same year; minimum ablation was recorded for the two fortnights constituting the second fortnight of August and first fortnight of September.

Average fortnightly ablation computed for each observation year, varied from 0.46 to 1.19×10^6 m^3 of w.e. Average ablation per fortnight for the entire observation period has been computed to be 0.61×10^6 m^3 w.e. (Table 3 (a)).

4.4.2 Relationship Between Glacier Ablation and Meteorological Variables

The correlations between fortnightly ablation and fortnightly climatic variables indicate that mean temperature, minimum temperature and relative humidity are the major factors affecting the ablation process. Results suggest that ablation correlated to mean temperature exponentially with an R^2 value of 0.79, i.e. ablation increases exponentially as the mean temperature increases. Similarly, maximum and minimum temperatures relay exponential relationship with R^2 values of 0.51 and 0.71 respectively. To identify the role of relative humidity and precipitation on ablation, scatter plots were made and precipitation gave a lower R^2 value of about 0.38 as compared to 0.60 for relative humidity (Table 3 (b)). The ablation and

Table 3 (a) Computed fortnightly ablation and net ablation (10^6m^{3}w.e.) during the ablation season from 1986 to 1989, (b) correlations between fortnightly ablation, with meteorological variables and (c) correlation matrix and (d) its interrelationship with temperature and comparision with other glaciers around the world

(a) Periods	Years				
	1986	1987	1988	1989	Mean Ablation
16th–31st July	1.19	0.89	0.68	0.87	0.91
1st–16th August	0.79	0.77	0.72	0.74	0.76
17th–31st August	0.46	0.84	0.63	0.59	0.63
1st–15th September	0.38	0.54	0.57	0.51	0.50
16th–30th September	0.1	0.37	0.29	0.33	0.27
Net Ablation					
(July – September)	2.92	3.41	2.89	3.04	3.07

(b) Equation	R^2
$Ab_{15}=0.03*e^{0.34*Tm}$	0.79
$Ab_{15}=0.01*e^{0.028*Tx}$	0.53
$Ab_{15}=0.29*e^{0.20*Tn}$	0.71
$Ab_{15}=0.006*Rn+0.39$	0.40
$Ab_{15}=0.012*e^{0.05*RH}$	0.60

(c)	Ab_{15}	T_m	T_n	T_x	RH	CC	WS	RFD	Rn
Ab_{15}	1.00								
T_m	0.81	1.00							
T_n	0.79	0.87	1.00						
T_x	0.75	0.65	0.49	1.00					
RH	0.73	0.68	0.84	0.33	1.00				
CC	0.47	0.40	0.58	−0.14	0.70	1.00			
WS	−0.39	−0.22	−0.29	−0.05	−0.40	−0.66	1.00		
RFD	−0.45	−0.27	−0.52	0.04	−0.72	−0.89	0.80	1.00	
Rn	0.62	0.44	0.59	0.22	0.72	0.80	−0.64	−0.81	1.00

(d) Glacier	Geographic location	Equation	R^2	References
Dunagiri Glacier	Garhwal Himalaya, India	$Ab_{15}=0.031*e^{0.344*Tm}$	0.79	Present Study
Dokriani Glacier	Garhwal Himalaya, India	$Ab_m=0.37*e^{0.21*Tm}$	0.89	Dobhal et al. 2007
Dokriani Glacier	Garhwal Himalaya, India	$G_m=0.49*T_{ga} – 0.24$	0.89	Singh et al. 1995
North Cascade glaciers	Rocky Mountains, USA	$Ab=3.75*T_m+7.62$	0.69	Pelto 2004
Tasman Glacier (Lower)	New Zealand	$Ab=6.03*e^{0.191*Tm}$	0.88	Kirkbirde 1995
Tasman Glacier (Upper)	New Zealand	$Ab=3.035*e^{0.216*Tm}$	0.71	Kirkbirde 1995
Hans Glacier	High Arctic, Norway	$Ab_5=0.764*\sum T_{x5} – 1.296$	0.70	Migała et al. 2006

[Ab_{15} = Fortnightly ablation; Q_{15} = Fortnightly discharge; Tm = Mean temperature; Tx = Maximum temperature; Tn = Minimum temperature; Rn = rainfall; RH = Relative humidity; CC = Cloud cover; WS = Wind speed; RFD = Rain free days; Ab_5 = 5 day ablation; Ab_m = Monthly ablation; T_{x5} = 5 day Maximum temperature; T_{ga} = Mean temperature at gauging site; G_m = Specific runoff from glacier]

precipitation data do not correlated well, this could be due to the fact that ablation for rain and non rain periods has not been estimated. Ablation data has been taken over an interval of

15 days (fortnightly) and the study period lies in the Indian Summer Monsoon period, during which there are very small dry spells as seen in Fig. 2a. The correlation matrix between ablation and meteorological variables are given in Table 3 (c).

Furthermore, stepwise multivariate regression analysis was carried out to established ablation model, using ablation (dependent), and available meteorological parameters (independent) for Dunagiri Glacier (1987–1989). It suggests that ablation mainly depends on two parameters i.e. rainfall and temperature. Giving the following equation-

$$Ab_{15} = -0.96 + 0.03 * Rn + 0.097 * Tx + 0.042 * Tn$$
$$R^2 = 0.86 \tag{1}$$

Where,

Ab_{15} Ablation in $10^6 * m^3$
Rn Rainfall in mm
Tn Minimum Temperature in °C
Tx Maximum Temperature in °C

A number of studies have been carried out to establish the relationships between ablation and meteorological variables. All studies carried out show that the glacier ablation has a good relationship with mean temperature (Kirkbirde 1995; Singh et al. 1995; Takeuchi et al. 1996; Pelto 2004; Migała et al. 2006). Dobhal et al. (2007) demonstrated that the ablation is exponentially dependent on mean temperature over Dokriani Glacier for the period of 1998–2000 (Table 3 (d)).

Principal component analysis of fortnightly data on runoff, glacier ablation and microclimatic parameters of Dunagiri Glacier (Swaroop and Srivastava 1999) indicate that glacier ablation and runoff correlation is significant at 99.90 % confidence level whereas correlation of runoff with mean temperature and average minimum temperature are significant at 99.50 % confidence level.

5 Conclusions

In the present study, assessment of meltwater discharge volume generated from glaciers of Himalaya during day and nighttime and its variability have been discussed.

As we know that availability of discharge from glaciers with suitable head in high altitude region provide excellent condition for hydropower generation. Several Run-off - the river hydropower projects exist or are under the stage of constructions in the high altitude region of Indian Himalaya. All the schemes are designed/built on a site with consistent or regulated runoff for power stations downstream; consequently, such kind of hydrological assessments are capable for formulation, exploitation and management of water resources through Run-off–the river hydropower projects; as local ecosystems may be adversely affected because of large dams in Himalaya.

This study also investigates the linkage between climate and melt-runoff, based on statistical analysis, for estimation of daily stream-flow in future from the glacierized basin, multiple regression equations have been developed considering the possible climatic factors, which may significantly influence the melt-runoff and compared to other published studies over the world. Present study shows debris covered Himalayan glaciers respond to changes in climate, depending on a variety of parameters such as air temperature, precipitation and other variables like solar radiation, extent of seasonal snow cover and degree of glacierization, which may be

combined with existing models to improve their efficiency. If glacier's response to climate were analyzed, a unique model to predict ablation and discharge may be developed and general model would apply to average, rather than individual glacier. We emphasize on the importance of field observations, but generating a time series is a time taking and difficult process, thus archival data is helpful for comparing and extending results to regional scale.

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