punjab geographer

A JOURNAL OF THE ASSOCIATION OF PUNJAB GEOGRAPHERS, INDIA

VOLUME 9 OCTOBER 2013

TEMPERATURE AND PRECIPITATION TRENDS AROUND GANGOTRI GLACIER

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Abstract

Glaciers are dynamic and fragile ice bodies on the landscape and are the product of climatic conditions prevailing in an area. They change their dimensions in response to climatic variables in the surrounding environment. The present study is a time series analysis of the observed temperature and precipitation trends of Gangotri glacier from 2000 to 2011 based on the daily meteorological data obtained from the standard meteorological observatory at Bhojwasa near the snout of Gangotri glacier. The study aims at analyzing the change in climatic elements like mean, maximum, minimum and diurnal temperature range, and total precipitation (rainfall and snowfall) affecting Gangotri glacier. The temperature trend analysis shows that the annual and seasonal mean maximum and minimum temperature is increasing and the highest increasing trend is found in the mean minimum summer temperature. Diurnal range of temperature also shows an increasing trend. Regarding trends in precipitation, annual rainfall shows an increasing trend along with number of rainy days and seasonal analysis reveals that the period of heavy rainfall is shifting towards later months of the year as the contribution of September rainfall has increased in the past decade (2002-2011). However, a decreasing trend is observed in annual average snowfall and similarly the number of snowy days has also decreased. The amount of snowfall received throughout the year has a direct influence on the temperature of that year.

Introduction

Global warming and associated regional climatic changes have attracted much attention in recent years as many studies related to climatic changes for different time periods and regions have been published. The studies on long-term variations in surface air temperature for the entire globe (Jones et al., 1986a; Hansen and Lebedeff 1987, 1988; Diaz et al., 1997; Easterling, 1997; Hansen et al. 2006; IPCC 2007) as well as for the hemispheres (Angell and Korshover 1978; Jones et al., 1986 b,c; Parker et al., 1994) have shown a rising trend during the last few decades. Studies on some parts of the Indian sub-continent (Kothawale and Kumar 2005; Bhutiyani et al., 2007; Pal and Tabbaa 2010) and the Tibetan Plateau region (Liu and Chen 2000; Duan et al., 2006; You et al., 2008) have also reported similar warming trends. Similar results have also been found in the Himalayan region (Bhutiyani 1999; Kulkarni et al. 2002, 2005; Kulkarni 2007; Bhutiyani et al., 2008; Hasnain 2008).

The Himalayas comprise approximately 33,000 sq km of glacierised area (Kaul, 1999; Dyurgerov and Meier, 2005; Rai and Gurung,

2005) and its glaciers are a source of 10 of the largest rivers in Asia. The rivers flow trans-boundary and meet the drinking water, irrigation, hydropower, fishery, inland navigation and other needs of more than 1.3 billion people living downstream. With about 9,575 small and large glaciers in the Himalayas they hold the largest reserves of water in the form of ice and snow outside the Polar Regions (GSI, 2001). However numerous publications have recently reported an 'alarmingly' rapid glacier melt in the Himalayas (Mayewski and Jeschke, 1979; Vohra, 1981; Dobhal, 2004; Kulkarni, 2007, Kulkarni et al., 2011) and their possible disappearance by the year 2035 (e.g. Cruz, 2007). Many impact studies have followed in the wake of these conclusions stating that water availability for the more than 1.3 billion people depending on the Himalayan 'water towers' is in threat (Kehrwald et al., 2008; Eriksson et al., 2009; Kumar and Venkataraman 2009). Himalayas have a number of hydrological and climatic regimes, extending from the cold-arid regions of Ladakh to the humid monsoon climate of the north-eastern Himalayas (Mani, 1981). While taking a closer look at the available data, one finds that the Himalayas are among the regions that have comparably few glacier observations available and a lack of standardized long-term data series (WGMS 2008).

Understanding the regimes of the glaciers is also important, because they are sources of information on high-mountain meteorology and hydrology, and also of palaeo-climatic data (Meier and Bahr, 1996). The meteorological records of the Himalayas are poorly documented due to rugged terrains, poor accessibility and harsh weather conditions but they are of utmost importance in order to track the climate changes in the high-altitude Himalayan region (Singh et al., 2005). An 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 it gives an insight to the problems related to natural hazards, viz. flash floods, cloudbursts, landslides/rockslides and avalanches (Naithani et al., 2001). Therefore this study describes the weather pattern around Gangotri Glacier in the Garhwal Himalayas based on the comprehensive results of meteorological parameters and their distribution with time.

Study Area

Gangotri glacier is one of the largest Himalayan glaciers. It is about 30 km long and 0.5 to 2.5 km wide. It is a valley-type compound basins glacier (Naithani et al., 2001) located in the Uttarkashi district of the Uttarakhand state in India (Fig.1). It lies within the latitudes 30°43'00" – 30°57' 15" north and longitudes 78°59' 30" – 79°17' 45" east, at an elevation of 4000 to 7000 m above mean sea level. It is a cluster of many glaciers comprising the main Gangotri Glacier as the trunk part of the system and occupies a longitudinal U-shaped valley. The total glacierised area of the catchment is 258.56 km^2, out of which the Gangotri system comprises 109.03 km^2, followed by Chaturangi (72.91 km^2), Raktvarn (45.34 km^2) and Kirti (31.28 km^2). Gangotri glacier originates from a narrow but large depression along the northern slopes of the Chaukhamba group of peaks and flows in a north-westerly direction. It forms the source of Bhagirathi River at Gaumukh i.e. the snout of Gangotri Glacier. Bhagirathi River after its confluence with the river Alaknanda at Devprayag is known as river Ganga.

Objectives

The main objective of this study is to

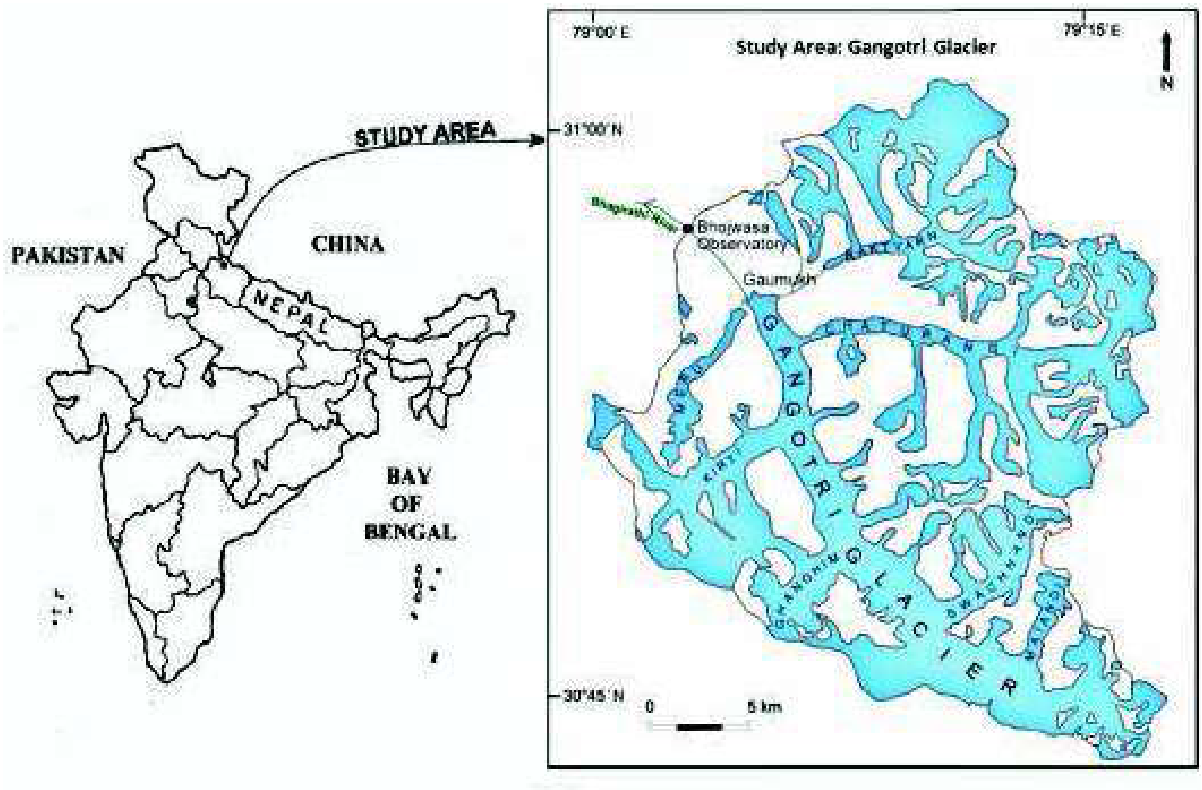

Fig. 1

analyze the characteristics of seasonal and diurnal changes in temperature and precipitation around Gangotri glacier and to understand its relationship with regional trends.

Data Base and Methodology

The meteorological data is collected from the standard meteorological observatory at Bhojwasa set up by Snow and Avalanche Study Establishment (SASE), Chandigarh, India in 1999 at an altitude of 3800m above mean sea level in Gangotri sub-basin. The observatory is located in the valley floor on right bank of the Bhagirathi River at a distance of 4 km downstream from the present snout (Goumukh) of Gangotri glacier and thus presents a true picture of the atmospheric parameters affecting Gangotri glacier.

Rainfall and air temperature are the most important parameters of meteorology for any particular region. Therefore, analysis of temperature and precipitation trends of Gangotri Glacier for a period of 12 years from 2000-2011 have been taken up in this study. As a preliminary quality control, daily recorded temperature and precipitation data were manually inspected for repitivity, homogeneity and data gaps for all the years. Homogeneity issue is covered as much as practically possible although no general homogeneity testing of data has been performed. Any suspicious values, for example a maximum temperature value that is lower than the corresponding minimum temperature value, were removed. The missing data were filled by temporal interpolation. In case of temperature, the trends of daily, monthly and seasonal temperatures were analyzed. The daily mean temperature was computed using average of daily maximum and minimum temperatures. Thereafter, seasonal and annual means were calculated based on monthly data. Seasonal analysis is attempted on the basis of four official seasons (Winter, Pre-monsoon, Monsoon and Post-monsoon) designated by India Meteorological Department (IMD). The annual mean was the average of January–December monthly means. Seasonal and annual temperature trends have been depicted with the help of graphs and trend lines. Similarly, daily precipitation data spanning over twelve years from 2000-2011are analyzed in order to decipher temporal variations. The seasonal and annual rainfall and snowfall totals were computed from daily recorded precipitation data. Temperature and precipitation changes over the period 2000-2011 are examined by established statistical trend line.

To ascertain the applicability of the results of this study over a wider region and to understand its relationship with regional trends, average annual temperature data obtained from the Bhojwasa observatory are compared with temperature data of National Centers for Environmental Prediction (NCEP) for a region extending between 30°-35° North latitudes, and 75°-80° East longitudes (Fig.2). Striking similarities are observed between these two records.

Bhojwasa manual observatory data shows a general trend of rise in annual average temperature from 2000 to 2009 interrupted by three episodes of cooling in 2000, 2003 and 2005. Similarly, the NCEP temperature data follows the similar trend, demonstrating the spatial coherence of these records despite tremendous contrast in the physiographic and demographic characteristics among the stations (Fig.2). This in turn suggests that the Bhojbasa meteorological station data reflects the regional climatic trends that predominate over the entire region.

Results and Discussion

A long-term time series analysis of meteorological observations provides information, which can be used for studying glacier fluctuations as a response to global

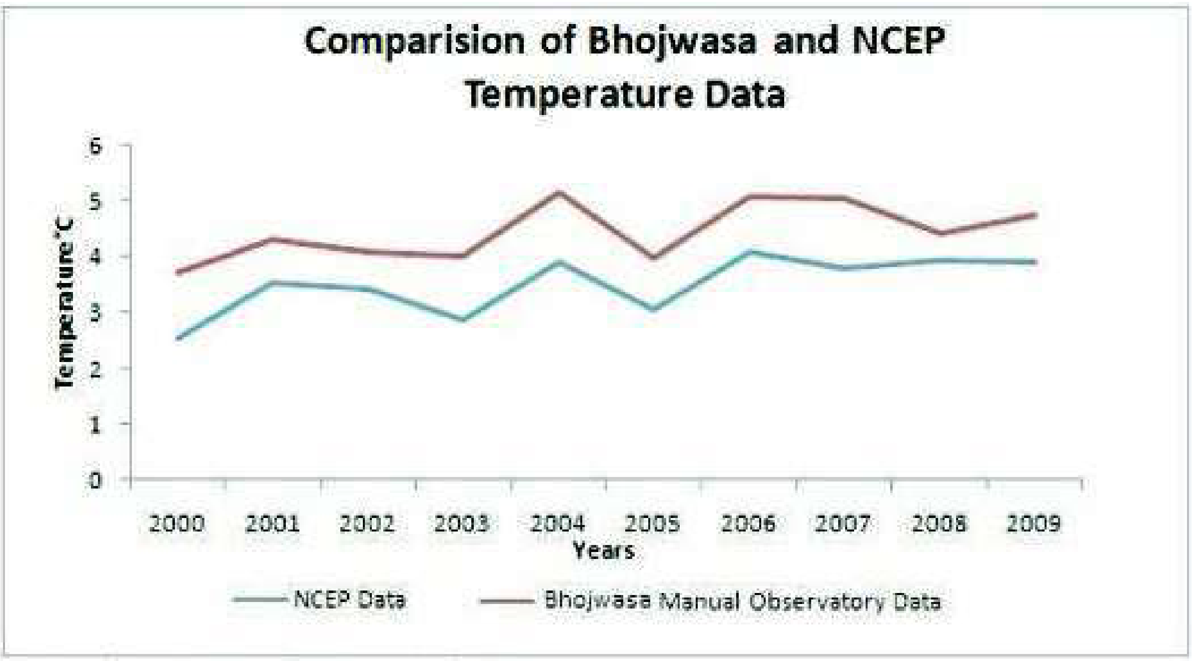

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Fig. 2

climate change (Bollasina, 2002). Particularly, rainfall and temperature analysis for trends, fluctuations and periodicities are deemed necessary as such information can indirectly furnish the "health" status of an environment. In addition, because of the sensitivity of mountain glaciers to temperature and precipitation, the behavior 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 (Haeberli and Beniston, 1998; WGMS, 2000). The discussion is divided into two parts:

1. Temperature

The data on weather parameters for Gangotri glacier (2000-2011) have been analyzed and the obtained results are presented as under:

a) Monthly Seasonal Temperature Trends

Average monthly seasonal temperature observed over Gangotri Glacier for the last 12 years is found to be almost similar for all the years (2000-2011) i.e. for the first three months of January (-4.87°C), February (-4.02°C) and March (-0.20°C) the average monthly temperature remains below zero degree Celsius and gradually rises in the months of April (3.96), May (8.09), June (10.72) and July (12.19°C) and then with the commencement of monsoon season, the temperature starts decreasing from August (11.69°C) onwards.(Fig.3a) During the winter season in the month of December to February the average temperature ranges between -2.12°C and -4.87°C. For detailed discussion the analysis of Temperature is divided into following four seasons:

i. Winter *(December of previous year, January, and February)*

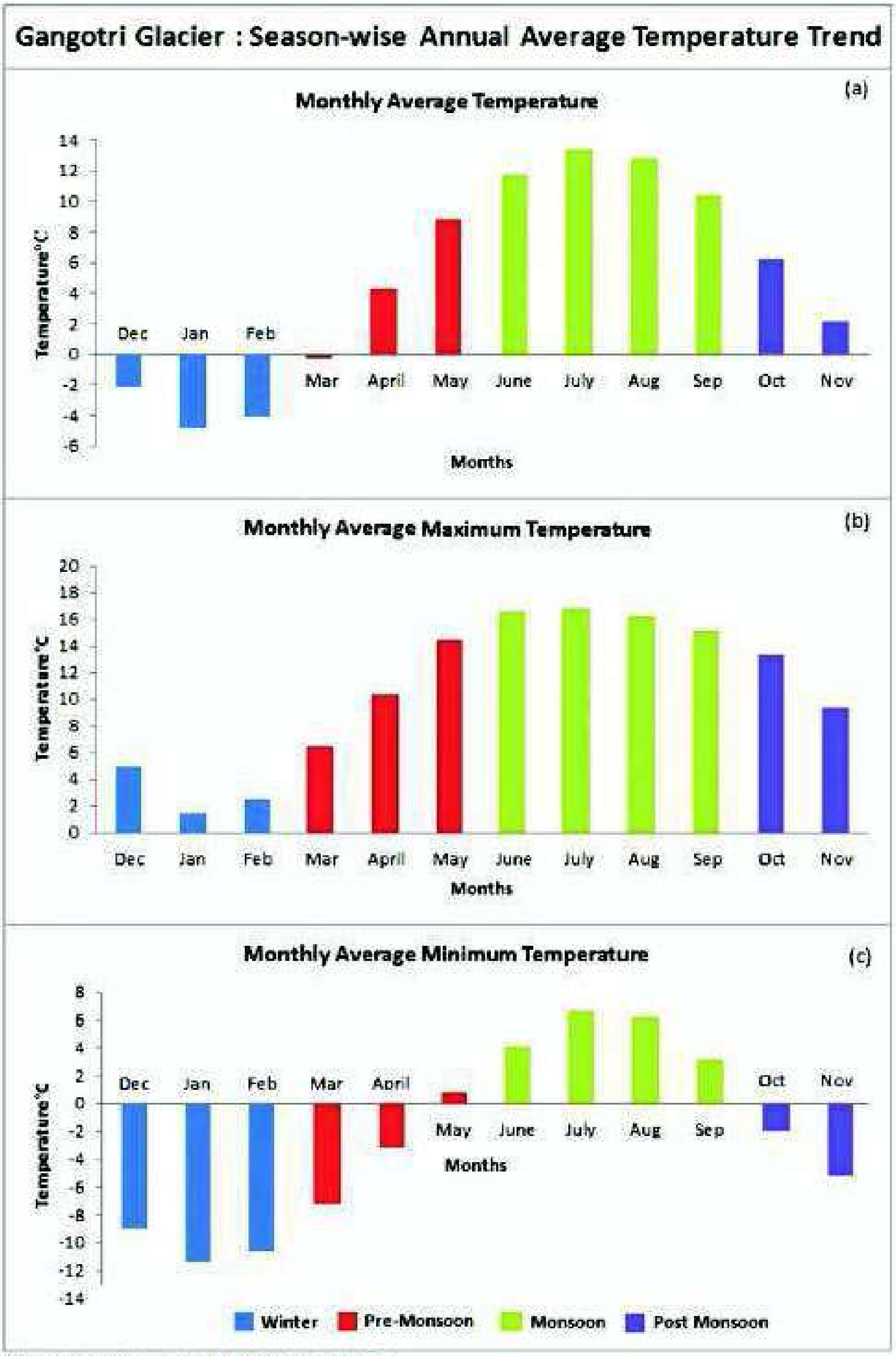
The winter in Gangotri spans for the months of December till February. The winter temperature in the region is quite low with mean minimum temperature of about -10 °C which even drop down to -12°C during snowfall events in the month of January (Fig.3c). Extremely low temperatures are complimented by heavy snowfall during winters. January is the coldest month of the winter season where average monthly temperature drops down to -4.87°C followed by February (-4.02°C) and December (-2.12°C) (Fig.3a). The average temperature of the winter season also remains below sub zero i.e. about -3.67 °C, even the maximum temperature remains as low as 2°C to 5°C (Fig.3b).

ii. Pre-monsoon *(March–May)*

During Pre-monsoon period (March to May) temperature gradually starts increasing. However the average minimum temperature remains below zero for the months of March (-7.18°C) and April (-3.10°C), while for the month of May it is slightly above zero i.e. (0.83°C) (Fig.3c). However maximum temperature gets its value above zero and varies from 6.8°C to 15.35°C for the months of March to May (Fig.3b). March experiences a monthly average temperature of about -0.20°C which increases to 3.96°C in April and reaches to 8.09°C in the month of May (Fig.3a). In late May, signs of the approaching monsoons start appearing.

iii. Monsoon *(June–September)*

The weather in the Gangotri basin is characterized by a distinct wet season during the period of south west monsoons (June to September). Average



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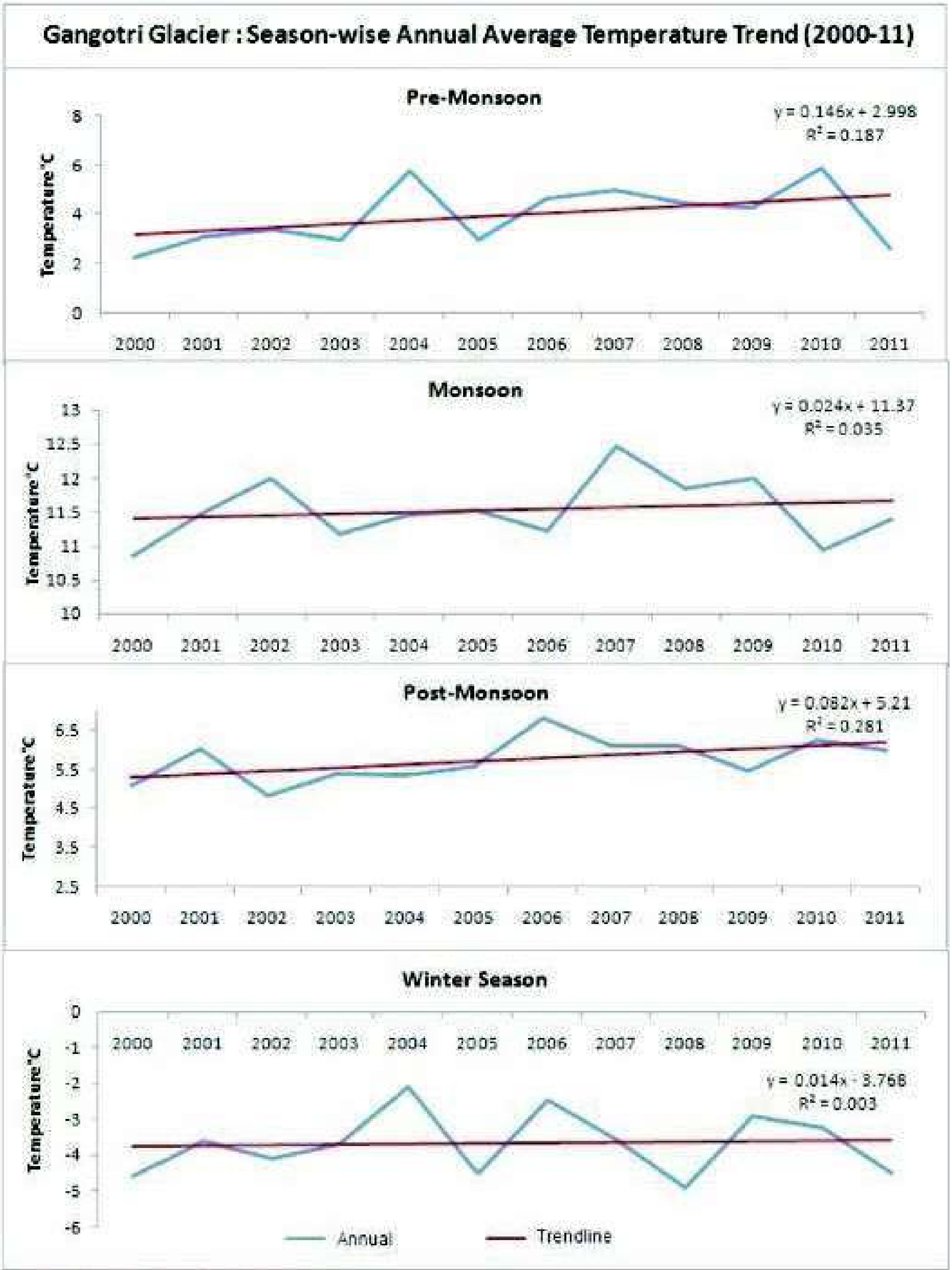

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Fig. 4

maximum temperature during the monsoon season is around 17°C which starts falling with the onset of the monsoons from June-July onwards (Fig.3b). Based on the available temperature records, it is found that July is the warmest month of the year (Fig.3a). Average minimum temperature during the monsoon season is around 3°C to 6°C.

iv. **Post-monsoon** *(October and November)*

The post-monsoon season spans over the months of October and November. During this season average monthly temperature is around 5.69°C in October and 2.04°C in November (Fig.3a). The average minimum temperature drops below 0°C (Fig.3c), while the average maximum temperature varies between 13.43°C to 9.36°C in the month of October and November.

b) **Annual Seasonal Temperature Trends**

Annual seasonal temperature trend (2000-2011) clearly indicates significant increasing trend in mean temperature for all the seasons (pre-monsoon, monsoon, post-monsoon and winter) with Pre-monsoon season showing the greatest rate of increase of 0.146°C followed by post-monsoon (0.082°C), monsoon (0.024°C), and the winter season showing the lowest rate of increase of 0.014°C (Fig.4). It is seen that the major contribution to increasing trend in average pre-monsoon temperature is by the mean maximum temperature in this season. However on monthly basis the greatest warming occurs in the months of February March and April with least warming in January and December. Thus, it also reveals that summers in the region are becoming warmer.

c) **Annual Average Temperature Trend**

The annual average temperature observed over Gangotri Glacier for the last 12 years (2000-2011) shows an overall rising trend, as the lowest average temperature is observed for the year 2000 (3.49°C) whereas highest temperature is observed for the year 2004 (5.12°C).

Over the study period, average annual maximum and minimum temperatures were computed to be 11.15°C and -2.24°C respectively. Average annual mean temperature was observed to be 4.38°C. The 12-year running means (2000-2011) are plotted to identify decadal variations in the series. Mean minimum temperature was found to be increasing at a rate of 0.018°C per annum whereas mean maximum temperature was found to be increasing at the rate of 0.132°C per annum (Fig.5). It is observed that maximum temperature is warming more than the minimum temperature as the changes in maximum temperature is higher than that in minimum temperature. Similar observations were also reported by Arora et.al. 2005; Fowler and Archer 2006; Das et al. 2007; Bhutiyani et al. , 2007; Pal and Tabbaa, 2010, for parts of the Indian subcontinent, the Himalayan region and the Upper Indus Basin.

d) **Monthly Diurnal Range of Temperatures**

Diurnal range of temperature is the difference between daily maximum and minimum temperature. Monthly diurnal

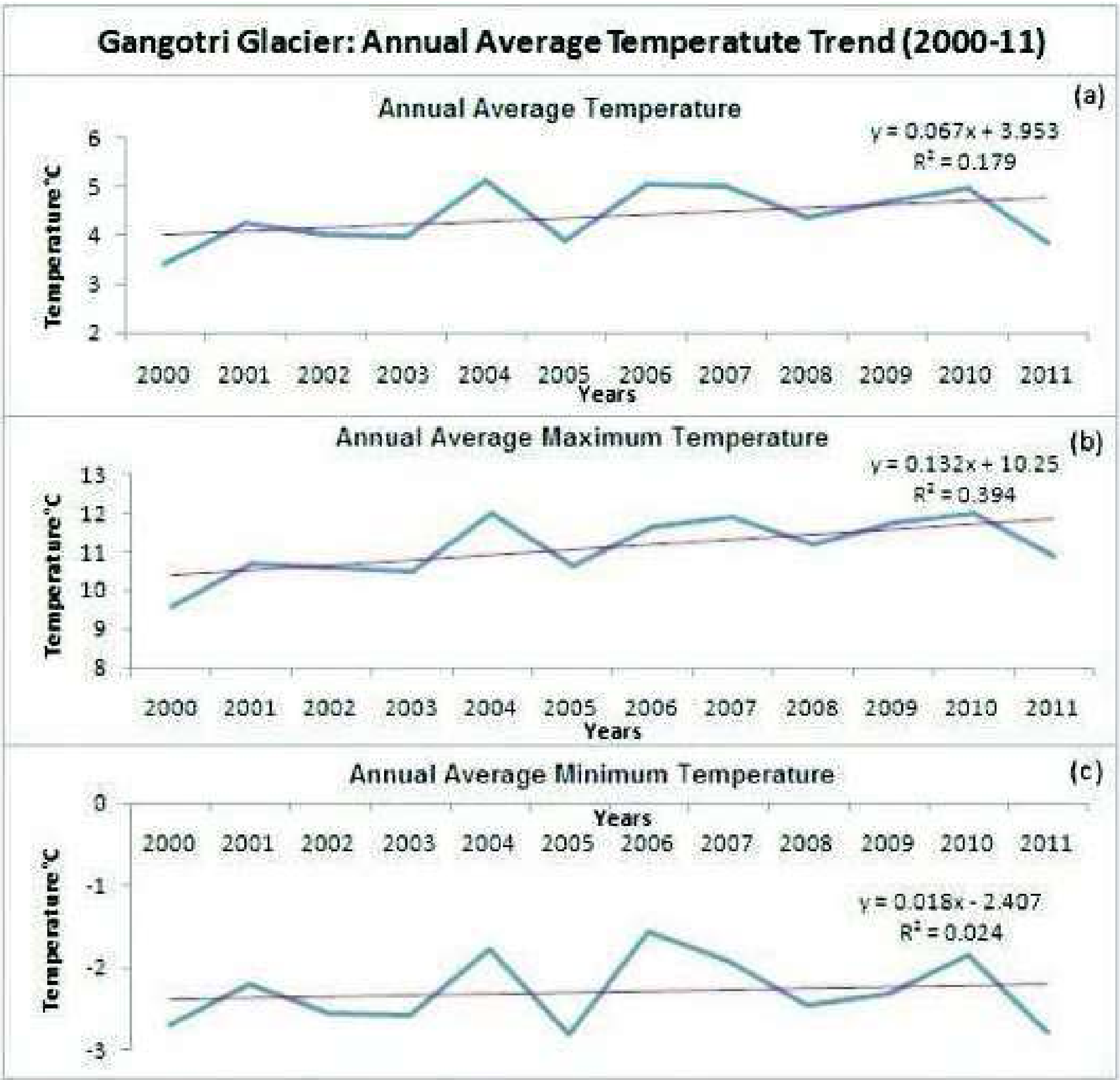

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Fig. 5

range of temperature is obtained from the average of daily diurnal range of temperature. The average monthly diurnal range of temperature i.e. the difference between maximum and minimum temperature from 2000-2011 on monthly basis is shown in Fig.6. It reveals that the monthly diurnal range of temperature gradually increases from January (12.8°C) to May (14.5°C). However, with the onset of monsoons diurnal range of temperature starts declining from June (13.2°C) to August (10.9°C). August has the lowest diurnal range of temperature and as soon as the monsoon period is over, the diurnal range of temperature starts increasing rapidly and is maximum in the month of October (15.4°C) after which it again starts declining till December (13.96°C) (Fig.6). Minimum diurnal range of temperature is found in August due to

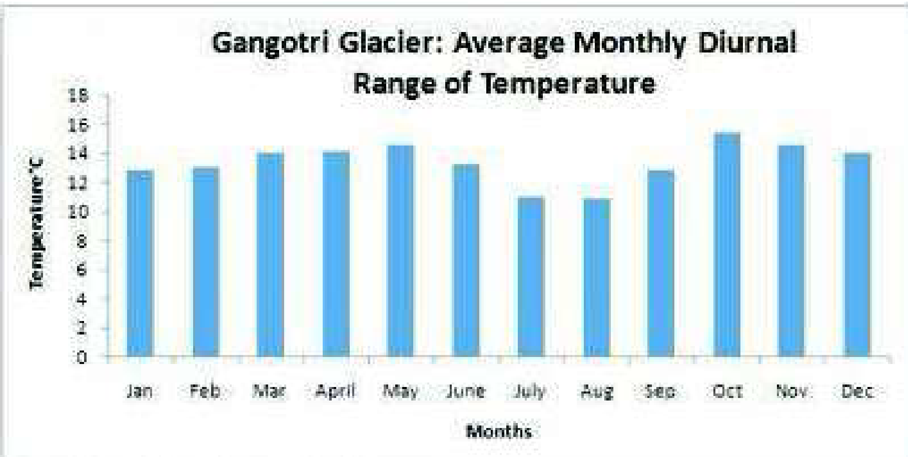

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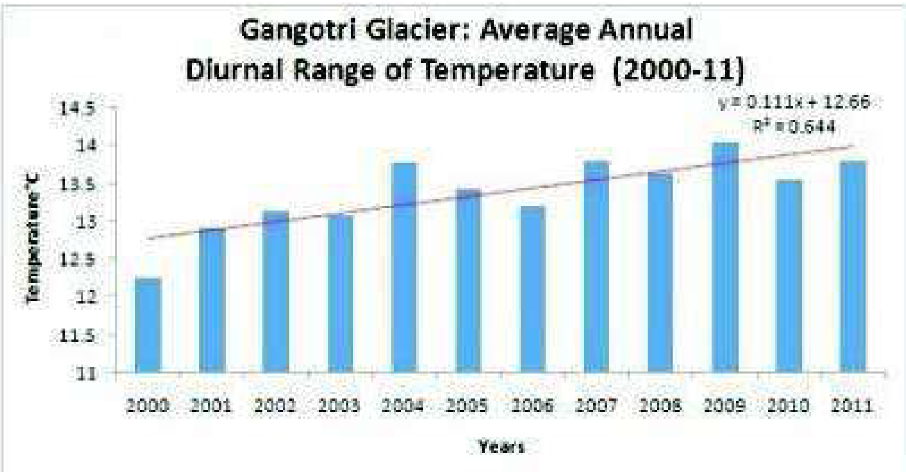
Fig. 6



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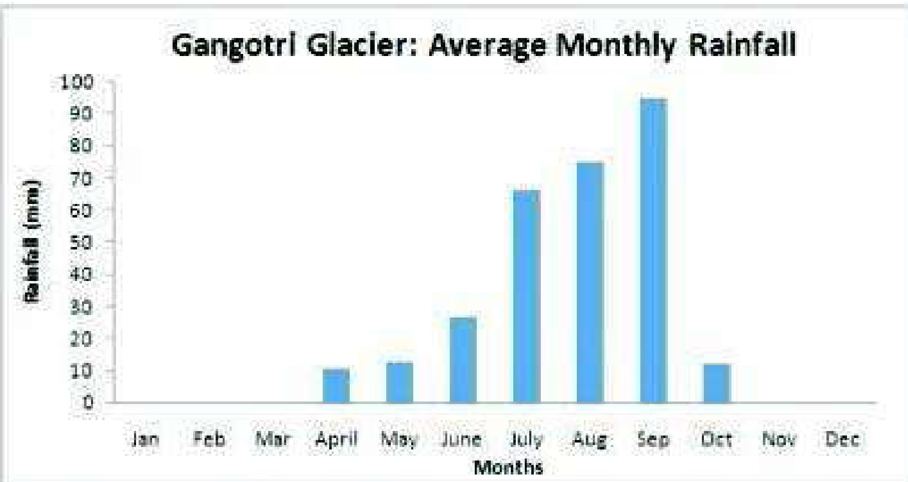

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Fig. 8

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 long wave radiation in the night-time to emit the heat, resulting in lower diurnal range of temperature. The reverse is true for the months of April, May and October.

e) Annual Diurnal Range of Temperatures

Analysis of annual average diurnal ranges of temperature from 2000-2011 over Gangotri glacier revels an increasing trend. Highest and lowest annual diurnal range of temperature is observed for the year 2009 and 2000 respectively (Fig.7).The increasing annual diurnal range of temperature is the result of increasing trend of maximum temperature. Studies by Kumar et al., (1994), Yadav et al, (2004), Arora et al., (2005), Fowler and Archer (2006), Bhutiyani et al., (2007), Das et al., (2007) and Pal and Tabbaa (2010) on the Indian sub continent have also suggested similar results.

2. Precipitation

Glacier usually receives precipitation in the form of snowfall during winter season and rainfall during summer season. Rainfall dominate the hydrology of "Himalayan catchments" from July to mid- September and snow from western disturbances dominates the winter months (NDJFMA). Thus, Gangotri Glacier receives snowfall every year usually between Decembers to April, sporadic snowfall during May and June, and no snowfall during July and August. However, rainfall is obtained between May and September each year with few rainfall days in April and October.

a) Rainfall

i. Average Monthly Rainfall

The rainfall observations clearly indicate that the rainfall in Gangotri glacier is mainly concentrated in the months of May, June, July, August and September each year but sometimes rainfall may start as early as by the end of April and continues till mid of October. The amount of rainfall is much lower in months of May and June, whereas in July, when the monsoon approaches, the amount of rainfall starts increasing and reaches to maximum in the month of September due to a combination of local convective activity and influence of monsoon (Fig.8). The mean south-west monsoon rainfall in the months of June, July, August and September contributes 96.62 % (262.78 mm) of annual average rainfall (271.97 mm). Contribution of pre-monsoon (March, April and May) and post-monsoon (October, November) rainfall to annual rainfall is almost negligible being 4.43 % and 0.89 % respectively.

Mean monthly rainfall (2002-12) during September (95mm) is highest and contributes about 34.9% of annual average rainfall (271.97 mm). Whereas the mean monthly rainfall during August (77.21mm) and July (65.94mm) is lower and contributes about 27.6% and 24.2% respectively to the annual average rainfall. Rainfall in the month of June is quite low and contributes 7.82% of the annual rainfall (12.7mm) (Fig.8).

The analysis of monthly rainfall data reveals that contribution of September rainfall has increased in the past decade (2002-2011) (Fig.9). Rainfall in August

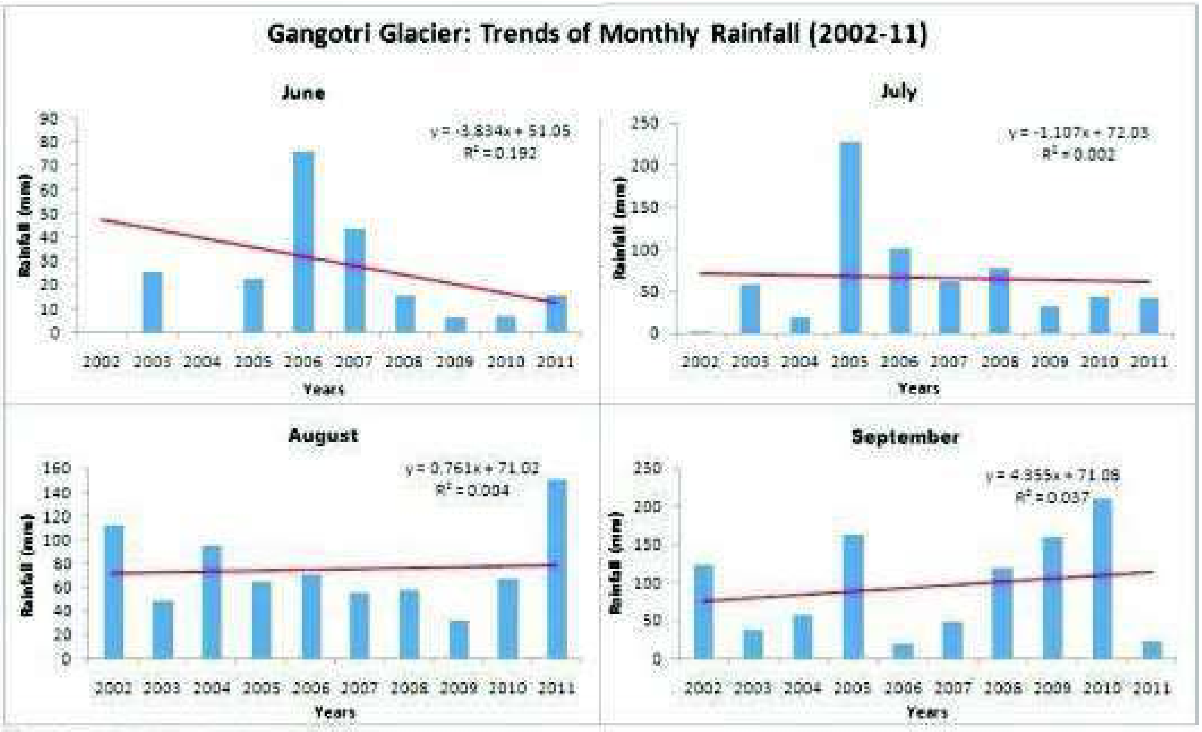

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Fig.9

shows a constant increasing trend, however for the months of June and July rainfall shows a negative trend (Fig.9). This reflects that the period of heavy rainfall is shifting towards later months as deviation is also increasing with the heaviest rainfall occurring towards the end of the monsoons.

ii. **Annual Rainfall Trend**

A significant variation is observed in monthly rainfall from year to year. As a result, annual rainfall varies accordingly. On an average, total rainfall for the years (2002-2011) is observed to be about 275.6 mm but high variability exist as it was as low as 170 mm in 2003 and as high as 493 mm in 2005 (Fig.10). However, trend analysis of precipitation (rainfall) in Gangotri reveals an increase of precipitation amounts in the last 10 years. This trend has been similar to the global trend, as analyses of yearly precipitation trends indicate a small positive global trend in precipitation over land during the twentieth century (IPCC, 2007).

iii. **Annual Rainy Days**

A rainy day is considered if any amount of rain occurred in that day. In analyzing the frequency of rainfall events maximum amount of rainy days are recorded in the year 2006 whereas minimum amount of rainfall days observed in the year 2009 and 2002. The trend analysis of annual rainy days shows an increasing trend from 2002-11 (Fig. 11).

b) **Snowfall**

i. **Average Monthly Snowfall**

Gangotri Glacier receives most of its precipitation in the form of snowfall during winter season between December to April every year, but sometimes it starts early by the end of

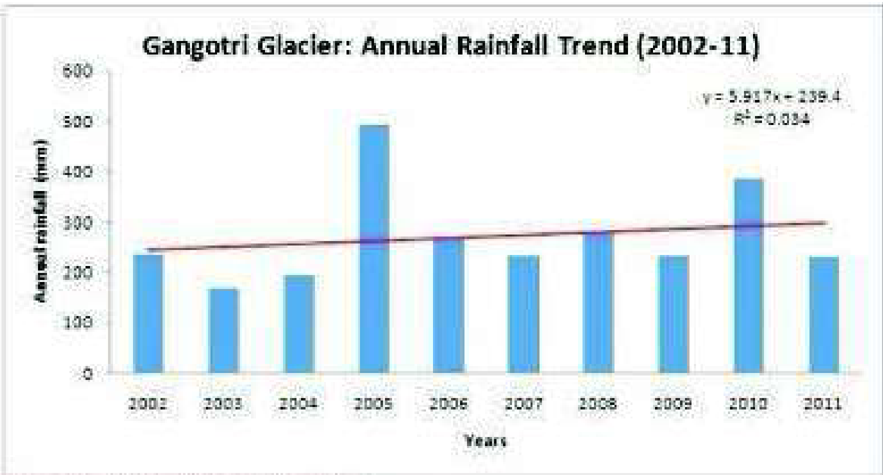

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Fig. 10

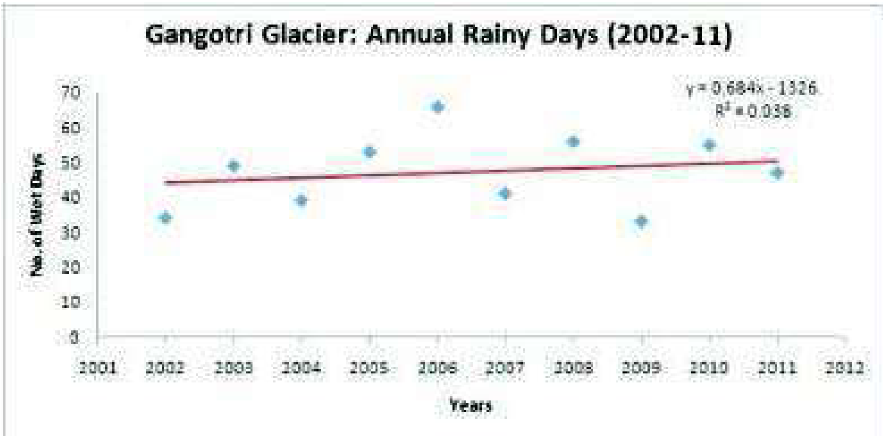

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Fig. 12

September and continues till mid of June. There is sporadic snowfall pattern between May and June. Mean monthly snowfall for the months of January, February March, April, May, November and December from 2000-11 has been computed to be 61cm, 74 cm, 58 cm, 38 cm, 11 cm, 9 cm and 28 cm respectively. Maximum amount of snowfall is received in the month of February followed by January, March, April and December. There is no snowfall in the months of July and August (Fig.12).

ii. Average Annual Snowfall

Based on twelve years data the annual average snowfall of Gangotri Glacier for the last 12 years from 2000 to 2011 is observed to be about 266 cm. However, significant variation is observed in monthly snowfall from year to year and total annual snowfall varies accordingly ranging from 422 cm the highest in 2002 to 137cm the lowest in 2009 (Fig.13). The snowfall data recorded for the last

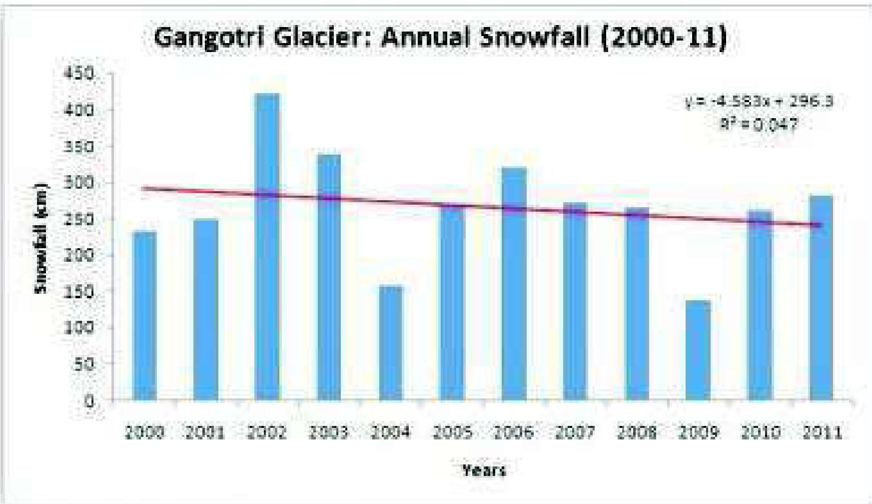

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Fig. 13

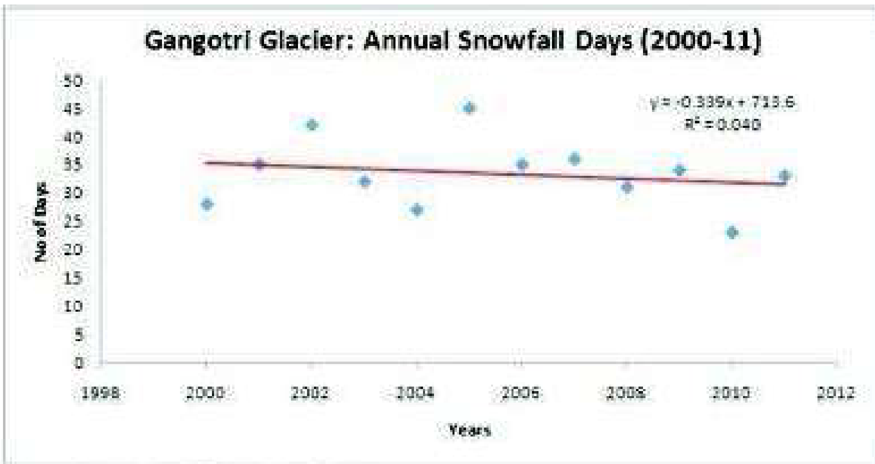

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Fig. 14

12 years show a decreasing trend of total annual snowfall (Fig.13). The amount of snowfall received throughout the year also has a direct influence on the temperature of that year. For example high amout of snowfall receivd for the years 2002 and 2003 is also reflected in the annual average temperature, as the lowest average temperature is recorded in these two years. On the other hand, years (2004 and 2009) with minimum amout of snowfall recorded the maximum annual average temperature of 5.12 and 4.71°C respectively during last twelve years.

iii. Annual Snowfall Days

A snowfall day is considered if any amount of fresh snowfall occurred in that day, and the sum of all the snowfall days in a year provides the annual snowfall days. The annual snowfall days recorded for the last 12 years from 2000 to 2011 show an overall decreasing trend.The highest number of fresh snowfall days are recorded for the year 2005 and 2002 whearas the lowest number of sniwfall days are recorded for the year 2010 (Fig.14).

The total annual snowfall data and the number of snowfall days recorded for the last 12 years from 2000 to 2011 exhibit a decreasing trend. Such observations were also reported by Mohite et al., (2007) and Negi et al., (2012). Mohite et al. on the basis of the analysis of snow cover maps of different months of 2003 and 2004 using LISS-III and AWiFS (Advanced Wide Field Sensor) data. They observed that the snowfall in 2002–2003 season was higher than in 2003–2004 and the melting of snow started in early March of 2004 and thus resulting in depletion of snow cover extent. Negi et al., (2012) estimated the snow covered area (SCA) using LISS-III multi temporal satellite data for seven years between October 2001 and May 2008 and observed an overall decreasing trend in snow cover area.

Conclusions

In the present analysis the period of study is small (i.e., twelve years) to know about the trend, however, this period provides the positive indication of warming in Gangotri glacier and decrease in snowfall. Mean maximum, mean minimum and average surface temperatures of the area on an annual basis show increasing trend. Higher magnitudes of linear trends are observed in the mean maximum temperatures than in the mean minimum temperatures. Thus, the major contribution to the warming trend is by the mean maximum temperatures. Similarly, seasonal temperature analysis reveals that it is the pre-monsoon warming which contributes most to the recent warming trend in Gangotri region, with pre-monsoon maximum temperatures accounting for most of this. The greatest warming occurs in months of March and April. It reveals that summers in the region are becoming warmer. The only evidence of decreasing temperatures is in the months of January, December and July. Range of temperature is increasing causing more variability in minimum and maximum temperatures. Striking similarities are observed between annual average temperature of Bhojbasa Observatory and the large scale temperature trends obtained from the NCEP (National Centers for Environmental Prediction).

The precipitation (rainfall) pattern of Gangotri Glacier for the last ten years (2002-2011) clearly shows that total annual rainfall exhibits a large variability (170-493 mm) from year to year, with high seasonal rainfall during the years 2005 and 2010 in comparison to other years. Based on twelve years data (2000-2011) annual average rainfall for Gangotri Glacier shows an increasing trend. Similarly, an increasing trend is observed in the number of annual rainy days. The analysis for the monthly rainfall shows that June and July rainfall has shown decreasing trend whereas the rainfall in August and September has increased. This reflects that the period of heavy rainfall is shifting towards later months. However, there is clear declining trend in seasonal snowfall during the last 10 years 2002- 2011. Similarly, the number of snowy days has also decreased. The amount of snowfall received throughout the year has a direct influence on the temperature of that year.

The impacts of higher atmospheric temperature and more liquid precipitation are perhaps already visible on Gangotri Glacier. Numerous studies (Naithani et al., 2001, Bahuguna et al., 2007, Kumar et al., 2008, Nainwal et.al. 2008, Negi et.al. 2012) have reported the recession of terminus/snout position of Gangotri Glacier which also reflects the influence of global climate change in the region.

Acknowledgements

The authors are grateful to Shri A. Ganju, Director and Mr. Sneh Maney, Dy.Director of Snow and Avalanche Study Establishment, Chandigarh, India for their cooperation and guidance along with all SASE's persons who helped in collecting the snow-meteorological data. We also thank the editor whose suggestions on the earlier version of the text helped a lot to improve it.

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