

Meteorological study for Gangotri Glacier and its comparison with other high altitude meteorological stations in central Himalayan region

Pratap Singh¹, Umesh K. Haritashya² and Naresh Kumar¹

¹National Institute of Hydrology, Roorkee-247 667(U.A.), India. E-mail: pratap@nih.ernet.in;
pratap_singh_1@yahoo.com

²Department of Earth Sciences, Indian Institute of Technology, Roorkee-247 667(U.A), India

Received 14 September 2005; accepted in revised form 28 June 2006

Abstract In spite of the vital role of high altitude climatology in melting of snow and glaciers, retreat or advancement of glaciers, flash floods, erosion and sediment transport, etc., weather conditions are not much studied for the high altitude regions of Himalayas. In this study, a comprehensive meteorological analysis has been made for the Gangotri Meteorological Station (Bhagirathi Valley, Garhwal Himalayas) using data observed for four consecutive melt seasons (2000–2003) covering a period from May to October for each year. The collected meteorological data includes rainfall, temperature, wind speed and direction, relative humidity, sunshine hours and evaporation. The results and their distribution over the different melt seasons were compared with available meteorological records for Dokriani Meteorological Station (Dingad Valley, Garhwal Himalayas) and Pyramid Meteorological Station (Khumbu Valley, Nepal Himalayas). The magnitude and distribution of temperature were found to be similar for different Himalayan regions, while rainfall varied from region to region. The influence of the monsoon was meagre on the rainfall in these areas. July was recorded to be the warmest month for all the regions and, in general, August had the maximum rainfall. For all the stations, daytime up-valley wind speeds were 3 to 4 times stronger than the nighttime down-valley wind speeds. It was found that the Gangotri Glacier area experienced relatively low humidity and high evaporation rates as compared to other parts of the Himalayas. Such analysis reveals the broad meteorological characteristics of the high altitude areas of the Central Himalayan region.

Keywords Gangotri Glacier; glacierized basin; high altitude; Himalayas; meteorology

Introduction

The worldwide distribution of fresh water shows that a significant quantity (~80%) of fresh water is stored in the form of snow and ice. In terms of areal extent, glaciers occupy about 11% of the total land area. About 3% of the permanent snow and ice is available in the mountains outside the polar regions. Asian high mountain glaciers occupy an area of about 50% of all glaciers existing in the mountains and a large proportion drain into the landmass of the Indian subcontinent. The glacial area of Central Asian mountains is over one million km² (Flint 1971) and, out of this, over 50,000 km² area is covered by glaciers, which drain into Himalayan rivers (Bahadur 1987). Major river systems such as the Indus, Ganga, Brahmaputra, Amu Darya, Hwang Ho and Yangtze, where important civilizations flourished, have originated from the Himalayan and trans-Himalayan mountains. The high altitude of the Himalayan mountains favours the large extent of snow and ice. Moreover, in terms of availability of snow and ice, the high altitude character of the Himalayas compensates for its location at low latitudes with high insolation.

Looking at the cyclic process of snow accumulation and melt in the Himalayan region, fresh snowfall starts in the upper reaches by the end of September and continues till March, providing maximum snow thickness during February/March. By the end of the winter season, the snow line moves down and touches an elevation of about 2000 m a.s.l. The major sources of moisture for the precipitation in the form of snow are the western disturbances. Such a pattern exists in most of the Himalayan glaciers with the exception of a few summer accumulation type glaciers where accumulation occurs during the monsoon period (Higuchi *et al.* 1982; Ageta and Higuchi 1984). Usually, melting of snow starts at the end of March and continues until October, providing a substantial contribution from snow and glaciers in the Himalayan rivers.

Hydro-meteorological records for the Alps, Caucasus and Tien Shan mountains are available since the early twentieth century, but detailed information on the climatic conditions in the high altitude regions of the Himalayas is rarely available. For example, there are very limited data available at and beyond 4000 m a.s.l. It is understood that poor accessibility, rugged terrain and harsh weather conditions make it considerably more difficult to install and monitor the climatic records. Consequently, pattern of precipitation, temperature and other meteorological parameters are not well known except for a few glaciers (Higuchi *et al.* 1982; Ueno *et al.* 2001). Lack of such information on climatic phenomena contributes to a poor understanding of melting and other flow generation processes in the high altitude regions. These analyses are necessary as, during summer, a substantial amount of melt runoff drains from the high altitude regions to the Himalayan rivers (Singh and Singh 2001; Singh and Jain 2002, 2003).

The present study involves a comprehensive analysis of meteorological data observed during 4 consecutive melt seasons (2000–2003) at Gangotri Meteorological Station (GMS) (3800 m a.s.l.) located near the snout of the Gangotri Glacier. The results of the analysis were compared with the data collected at Dokriani Meteorological Station (DMS) (4000 m a.s.l.) located near the snout of the Dokriani Glacier during 4 consecutive melt seasons (1995–1998) and at Pyramid Meteorological Station (PMS) (5050 m a.s.l.) located in the Khumbu Valley on the confluence of the Lobuche Glacier and Khumbu Glacier for 5 consecutive melt seasons (1994–1998). Although the timeframe for which data sets were collected at GMS is different from DMS and PMS we consider that such analysis provides an insight into the climatology, hydrology and sediment generation process studies of the glacierized basin (Haritashya *et al.* 2005), which is important for the management of water resources and other natural disasters like landslides/rockslides, etc.

Study area

For this study the data sets observed at Gangotri Meteorological Station (GMS) (lat. 30°57'N and long. 79°03' E; 3800 m a.s.l.) located near the snout of the Gangotri Glacier is taken as the base data. The Gangotri Glacier is the largest and most important glacier of Bhagirathi Valley in the Garhwal Himalayan region. The valley shows a NW–SE trend within the granitic terrain. The inventory of Himalayan glaciers indicates that glaciers of varying dimensions occupy about 10% area of the Bhagirathi basin. The proglacial melt water stream, known as Bhagirathi River, which is one of the major sources of the river Ganges, emerges from the snout of Gangotri Glacier at an elevation of 4000 m a.s.l. The Gangotri Glacier system, most commonly known as the Gangotri Glacier, is a cluster of many glaciers. Total glacierized area of the Gangotri Glacier system is about 286 km². Therefore, climatic studies are very useful in estimating the melt runoff from the glacierized part of the basin. The hydrological characteristics of the glacier suggest that melting from this area is temperature-driven. Monthly distribution of runoff indicates maximum runoff in July

(30.2%) followed by August (26.2%). Distribution of SSC is similar to discharge: the maximum in July is followed by August (Haritashya et al. 2005).

The results of this study have been compared with such records available for the Dokriani Meteorological Station (DMS) (lat. 31°51' N and long. 78°47' E; 4000 m a.s.l.) located near the snout of the Dokriani Glacier in Dingad Valley, Garhwal Himalayas during melt season 1995–1998 and for Pyramid Meteorological Station (PMS) (lat. 27°58' N and long. 86°48' E; 5050 m a.s.l.) located in the Khumbu Valley (Nepal Himalayas) on the confluence of the Lobuche Glacier and Khumbu Glacier during melt season 1994–1998. The PMS is an automatic weather station (AWS) installed by the Italian National Research Council Institute of Water Research (IRSA/CNR) in the vicinity of Mount Everest. This is one of the highest operating meteorological stations in the Himalayan range. All three stations (GMS, DMS and PMS) lie in the Central Himalayan region (Figure 1). Bollasina et al. (2002) and Singh et al. (2003) reported a detailed description of the PMS and DMS, respectively.

Establishment of Gangotri Meteorological Station (GMS) and data collection

To collect the information on meteorological parameters, a standard meteorological station (GMS) (30 m × 30 m) was set up at about 3800 m a.s.l in the valley floor on the right bank of the Bhagirathi River, about 3 km downstream from 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 Indian birch (*Betula utilis*) is the only tree found in and around the observatory. Several meteorological instruments are installed in the observatory from which automatic recording instruments provide round-the-clock (24 h) observations, while some were observed manually following standard frequency of observations during the daytime. Time intervals of data collection were adopted according to the practice

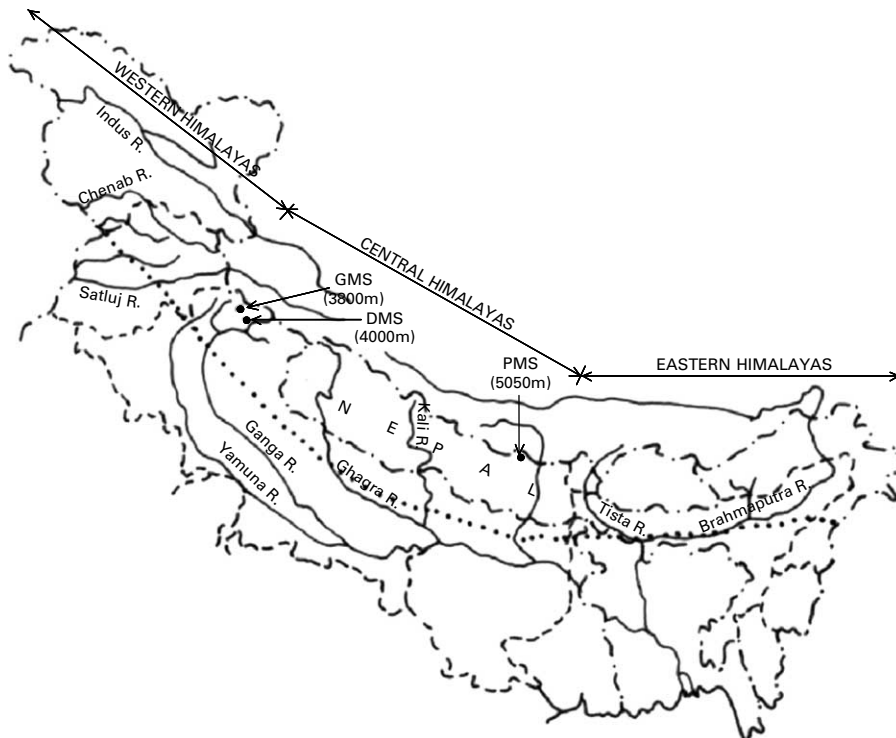


Figure 1 Location of the Gangotri Meteorological Station (GMS: 3800 m a.s.l.), Dokriani Meteorological Station (DMS: 4000 m a.s.l.) and Pyramid Meteorological Station (PMS: 5050 m a.s.l.)

followed by the Indian Meteorological Department (IMD). The continuous records provided short-term (hourly) information for these variables. Table 1 gives the information on the different types of instruments, their observations and measuring time intervals. These observations were made for four consecutive melt seasons 2000–2003 (May–October).

Data collected from the GMS (2000–2003) were compared with the data collected at DMS (1995–1998) and PMS (1994–1998). Like GMS (3800 m a.s.l.), DMS is located at an altitude of about 4000 m a.s.l. and equipped with all the above listed instruments. PMS had an automatic weather station located at an elevation of 5050 m a.s.l and was equipped with sensors shown in Table 2.

Analysis of meteorological data

Precipitation

Records of daily rainfall observed for 2000, 2001, 2002 and 2003 GMS are shown in Figure 2(a). These observations indicate that daily rainfall hardly exceeds 15 mm in the study area. Analysis of rainfall records shows that, out of the total rain events, about 77% of events provided a daily rainfall less than or equal to 5 mm, 15% in the range of 5–10 mm and only 4% between 10–15 mm. These results suggest that during the melt season mostly light rain occurred in the study region, except for some unusual heavy rainfall events. During the period of observations, two major storms were observed in this area. The first major storm occurred in June 2000 and the second one in September 2002. During the first major storm, the rainfall occurred for 6 days (5–10 June, 2000) providing a total rainfall of 131.5 mm and maximum daily rainfall of 55.5 mm on June 8, 2000. The second major storm lasted for 8 days (6–13 September, 2002) and provided a total rainfall of 222.8 mm. The maximum daily rainfall observed during this event was 72.2 mm, which occurred on September 13, 2002.

Distribution of monthly rainfall for different years at GMS 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 during the melt season 2000, 2001, 2002 and 2003 was found to be 322.3, 131.4, 368.8 and 215.5 mm. Based on available rainfall records, average monthly total rainfall for May, June, July, August, September and October has been computed to be 12.0, 56.1, 45.2,

Table 1 Meteorological instruments, observations and time interval installed at the Gangotri Meteorological Station (GMS) located at 3800 m a.s.l

S. no.	Instruments	Observations	Time of observations
1	Ordinary raingauge	Rainfall	08:30 & 17:30 h
2	Self recording raingauge	Continuous rainfall/rain intensity	24 h
3	Bimetallic thermograph	Continuous temperature	24 h
4	Max. & min. thermometers	Max. & min. temperatures	08:30 & 17:30 h
5	Hair hygograph	Relative humidity	24 h
6	Pan evaporimeter	Pan evaporation	08:30 & 17:30 h
7	Cup-type anemometer	Wind speed	08:30, 11:30, 14:30 & 17:30 h
8	Wind vane	Wind direction	08:30, 11:30, 14:30 & 17:30 h
9	Campbell–Stokes sunshine recorder	Sunshine hours	06:00 h

Table 2 Meteorological observations and sensor technical characteristics installed at the Pyramid Meteorological Station (PMS) located at 5050 m a.s.l

S. no.	Observations	Sensor characteristics
1	Rainfall	Tipping bucket
2	Air temperature	Thermistor
3	Wind speed	3 cups rotor, photochopper type
4	Wind direction	Direction vane, optical encoder
5	Relative humidity	Hygrometer

68.5, 76.9 and 0.8 mm, respectively. It shows that August and September experienced relatively higher rainfall during the melt period.

Hourly rainfall observations were used to study the rainfall intensity and its variation with time. The frequency distribution of hourly rainfall at GMS is shown in [Figure 3\(a\)](#) and the observed range of rain intensity is given in [Figure 3\(b\)](#). It is found that about 63% of hourly rainfall events represented the rainfall intensity between 0.1 and 0.5 mm/h and 20% events between 0.5 to 1.0 mm/h. There were very few events representing intensities higher than 3 mm/h. The maximum intensity of rain (7.6 mm/h) was observed on September 22, 2003 at around 24:00 h. Results show that mostly light intensity rain (drizzle type) was predominant providing daily rainfall < 5.0 mm over the whole day.

Diurnal pattern of rainfall observed during four consecutive melt seasons provides information on the timing of rainfall occurrence and can also be used to study the influence of the monsoon on the occurrence of rainfall in and around the GMS. Monthwise average rainfall intensity and corresponding rainfall events are shown in [Figure 4](#). These observations clearly indicate that, although the intensity was higher in May, the numbers of rain events were much lower in this month, whereas in July, the total number of rain events increased due to drizzle type of rainfall throughout the day. [Figure 4](#) shows that the timings of rainfall occurrence varied over the melt period. Maximum rainfall events occurred either in the evening or early morning and, generally, the least rainfall events were recorded between 08:00 h to 14:00 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, the frequency of rainfall increased due to a combination of local convective activity. This results in the possibility of rainfall at any time during the day and night. However, the trend of rainfall occurrence still shows that late evening or early morning is the most probable time for the occurrence of rainfall. It has to be pointed out that most of the moisture of monsoon clouds precipitates before they reach the high altitude region beyond 4000 m a.s.l. like the GMS and, therefore, has little influence on rainfall ([Singh et al. 1995](#); [Singh and Kumar 1997a, b](#)). The two major storms as discussed above were also a result of local convective activity.

Generally, during the melt period a little precipitation (100–300 mm) is observed at such high altitudes in the Himalayan region ([Singh et al. 2003](#)). Therefore, it is interesting to compare the observed quantity of monthly and seasonal rainfall at GMS with other available records of high altitude meteorological stations such as DMS and PMS ([Figure 5](#)). This comparison shows that, however, the distribution of rainfall was similar, being maximum rainfall in August, in different Himalayan regions, but monthly and seasonal rainfall varied significantly from region to region. For example, [Singh and Ramasastri \(1999\)](#) reported unusually high seasonal rainfall (1041 mm) at DMS, which is located at an altitude of 4000 m a.s.l. near Dokriani Glacier. The rainfall was maximum in August (376 mm), followed by July (245 mm). The presence of dense forest cover in the downvalley, which provides sufficient moisture through evapotranspiration, is believed to be the main cause of such high

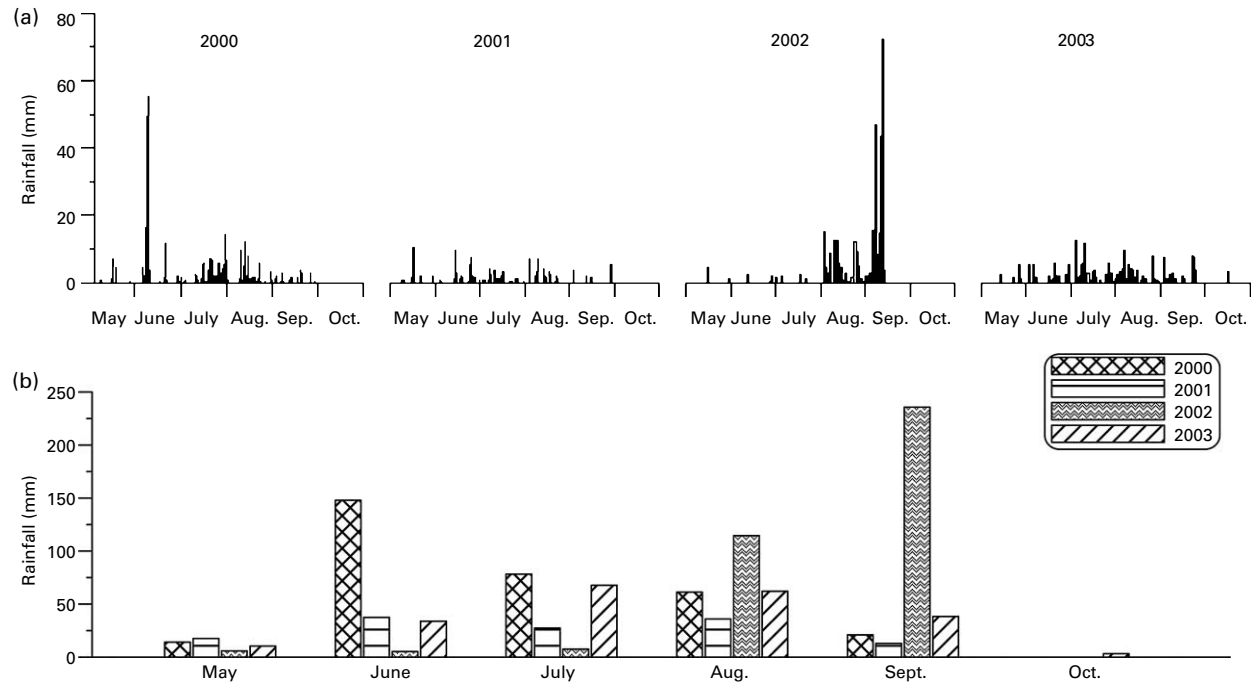


Figure 2 (a) Daily rainfall and (b) monthly rainfall observed at Gangotri Meteorological Station (GMS) during different melt seasons

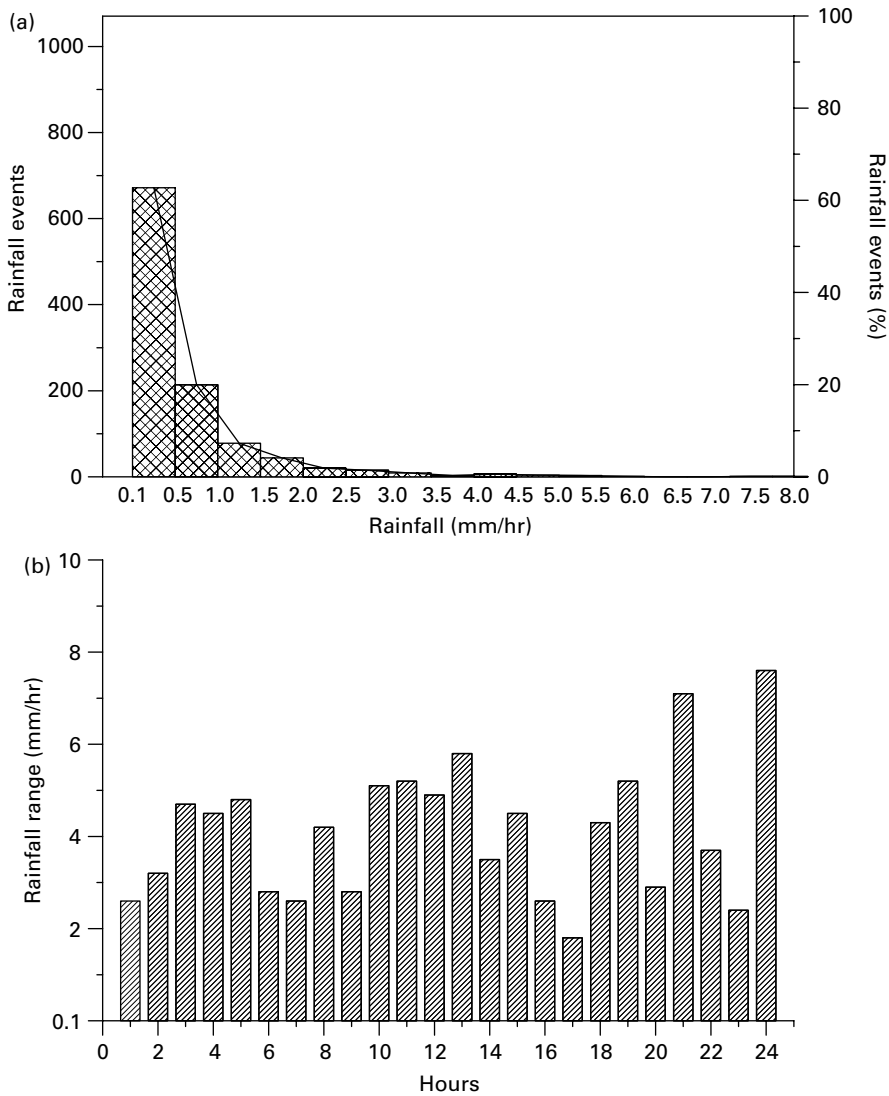


Figure 3 (a) Frequency distribution of hourly rainfall and (b) range of hourly rainfall observed at Gangotri Meteorological Station (GMS)

rainfall in this area. Availability of moisture helps in the formation of local convective clouds in the high altitude region, which results in rainfall. Strong winds in the region have added to strengthen the rain making processes. We would like to point out that the raingauge at DMS is neither in the dense forest nor has been sheltered from strong winds.

Recently, [Bollasina et al. \(2002\)](#) have reported the distribution of precipitation at PMS for a period of 5 years (1994–1998). The comparison of rainfall suggests that, although PMS was located at a higher altitude, the rainfall received at this station was higher than GMS. Average monthly total rainfall recorded at PMS for May, June, July, August, September and October was 17.5, 66.3, 126, 147.6, 58.9 and 10.4 mm, respectively. The average seasonal (May–October) precipitation was around 427 mm. From June to September, precipitation occurred on more than 85% of the days, with the highest frequency in August, whereas at GMS precipitation occurred during this period on 44% of the days. Rain occurred here mainly from the afternoon through the night. Moreover, the rainfall intensity at PMS was

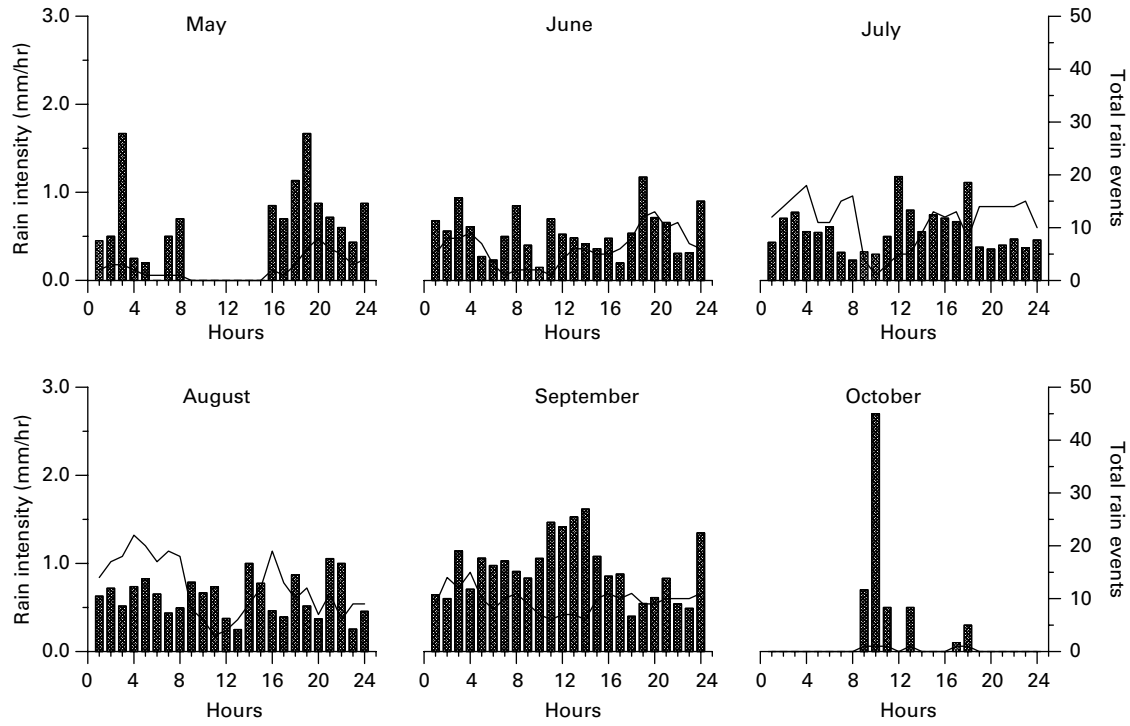


Figure 4 Diurnal variation in mean rainfall intensity (bar and left side axis) and total number of rainfall events (continuous line and right side axis) for different months observed at Gangotri Meteorological Station (GMS)

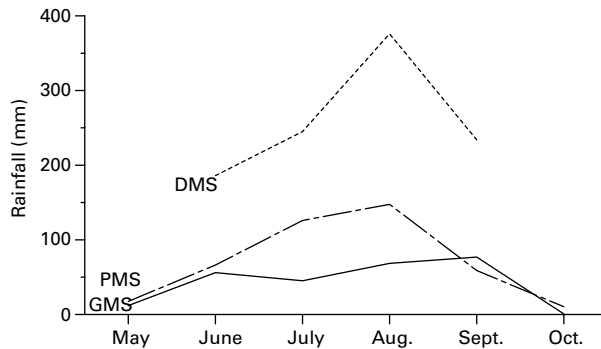


Figure 5 A comparison of mean monthly total rainfall observed at Gangotri Meteorological Station (GMS: 3800 m a.s.l.), Dokriani Meteorological Station (DMS: 4000 m a.s.l.) and Pyramid Meteorological Station (PMS: 5050 m a.s.l.) during different melt seasons

about 0.3–0.55 mm/h, which is less than GMS (0.1–3 mm/h), which may be because of elevation difference of about 1,200 m in these two sites. These results suggest that perhaps the influence of the monsoon is higher at PMS as compared to the Gangotri Glacier station.

Air temperatures

Air temperature is one of the most important meteorological parameters associated with the climatic characteristics of the area. It can also be used as a climatic indicator for a particular region. Daily maximum, minimum and mean air temperatures observed at GMS for different years are shown in Figures 6(a, b). In order to eliminate aberrations and reveal the real trend of data series, a 7-d running mean is also shown in this figure. Generally, the trend of changes in temperatures over the melt season is found to be almost similar for all the years, i.e. it follows an increasing trend till July and then starts decreasing. It is observed that the changes in minimum temperature are more significant than the changes in maximum temperature. Diurnal variations in temperature indicate that, generally, maximum temperature is observed around 14:00 h, while the minimum is observed in the early morning. Over the study period, average daily maximum and minimum temperatures were computed to be 14.8 °C and 4.1 °C, respectively, whereas average mean temperature was 9.4 °C. The frequency analysis of hourly temperature records shows that the most frequently prevailing temperature was between 8.0–10.0 °C. Sudden drops in air temperatures were observed during rain or snowfall events. For example, during a 6-d rain storm in June 2000, the mean temperature dropped to about 6.4 °C, which represents a change of -3.0 °C from the mean temperature of June 2000 (9.45 °C). Similarly during an 8-d storm in September 2002, the mean temperature dropped to 3.8 °C, which represents a change of -2.3 °C with respect to the mean value of September 2002 (6.1 °C).

The mean monthly maximum temperatures for May, June, July, August, 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. The corresponding mean monthly temperatures for these months were computed to be 8.9, 10.3, 11.7, 10.8, 8.0 and 5.3 °C, respectively. Based on the available temperature records it is found that July was the warmest month of melt season in this region. The diurnal range of temperature (difference between maximum and minimum temperature) and its variation during the melt period is presented in Figure 7. The average diurnal temperature range for the months of May, June, July, August, September, and October was 13.2, 10.6, 9.2, 8.5, 10.3 and 13.9 °C, respectively. It reveals that the diurnal temperature range was highest in May and October, and lowest in August. The minimum diurnal temperature range in August is

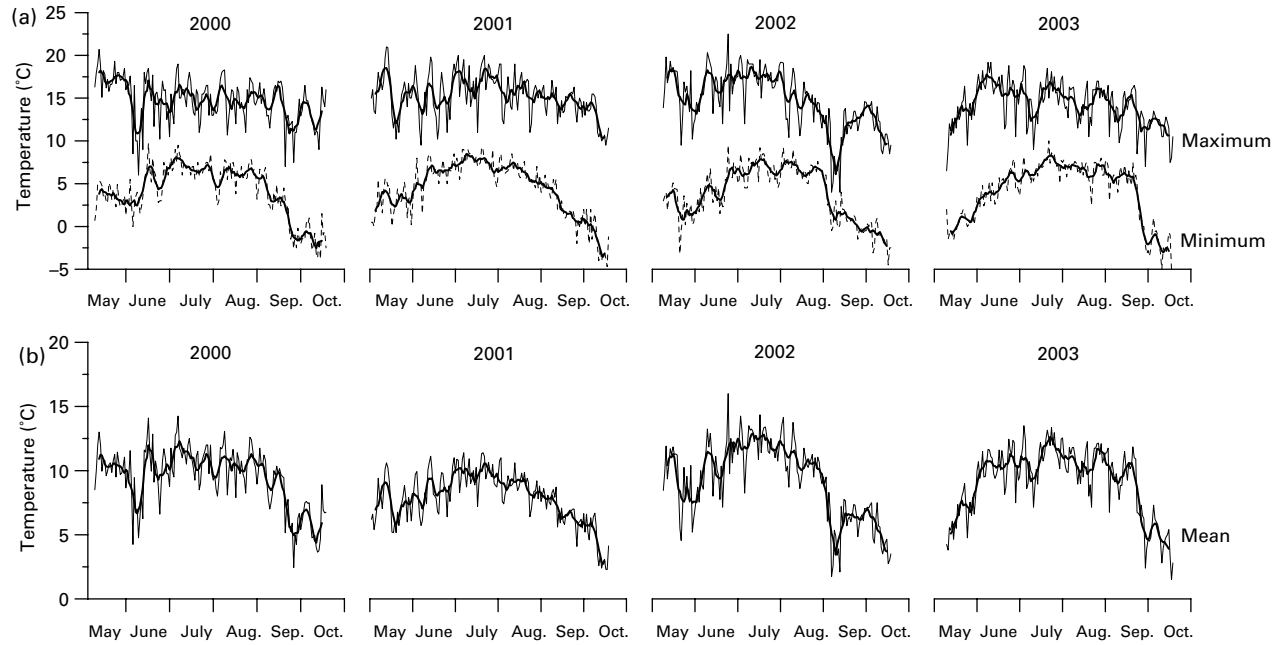


Figure 6 (a) Daily maximum and minimum air temperatures and (b) daily mean temperatures observed at Gangotri Meteorological Station (GMS: 3800 m a.s.l.) during different melt seasons. A 7-day running mean average can also be seen in the figure

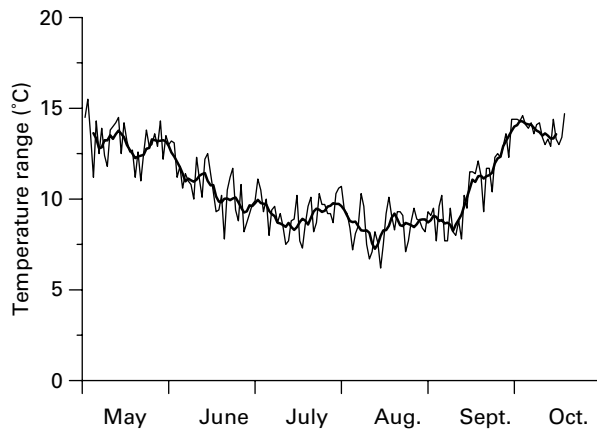


Figure 7 Variations in daily temperature range observed at Gangotri Meteorological Station (GMS) during different melt seasons. Temperature range for the melt seasons is computed based on 4 years of daily data

possible due to minimum sunshine hours (or presence of more clouds) in this month. The presence of clouds prevents the short-wave solar radiation in the daytime to heat the surface and long-wave radiation in the nighttime to emit heat, resulting in lower temperature range. The reverse is true for the months of May and October.

A comparison of distribution and magnitude of temperatures observed at GMS has been carried out with temperature records available for DMS and PMS (Figure 8). However, contemporary records were not available, but average temperatures computed using a data set of a few years has been used for this study. It is found that distribution of temperature at GMS was similar to the temperature distribution at DMS (Singh and Ramasastri 1999). The magnitude of the seasonal mean temperature for GMS (9.4 °C) was comparable to the seasonal average temperature for DMS (9.4 °C). The mean monthly temperatures at DMS for the months of June, July, August and September were 9.5, 10.5, 9.7 and 8.5 °C, which are almost in the same range as observed at GMS. July was observed to be the warmest month at both the stations. Bollasina *et al.* (2002) reported mean monthly temperatures at PMS (5,050 m a.s.l.). In order to compare the distribution and magnitude, temperatures observed at GMS were extrapolated to an elevation of 5 050 m a.s.l. using a standard temperature lapse rate (0.6 °C/100 m) (Singh and Singh 2001). The extrapolated mean temperatures of GMS for 5,050 m altitude for May, June, July, August, September and October were 2.1, 2.7, 4.3, 3.3,

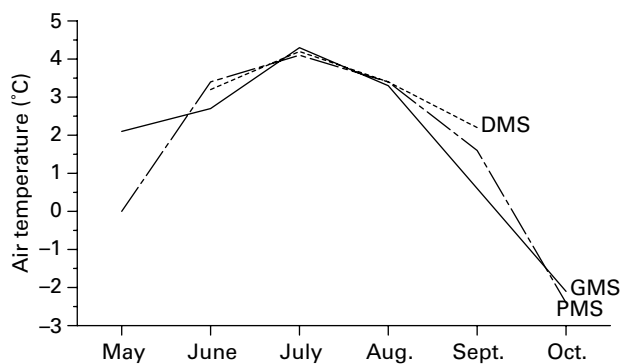


Figure 8 A comparison of mean monthly air temperature observed at Gangotri Meteorological Station (GMS), Dokriani Meteorological Station (DMS) and Pyramid Meteorological Station (PMS) during different melt seasons. GMS and DMS temperature has been extrapolated for 5050 m a.s.l. elevation (similar to PMS) using a lapse rate of 0.6 °C

0.6 and -2.1 °C, respectively, while for PMS these were 0.0, 3.4, 4.1, 3.4, 1.6 and -2.4 °C. It can be noted that the temperatures for different months are comparable for both sites except for the month of May. The average seasonal temperature for the PMS and the GMS (extrapolated to 5050 m a.s.l.) are 1.7 and 1.8 °C, respectively.

Wind speed and direction

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 present study, the wind speed and directions at GMS were observed four times a day: 08:30, 11:30, 14:30 and 17:30 h. Availability of wind data at different time intervals made it possible to study the changes in wind speed and direction on different time scales and also helped in determining the daytime and nighttime wind regimes. Daytime (08:30–17:30 h), nighttime (17:30–08:30 h) and mean daily wind speeds (08:30–08:30 h) observed for different years are shown in Figure 9. The daily mean wind speeds for May, June, July, August, September and 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 6.5 km/h. On the seasonal scale, mean daytime and nighttime winds were 12.6 and 2.9 km/h, respectively. In other words, average daytime wind speed is about 4 times higher than the nighttime wind speed. On some specific conditions, instant wind speed reached up to 30 km/h on a very bright sunny day (September 12, 2000) due to the strong driving force caused by the heating of the ground. The diurnal variation in daytime wind speed shows that strong winds (> 10 km/h) blow during the daytime, being at a maximum of about 15 km/h at 14:30 hours (Figure 10).

Wind directions observed over the melt period for different seasons have been depicted through wind roses (Figure 11). The observations for wind direction is made only during the daytime, which shows that most of the time wind blew from the northwest direction, i.e. upvalley wind from valley towards mountain or anabatic wind. But a change in the wind direction, i.e. downvalley wind from mountain towards valley or katabatic wind, is being observed every day during late evening and it persists till sunrise in the morning. These diurnal wind systems develop frequently over areas with large differences in relief. 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 in the cooler air blowing into the downvalley. The upslope valley wind in the mountain areas sometimes accelerates the formation of cumulus clouds, which may result in the afternoon showers on warm and humid days.

While comparing the daily mean wind speed observed at GMS with DMS, it is found that GMS experiences much stronger wind speed as compared to the DMS. For example, on the seasonal basis, average daily wind speed at GMS was computed to be 6.7 km/h, while at DMS it was only 2.3 km/h. Generally, at both stations the daytime wind speed was found to be 3–4 times greater than the nighttime wind speed. Wind data collected at PMS shows a similar trend as observed at GMS. Mean monthly wind speed at PMS for the month of May, June, July, August, September and October was 6.9, 6.5, 5.0, 5.0, 5.0 and 5.4 km/h, respectively (Bollasina et al. 2002). The average seasonal wind speed at PMS was 5.7 km/h. These results show that the GMS area experiences stronger wind than the PMS area and the DMS area. Both the regions show strong wind during the daytime and weaker wind during the nighttime for the whole melt season. Moreover, for both valleys, maximum wind speed was observed at about 14:00 h.

Relative humidity

Atmospheric humidity has a close relationship with air temperature as the capacity of air to hold the water vapour depends upon its temperature. Relative humidity is the ratio of the

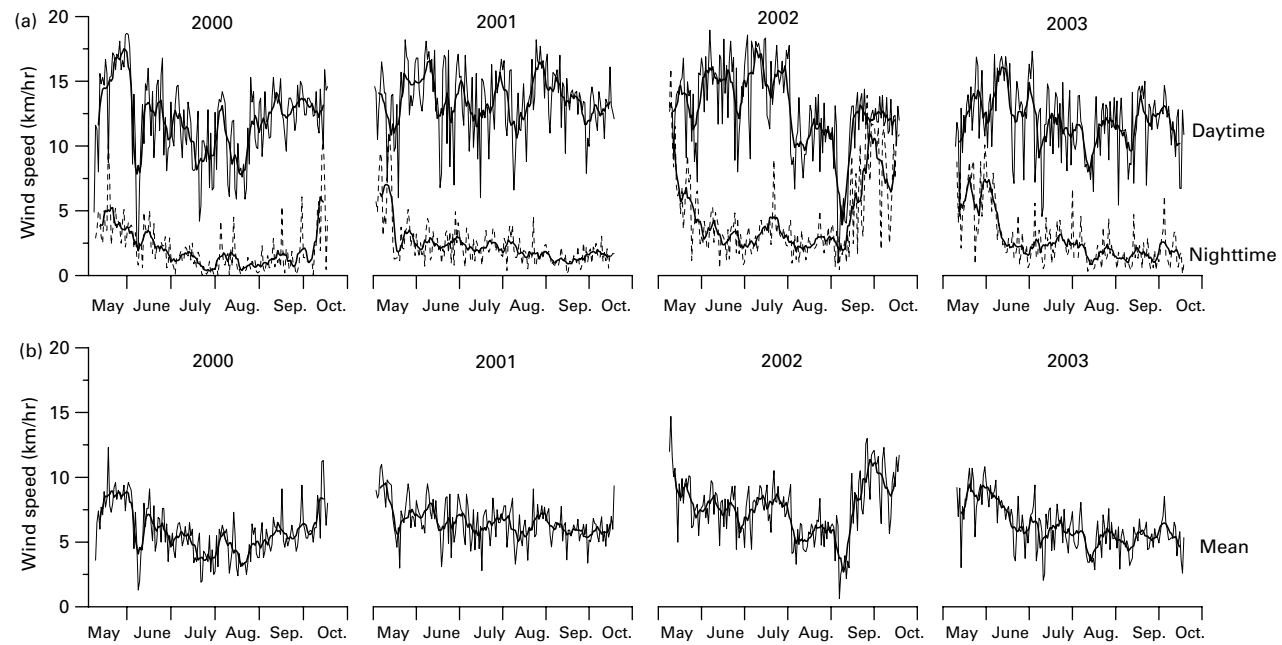


Figure 9 (a) Daily daytime (08:30–17:30 h) and nighttime (17:30–08:30 h) wind speeds, and (b) daily mean (08:30–08:30 h) wind speed observed at Gangotri Meteorological Station (GMS) during different melt seasons. A 7-day running mean average can also be seen in the figure

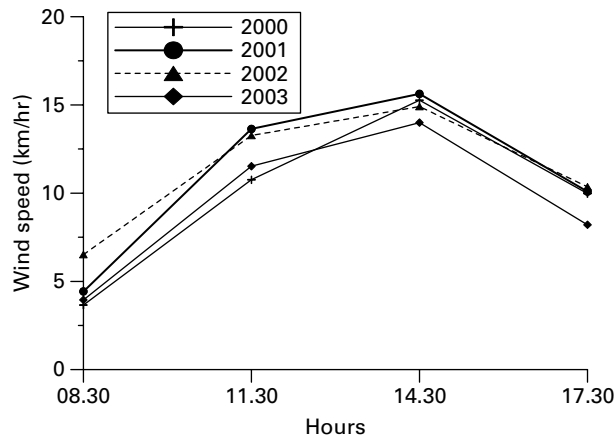


Figure 10 Diurnal variation in wind speed at different hours observed at Gangotri Meteorological Station (GMS) during different melt seasons

air's water vapour content to its water vapour capacity. It increases with the addition of moisture due to evaporation. Relative humidity data were collected round the clock and then mean daily values were computed. [Figure 12\(a\)](#) shows the daily mean relative humidity for different melt seasons. There were no significant changes in relative humidity from year to year. Over the study period, daily values of relative humidity ranged between 44–100%. Minimum humidity (44%) was observed in October 2000 and May 2001 whereas maximum humidity (100%) was observed during August 2002. Maximum humidity is always associated with low air temperature and high rainfall and the opposite is true for the minimum humidity. Average relative humidity over the different melt seasons varied between 77–83%, respectively. Mean monthly relative humidity was 69, 83, 88, 89, 78 and 68% for the month of May, June, July, August, September and October, respectively. These results suggest lower moisture content in the air (low relative humidity, 69%) in the beginning (May) and end (October) of the melt season. But for other months (June–September) relative humidity was quite high (85%) representing high moisture content in the air. It can also be stated as that specific humidity, which is the weight of water vapour per weight of a given mass of air including the water vapour, remains constant then any decrease in air temperature will increase relative humidity or vice versa.

Relative humidity observed at GMS has been compared with the relative humidity observed at DMS and PMS ([Figure 13](#)). Trends in changes in relative humidity at GMS were found similar to PMS, i.e. less in May and October, and higher in June, July and August. The mean monthly relative humidity ranged between 69–92% at PMS, while at GMS it was between 68–89%, showing a little higher moisture content at PMS. For the DMS, mean monthly humidity was higher (83–93%) in comparison to both GMS and PMS. A higher humidity at DMS was due to frequent rains in this area ([Singh and Ramasastry 1999](#)).

Sunshine hours

The solar energy obtained on the earth surface on a particular day is very much controlled by the sunshine hours. Daily sunshine hours recorded at GMS for melt season 2000, 2001, 2002 and 2003 are presented in [Figure 12\(b\)](#). On average, for May, June, July, August, September and October, the sunshine hours were observed to be 7.1, 5.4, 4.7, 4.0, 5.2 and 6.7, respectively. Results indicate that this area experiences maximum sunshine hours in May followed by October when the rainfall is either negligible or not at all. On the other hand, minimum sunshine hours were recorded for August, when higher rainfall occurs. Over the

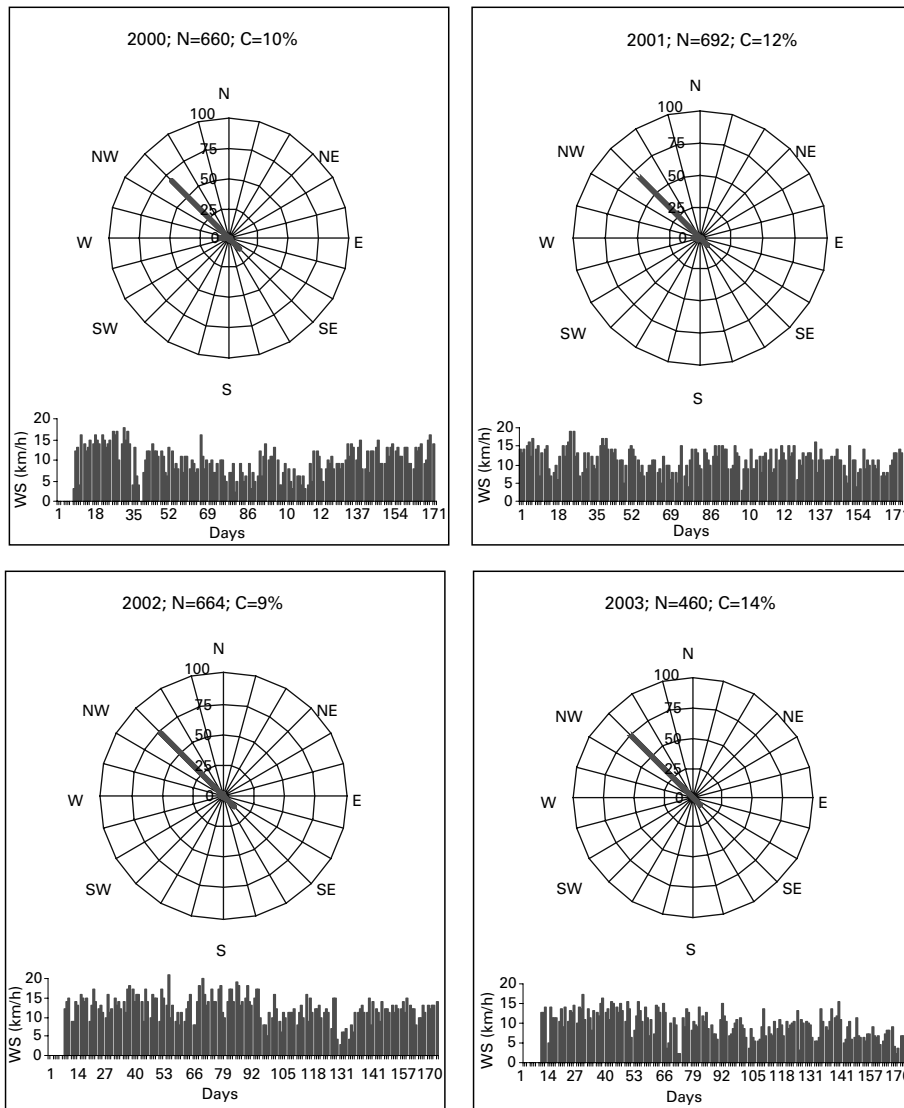


Figure 11 Average daily wind speed (WS) and direction observed at Gangotri Meteorological Station (GMS) during different melt seasons. *N* represents number of observations and *C* represents calm wind

study period, the maximum daily sunshine hours reached up to 11.1 h (June 28, 2001), while minimum sunshine hours were equal to zero. On the seasonal scale mean daily sunshine hours were computed to be 5.5 h.

A comparison of sunshine hours observed at GMS with DMS indicates that GMS has higher and bright sunshine hours. For DMS, mean monthly bright sunshine hours for June, July, August and September were 3.7, 2.5, 1.3, and 1.6 h, which are much less than the GMS. Lower sunshine hours were due to higher frequency of clouds around DMS. No sunshine hours data are available at PMS for comparison.

Evaporation

Evaporation is an extremely 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, relative

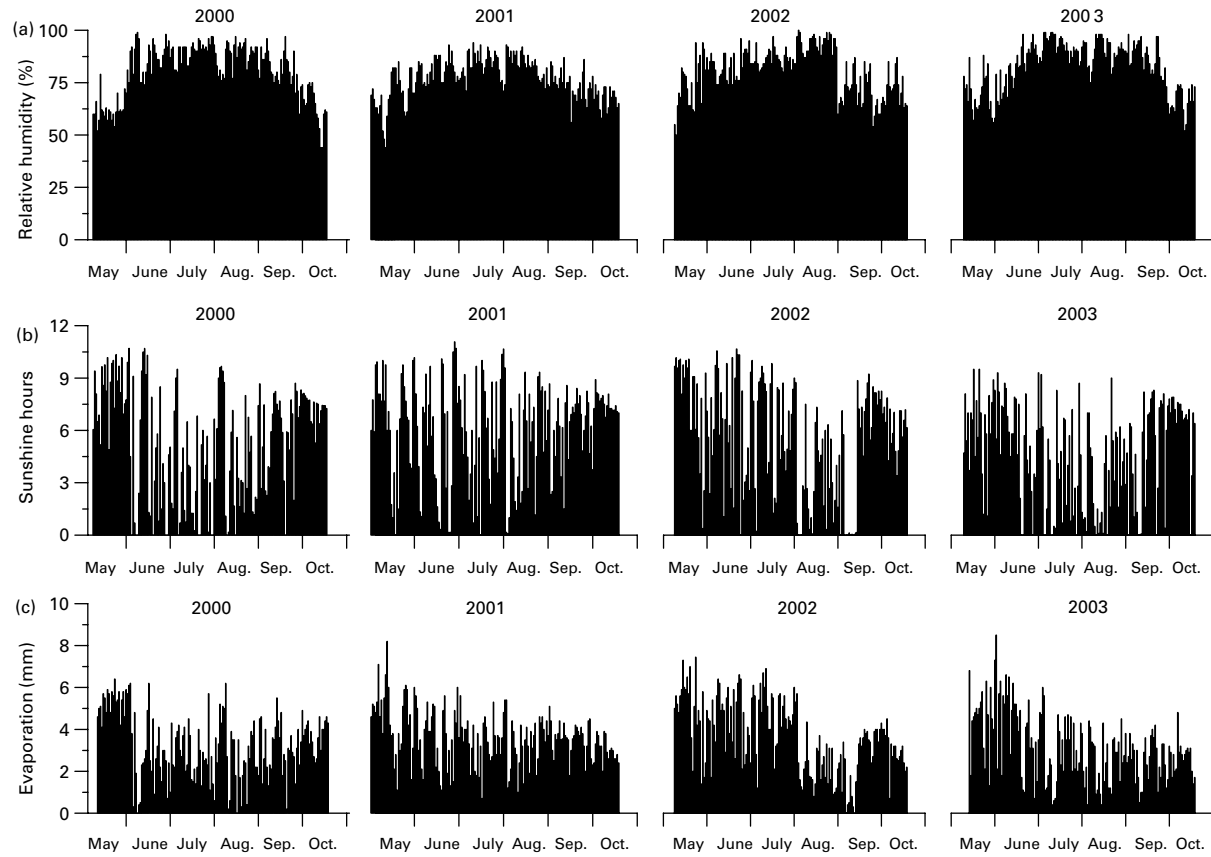


Figure 12 (a) Daily relative humidity (b) daily sunshine hours and (c) daily evaporation observed at Gangotri Meteorological Station (GMS) during different melt seasons. N represents number of observations and C represents calm wind

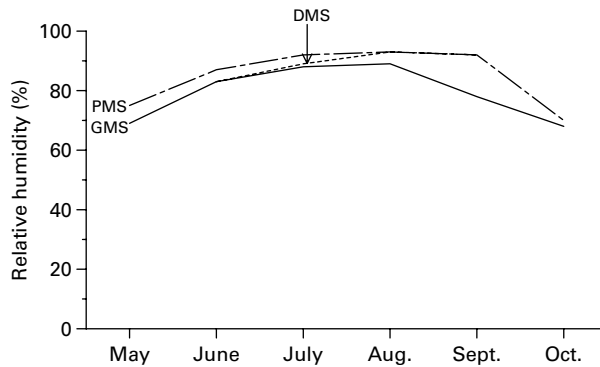


Figure 13 A comparison of mean monthly relative humidity observed at Gangotri Meteorological Station (GMS), Dokriani Meteorological Station (DMS) and Pyramid Meteorological Station (PMS) during different melt seasons

humidity and air pressure are the main meteorological variables that control evaporation from the basin. Daily pan evaporation records over the ablation season at GMS are shown in Figure 12(c). Mean daily pan evaporation observed is 4.8, 3.8, 3.5, 2.8, 2.9 and 3.0 mm for the months of May, June, July, August, September and October, respectively. Evaporation was maximum in May and minimum in the month of August. The low relative humidity, high sunshine hours and high wind speed contribute to higher evaporation observed for May, while low evaporation in August is possible due to less number of sunshine hours. The one-day maximum value of pan evaporation was observed to be 8.5 mm, while the minimum was recorded to be zero. Mean monthly total evaporation during 4 ablation periods was 150.7, 113.4, 106.9, 85.5, 87.7 and 96.6 mm for the months of May, June, July, August, September and October, respectively. The total pan evaporation during the melt seasons 2000, 2001, 2002 and 2003 was 628.7, 660.6, 680.2 and 593.6 mm. Based on total records, mean daily evaporation for the melt season as a whole is found to be 3.5 mm.

Pan evaporation data observed at GMS has been found two times higher than DMS. At DMS mean monthly evaporation for the months of June, July, August and September is investigated to be 1.59, 1.75, 1.29 and 1.91 mm, respectively, and mean daily evaporation for the whole melt season is about 1.5 mm. It is to be pointed out that mean daily evaporation for the melt season (May–October) at Roorkee (272 m a.s.l.) situated at the foothills of the Himalayas has been observed to be 3.6 mm, which is equal to what we observed at GMS.

Variation in meteorological parameters

The variability of different meteorological parameters over the melt season at GMS in terms of coefficient of variation (C_v) is shown in Figure 14. It can be noted that sunshine hours and evaporation were the highly variable parameters, whereas temperature was relatively less variable. Wind velocity and relative humidity did not show any significant variation over the melt season.

Discussion and conclusions

A detailed meteorological analysis is carried out using data collected for four melt seasons at GMS and results are compared with similar data available for two other high altitude meteorological stations (DMS and PMS) located in the Central Himalayan region. Little rainfall (260 mm) was observed around the GMS area. Daily rainfall hardly exceeded 15 mm and about 77% of rain events recorded a daily rainfall of less than 5 mm. Average monthly rainfall for May, June, July, August, September and October has been computed to be 12.0, 56.1, 45.2, 68.5, 76.9 and 0.8 mm, respectively, suggesting that August and September have

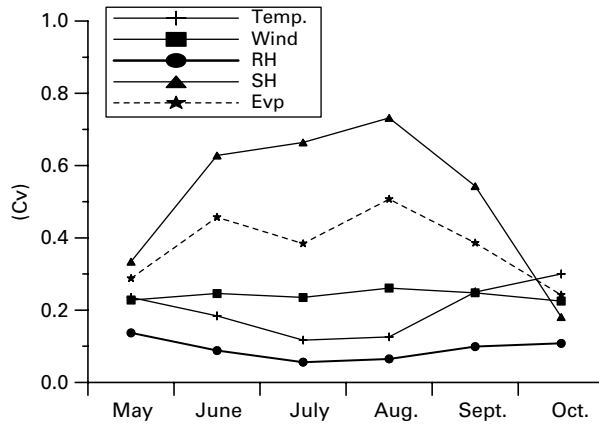


Figure 14 Changes in coefficient of variation (C_v) over the melt season for different meteorological variables observed at Gangotri Meteorological Station (GMS)

received relatively higher rainfall than other months. The total rainfall and its distribution over the melt period are found to be very variable from year to year. For example, the total rainfall for the melt seasons 2000, 2001, 2002 and 2003 at GMS was found to be 322.3, 131.4, 368.8 and 215.5 mm. For the first two years, the maximum occurred in the month of June, while for the third and fourth year it was found in the month of September and July, respectively. Analysis of rainfall intensity shows that about 63% hourly rainfall events represented the rainfall intensity between 0.1 and 0.5 mm/h, showing that mostly light intensity rain (drizzle type) occurs in the study area. Maximum rainfall events occurred either in the evening period or in the early morning.

The average daily maximum and minimum temperatures at GMS over the melt season were computed to be 14.8 °C 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 14:00 h and minimum in the early morning. Mean monthly temperatures for May, June, July, August, September and October were 8.9, 10.3, 11.7, 10.8, 8.0 and 5.3 °C, respectively, suggesting that July was the warmest month. Results indicate that changes in minimum temperature are more significant than the changes in maximum temperature. On average the daytime wind speeds were much stronger (4 times) than the nighttime winds. In the beginning and end of the melt season, the relative humidity was about 69%, but during rainy months (June–September) it increased to 85%. Average relative humidity over the different melt seasons varied between 77–83%, respectively. The duration of daily mean sunshine hours at GMS ranged between 3.1 and 8.3 h, being maximum in May and minimum in August. On the seasonal scale daily mean sunshine hours were 5.5 h. Monthly total pan evaporation was 150.7, 113.4, 106.9, 85.5, 87.7 and 96.6 mm for the months of May, June, July, August, September and October, respectively. It is understood that a 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. Mean daily evaporation for the melt season as a whole is found to be 3.5 mm, which is comparable to the pan evaporation data observed at the foothill station of the Himalayas.

It was interesting to compare the meteorological records of GMS with two other high altitude meteorological stations (DMS and PMS). Although the data set available for GMS (2000–2003) was of different years than DMS (1995–1998) and PMS (1994–1998) it is assumed that this data set represents the general meteorological characteristics of the respective areas and can be compared. A comparison of results shows that the area around GMS receives low rainfall (260 mm) during melt season in comparison to the area around

DMS (1041 mm) and PMS (427 mm). It is noted that the average seasonal temperatures for all the sites are comparable and for all the three sites July was found to be the warmest month. Wind speed and wind direction trends were also similar, i.e. strong valley wind in the daytime and light mountain wind during nighttime. Relative humidity for the GMS was lower than the DMS and PMS. The GMS area recorded bright sunny days with higher sunshine hours and higher evaporation compared to the other two stations.

Acknowledgements

The authors are grateful to the Department of Science and Technology, Government of India for providing financial support to carry out the reported investigations at Gangotri Glacier in the Garhwal Himalayas.

References

- Ageta, Y. and Higuchi, K. (1984). Estimation of mass balance components of a summer-accumulation type glacier in the Nepal Himalaya. *Geog. Ann.*, **66A**(3), 249–255.
- Bahadur, J. (1987). Himalayan water from snow, ice and glaciers. *Proc. 1st National Water Convention (vol II)*, CBIP, New Delhi, 1–32.
- Bollasina, M., Bertolani, L. and Tartari, G. (2002). Meteorological observations at high altitude in the Khumbu Valley, Nepal Himalayas, 1994–1999. *Bull. Glaciol. Res.*, **19**, 1–11.
- Flint, R.F. (1971). *Glacial Quaternary Geology*, Wiley, New York.
- Haritashya, U.K., Singh, P., Kumar, N. and Gupta, R.P. (2005). Suspended sediment from the Gangotri Glacier: quantification, variability and associations with discharge and air temperature. *J. Hydrol.*, **321**, 116–130.
- Higuchi, K., Ageta, Y., Yasunari, T. and Inoue, J. (1982). Characteristics of precipitation during the monsoon season in high-mountain areas of the Nepal Himalaya. In: *Hydrological Aspects of Alpine and High-Mountain Areas. IAHS/AISH Publ.* **138**, 21–30.
- Singh, P. and Jain, S.K. (2002). Snow and glacier melt in the Satluj river at Bhakra Dam in the Western Himalayan region. *Hydrol. Sci. J.*, **47**, 93–106.
- Singh, P. and Jain, S.K. (2003). Modelling of streamflow and its components for a large Himalayan basin with predominant snow melt yields. *Hydrol. Sci. J.*, **48**, 257–275.
- Singh, P. and Kumar, N. (1997a). Impact of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan River. *J. Hydrol.*, **193**, 316–350.
- Singh, P. and Kumar, N. (1997b). Effect of orography on precipitation in the western Himalayan region. *J. Hydrol.*, **199**, 183–206.
- Singh, P. and Ramasastri, K.S. (1999). *Temporal Distribution of Dokriani Glacier Melt Runoff and its Relationship with Meteorological Parameters*, Project report on Dokriani Glacier. National Institute of Hydrology, Roorkee, India.
- Singh, P., Ramasastri, K.S. and Kumar, N. (1995). Topographical influence on precipitation distribution in different ranges of western Himalayas. *Nordic Hydrol.*, **26**, 259–284.
- Singh, P., Ramasastri, K.S., Kumar, N. and Bhatnagar, N.K. (2003). Suspended sediment transport from the Dokriani Glacier in the Garhwal Himalayas. *Nordic Hydrol.*, **34**(3), 221–244.
- Singh, P. and Singh, V.P. (2001). *Snow and Glacier Hydrology*, Kluwer, The Netherlands.
- Ueno, K., Kayastha, R.B., Chitrakar, M.R., Bajracharya, O.R., Pokhrel, A.P., Fujinami, H., Kadota, T., Iida, H., Manandhar, D.P., Hattori, M., Yasunari, T. and Nakawo, M. (2001). Meteorological observations during 1994–2000 at the Automatic Weather Station (GEN-AWS) in Khumbu region. *Nepal Himalayas. Bull. Glaciol. Res.*, **18**, 23–30.