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Prevailing Weather Conditions During Summer Seasons Around Gangotri Glacier

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Prevailing weather conditions during summer seasons around Gangotri Glacier

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Meteorological data collected near the snout of the Gangotri Glacier suggest that the study area receives less rainfall. The average seasonal rainfall is observed to be about 260 mm. The rainfall distribution does not show any monsoon impact. Amount of seasonal rainfall is highly variable (131.4–368.8 mm) from year to year, but, in general, August had the maximum rainfall. Average daily maximum and minimum temperatures were 14.7 and 4.1°C respectively, whereas average mean temperature was 9.4°C. July was recorded as the warmest month. During daytime, wind speed was four times higher than that at night-time. The average daytime and night-time winds were 12.6 and 3.0 km/h respectively. Mean seasonal evaporation was 640.8 mm, which is high with respect to the high altitude. Average relative humidity and daily sunshine duration were also high throughout the melting season.

MOST of the river systems such as the Indus, Ganga, Brahmaputra, Amu Darya, Hwang Ho and Yangtze, where major civilizations flourished, originate from the Himalayan and Trans-Himalayan glacierized mountains. The climatology of the upper part of the basins where glaciers exist, influences the hydrology of the downstream area. Climatology of upstream regions is particularly important for water storage, groundwater replenishment and flood control. The glacier melt run-off represents the integrated basin response to various climatic inputs, with precipitation and temperature being important. A long-term time series analysis of meteorological observations provides information, which can be used for studying glacier fluctuations as a response to global climate change[1].

Using a synthesis based on scaling, Meier and Bahr[2] globally estimated that there are at least 160,000 mountain glaciers and ice caps, totalling 680,000 km^2 in area, with a volume of 180,000 km^3 equivalent to a sea-level rise of 0.50 m (the statistics does not include the Greenland and Antarctic continental ice sheets). Snow and ice are, for many mountain ranges, key components of the hydrological cycle, and the seasonal character and amount of run-off is closely linked to the cryospheric processes. In addition, because of the sensitivity of mountain glaciers to temperature and precipitation, the behaviour of glaciers provides some of the clearest evidence of atmospheric warming and changes in the precipitation regime, both modulated by atmospheric circulation and flow patterns over the past decades[3,4].

Himalayan glaciers are particularly important natural archives of freshwater. Himalayan glaciers have a large variation in their size and their glaciation is also more intense than the Alps and Rockies. Understanding the regimes of the glaciers is important, because they are sources of information on high-mountain meteorology and hydrology, as also of palaeoclimatic data[5]. Meteorological records of the Himalayas are poorly documented in comparison to Alps, Caucasus and Tien Shan mountains. Poor accessibility, rugged terrains and harsh weather conditions are considered to be the major barrier to establish such a database. Although it is difficult to install and monitor the instruments required to collect data, it is of utmost importance in order to track the climate changes in the high-altitude Himalayan region. It is necessary to strengthen hydrometeorological network in high-altitude areas and improve the database. Analysis of such data helps to understand weather conditions, available water resources of the region, melting and other flow-generation processes, sediment transport processes, development of tourism and also to give an insight to the problems related to natural hazards, viz. flash floods, cloudbursts, landslides/rockslides and avalanches[6–12]. Recently, several events have been observed in the hilly terrain, when high-intensity rainfall during short intervals severely affected life and property. Cloudburst observed on 10 August 2002 in Tehri District[9], and 31 August 2001 in Tehri District[10], flood and landslide of June 2000 in Bhagirathi Valley[11] and flash flood of Chirgaon in August 1998 in the Yamuna Valley[12], are the few recent examples of such events that occurred in the Garhwal Himalayas. Here we describe the weather pattern around Gangotri Glacier in the Garhwal Himalayas based on the comprehensive results of meteorological parameters and their distribution with time. Required data were collected at an altitude of about 3800 m asl near the snout of the Gangotri Glacier for four consecutive melting seasons (May–October; 2000–2003). Such continuous climatic records for the whole summer season are usually not available.

Gangotri Glacier area and data collection

Gangotri Glacier is one of the largest glaciers in Garhwal Himalayas. It lies in the central crystalline zone within

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the latitudes 30°43′–31°01′N and longitudes 79°0′–79°17′E. The proglacial melt-water stream, known as Bhagirathi River, emerges from the snout of the Gangotri Glacier at an elevation of 4000 m asl. The Gangotri Glacier system (most commonly known as Gangotri Glacier) is a cluster of many glaciers comprising the main Gangotri Glacier (length: 30.20 km; width: 0.20–2.35 km; area: 86.32 km^2) as the trunk part of the system. Total catchment area of the Gangotri Glacier system up to the meteorological site established downstream the snout is about 556 km^2, out of which the glacierized area is about 286 km^2. Location map of the Gangotri Glacier system is shown in Figure 1.

For the present study, a standard meteorological observatory (30 m × 30 m) was established at about 3800 masl near the snout of the Gangotri Glacier and required data were collected. This observatory was equipped with ordinary raingauge, self-recording raingauge, thermograph, maximum and minimum thermometers, dry and wet bulb thermometers, hygrograph, evaporimeter, anemometer, wind vane and sunshine recorder. Standard timings for data collection were according to the practice followed by the India Meteorological Department (IMD). The observatory is located in the valley floor on right bank of the Bhagirathi River, about 3 km downstream to the snout of the glacier and surrounded by steep sloping hills. The valley floor has been extensively reworked and resedimented by glacial and paraglacial activity. The valley shows NW–SE trend within the granitic terrain. The Indian birch (*Betula utilis*) is the only tree found in and around the observatory.

Results and discussion

Rainfall

Rainfall and air temperature represent the most important parameters of meteorology for any particular region. They can be used as a climatic indicator of the region. Records of daily rainfall observed for the period 2000–03 near the snout of the Gangotri Glacier are shown in Figure 2 *a*. Analysis of rainfall records shows that out of the total rain events about 77% events provided daily rainfall less than or equal to 5 mm, contributing 33% of the total seasonal amount of rainfall. The rain events in the range of 5–10 mm represented about 13% of total rain events and contributed about 26% to the seasonal rainfall. Further, rain events having rainfall between 10 and 15 mm were only 4% and had contributed 12% of the total seasonal rainfall. Beside these light rain events, few major storms were observed in the study area, which contributed to the remaining part of seasonal rainfall. These results suggest that during the summer season daily rainfall hardly exceeds 15 mm in the study area, except some unusual heavy rainfall events. During the period of observation, two major storms occurred in the study area. The first major storm occurred in June 2000 and second one in September 2002. During the first major storm, rainfall occurred continuously for 6 days (5–10 June 2000) and a flash flood was generated. Rainfall observed at the site for 5–10 June was 4.5, 1.8, 16.5, 49.6, 55.5 and 3.6 mm respectively. Rainfall was not

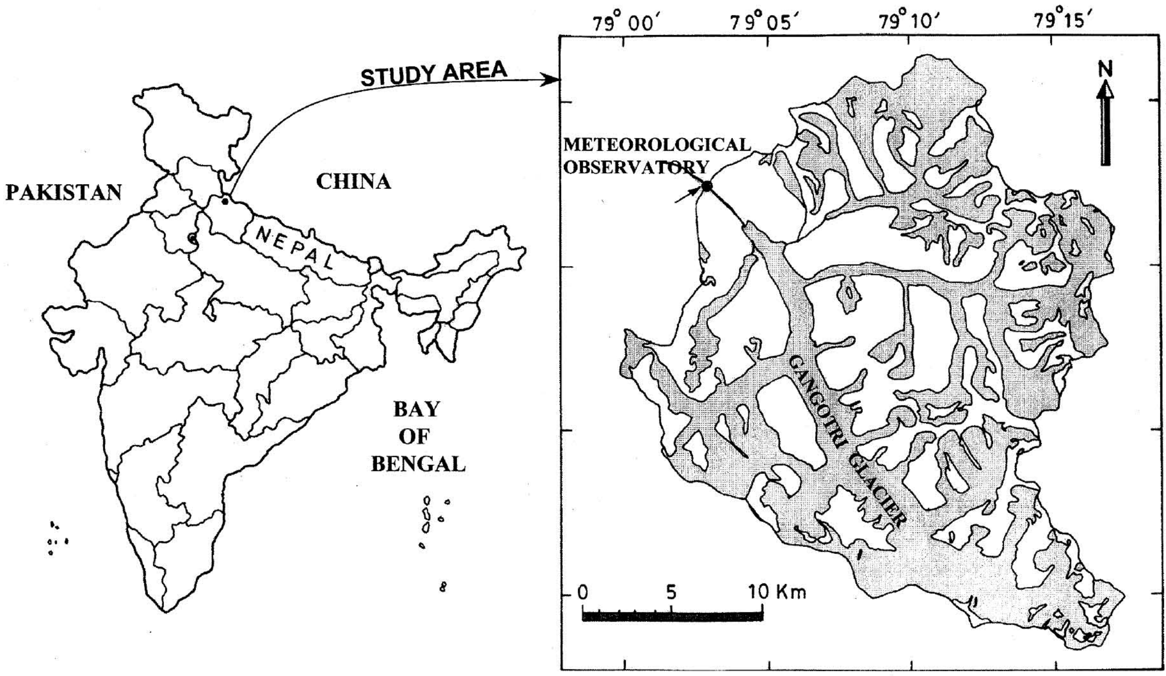

Figure 1. Location map of the study area showing meteorological observatory established near the snout of Gangotri Glacier (Bhojwasa, 3800 m). Dark portions represent the glacierized part of the study basin.

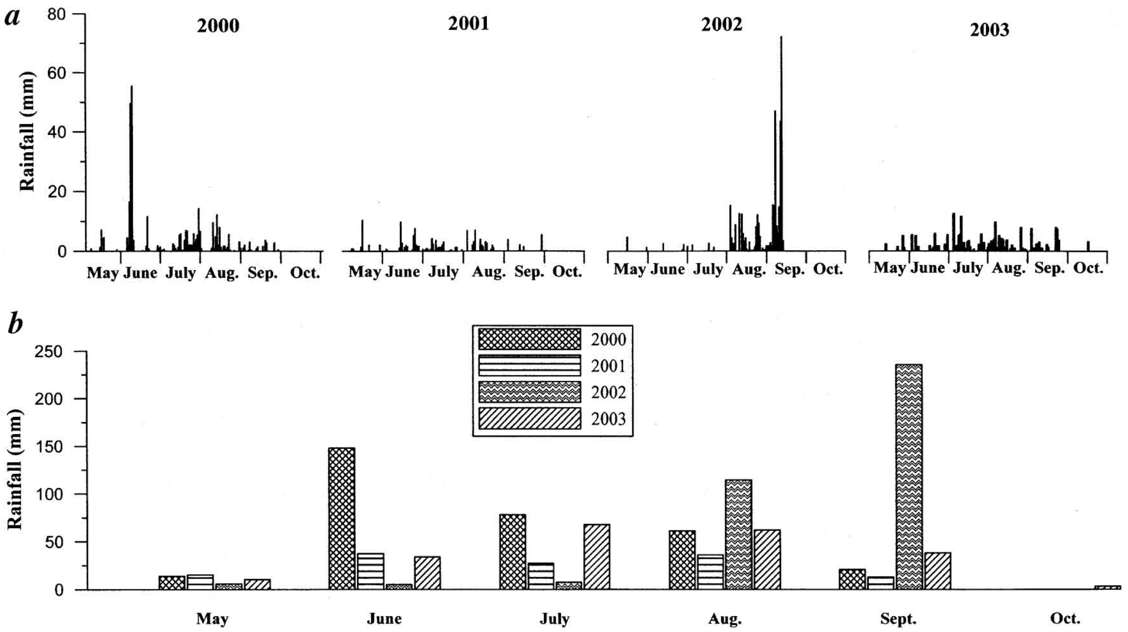

Figure 2. (*a*) Daily rainfall and (*b*) monthly rainfall observed near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during summer seasons 2000 to 2003.

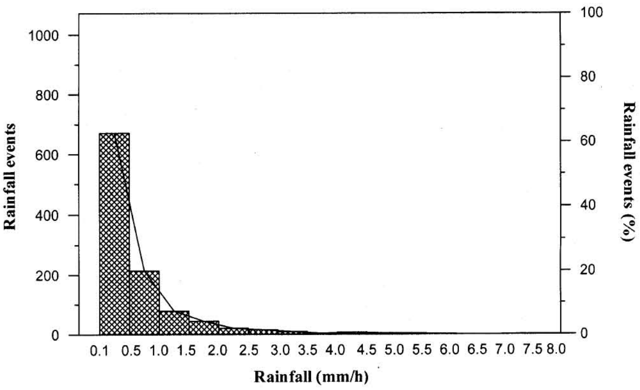

Figure 3. Frequency distribution of hourly rainfall observed near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during different summer seasons.

much (6.3 mm) on the first two days (5 and 6 June), but it was very high (121.6 mm) for the subsequent 3 days (7–9 June 2000) providing total rainfall of 131.5 mm. The maximum rainfall (55.5 mm) was recorded on 8 June 2000, the day on which the flood occurred. The second major storm sustained for 8 days (6–13 September 2002) and provided total rainfall of 222.8 mm. Day-wise rainfall was 15.4, 15.2, 47.0, 8.4, 6.1, 14.9, 43.6 and 72.2 from 6 to 13 September 2002, respectively. During the storms, rainfall was more or less continuous.

Records of daily rainfall during 2000–03 summer season indicate that highest rainfall (other than these two storms) observed was 14.3, 10.4, 15.3 and 12.6 mm respectively. A comparison of rainfall records indicates that maximum rainfall observed during the first storm was about four times higher than the highest daily rainfall of that year, whereas maximum rainfall during the second storm was about five times higher than the maximum rainfall recorded during that year. Furthermore, the total rainfall during the first storm was even equal to the total melt season rain during the storm-free year 2001, which was 131.4 mm. The total rainfall during the second storm was much higher than the total rain during year 2001 and almost equal to the total rain observed during the melting season 2003 (215.5 mm).

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 during July–September, and total seasonal rainfall varied accordingly. For example, the total rainfall for the whole summer season (May–October) for the period 2000–03 was found to be 322, 131, 369 and 216 mm respectively. Based on available rainfall records, average monthly rainfall for May–October has been computed to be 12.0, 56.1, 45.2, 68.5, 76.9 and 0.8 mm respectively. It shows that August and September experienced relatively higher rainfall during summer period. The average seasonal rainfall was observed to be about 260 mm.

Hourly rainfall observations were used to study the rainfall intensity and its variation with time. The frequency distribution of hourly rainfall for the Gangotri Glacier area is shown in Figure 3. It is found that about 63% hourly rainfall events represented rainfall intensity between 0.1 and 0.5 mm/h and 20% events between 0.5 and 1.0 mm/h. There were very few events representing intensity higher than 3 mm/h. The maximum intensity of rain (7.6 mm/h) was observed on 22 September 2003 at 2400 h. Results show that mostly light-intensity rain (drizzle-type) was predominant, providing daily rainfall < 5.0 mm over the whole day.

Rainfall observations clearly indicate that although the intensity was higher in May, the number of rainy events was much lower during this month. Whereas in July, when the monsoon approaches, the total number of rain events increased due to drizzle-type of rainfall throughout the day. It also shows that the timings of rainfall occurrence varied over the summer season. Maximum rainfall events occurred either in the evening or early morning and, generally, the least rainfall events were recorded between 0800 and 1400 h, except in August and September. At the start of the melt season, the rainfall occurs mostly due to formation of convective clouds. As the melting season advances and monsoon season (July–September) approaches, the frequency of rainfall increased due to a combination of local convective activity and a partial influence of monsoon. It resulted in the possibility of rainfall any time during the day and night. However, the trend of rainfall occurrence shows that late evening or early morning was the most probable time for the occurrence of rainfall. It is to be pointed out that most of the moisture in the monsoon clouds precipitates before they reach the high-altitude regions beyond 4000 masl, like the present study area and, therefore, have only limited influence on rainfall[13,14].

Generally, orographic effect on precipitation is found in the high-altitude mountainous regions[15]. Altitude controls both temperature and rainfall. Mountains act as barriers and force the moisture-bearing winds to ascend, resulting in such effects on precipitation. Precipitation is concentrated on the windward slopes, and a rain shadow is produced on the leeward side. The summer monsoon in India produces heavy rainfall on the southern slopes of the Himalayas, whereas north Himalayan ranges are deprived of precipitation[16]. Some studies show that rainfall increases with altitude up to about 2500 masl, and then starts decreasing. Studies related to rainfall characteristics during monsoon season in high mountain areas of Nepal Himalayas suggest that rainfall decreases with altitude in the range from 2800 to 4500 masl[17]. Loukas and Quick[18] have shown that rainfall depth per event increased up to mid-elevation of a mountainous watershed in British Columbia, and then decreased at higher elevations. It was observed that in the Greater Himalayan range, rainfall decreased exponentially with elevation[13]. Generally, during the summer period a little precipitation (100–300 mm) is observed at high altitudes in the Himalayan region[19]. Rainfall in the Gangotri region was also in the same range. However, orographic effect on rainfall in the study region is yet to be investigated.

Air temperature

Daily maximum and minimum air temperatures observed near the snout of Gangotri Glacier for different years are shown in Figure 4. In order to eliminate aberrations and reveal the real trend of data series, a seven-day running mean is also shown in Figure 4. Broadly, the trend of changes in temperature over the summer season is found to be almost similar for all the years, i.e. it follows increasing trend till July and then starts decreasing. It is observed that changes in minimum temperature are more significant than those in maximum temperature. Diurnal variations in temperature indicate that, generally, maximum temperature is observed around 1400 h, while the minimum is observed in the early morning hours. Over the study period, average daily maximum and minimum temperatures were computed to be 14.7 and 4.1°C respectively, whereas average mean temperature was 9.4°C. As usual, sudden drops in air temperature were observed during rain or snowfall events. For example, during a six-day rainstorm in June 2000, the mean temperature dropped to about 6.4°C, which represents a deviation of –3.0°C from the mean temperature of June 2000 (9.45°C). Similarly, during an eight-day storm in September 2002, the mean temperature dropped to 3.8°C, which represents a deviation of –2.3°C with respect to the mean value of September 2002 (6.1°C).

The distribution of temperature over the summer season has also been studied. The mean monthly maximum temperatures for May–September and October were 15.4, 15.6, 16.2, 15.0, 13.2 and 12.4°C respectively, whereas mean monthly minimum temperatures for these months were 2.3, 5.0, 7.0, 6.5, 2.9, and –1.5°C respectively. The corresponding mean monthly temperatures for these months were computed to be 8.8, 10.3, 11.7, 10.8, 8.0 and 5.4°C respectively. Based on the available temperature records, it is found that July was the warmest month of the summer season in the study area. The average diurnal range of temperatures (difference of maximum and minimum temperature) for May–October were 13.2, 10.6, 9.2, 8.5, 10.2 and 13.4°C, respectively. It reveals that the diurnal temperature range was highest in May and October, and lowest in August. Minimum diurnal temperature range in August is possible due to minimum sunshine hours (or presence of more clouds) in this month. The presence of clouds prevents the shortwave solar radiation in the daytime to heat the surface and longwave radiation in the night-time to emit the heat, resulting in lower temperature range. The reverse is true for the months of May and October.

Wind speed and direction

In the high-altitude regions the transport of moisture, formation of clouds, occurrence of precipitation and melting of glaciers are primarily affected by the wind regime. Wind speed and directions were observed four times a day (0830, 1130, 1430 and 1730 h) which made it possible to study the changes in wind speed and direction. It also helps in determining the daytime and night-time wind regimes. Daytime (0830–1730 h) and night-time (1730–0830 h)

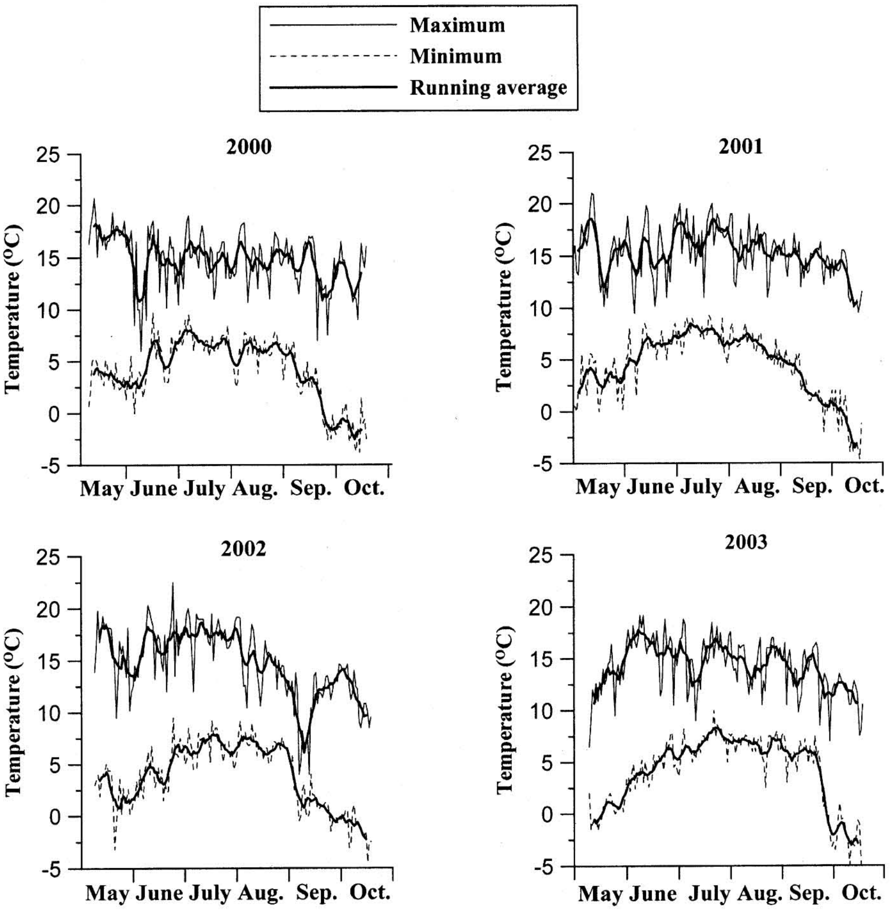

Figure 4. Daily maximum and minimum air temperature observed near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during summer seasons 2000–03. A seven-day running mean average can also be seen.

wind speeds observed for different years are shown in Figure 5. On the seasonal scale, mean daytime and night-time winds were 12.6 and 3.0 km/h, respectively, which shows that the average daytime wind speed is about four times higher that at night-time. The daily mean wind speeds for May–October were 8.3, 6.9, 6.2, 5.5, 5.9 and 7.1 km/h, respectively. Average wind speed for the whole season was found to be 6.6 km/h. Wind directions observed over the melt period for different seasons have been depicted through wind roses (Figure 6). It shows that during the summer season, the wind blew from northwest direction most of the time, i.e. from the valley towards the mountain. The diurnal variation in daytime wind speed shows that strong winds (>10 km/h) blew during the daytime, being maximum (about 15 km/h) at 1430 h. A change in the wind direction was noted after sunrise and during late evening. 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 about rapid cooling of the mountain slopes resulting into cooler air blowing into the valley below. The upslope valley wind in the mountain areas accelerates the cloud formation processes.

Evaporation

Evaporation is an important component of the hydrological cycle and plays a vital role in studying the hydrology of the basin/region, especially for water balance and modelling of streamflow studies. Atmospheric temperature, wind velocity, wind direction and relative humidity are the main meteorological parameters that control evaporation from the basin. Mean daily pan evaporation observed is 4.9, 3.8, 3.5, 2.8, 2.9 and 3.1 mm for May–October respectively. Evaporation was maximum in May and minimum in August. Lower relative humidity, high sunshine hours and high wind speed are responsible for higher evaporation observed during May, while low evaporation in August is possible due to less number of sunshine hours and high relative humidity. The one-day maximum value of pan evaporation was observed to be 8.5 mm, while minimum

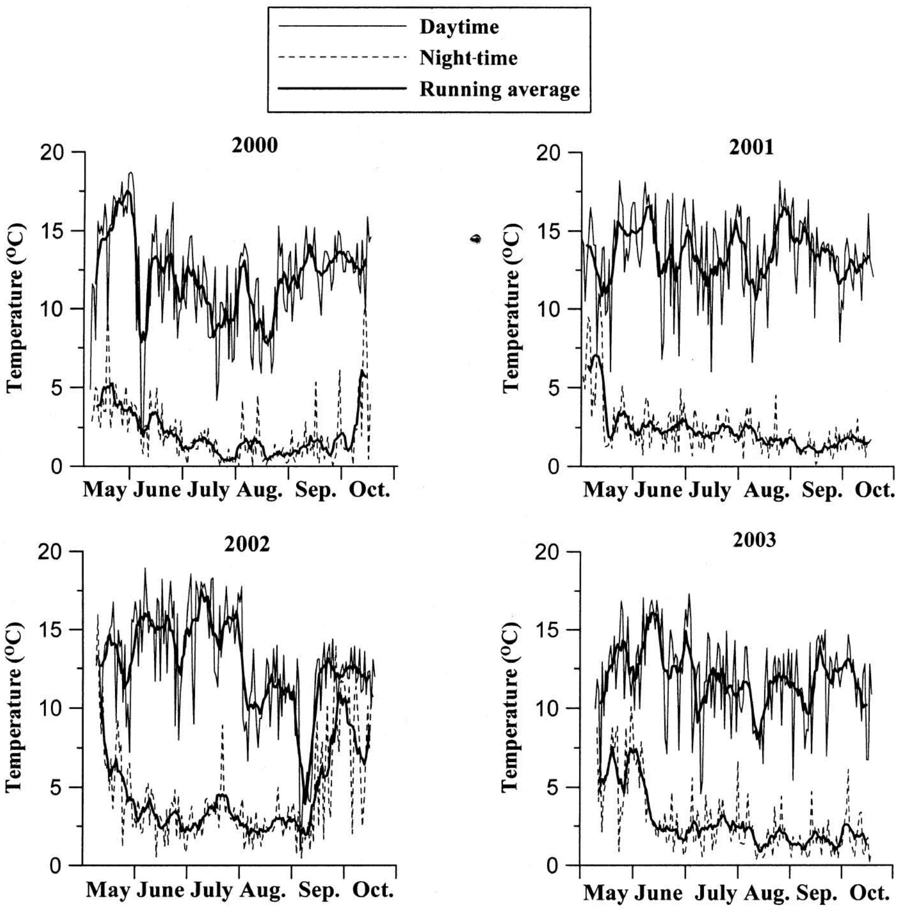

Figure 5. Daily daytime and night-time wind speeds observed near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during summer seasons 2000–03. A seven-day running mean average can also be seen.

was recorded to be zero. Mean monthly total evaporation during four ablation periods was 150.6, 113.4, 106.9, 85.5, 87.7 and 96.6 mm for May–October respectively. Distribution of monthly pan evaporation is shown in Figure 7. The total pan evaporation during the summer seasons 2000–03 was 628.7, 660.6, 680.2 and 593.6 mm respectively. Based on total records, mean daily evaporation for the summer season as a whole is found to be 3.5 mm.

Relative humidity

No significant changes were observed in relative humidity from year to year. Over the study period, daily values of relative humidity ranged between 44 and 100%. Maximum humidity is always associated with low air temperature and high rainfall or cloudy conditions and the opposite is true for minimum humidity. Mean monthly relative humidity was 69, 83, 88, 89, 78 and 67% for May–October respectively. These results suggest the dependency of relative humidity over air temperature, rainfall and cloud cover. As such, in the beginning (May) and at the end (October) of the summer season, the air temperature is low, rainfall and cloud cover are less in comparison to the other months (June–September). Therefore, it is possible that a combination of such weather conditions would have contributed to a lower value of relative humidity during May and October. Average relative humidity over the different summer seasons varied between 77 and 83%.

Sunshine hours

The average sunshine hours for May–October were observed to be 7.2, 5.4, 4.7, 4.0, 5.2 and 6.8 respectively. Results indicate that the study area experienced maximum sunshine hours in May followed by October, when the weather condition is clear and the rainfall is either negligible or nil. On the other hand, minimum sunshine hours were recorded during August, when high rainfall occurs. Over the study period, maximum daily sunshine hours reached up to 11.1 h (28.06.2001), while minimum sunshine hours were almost zero. On the seasonal scale mean daily sunshine hours were computed to be 5.6 h.

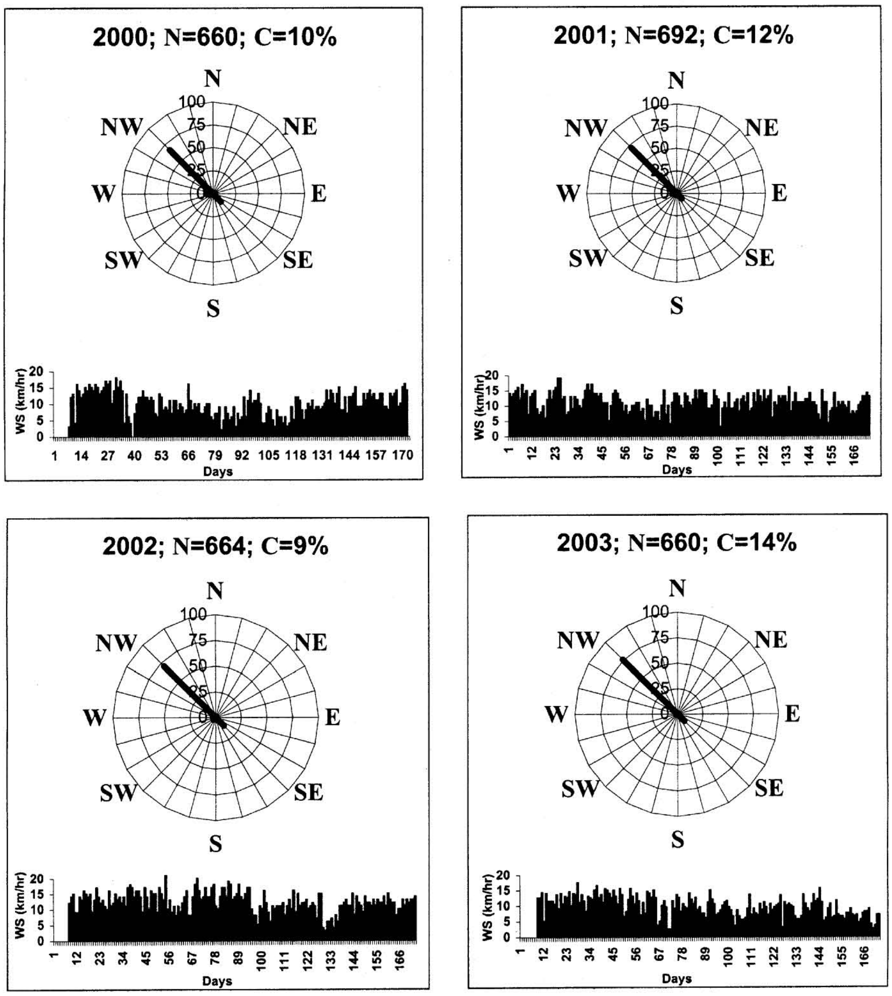

Figure 6. Average daily wind speed (WS) and direction observed near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during different summer seasons. *N*, Number of observations, *C*, Calm wind.

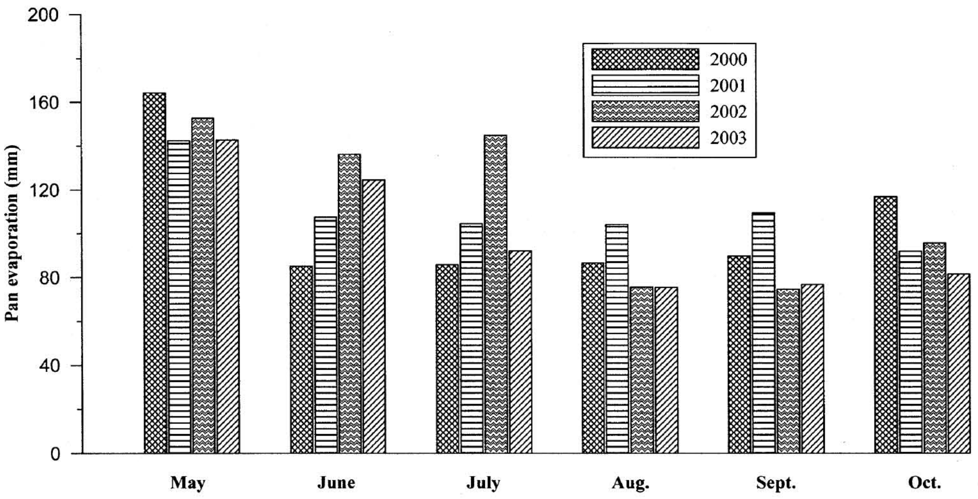

Figure 7. Monthly pan evaporation observed for different months near the snout of Gangotri Glacier (Bhojwasa, 3800 m) during summer seasons 2000–03.

Conclusions

Climatology of the high-altitude, glacierized region is different from that in the plains. This article presents the results of detailed meteorological observations conducted for four-summer seasons (May–October; 2000–03) on the Gangotri Glacier. Results show less rainfall, low air temperature, high wind speed, high evaporation and moderately high humidity. Average seasonal (May–October) rainfall was about 260 mm. Daily rainfall hardly exceeds 15 mm in the study area. About 77% rain events recorded daily rainfall of less than 5 mm. Relatively good rainfall occurs in this area during July–September. Inter-seasonal variability of rainfall over the summer season is much higher. Analysis of rainfall intensity shows that about 63% hourly rainfall events represented rainfall intensity between 0.1 and 0.5 mm/h, showing that mostly light intensity rain (drizzle type) occurs in the study area. Daily rainfall was recorded to be < 5.0 mm.

The average daily maximum and minimum temperatures over the summer season were computed to be 14.7° and 4.1°C respectively, whereas average mean temperature was 9.4°C. Diurnal variations in temperature indicate that generally maximum temperature is observed around 1400 h, while the minimum is observed at the early morning hours. July was observed as the warmest month in all years. Diurnal range of temperature was found to be higher in May and October due to relatively cloud-free weather conditions, while it was lowest in August due to generally cloudy conditions. Results indicate that changes in minimum temperature are more significant than the changes in maximum temperature. Strong winds were observed during daytime and would have contributed to high rate of evaporation even at high altitudes. High sunshine hours in the region are also responsible for higher evaporation. In general, high relative humidity was observed throughout the melt period.

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