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MONITORING AND MODELLING OF THE STREAMFLOW FOR THE GANGOTRI GLACIER

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PREFACE

Majority of the rivers originating from the Himalayas have their upper catchment in the snow covered and glaciated areas. The Indus, Ganga and Brahamputra river system, which receive a substantial amount of melt water from the Himalayas, are considered as the life line of the Indian sub-continent. Accurate assessment and forecasting of total availability of water, melt rate and its distribution in time is considered very essential for the management of water resources. Flood control, reservoir operation, agriculture planning, and hydroelectric production are directly related to the management of water resources. Because streamflow from the glaciers originate from the high altitude regions, therefore, availability of dependable flows and suitable head provide excellent conditions for hydropower generation. Planning of new multipurpose projects on the Himalayan rivers in the country further emphasizes the need for reliable estimate of snow and glacier melt runoff. Evidently, to exploit and develop available water resources, a better understanding of melting, storage and drainage processes, and routing of the melt water or storm precipitation through glaciers is essential.

National Institute of Hydrology is carrying out detailed hydrological investigations on the Gangotri Glacier since 1999. The Institute has established permanent discharge monitoring stations near the snout of the glacier. The data set includes rainfall, temperature, humidity, wind speed and direction, sunshine hours, radiation, evaporation, discharge and suspended sediment. The monitoring of Gangotri glacier is intended to be carried for a long period to establish a good data base. An AWS has also to be installed at Bhojwasa site.

This study has been carried out by Dr. Manohar Arora, Sc. 'C', Dr Rakesh Kumar, Sc F and Shri Naresh Kumar PRA, Surface Water Hydrology Division. In this study the data collected for the ablation season 2008 to 2010 have beeen analysed.

R.D. Singh
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ABSTRACT

The Himalaya is one of the focal regions, both in terms of its cryospheric resources and the dependency of a huge population on rivers originating from this mighty mountain chain. All the major rivers of India, namely, the Indus, the Ganga and the Brahamaputra originate from the Himalayas and receive a substantial amount of melt water from the snow and glaciers. The perennial nature of these rivers and appropriate topographic setting provide excellent conditions for the development of hydropower resources. These rivers have substantial exploitable hydropower potential.

Gangotri Glacier is located in Uttarkashi District, Uttarakhand, India in a region bordering China. This glacier, source of the Ganges, is one of the largest in the Himalayas. The glacier is about 30 kilometres long and 0.2 to 2.5 km wide. Around the glacier are the peaks of the Gangotri Group.The Ganga originates as Bhagirathi from the Gangotri Glaciers. The Bhagirathi is joined by the Alaknanda at Deoprayag and the combined stream is thereafter named as Ganga. It is joined by a large number of tributaries on both the banks in the course of its total run of 2,525 km before its outfall into the Bay of Bengal.

Understanding of glaciers assume importance when difficult scientific and ethical questions need to be answered about sustainable development of mountain ranges and adjoining plains, especially with regard to hydropower, water supply and environmental quality, which has direct bearing on the national growth. In this regard the fluctuation of glaciers, change in runoff, annual balance, sediment transportation and their roles in controlling the climate of the subcontinents are of great significance.

The Institute has established permanent discharge monitoring stations near the snout of the glacier. The data set includes rainfall, temperature, humidity, wind speed and direction, sunshine hours, radiation, evaporation, discharge and suspended sediment. The monitoring of Gangotri glacier is intended to be carried for a long period to establish a good data base. The Scientific team visits and carries on investigations for the complete ablation season. In this study the data collected for three years from 2008 to 2010 have analysed and presented.

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1.0 INTRODUCTION

Mountain glaciers, such as those of the Alps in Europe, the Himalayas of Asia, and the Cascades of North America, cover the major parts of glaciers and mountain ice caps. About 3-4% of the total ice is found in the form of glaciers and mountain ice caps. Glaciers are formed in the regions where precipitation in solid form exceeds the melting and evaporation. The altitude of existence varies with latitude because the ratio of solid precipitation to the total precipitation significantly changes with latitude. Glaciers store a substantial amount of water in the form of snow and ice. The seasonal, character and amount of runoff is closely linked to cryosphric processes. Glaciers, including the Antarctic and Greenland ice sheets, ice caps and valley glaciers in polar regions and in high mountains retain significant amount of water land, and they are the largest fresh water reservoir. They contain more than 75% of the total fresh water on the surface of the earth.

Hydrology of glaciers has been given by several investigators and important regulatory role exerted by the glaciers in a basin was illustrated (Meier 1973. Delayed response of the glacier melt water has been considered by Stenborg (1970). Hodgkins (2001) studies the seasonal evolution of melt water generation, storage and discharge at a non-temperate glacier in Svalbard, Arctic region. A major difference in the melt water storage characteristics of the polar and temperate glacier was reported. Recently, Bollasina et al. (2002) in the Nepal Himalayas based on the records collected at Pyramid Meteorological Station (5050 m.a.s.l.) for a period of 5 years (1994-1998). The status of the studies clearly indicates that hydrological processes, modelling of melt runoff and separation of different components of using isotopic method are the important research areas and limited research work has been carried out these topics for the Himalayan region. Meltwater draining from outlet of the glacier causes erosion, and the development of complex drainage networks within all glacial environments (Menzies, 1995). Hydrology of glacierized basins, therefore, is an integral element in understanding all glacial environments and processes. Data published in the world Atlas of Snow and Ice. There are about 30 million km^3 of Ice on our planet. In winter, snow covers about 66% of the land surface. The total glacier-derived runoff, equal to 3,450 km^3 of water, accounts for about 8% of the total surface water runoff to the ocean (44,700 km^3) and for about 3% of the land precipitation (119,000 km^3). Of this amount, Antarctica and Arctic Islands contribute 3,010 km^3, and mountain glaciers 440 km^3, or 1.0 % of the land surface runoff. Nearly another 1% (370 km^3) is contributed by the seasonal runoff of glacier snow in summer periods in the absence of melt-water runoff from ice-free areas; the latter factor is very important in enhancing the value of glacier-derived runoff as a water resource (Kotyakov, 1996). In Himalayas, it is possible to observe the distribution of runoff where the upper parts of the basins experience a meltwater runoff and at the same time in the lower parts of the basins is dominated by rainfall. In glaciated areas, much of the precipitation falls in solid form of throughout the year, so that it contributes to mass storage rather than directly to runoff. For example in the Alps, a minimum variation in annual runoff is observed from the river basin with 30-40% glacier cover (Kasser, 1959).

1.1 Importance of The Himalayas

The Himalayas constitute the largest reservoir of snow and ice outside the Polar Regions. The Himalayan mountain, system is the source of one of the world's largest supplies of fresh water. All the major south Asian rivers originate in the Himalayan and their upper catchments are covered with snow and glaciers. The Indus, the Ganga and the Brahmaputra river systems originating in from the Himalayan region receive substantial amount of precipitation in the form of snow and glaciers in the mountains, like Himalayas, over a long period provides a large amount of water potentially available and also regulates the annual distribution of the water. The perennial nature of Himalayan Rivers and appropriate topographic setting of the region provide a substantial exploitable hydropower in this area. In the Himalayan range there are more than >10,000 glaciers (GSI, 1999) and feed a number of Himalayan rivers. The melting of glaciers starts after depletion of seasonal snow cumulated during winter over the glaciers. The melting of glaciers starts after depletion of seasonal snow exposes the ice surface of the glacier. This ice exposed surface of the glacier increases with time resulting in higher quantum of runoff. As the melt season advances, the melt water contribution from the glaciers increases. By the end of melt season, the melt runoff is reduced due to increases in air temperature and fresh snowfall on the higher reaches. Evidently, runoff generated from the glaciers in the Himalayan basins has a significant influence on the streamflow of the river. The melt rate of the glacier is determined by the prevailing climatic conditions and, therefore, varies from year to year. The physical changes in the glacier, like trend of exposition of glacier surface, influence the melting and runoff pattern of the glacier. The runoff processes including the storage and drainage of melt water from the glaciers, which control the emerging outflow, are not well understood, and need investigations. Further, contribution of snow and ice melt to the total increase with altitude, but variation in the different components of runoff with season has not been quantified for any Himalayan rivers. There is need to carry out such hydrological investigation for the Himalayan glaciers. Similarly, major detrimental effects of suspended sediment, which include loss of storage capacity, damage to or impairment of hydro equipment, have to be studied.

2.0 STUDY AREA

2.1 Location and Accessibility

The present study was carried out for the Gangotri Glacier, which is one of the largest glaciers of Himalayas. This glacier is located in the Uttarkashi District of Uttarakhand State (U.A.) falling in the Garhwal Himalayan region. The location of Gangotri Glacier is shown in Figure 1. The study area lies within the latitudes 30°43'N - 30°01'N and longitudes 79°0'E - 79°17'E. The proglacial melt water stream, known as Bhagirathi River, emerges out from the snout of the Gangotri Glacier at an elevation of 4000 m. The snout of the Gangotri Glacier is known as "Gomukh". The approach to the snout of the Glacier includes a trekking of about 18 km distance starting from the Gangotri town. The major part of the trekking is along the Bhagirathi River.

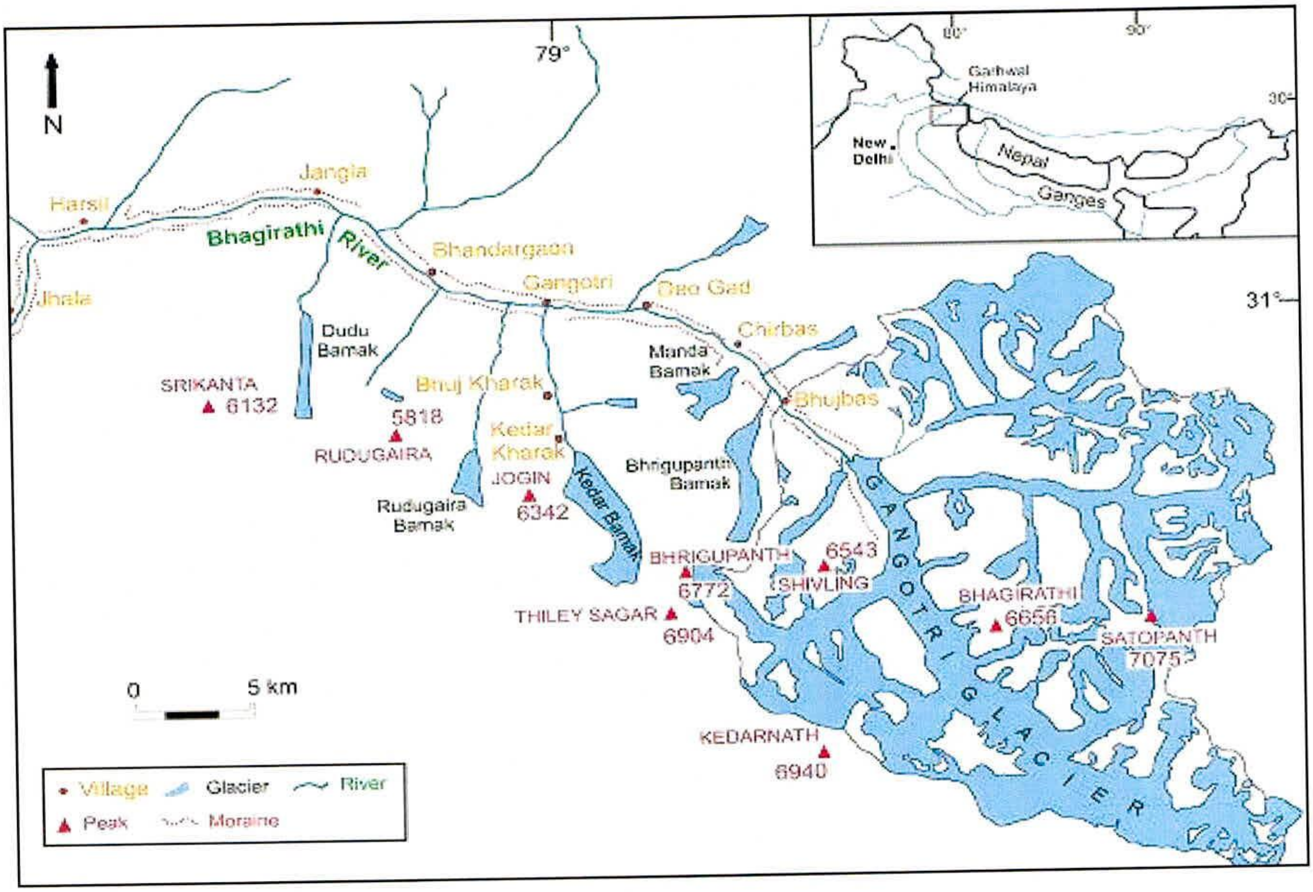


Fig. 1: Location of map of the study area.

2.2 Gangotri Glacier Systems

The Gangotri Glacier system most commonly known as Gangotri Glacier, is a cluster of many glaciers comprising of main Gangotri Glacier (length: 30.20 km; width: 0.20 - 2.35 km; area: 86.32 km^2) as trunk part of the system. It flows in the northwest direction. The major glacier tributaries of the Gangotri Glacier system are Raktvarn Glacier (55.30 km^2), Chaturangi Glacier (67.70 km^2), Kirti Glacier (33.14 km^2), Swachand Glacier (16.71 km^2), Ghanohim Glacier (12.97 km^2), Meru Glacier (6.11 km^2), Maindi Glacier (4.76 km^2) and few others having glacierised area of about 3.08 km^2. The Raktvarn, Chaturangi, Swachand and Maindi glaciers are merging with trunk glacier from north-east while the Meru, Kirti and Ghanohim glaciers are meeting the trunk glacier from south-west. The Gangotri Glacier is a valley type glacier system with total glacierized area of about 286 km^2. Total catchment area of the Gangotri Glacier and melt stream up to the discharge-gauging site established downstream of the snout by NIH is about 556 km^2. The elevation range of the Gangotri Glacier varies from 4000 to 7000 m, whereas elevation of the study area up to the gauging site lies between 3800-7000 m. The Gangotri Glacier area also has several high peaks around it.

3.0 MONITORING AND ANALYSIS OF METEOROLOGICAL DATA

The meteorological variables are the important input to the hydrological modeling studies. The meteorological data such as rainfall, maximum and minimum temperature, humidity, evaporation, wind speed and direction, sunshine hours are measured to provide the data base for the ablation season. Wind speed and wind direction are at least partial determinants of rain or snow distribution over a basin, and temperature data are vital to parameters such as snow melt. The hydrologic regime of the glaciated catchments is intimately related to climactic factors. For the present study, observations were made during the ablation period (May to October) of 2008, 2009 and 2010. Table 1 shows the period of data collection in different years.

3.1 Meteorological Parameters Monitoring

In order to monitor the meteorological variables for the Gangotri glacier, a standard meteorological observatory (30 m x 30 m) was set up at about 3800 m altitude near the gauging site at Bhojwasa. While selecting the site proper care was taken to consider the criteria laid down by India Meteorological Department (IMD) for establishing an observatory. As per the conditions the site chosen should be well exposed levelled plot of size 25 m NS x 15 m EW. The key meteorological parameters observed with the different kinds of meteorological instruments are given in Table 2.

Some of the observations were made round the clock using automated instruments, while some were observed manually at a standard frequency during the daytime.

In addition to the manual meteorological instrument an Automatic Weather Station (AWS) was installed at the site on 30.05.2009 for continuous recording of meteorological data through out the year. The parameters being monitored by the AWS are given below in Table 3 and 4.

Observation for dry and wet bulb temperatures, wind speed and wind directions were made at 0830, 1130, 1430 and 1730 hours, whereas observation for maximum and minimum temperatures, rainfall and evaporation were made at 0830 and 1730 hours. Continuous records of temperature, relative humidity, rainfall and sunshine hours were collected using thermograph, hygrograph, self recording rain gauge and sunshine recorder respectively. The statistical characteristics of the hydrometeorological data provide the basic information about their frequency distributions and variabilities.

3.2 Precipitation

A team of NIH Scientist and staff has monitored the daily rainfall data at the NIH site of the Gangotri glacier. The temporal variation in the daily observed rainfall, observed during the ablation season is shown in Figure 2(a) for the years 2008 - 2010. The results suggest that during the summer season mostly light rain occurred in the study region, except some unusual heavy rainfall events.

The observed daily rainfall values have been aggregated in order to get the monthly values. The distribution of monthly rainfall for different years is shown in Figure 2(b). A significant variation was observed in monthly rainfall from year to year, particularly in July, August and September, and total seasonal rainfall varied accordingly. For example, the total rainfall for the whole summer season (10 May - 30 September) for 2008, 2009, and 2010 was found to be 295.5, 177.2 and 477.1 mm. Based on available rainfall records, average monthly rainfall for, June, July, August, September has been computed to be 21.9, 71.7, 52.1, and 116.7 mm, respectively. It shows that July and September experienced relatively higher rainfall during summer period.

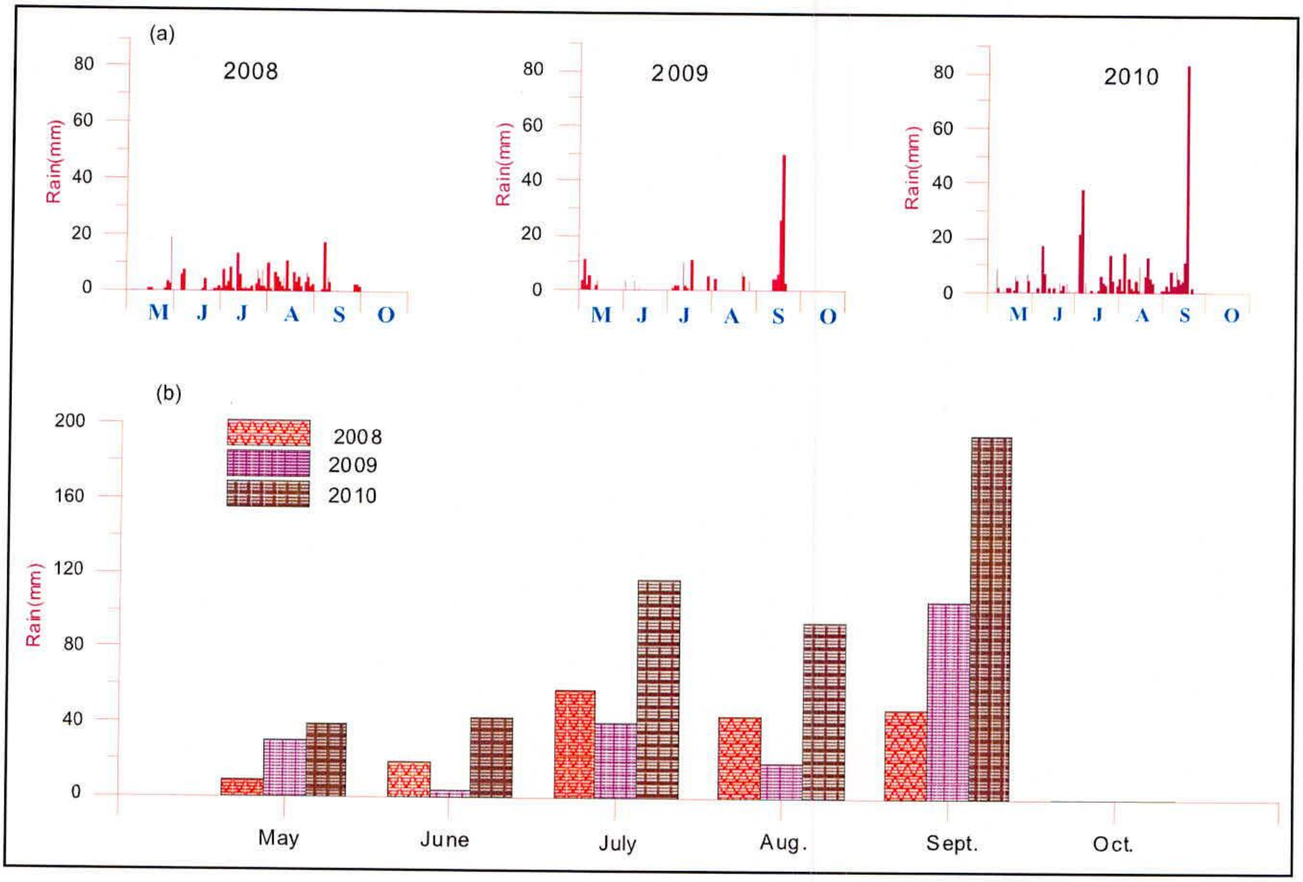


Fig. 2: a) Daily Rainfall and (b) Monthly Rainfall observed during different summer seasons (2008-2010) near the snout of Gangotri Glacier

3.3 Air Temperatures

Air temperature is an important parameter for hydrological studies. For continuous monitoring of air temperature, a thermograph has been installed at Bhojwasa site and the temperatures at the higher altitude have been extrapolated using the lapse rate method during the hydrological modeling.

Daily maximum, minimum and mean air temperatures observed near the snout of Gangotri Glacier for different years are shown in Figure 3(a) and 3(b). Diurnal variations in temperature indicate that, generally, maximum temperature is observed around 1400 hours, while the minimum is observed in the early morning.

The distribution of temperature over the ablation season has been studied. The mean monthly maximum temperatures for June, July, August and September were 16, 15.7, 15.4 and 13.3°C, respectively, whereas mean monthly minimum temperatures for these months were 4.0, 6.7, 6.1 and 3.1°C respectively. Based on the mean monthly temperature data, it is observed that the June was the warmest month of ablation season in the study area for three years.

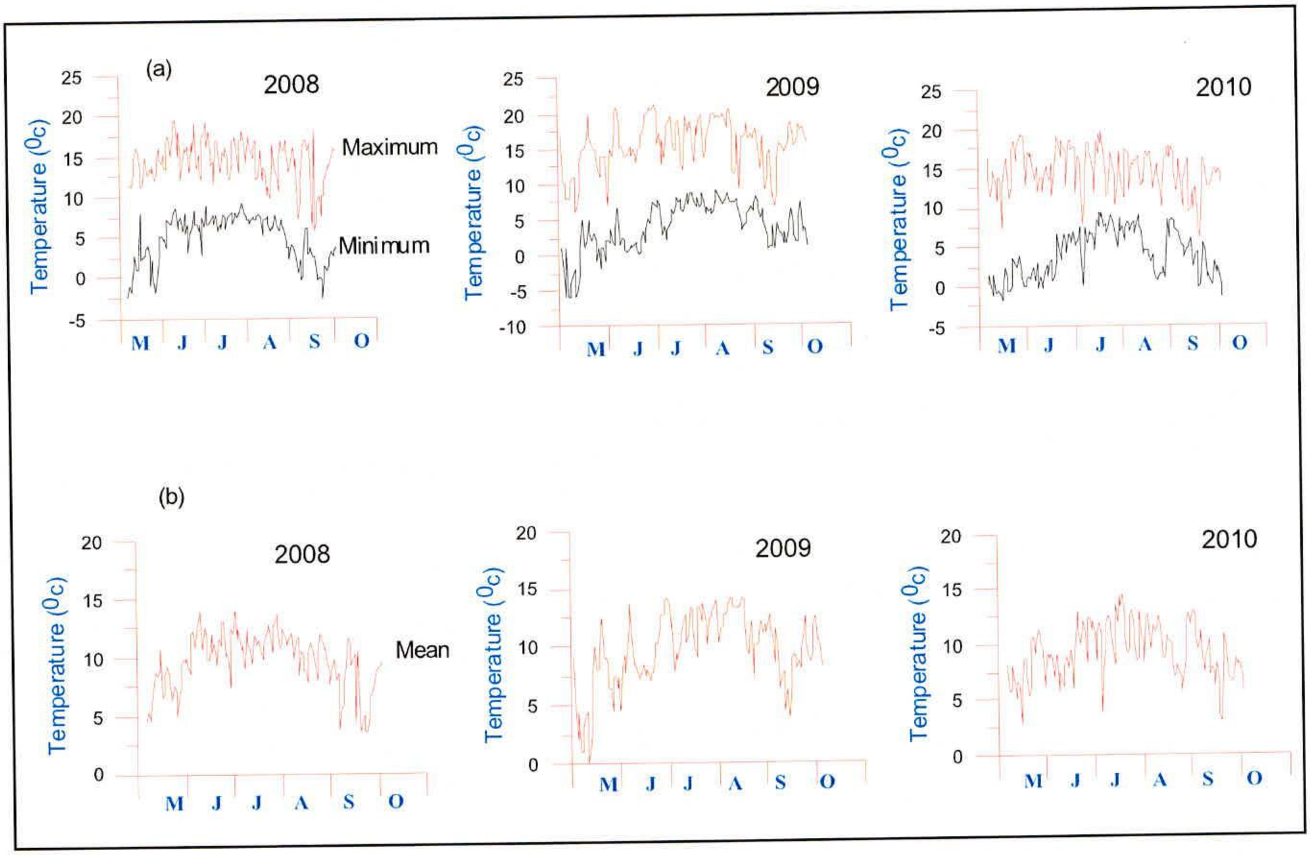


Fig. 3: (a) Daily Maximum and Minimum air temperature, and (b) Daily Mean temperature observed during different summer seasons (2008-2010) near the snout of Gangotri Glacier

3.4 Wind Speed and Direction

Wind speed and direction can encourage the initiation of precipitation thunderstorms with a number of physical processes. The wind regime of the high altitude regions is one of the decisive factors affecting the transport of moisture, formation of clouds, occurrence of precipitation and melting of glaciers. In the mountain regions, during daytime the slopes of the mountains heat up rapidly because of intense insolation and warm air moves up along the slope, while nocturnal radiation brings a rapid cooling of the mountain slopes resulting into the cooler air blows into the down valley. The daytime wind blowing from the valley towards mountain is also known as up valley wind and due to this wind in the mountain areas accelerates the cloud formation processes.

In the present study, the wind speed and directions in the study area were observed using the anemometer at the Bhojwasa site for four times a day: 0830, 1130, 1430 and 1730 hours. Daytime (0830-1730 hours), nighttime (1730-0830 hours) and mean daily wind speeds (0830-0830 hours) observed for different years. Wind directions observed over the melt period for different seasons have been depicted through wind roses (Figure 4-6). It shows that during the ablation season most of the time wind blew from northwest direction, i.e., from valley towards mountain.

3.5 Relative Humidity

Relative humidity data were measured using hygrograph at the Bhojwasa site round the clock and then mean daily values were computed. Figure 7 (a) shows the daily mean relative humidity for different summer seasons. There were no significant changes in relative humidity from the year to year. Over the study period, daily values of relative humidity ranged between 35-100%. Maximum humidity was always associated with the low air temperature and high rainfall and *vice-versa* was true for the minimum humidity. Mean monthly relative humidity was 66, 76, 77 and 68 % for the months of June, July, August and September respectively. As compared to the mean monthly relative humidity for the month of July and August, their values are lower for the month of May and June.

3.6 Sunshine Hours

Sunshine duration with temperature data is used in snowmelt and evaporation computations in few hydrological models. Total bright sunshine hours are a useful extra parameter against which to interpret other climate statistics. The sunshine hours for the ablation season for the years 2008, 2009 and 2010 are presented in Figure 7 (b) On average, for June, July, August and September, the mean monthly sunshine hours were observed to be 5.7, 5.1, 4.9 and 5.7 respectively.

3.7 Evaporation

Evaporation from any basin can be broadly divided into two groups, meteorological factors and surface factors. A pan evaporimeter was installed at the meteorological observatory located at Bhojwasa. Daily pan evaporation records over the ablation season near Gangotri Glacier are shown in Figure 7 (c). Mean monthly total evaporation during 3 ablation period was 122.5, 96, 78, and 72.3 mm for the month of June, July, August and September respectively. The total pan evaporation during the summer season 2008, 2009 and 2010 was 367.7, 288, 234 and 216.8 mm, respectively.

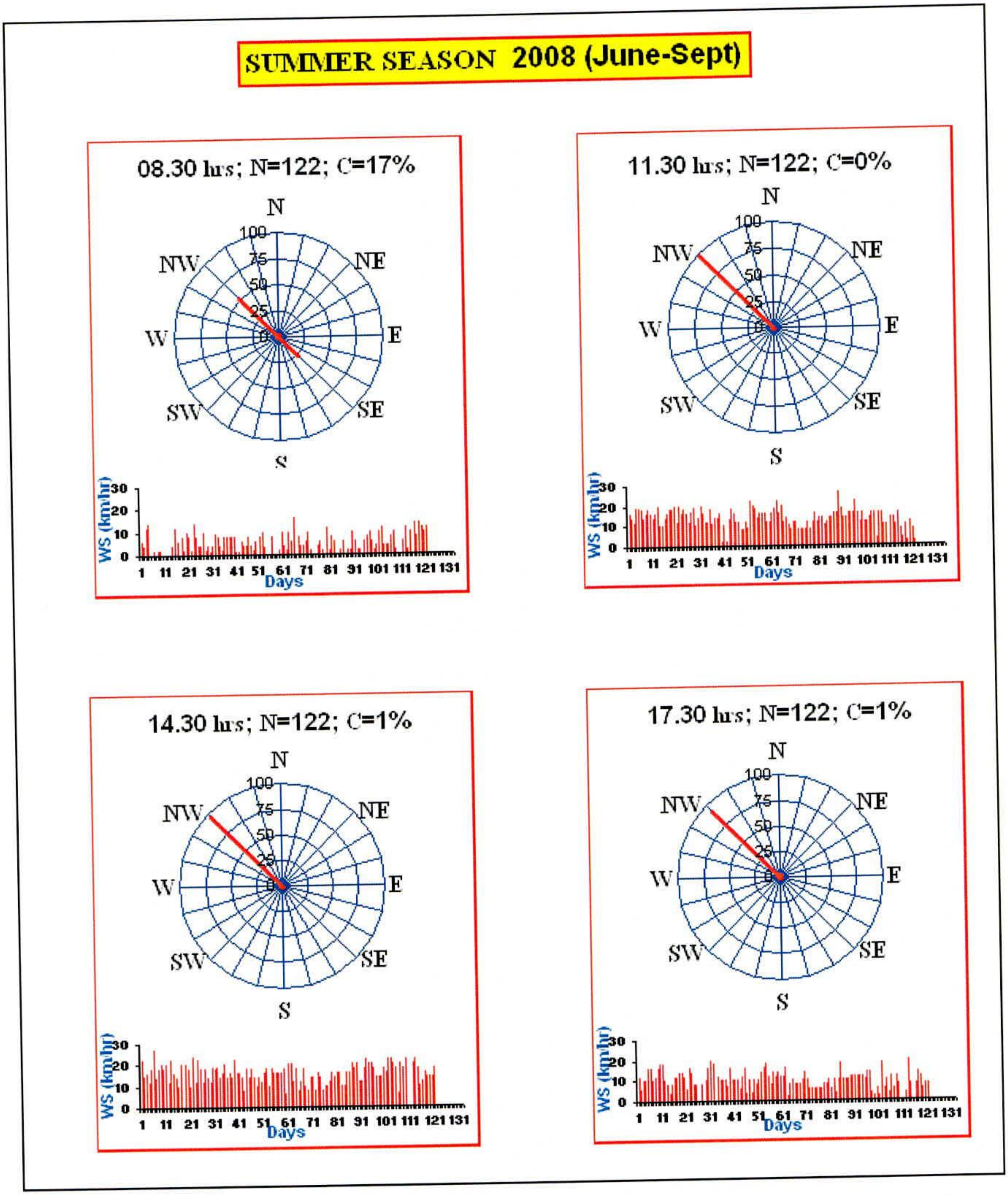


Fig. 4 : Wind speed (km/hr) and direction observed at 08.30, 11.30, 14.30 and 17.30 hours near the snout of Gangotri Glacier (Bhojwasa, 3800m) during Summer Season 2008.

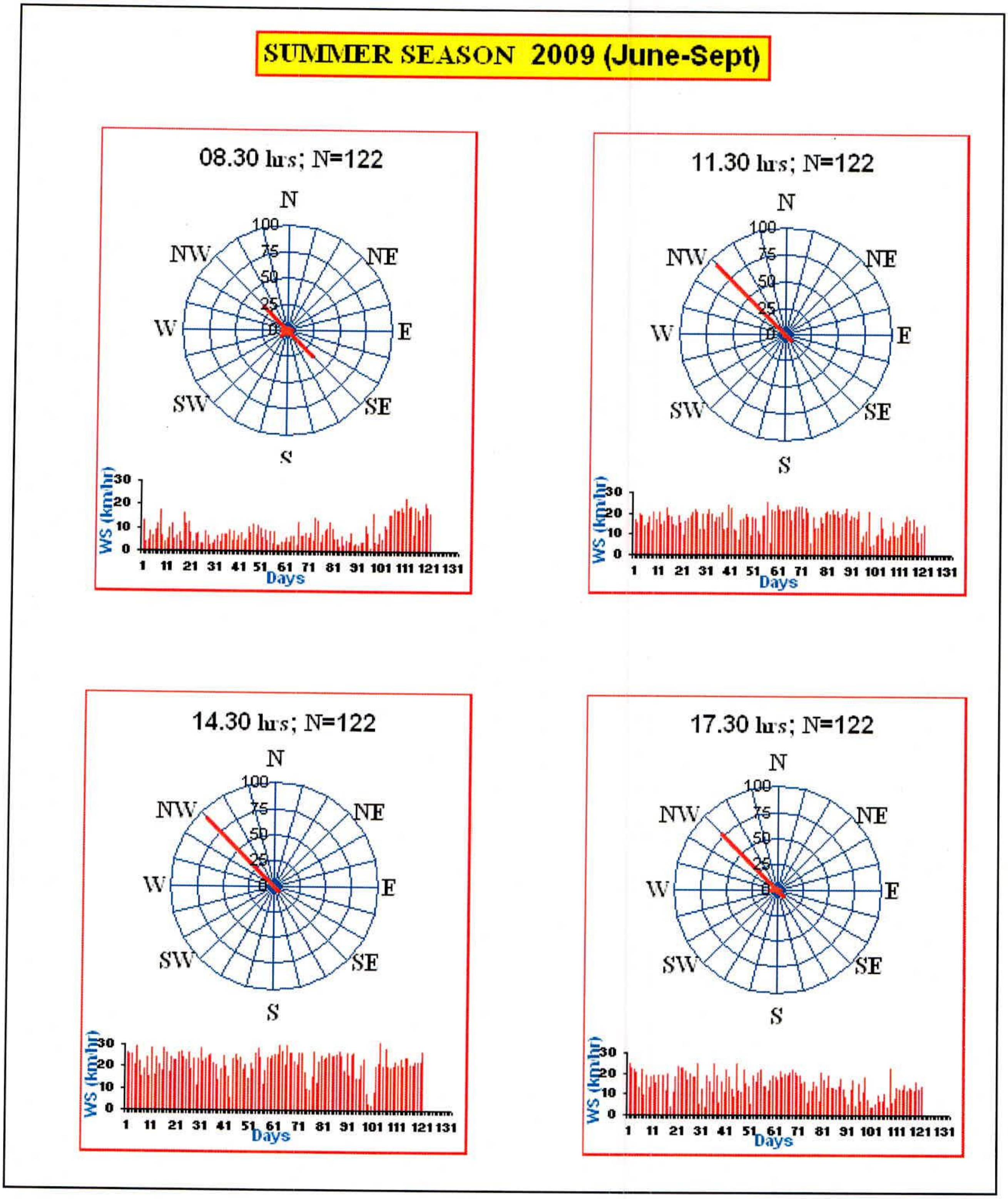


Fig. 5 : Wind speed (km/hr) and direction observed at 08.30, 11.30, 14.30 and 17.30 hours near the snout of Gangotri Glacier (Bhojwasa, 3800m) during Summer Season 2009.

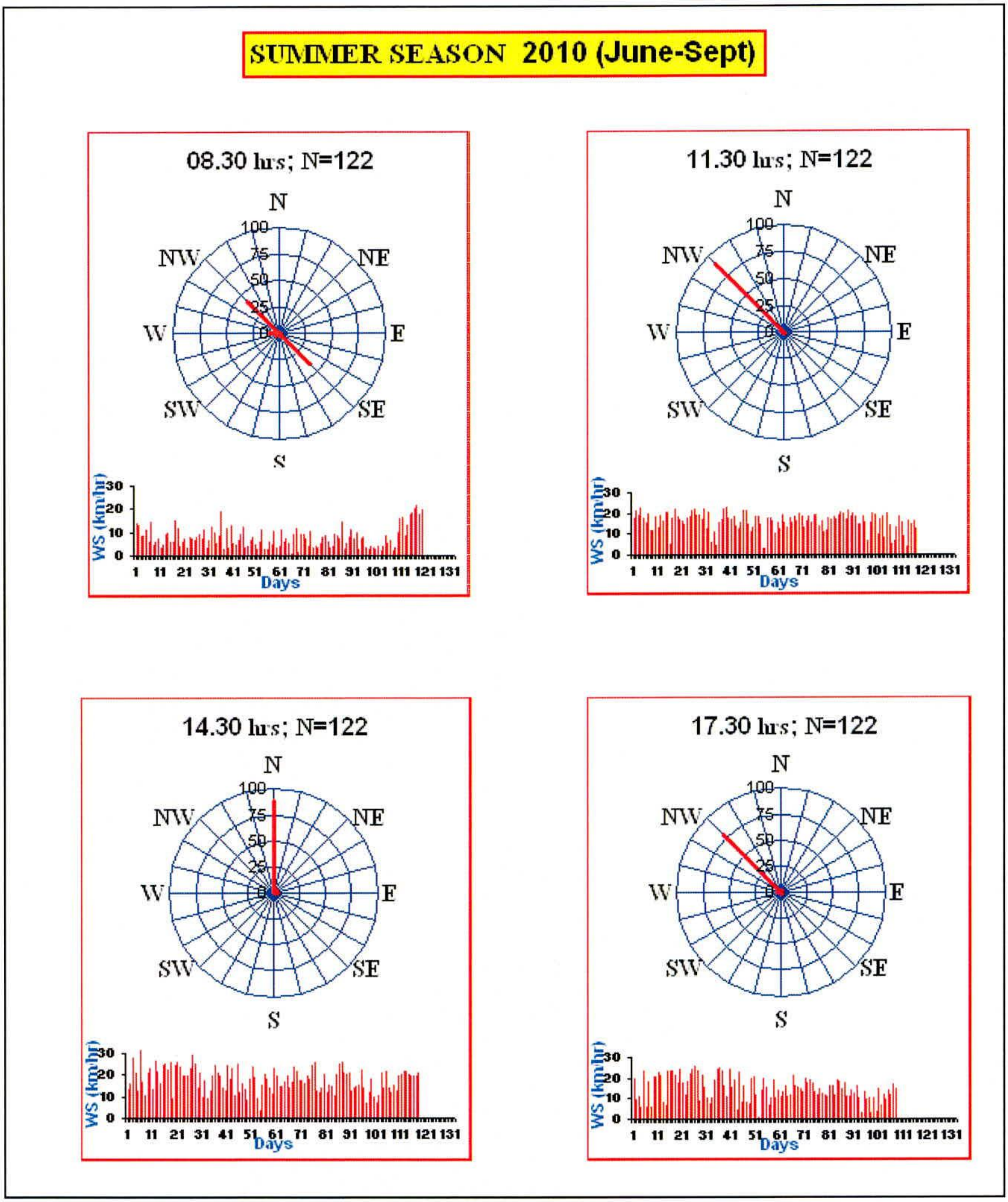


Fig. 6 : Wind speed (km/hr) and direction observed at 08.30, 11.30, 14.30 and 17.30 hours near the snout of Gangotri Glacier (Bhojwasa, 3800m) during Summer Season 2010.

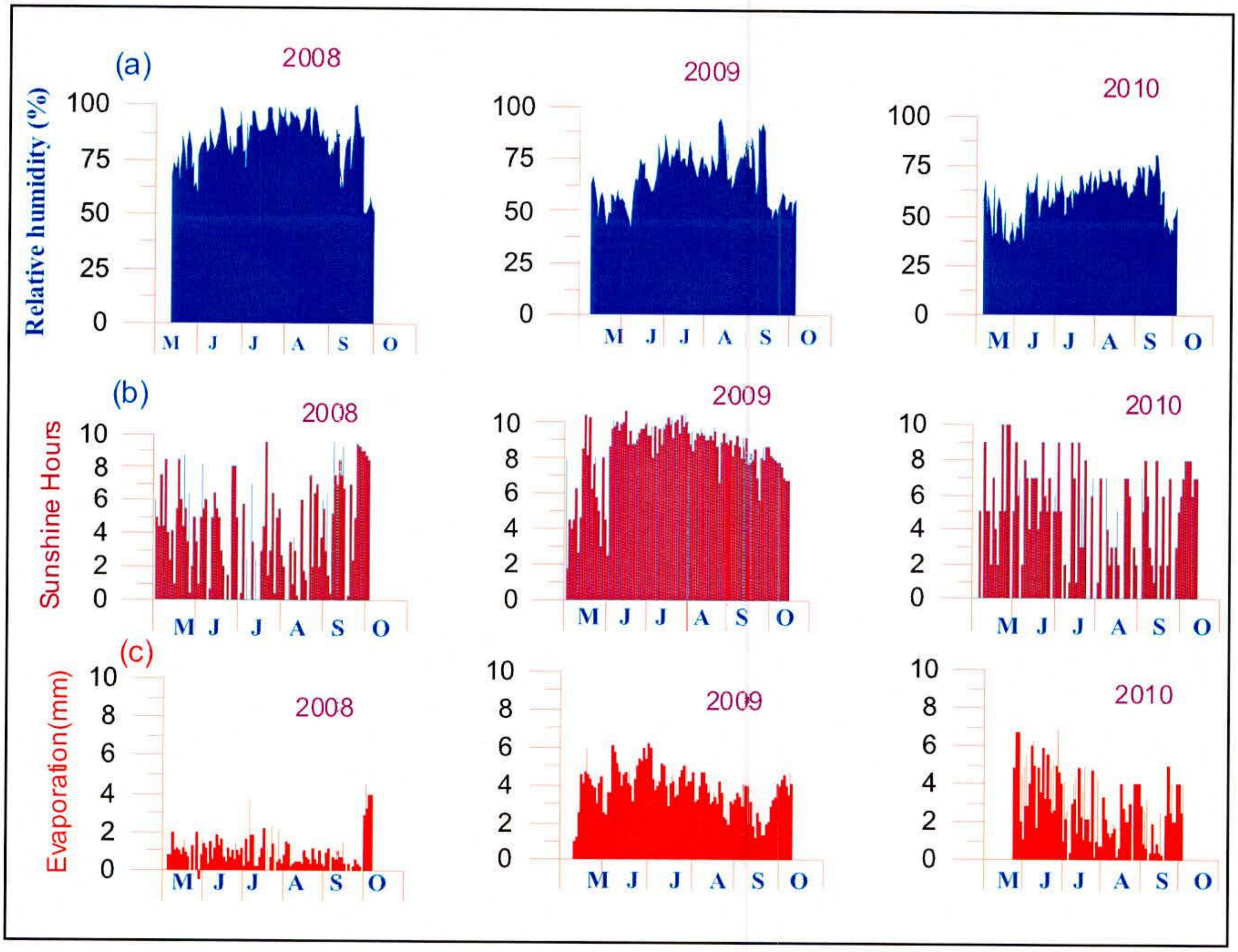
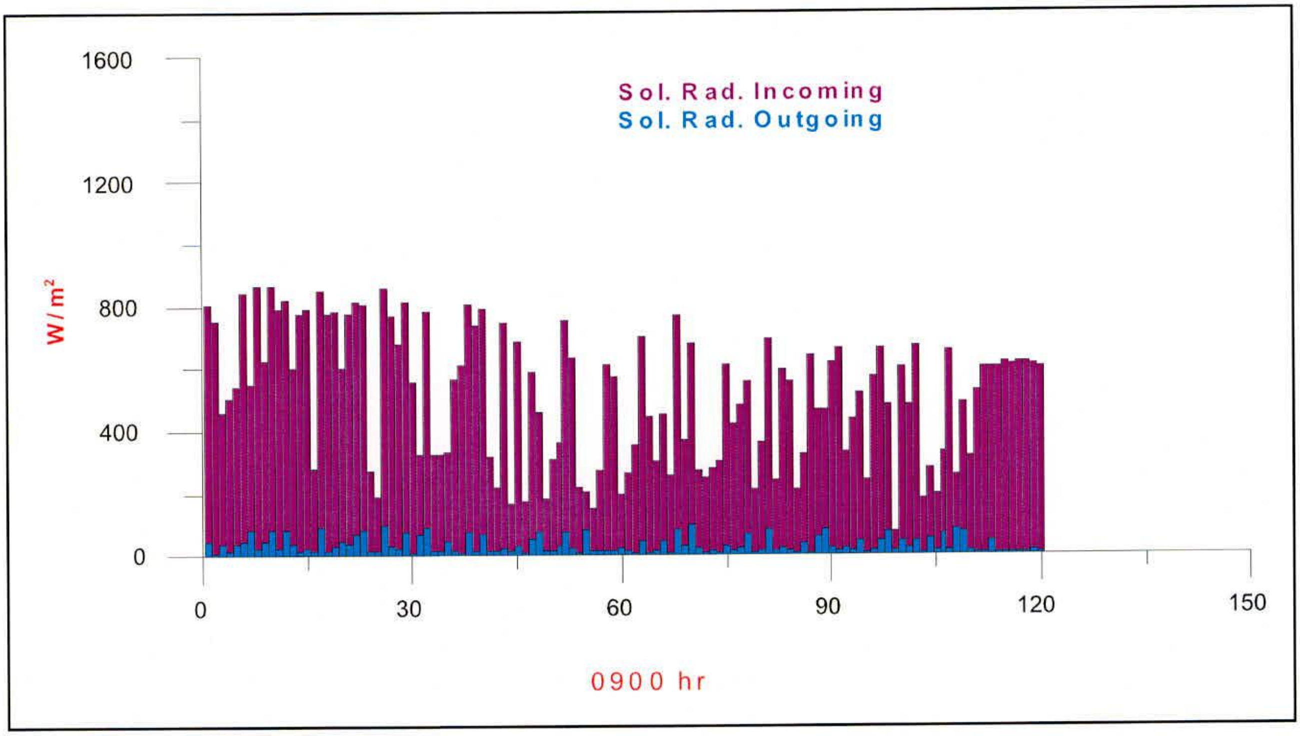
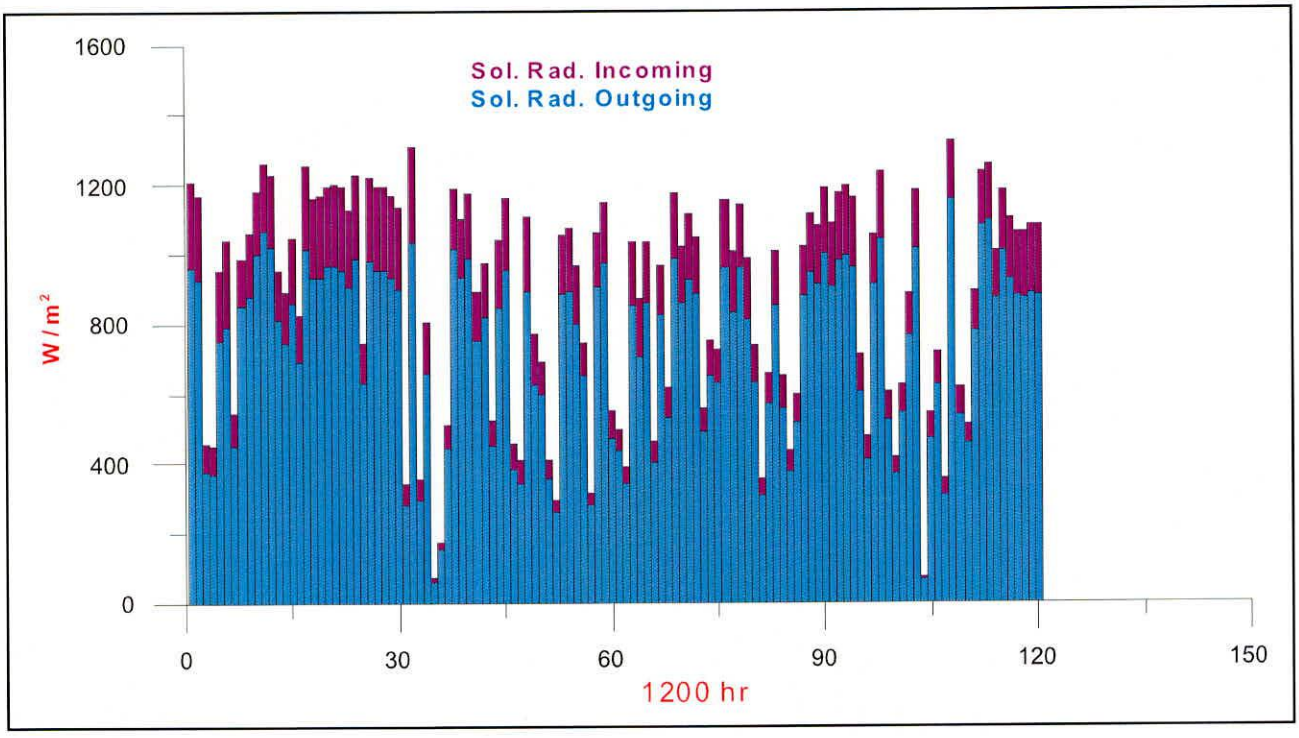


Fig. 7: Daily (a) Relative Humidity (b) Sunshine hours (c) Evaporation observed during different summer seasons (2008-2010) near the snout of Gangotri Glacier

4.0 SOLAR RADIATION OBSERVED DURING DIFFERENT SUMMER SEASONS 2008, 2009 AND 2010 NEAR THE SNOUT OF GANGOTRI GLACIER





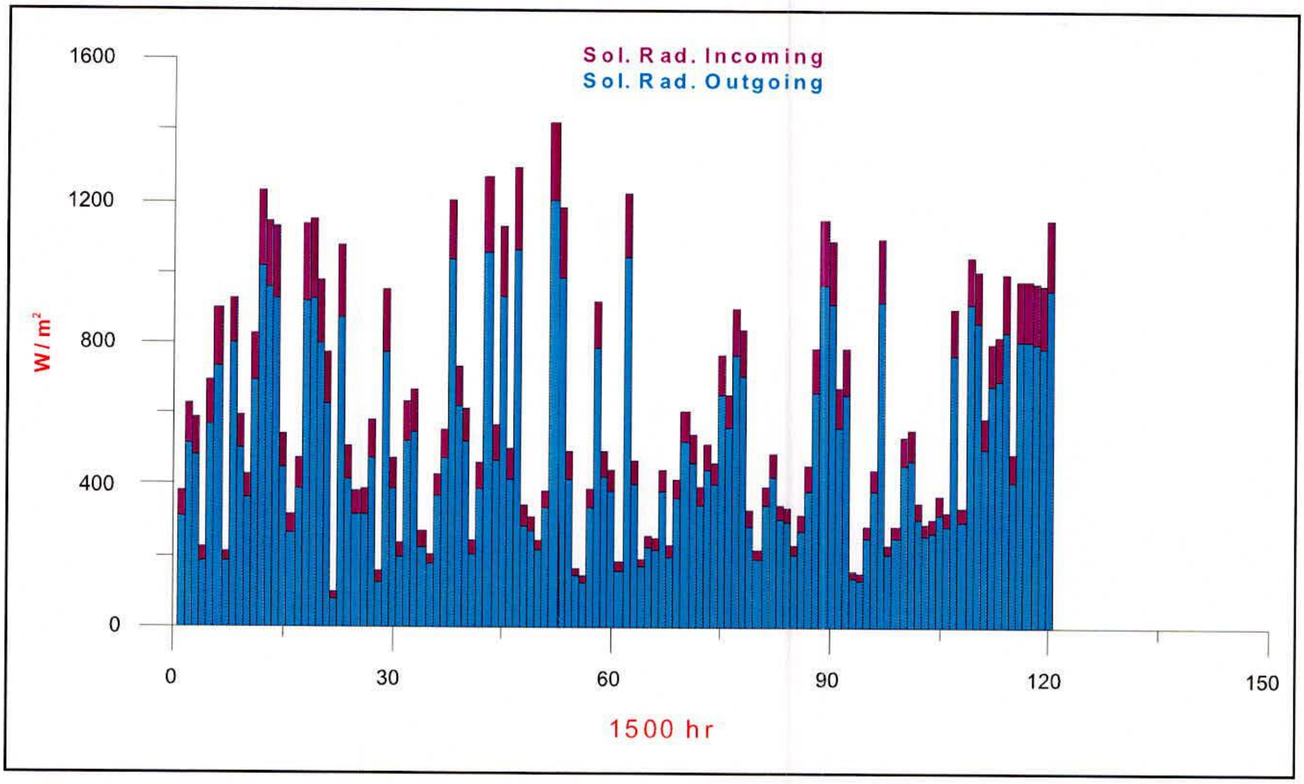
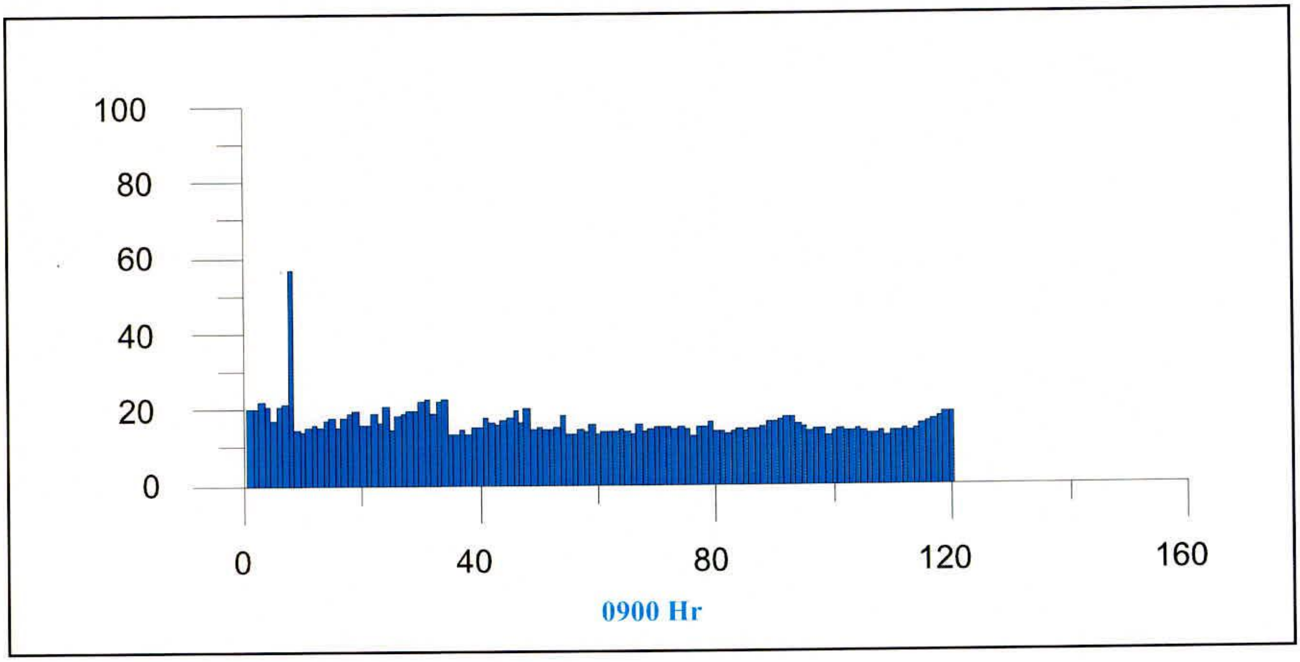
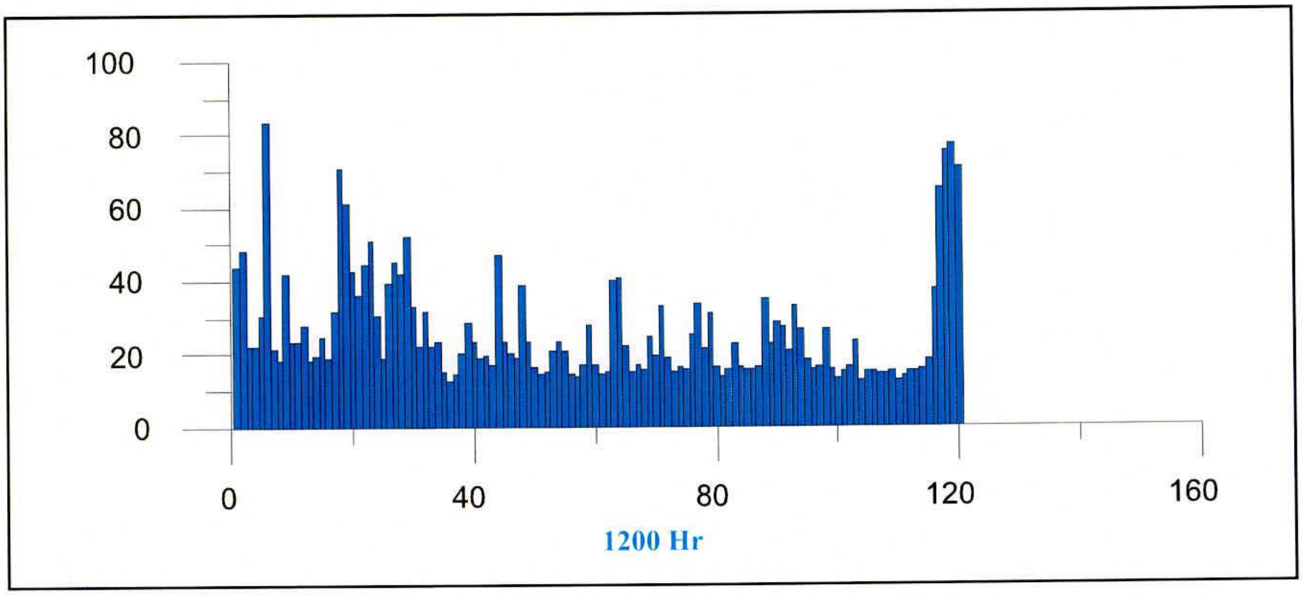

Sol. Rad. Incoming
Sol. Rad. Outgoing
1600
1200
800
400
0
W / m²
0
30
60
90
120
150
1500 hr

Fig. 8

5.0 ALBEDO GRAPHS



0900 Hr



1200 Hr

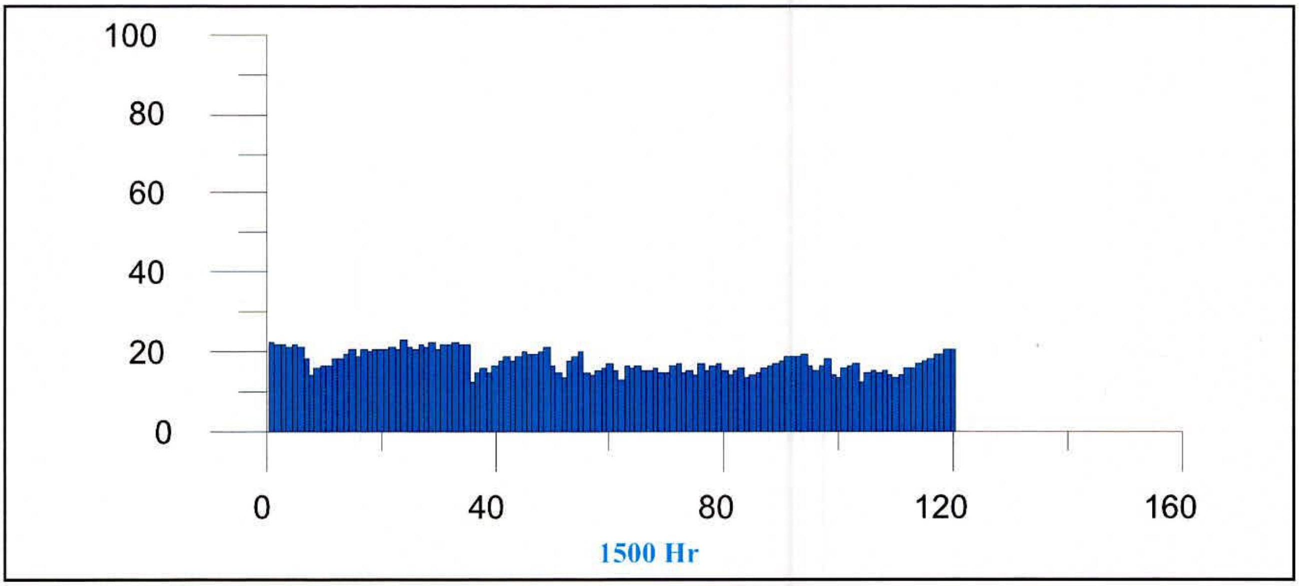


Fig. 9

6.0 MONITORING OF RIVER GAUGE AND DISCHARGE DATA AND ITS ANALYSIS

6.1 Measurement of gauge and discharge data and development of stage discharge curve

In order to measure the water level data, an automatic water level recorder was installed on the stilling on the river bank of River Bhagirathi at Bhojwasa. The daily charts mounted on the automatic water level recorder were utilised for deriving the hourly gauge values for each day. During peak melt period, sediment was removed from the well at least once a week.

A graduated staff gauge was also installed on the gauging site near the stilling well for manual observations of water level. Manual observations of water levels were made during day and night time. This manual data set was used for cross checking of recorded level fluctuations in the river flow. Wooden floats were used to compute the velocity of flow and the time travelled by the floats was recorded. The float travelling length at the gauging site was 20 m. For accuracy in velocity, the readings were repeated at least three times and an average value was adopted for further computations. The surface velocity of streamflow was observed in the range of 0.5 to 4.5 m/s, being maximum during peak melt period. For the measurement of water velocity the channel was divided into four segments. Further, because surface velocity of flow is higher than the mean flow velocity, therefore, the mean flow velocity was determined by multiplying the surface velocity by a factor of 0.90.

A relationship were developed for each summer season separately and used to convert water levels into discharges. The computed hourly discharge values for a day are averaged in order in estimate the daily average values. Figure 10(a) illustrates the daily average discharge hydrograph at the gauging site for the ablation season of the year 2008 to 2010. Monthly mean values of the discharge were computed from the daily mean values for each month of the ablation season. Figure 10(b) shows the bar chart of the monthly mean values for the ablation seasons of the years 2008 to 2010. From the figure 10(a) it is observed that the daily mean discharge shows increasing trend from May onward and reaches to its maximum value sometimes in the month of July/August during the years 2008 to 2010. Subsequently it shows the decreasing trend till the end of the ablation season.

6.2 Distribution of Streamflow and Water Yield

The main sources of runoff from the Gangotri Glacier area are: (i) melting of ice and snow, and (ii) rainfall. In the study area, the contribution of the rainfall is less than the contribution of the melting of ice and snow during the ablation season. Melt water hydraulic systems of the glacier include supraglacial system, englacial and subglacial system. The first two systems exhibit considerable fragility, being easily susceptible to rapid change, whereas the third system is more resistant to alteration

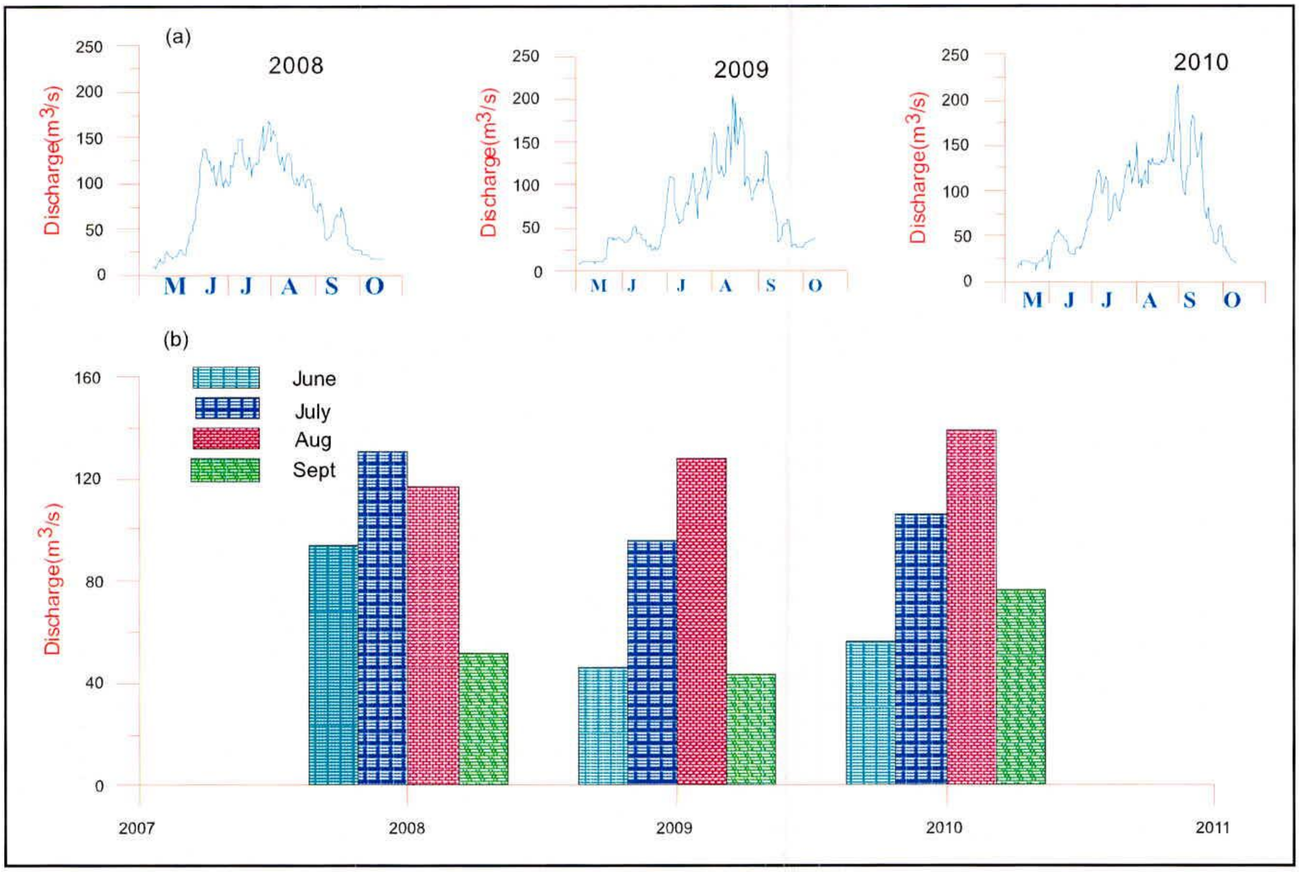


Fig. 10 : (a) Daily Mean Discharge (b) Monthly Mean Discharge observed during different summer seasons (2008-2010) near the snout of Gangotri Glacier

unless ice conditions are dramatically transformed. Finally total melt water emerges out as integrated runoff through the snout of the glacier. In the present case, the runoff drained from the glacier into a single melt stream.

Based on the three years (2008 to 2010), the average monthly discharge computed for June, July, August and September are 65.3, 110.7, 127.8 and 57.3 m^3/s respectively. The average monthly volume of water flowing from the gauging site are 169.3, 296.4, 342.4 and 148.6 MCM for June, July, August and September are, respectively. Distribution of runoff volume indicates maximum runoff in July (29.15%) followed by August (33.67%). As such, July and August contribute about 62.82% to the total melt runoff. High melt rate is observed due to dry weather conditions in the study area.

In terms of volume, the total melt water from the Gangotri Glacier for the ablation period (10 May - 11 October) was estimated to be 1099.6, 910.2 and 1061.1 MCM for 2008, 2009 and 2010.

7.0 SUSPENDED SEDIMENT DATA COLLECTION AND ANALYSIS

The sedimentary system of the glacier can be defined in the terms of sediment sources, processes of erosion and entrainment, modes and medium of transport, sediment concentration and load in the melt water. Glacier melt streams transport a significant amount of sediment in the form of silt, gravel and boulders into the rivers and then to the reservoirs located in the downstream. Due to their own movement, glaciers transport enormous debris material in the form of moraines, which becomes the source of fine sediment and silt. Assessment of these sediments transported by the melt stream is important because it has direct influence on the capacity of the reservoirs. The glaciers melt water carries sediment as suspended sediment or bed load. Suspended sediment refers to the grains flow with water above the bed of channel and is considered as a characteristic of the turbulent flows. Suspended sediment concentration in the glacial streams reflects the availability of sediments. Bed load, which are bigger in size, refers to the grains swept along with the bed of a stream, in continuous or intermittent contact with the bed. In the present case, sediments transported as bed load are much less in comparison to the suspended sediment at the gauging site.

7.1 Sources of Sediment

The main sources of sediment production in the glacier fed channels are the glacier system, bedrock system and channel system. The glacier system includes sedimentation from different parts of the glacier such as the accumulation zone, ablation zone, snout and the lateral moraines, whereas bedrock system deals with glacier bottom ice and bedrock. These sediments transported by the glacier follow three basic routes: supraglacial, englacial and subglacial. Processes like sliding of rocks and debris, snow and glacier avalanches accelerate the transport of moraines and sediment. Over wide areas in the glaciated regions the bedrock is markedly abraded and becomes the important source of sediment transport.

Like all other Himalayan glaciers, Gangotri Glacier is also covered with boulders, moraines. Obviously, one of the important sources of sediment from the study glacier becomes the presence of sediment material like boulders, debris and moraines over the glacier surface. During the active melting period supraglacial material remains in contact with melt water and becomes a regular source of sediment. The ablation zone of the glacier contributes a large amount of sediment because a large quantity of such material is found in this area and water travels by surface pathways in the ablation zone of the glacier. A part of the sediment material available on the glacier surface is also transported down through extensive longitudinal and transverse crevasses into englacial and subglacial tunnels. From the features of the surface texture of the lateral moraines, it could be expected that chemical and mechanical processes might also mobilise the lateral moraines sediment into the glacier melt stream.

7.2 Suspended Sediment Concentration

To determine the mean suspended sediment concentration, load, yield and particle size in the Gangotri Glacier melt stream, two water samples at 0830 and 1730 hours were directly scooped from the channel at the gauging site in a cleaned polyethylene bottle (500 ml). A sample was collected from the stream at about mid depth and filtered at the site itself using Whatman-40 ashless filter paper. The suspended sediment samples thus collected on the filter papers were properly packed in the self locking small polythene bags and details such as, time and date of sample collection, were marked on it. These packed samples were brought to the laboratory at the National Institute of Hydrology (NIH), Roorkee for further analysis. In the laboratory these sediment samples were dried in an oven at 200°C for a period of 24 hours and then suspended sediment concentration (SSC) for each sample was determined by weighing the individual sample.

Suspended sediment concentration in the melt runoff from the study area was very high. Daily mean suspended sediment concentrations in the melt stream varied from 20 to 10540 ppm. Distribution of sediment transport over the ablation season was found almost like the distribution of streamflow. It begins to increase with discharge from May onwards, as the melting season advances, attains its maximum in July and then again it starts reducing. Daily mean suspended sediment concentration recorded at gauging site near the snout of the Gangotri Glacier for 2008, 2009 and 2010 are given in Figure 11(a). Mean monthly suspended sediment concentration, as shown in Figure 11(b), for May, June, July, August and September during the study period was 992, 1411, 2123, 1862 and 561 ppm, respectively. Maximum daily mean suspended sediment concentrations observed in May, June, July, August and September were 10540, 7188, 4710, 10540 and 4660 ppm, respectively. For the entire melt season, the mean daily suspended sediment concentration was computed to be 1301 ppm.

7.3 Suspended Sediment Load and Yield

Suspended sediment load (SSL) can be determined by multiplying SSC with discharge and changing the unit into tonnes. The variation in daily suspended sediment load and daily mean discharge during the ablation period is shown in Figure 12(a). Daily suspended sediment loads ranged between 47 and 121243 tonnes. The monthly distribution of suspended sediment loads for the different years is shown in Figure 12(b). Mean monthly total suspended sediment loads for May, June, July, August and September during the study period was found to be 60, 294, 664, 670 and 101 $\times 10^3$ tonnes respectively. The total suspended sediment from the Gangotri Glacier was estimated to be 2.54, 1.18 and 1.54 $\times 10^6$ tonnes for 2008, 2009 and 2010. The average total suspended sediment load for the melt season was computed to be 1.76 $\times 10^6$ tonnes.

Proglacial meltwater has very high sediment yield in response to glacial and fluvioglacial erosion within the source catchment. The high sediment yields recorded from glacial meltwaters to some extent mask the high temporal variability that characterizes these inputs of sediment to the proglacial

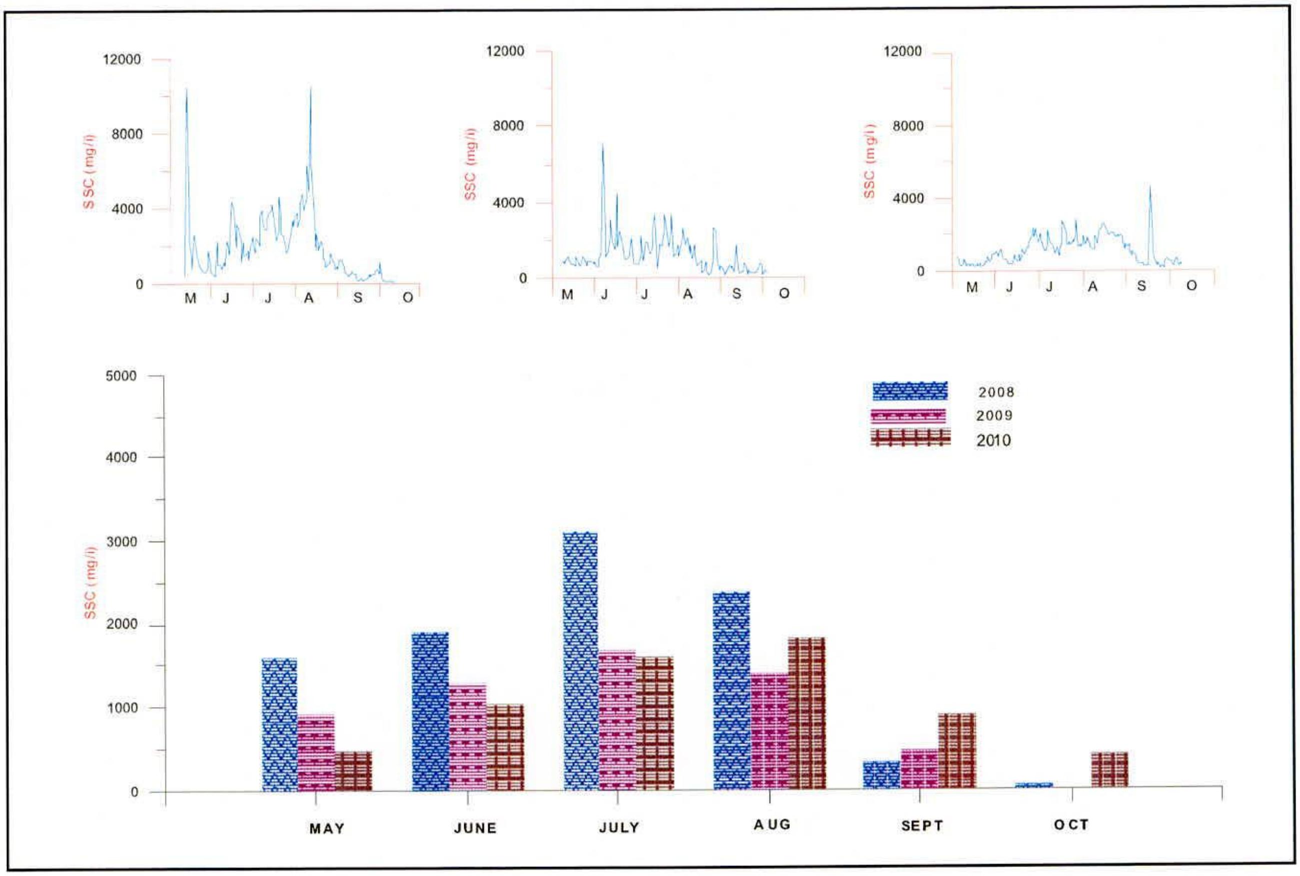


Fig. 11: (a) Daily mean suspended sediment Concentration(SSC), and (b) mean monthly SSC observed for different months near the snout of Gangotri glacier during different summer seasons(2008-2010).

channel system. It shows wide seasonal and interannual variations, which are partly due to switches in the subglacial drainage system. Sediment yield can be affected by five factors, (1) basin geology and thus the erodibility of materials beneath the glacier, (2) climate and its effects on mass balance and runoff (3) glacier dynamics and thermal regime and their effects on erosion and sediment entrainment by ice (4) the percentage of glacier cover and its state of change, and (5) the type and extent of the subglacial drainage system in relation to the location and quantity of sediment available for transport. Sediment yields can be used to estimate long-term erosion rates.

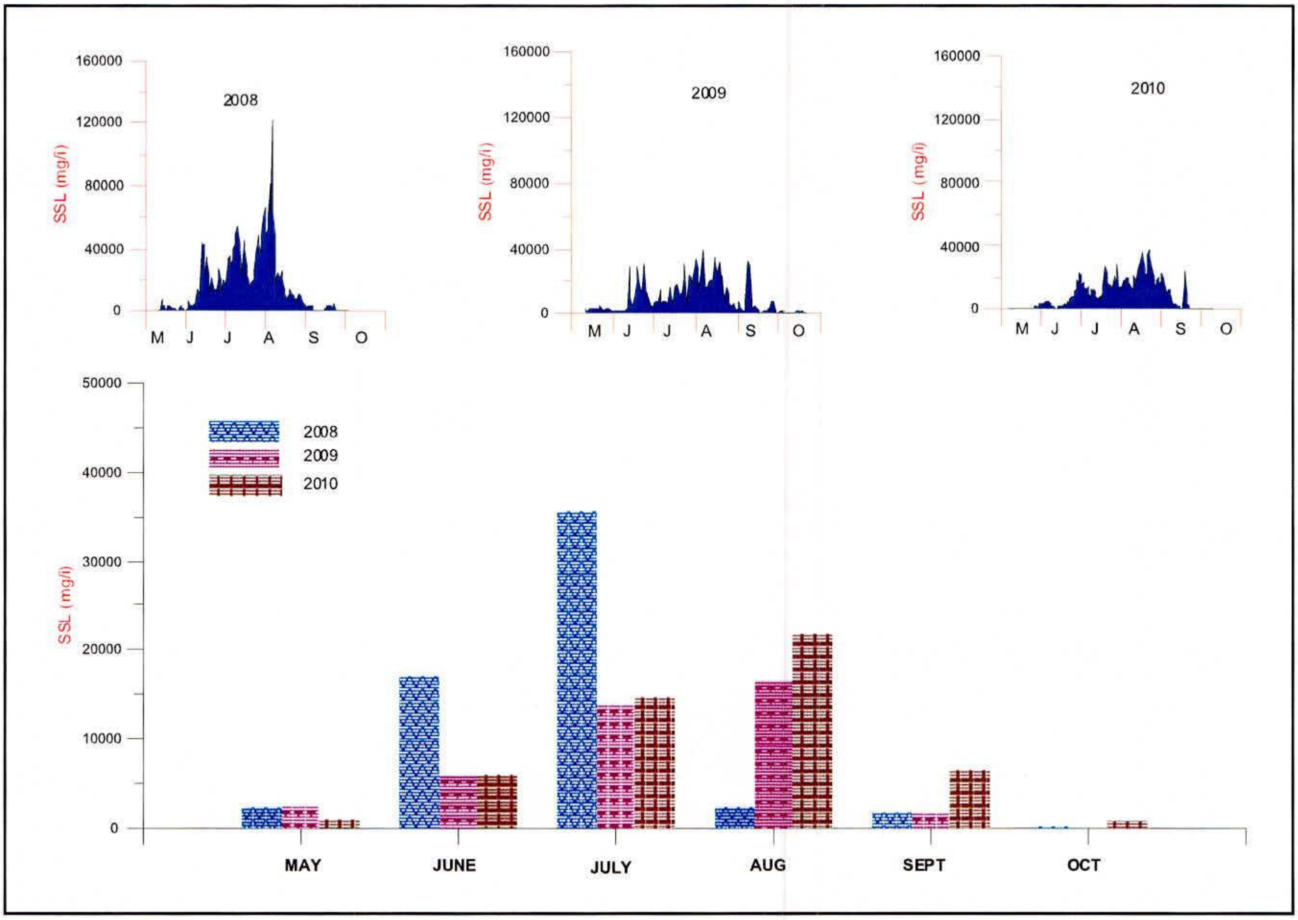


Fig. 12: (a) Daily mean suspended sediment Load (SSL), and (b) mean monthly SSL observed for different months near the snout of Gangotri glacier during different summer seasons (2008-2010).

8.0 DISCUSSION OF RESULTS AND CONCLUSIONS

a) Hydrometeorology of The Study Basin

Hydrometeorological data for the Gangotri Glacier was collected under the project by establishing a standard meteorological observatory and a gauging site near the snout of the glacier. The required data were collected for 3 ablation seasons (10 May-30 September) during 2008 to 2010 and analysis was made to understand the weather conditions and melting pattern of the glacier. Average monthly rainfall for June, July, August and September has been computed to be 21.9, 71.7, 52.1 and 116.7 mm, respectively. The total rainfall and its distribution over the summer season are found to vary from year to year. For example, the total rainfall for the summer season (10 May to 30 September) for 2008, 2009 and 2010 was recorded to be 295.5, 117.2 and 477.1 mm. Based on 3 years data average seasonal rainfall for the Gangotri Glacier was observed to be about 316.6 mm.

The average daily maximum and minimum temperatures over the summer season were computed to be 14.9°C and 4.4°C, respectively, whereas average mean temperature was 9.6°C. Diurnal variations in temperature indicate that generally maximum temperature is observed sometimes around 1400 hours while the minimum at the early morning. Mean monthly temperatures for June, July, August and September were 16.0, 15.7, 15.4 and 13.3°C, respectively, suggesting that July was the warmest month.

Analysis of wind data shows that on an average the daytime wind speeds are much stronger (4 times) than the nighttime winds. Generally, the duration of daily mean sunshine hours becomes maximum in May and minimum in August. On the seasonal scale daily mean sunshine hours were 5.4 hours. Monthly total pan evaporation was 59.6, 122.5, 96, 78, and 72.3 mm for the month of May, June, July, August and September respectively. Mean daily evaporation for the summer season as a whole is found to be 3.0 mm, which is comparable to the pan evaporation data observed at foothill station of the Himalayas. The combination of weather conditions like longer sunshine duration, little rainfall, low humidity and high wind speed could have attributed to higher evaporation in the month of May. On the other hand, weather conditions allowed for lower evaporation in October.

b) Hydrology and Glacio-Fluvio Sediment transfer in The Basin

The discharge showed increasing trend from May onward, reached to its highest value in July and then started reducing. The maximum and minimum daily mean discharge observed during study period was 7.9 to 216.8 m^3/s. The mean monthly discharge observed for May, June, July, August and September was 35.8, 65.3, 110.7, 127.8 and 57.3 m^3/s, respectively. Almost similar trend of distribution of runoff is observed for all the years.

Suspended sediment concentration in the observed discharge was very high. More over it was very much variable over the melt season. Daily mean concentration varied between 20 to 10540 ppm. Mean monthly suspended sediment concentration for May, June, July, August and September during the study period was 992, 1411, 2123, 1862 and 561 ppm, respectively. Mean monthly total suspended sediment loads for may, June, July, August and September during the study period was found to be 60, 294, 664, 670, 101 $\times 10^3$ tonnes respectively.

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Table 1: Data collection period for different years

Year	Period	Days
2008	09 May-03 October	146
2009	01st May-20th October	171
2010	05th May 4th October	151

Table 2: Meteorological instruments installed and observations taken at the meteorological observatory

S. No.	Instrument	Observations
1	Ordinary raingauge	Rainfall
2	Self recording raingauge	Continuous rainfall/rain intensity
3	Thermograph	Continuous temperature
4	Max. & min. thermometers	Max. & Min. temperatures
5	Dry & wet bulb thermometers	Dry & wet bulb temperatures
6	Hygrograph	Relative humidity
7	Pan evaporimeter	Pan evaporation
8	Anemometer	Wind speed
9	Wind vane	Wind direction
10	Sunshine recorder	Sunshine hours

Table 3: Parameters being monitored by the AWS

TIMESTAMP	RECORD	Air_Temp_Avg	Air_Temp_Max	Air_Temp_Min	RH	W_Spd_S	W_Dir_D1	W_Dir_SD1	SRad_In_Avg	SRad_Out_Avg
TS	**RN**	**Deg C**	**Deg C**	**Deg C**	**%**	**meters/sec**	**Deg**	**Deg**	- -	**W/m²**
		Avg	**Max**	**Min**	**Smp**	**WVc**	**WVc**	**WVc**	**Avg**	**Avg**
5/31/2009 10:00	0	11.1	11.28	10.84	38.57	2.458	316.3	17.1	1038	204
5/31/2009 11:00	1	12.64	12.74	12.6	32.03	3.6	321.6	10.16	1234	251.9
5/31/2009 12:00	2	13.41	14.06	12.7	30.84	5.075	312.3	11.98	876	272.4
5/31/2009 13:00	3	13.9	14.83	12.9	34.43	6.565	313.2	11.57	1293	289.2
5/31/2009 14:00	4	13.29	14.52	12.35	37.55	6.794	311.4	14.45	894	216.5
5/31/2009 15:00	5	12.68	14.02	10.93	33.42	4.663	342.6	65.05	658.2	151.7

Table 4: Parameters being monitored by the AWS

Albedo_Avg	Sun_Dur	CNR_Wm2_Avg	Snow_Depth	Rain_Tot	SST_Avg	SST_Max	SST_Min	Airpress_Avg	SBT_C_Avg	TT_C_Avg
%	**min**	**Watts/meter²**	**Meter**	**mm**	**Deg C**	**Deg C**	**Deg C**			
Avg	**Smp**	**Avg**	**Smp**	**Tot**	**Avg**	**Max**	**Min**	**Avg**	**Avg**	**Avg**
19.65	3.167	600.9244	-1.927	0	37.09	189.6	0	140.1	NAN	NAN
20.41	1.5	682.7311	-2.923	0	0.135	0.135	0.135	326.9	16.09	26.93
43.77	37.5	756.5275	-2.942	0	0.135	0.135	0.135	13.08	16.31	27.39
22.39	97.5	743.3048	-2.91	0	0.135	0.135	0.135	981	16.1	28.84
24.3	157.5	500.2143	-2.93	0	0.135	0.135	0.135	981	15.21	26.75
22.97	217.5	275.8227	-2.922	0	0.135	0.135	0.135	981	13.83	21.44

Table 5: Mean monthly maximum temperatures observed at Gangotri Glacier during 2008, 2009 and 2010

		Month		
Years	**June**	**July**	**Aug**	**Sept**
2008	15.7	15.5	14.2	12.6
2009	16.9	16.6	17.2	14.4
2010	15.5	15.1	14.7	12.9
Avg.	16	15.7	15.4	13.3

Table 6: Mean monthly minimum temperatures observed at Gangotri Glacier during 2008, 2009 and 2010

		Month		
Years	**June**	**July**	**Aug**	**Sept**
2008	6.1	7.1	6.4	1.8
2009	2.9	6.4	6.7	3.4
2010	3	6.7	5.1	4
Avg.	4	6.7	6.1	3.1

Table 7: Mean monthly relative humidity observed at Gangotri Glacier during 2008, 2009 and 2010

		Month		
Years	**June**	**July**	**Aug**	**Sept**
2008	85	91	92	76
2009	55	74	73	64
2010	57	63	67	64
Avg.	66	76	77	68

Table 8: Mean monthly sun shine hours observed at Gangotri Glacier during 2008, 2009 and 2010

		Month		
Years	**June**	**July**	**Aug**	**Sept**
2008	2.8	3	2.9	5.8
2009	9.4	9.6	8.9	7.6
2010	4.9	2.9	3	3.7
Avg.	5.7	5.1	4.9	5.7

Table 9: Mean monthly Total Evaporation observed at Gangotri Glacier during 2008, 2009 and 2010

	Month			
Years	**June**	**July**	**Aug**	**Sept**
2008	99.4	91.6	73.1	81.6
2009	143.2	124.8	105.6	87.1
2010	125.1	71.6	55.3	48.1
Avg.	122.5	96	78	72.3

Table 10: Mean Daily Evaporation observed at Gangotri Glacier during 2008, 2009 and 2010

	Month			
Years	**June**	**July**	**Aug**	**Sept**
2008	3.3	3	2.4	2.7
2009	4.8	4	3.4	2.9
2010	4.2	2.3	1.8	1.6
Avg.	4.1	3.1	2.5	2.4

Table 11: Total seasonal volume of discharge observed during different melt seasons (10 May - 11 October).

Year	V = Seasonal Volume MCM	Date of peak
2008	1099.6	**30.07.08**
2009	910.2	**08.08.09**
2010	1061.1	**22.08.10**
Mean	**1023.6**	-
SD	**100.1**	-
CV	**0.097**	-

Table 12 : Date of pass of maximum peak discharge during the melting seasons.

Year	Dis cumecs	Value of Centre of Gravity	Centre of Gravity pass on date	Values of Gravity on date of pass
2008	12727.5	**77**	25/07/08	145.6
2009	10534.9	**87**	04/08/09	136.1
2010	12281.8	**89**	06/08/10	130.5