Study of Temporal Changes in Snout Position and Wet Snow Line for Gangotri Glacier using Remote Sensing, Ground Observations and Meteorological Data

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Abstract

The temporal changes (1891-2010) in snout position of Gangotri glacier were monitored using Landsat images, ground observations and SoI (Survey of India) toposheets. Temporal changes (2001-09) in wet snow line (wsl) altitude were also observed using LISS-III images and high resolution (6 m pixel size) DEM generated using Cartosat stereopair. These observations were correlated and justified with available snow meteorological data. OCGM (Oerlemans Coarse Grained Model) was run in parallel using meteorological inputs to support the obtained glacier retreat using Landsat data during 2001-10. The retreats observed were 73 m and 54 m respectively using Landsat data and OCGM. The difference was less than 20 m (less than a pixel of Landsat image) thus supporting the usefulness of remote sensing observations for monitoring of rough and hard to access terrain. The wsl altitude showed an overall ascending trend during melting season (May to September). Some atypical fluctuations in this trend were observed for different years which could be explained using available meteorological records.

1. Introduction

Glaciers are considered as sensitive indicators of climate change (Paul et al., 2004). Climatic transformations evidently reciprocate in form of changed mass balance and geometry of the glaciers (Elsberg et al., 2001). Shifting snout position and wet snow line of the glacier over a period of few years or decades tells about the response of the glacier to the changing atmospheric conditions. The temporal changes in geometry and mass balance of a glacier are not constant but rather irregular in amount, rate and time of occurrence, depending upon the prevailing climatic conditions (Elsberg et al., 2001). Thus in order to correlate the physical changes with the atmospheric phenomena, a constant monitoring of glaciers is important to evaluate the changes that occur in their ice mass, surface area and geometry. Most of the Himalayan glaciers are undergoing recession like rest of the glaciers around the globe. Their study can be complicated due to the fact that these glaciers are often in remote and inaccessible locations (Rau et al., 2000). This makes remote sensing techniques an important tool in glaciological studies.

Owing to synoptic view and repetitive coverage, remote sensing in conjunction with field based glaciological measurements is a powerful and efficient tool to study glaciers that are usually located in remote, inaccessible and inhospitable environments (Krishna, 1996, Kulkarni et al., 2002a, 2007a, Konig, 2001 and Bahuguna et al., 2007). Global warming and climate change have been focus of most of the glacier recession studies on Indian Himalayas (Kulkarni et al., 2002b, 2005, 2007b, Bhutiyani, 1999 and 2008 and Hasnain, 2008). Snout of the Gangotri glacier, as is typical of many glaciers in the Himalayas, is marked by a prominent ice cave and is covered with supra-glacier debris (Bhambri et al., 2011). Gangotri Glacier is one of the best studied and documented glaciers in the Himalayas. The terminus of Gangotri Glacier has been retreating since 1780 A.D. (Naithani et al., 2001). Several studies have been carried out for the mapping of Gangotri glacier based on remote sensing data and GIS technology to study the changes in the glacier parameters (Bahuguna et al., 2007, Kumar et al., 2008, Naithani et al., 2001 and Singh et al., 2002). In the present study, using temporal remote sensing data of Landsat and field observations, an attempt was made to mark changing snout position. The retreat rates were calculated between the observations for different years. The retreat from 2001 to 2010 was further validated using available meteorological data from the observatory near the snout by running OCGM in parallel. The monitoring of different changes taking place on higher reaches of the glacier is also significant since the varying altitude of wet snow line is important in hydrological modeling. In the present study observation of snow cover area (SCA) and wet snow line were carried out for Gangotri glacier using band-3 (NIR) of LISS-III images for a period of nine years (2001-09). The changes were justified by correlating them with snow-meteorological data.

2. Study area and data used

Gangotri glacier is one of the largest Himalayan glaciers, with a length of about 30 km and width varying from 0.5 to 2.5 km covering a surface area of about 143.48 sq km. It is a valley-type compound basins glacier, located in the Uttarkashi district of the Uttarakhand state in India (Figure 1). According to Geological Survey of India (GSI), the glacier lies between 30°43′22″N and 30°55′49″ N latitudes and 79°04′41″E and 79°16′34″ E longitudes, extending in altitude from around 4000 m to 7138 m above mean sea level (msl). It is a cluster of many glaciers comprising the main Gangotri glacier as the trunk of the system occupying a longitudinal U-shaped valley. It flows in the northwest direction forming the source of Bhagirathi river at Gaumukh (snout of Gangotri glacier). The satellite data used for snout demarcation was Landsat TM/ETM+/MSS (Table 1). In addition, SoI toposheets of 1935 and 1962 were also used. For wsl altitude demarcation, cloud free IRS 1C/1D LISS-III images of March to December months for different years were used (Table 2). The snow-meteorological data (snowfall, rainfall, temperature) used to run OCGM and correlation analysis was recorded at Snow and Avalanche Study Establishment (SASE) manned observatory located near the snout at Bhojbasa in Gangotri sub-basin. A 6 m pixel resolution DEM of the study area was generated using Cartosat stereopair (28 September, 2006).

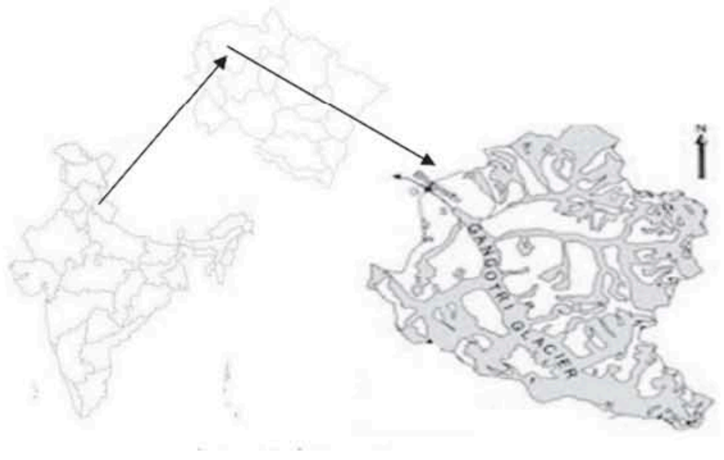

Figure 1: Location of the study area

Table 1: Total numbers of Landsat scenes used for snout demarcation of Gangotri glacier

S. No.	Date of Pass	Landsat Sensor
1	14 Oct 1976	Landsat MSS
2	15 Nov 1990	Landsat TM
3	15 Oct 1990	Landsat ETM+
4	2 Sep 2001	Landsat ETM+
5	6 Nov 2010	Landsat TM

Table 2: Total numbers of LISS-III scenes used for the snow cover monitoring of Gangotri glacier

S. No.	Date of Pass	Satellite
1	17 Oct, 2001	IRS-1C
2	19 Sept, 2004	IRS-1D
3	12 Dec, 2004	IRS-1C
4	9 Oct, 2006	IRS-1D
5	10 June, 2009	IRS-1D
6	23 May, 2002	IRS-1D
7	2 June, 2003	IRS-1D
8	17 May, 2004	IRS-1C
9	21 June, 2005	IRS-1D
10	8 March, 2007	IRS-1D
11	6 May, 2008	IRS-1D

Figure 2: Cemented benchmark on the huge boulder set up by D.S.T. (GoI) in the field showing snout position for 1891.

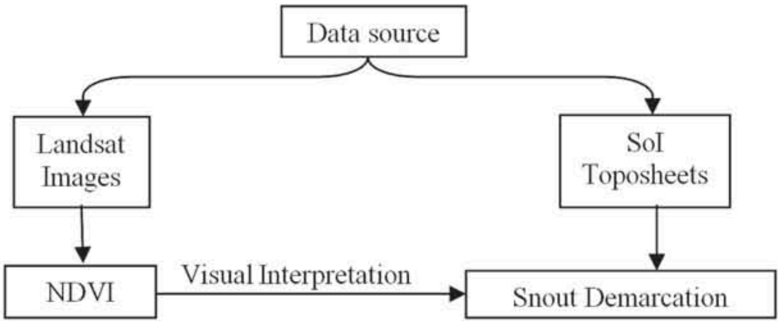

Figure 3 : Methodology used for Demarcation of Snout position of Gangotri Glacier

3. Methodology

3.1 Snout and Retreat Monitoring

Multi temporal satellite data of Landsat MSS, TM and ETM+ in combination with SoI toposheets and field based data were used to observe the changes in glacier snout position and retreat rate over a period of 119 years (1891-2010). The snout position of 1891 was marked on the basis of GPS point reading of the cemented benchmark on the huge boulder set up by D.S.T. (Department of Science and Technology), GoI (Government of India) (Figure 2). Thereafter glacial extent available on Survey of India (SoI) topographic maps of 1935 and 1962 were used for snout demarcation. Finally remote sensing images of Landsat MSS (date of acquisition: 14 Oct 1976), Landsat TM (date of acquisition: 15 Nov 1990), Landsat ETM+ (date of acquisition: 15 Oct 1999 and 2 Sep 2001), Landsat TM (date of acquisition: 6 Nov 2010) were used for snout demarcation. The details of datasets are given in Table 1. Pre-winter imageries were selected for studying the glacier retreat and demarcating the snout (Figure 3). Since the snout of Gangotri glacier is covered with debris, in order to mark it on satellite images, we assumed that the snout position was same as the point of origin of river water. Simple visual interpretation of NDVI (Normalized Difference Vegetation Index) images gave us a very clear picture of snout positions on different images. Formula for calculating NDVI image is:

$$NDVI = (NIR - \mathrm{Re}\,d)/(NIR + \mathrm{Re}\,d)$$

Equation 1

NDVI was applied to the Landsat images because water pixels appeared dark in NDVI images as water absorbed most of the incoming radiation in NIR band.

3.2 OCGM to Obtain Retreat from 2001-2010

Atmospheric and climatic parameters (solar radiation, air temperature, precipitation, wind and cloud cover) influence the mass balance and energy balance of the glacier (Oerlemans, 2001). The characteristic response time of a glacier ranges from years to centuries and any given glacier will reflect an integrated climate history on those timescales (Oerlemans, 2001, 2005). Oerlemans coarse grained model (OCGM) was applied for Gangotri Glacier (Figure 4). The model uses two climatic parameters, temperature and precipitation as inputs to calculate the change in length and rate of recession for any glacier. The model relates the recession of the glacier to its local climate (temperature and precipitation). The temperature and precipitation data for Gangotri Glacier were available for the past eleven years (2000 - 2011). These climate data sets were used to validate the strength of OCGM model in Himalayan terrain. To the best of our knowledge, this is the first attempt to measure the change in length and rate of Gangotri glacier recession from OCGM. All meteorological data were collected as per World Meteorological Organization (WMO) standards. The daily maximum and minimum temperatures were averaged out to calculate average temperature of a particular day. Similarly average monthly temperatures were calculated from the mean of daily temperature and these were further used to calculate yearly average temperatures (Table 3). The OCGM model is based on following assumptions:

1) Corresponding to a climatic condition and glacier geometry, there is a unique equilibrium length of the glacier which it will attain if the climatic conditions are unchanged for a long enough period.
   (a) To first approximation, the climatic conditions that determine the equilibrium length are annual average precipitation and annual average temperature.
   (b) The most important factor of the glacier geometry that determines the equilibrium length is its slope.
2) The change in equilibrium length per unit change in climatic conditions is called glacier's climate sensitivity. If climatic conditions change the glacier responds by attaining its new equilibrium length. The time scale over which it attains its new equilibrium length is called its response time.
3) The variation in precipitation mainly influences the accumulation zone and variations in temperature mainly influence the ablation zone. The front position thus responds directly to the temperature fluctuations. The effects of precipitation fluctuations tend to get averaged out as their influence slowly propagates from accumulation zone to the snout region.

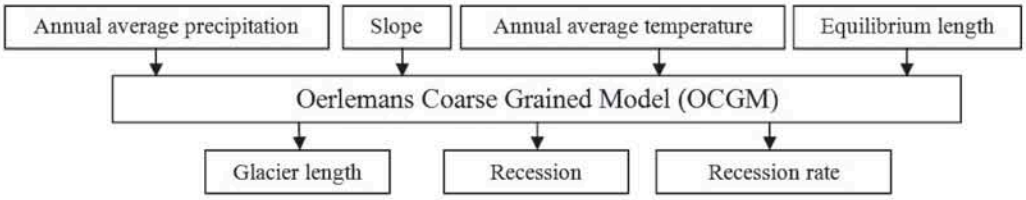

Figure 4: Methodology used for OCGM.

Table 3: Annual average temperature and precipitation data for Bhojbasa manual observatory

Year	Max. Temperature (°C)	Min. Temperature (°C)	Annual Avg. Temperature (°C)	Annual Precipitation	
				Rainfall (mm)	Snowfall (cm)
2000	09.56	-2.69	3.41	—	232
2001	10.71	-2.19	4.25	—	249
2002	10.59	-2.54	4.02	270	422
2003	10.50	-2.57	3.96	170	337
2004	12.01	-1.76	5.12	194	584
2005	10.62	-2.80	3.90	493	269
2006	11.64	-1.55	5.04	269	319
2007	11.90	-1.90	5.00	232	271
2008	11.18	-2.44	4.37	280	265
2009	11.73	-2.13	4.71	233	135
2010	11.98	-1.82	5.37	385	260

Based on these physical assumptions, mathematical model generated by Oerlemans to describe climate sensitivity and glacier response time was modified as per the glacier geometry and meteorological data availability and was used for present study. A reference time t_0 was taken and temperature at $t = t_0$ was assumed to be $T(t_0)$ with an equilibrium length, L of the glacier corresponding to this temperature. Further it was assumed that the actual length of the glacier at some time, t be $L + l(t)$ with a temperature $T(t)$ and $\Delta T(t) = T(t) - T(t_0)$ denoting the variation of the temperature. The equation for the time variation of the length is:

$$\frac{dl}{dt} = -\frac{(c\Delta T + l)}{\tau}$$

Equation 2

Where c is the climate sensitivity and τ is the response time. Based on comparison with more detailed models and field data, Oerlemans gives the following empirical formulae for these two quantities:

$$c = \frac{230p^{0.6}}{s}$$

Equation 3

$$\tau = \frac{13.6}{(\sqrt{(1+20s)L})s(0.006)p^{0.5}}$$

Equation 4

Where p is the average precipitation in meters/year, s is the slope and L is the length in meters. The value of 230 is the result of calibration with set of numerical models that take glacier geometry into account. The climate sensitivity (c) and response time (τ) parameters depend upon the glacier geometry and local precipitation (at the snout). The slope (ratio of vertical rise to horizontal reach) calculated for Gangotri glacier was 0.083. The formulas for glacier length, *l(t)* (equation 5) and rate of recession *v(t) at time t* (equation 6) are given below.

$$l(t) = e^{-t/\tau}(l_0 e^{t_0/\tau} - \frac{c}{\tau}\int_{t_0}^{t} dt' e^{t'/\tau}\Delta T(t'))$$

Equation 5

$$v(t) = \frac{1}{\tau(1 - e^{-(t/t_0)/\tau})}(\Delta l e^{-(t/t_0)/\tau} + \frac{c}{\tau}\int_{t_0}^{t} dt' e^{(t'-t)/\tau}\Delta T(t'))$$

Equation 6

In order to validate the recession between years 2001 and 2010 obtained from the satellite data, we took 2001 as t_0 and the measured length in 2001 using satellite data, 29069.04 m as L. Taking 2010 as t gave us the length of glacier in 2010 and corresponding recession rate in between the time gap.

3.3 Marking Wet Snow Line (wsl) Elevation

Gupta et al., (2005) observed that the NIR band of LISS-III sensor saturates at reflectance of approximately more than 50%. They took it as a threshold to classify snow cover area into dry and wet snow classes: NIR reflectance >50% (dry snow) and <50% (wet snow). Similar methodology (Figure 5) has been adopted in the present study with further refinement of the reflectance thresholds for Gangotri glacier based on field readings. LISS-III NIR band was used to classify snow into different classes in terms of increasing order of wetness (e.g. dry, moist and wet snow). Thresholds set for all snow classes were: Glacier Ice = 40-60%, Moist snow = 60-88% and Dry snow > 88% in NIR band. The wet snow line altitudes were observed by draping the classified image over DEM. The corresponding areas under each type of snow cover were also calculated and change detection analysis was performed. All these results were supported by snow-meteorological data.

4. Results and Discussion

As documented, the glacier has been under the state of continuous recession since 1891 till 2010. The geographical coordinates of the snout positions are given in Table 4. The data revealed that the glacier has retreated by 2281 m, with an average rate of 18m/y from 1819 to 2010 (Figure 6). GSI (Geological Survey of India) has monitored the glacier since 1935 and the first two snout positions are marked using SOI topographical sheet of the years 1935 and 1962, obtained from the archive of Geological Survey of India (Figure 3).

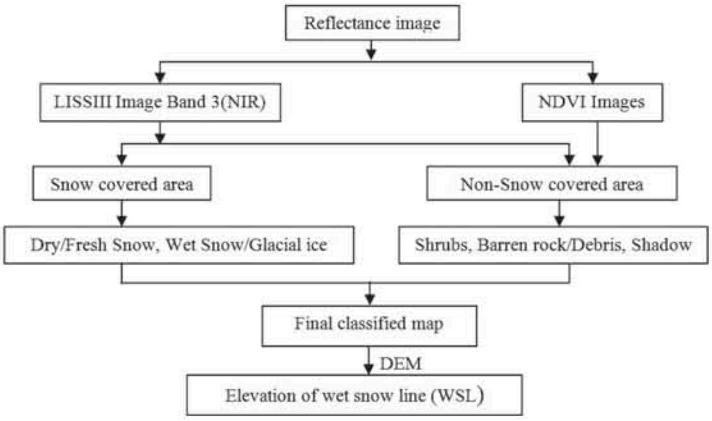

Figure 5: Methodology used for Classification

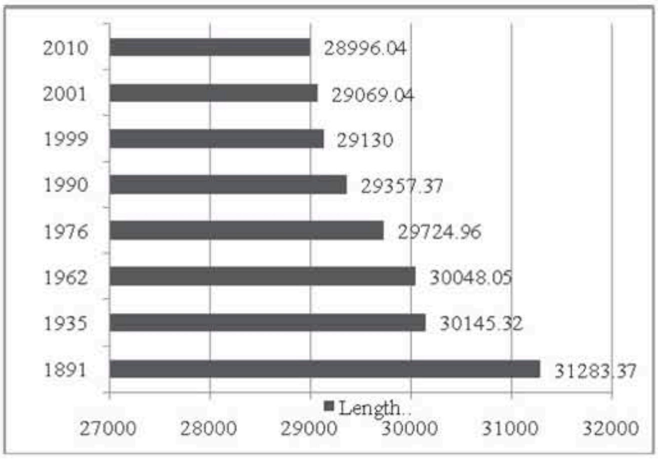

Figure 6: Change in length of Gangotri glacier (1891-2010)

Table 4: Gangotri snout Positions (1891-2010) and retreat rates

Year	latitude	longitude	Altitude (in m)	Retreat Rate (m/y) between current and previous reading	Reference
1891	30°56'23.123"N	79°3'45.612"E	3874	---	GPS point of Benchmark set by D.S.T. GoI
1935	30°55'58.969"N	79°4'17.976"E	3914	25.68	SoI Toposheet
1962	30°55'58.244"N	79°4'21.341"E	3932	03.56	SoI Toposheet
1976	30°55'49.9"N	79°4'28.7"E	3936	23.11	Landsat MSS (14 Oct 1976)
1990	30°55'43.165"N	79°4'40.113"E	3986	26.27	Landsat TM (15 Nov 1990)
1999	30°55'38.042"N	79°4'46.182"E	3991	25.32	Landsat ETM+ (15 Oct 1999)
2001	30°55'36.301"N	79°4'47.524"E	3998	30.90	Landsat ETM+ (2 Sep 2001)
2010	30°55'35.157"N	79°4'49.753"E	4016	08.10	Landsat TM (6 Nov 2010)

Table 5: Comparison of satellite observations with previous studies

Years	Obtained Retreat rate (m/y)	Years	Retreat rate (m/y) from previous works	Validation (reference)
1935-1962	03.50	1936-1956	02.80	Raina, 2009
1935-1999	19.56	1935-1999	20.52	Vohra (1971), Naithani (2001)
1976-1990	26.70	1976-1990	29.00	GSI
		1977-1990	28.08	GSI
1990-1999	25.30	1994-1998	25.00	A.K. Tangri,2004
2001-2010	08.00	2000-2008	10.00	Milap Sharma (2010)
		2005-2008	6.00	K. Kumar (2008)
		2001-2006	7 ± 4	Bhambri (2011)

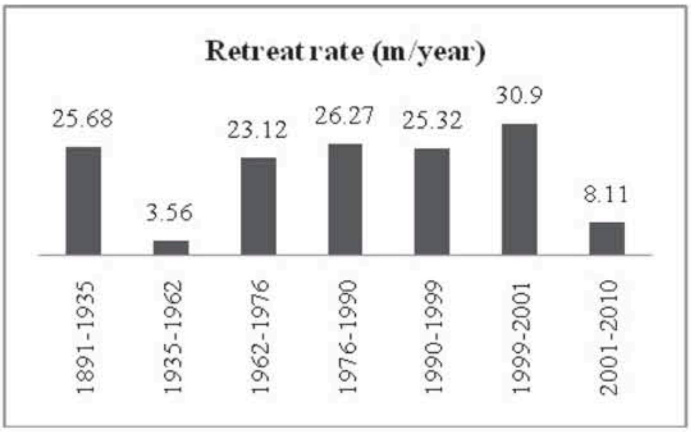

Figure 7: Retreat rates for Gangotri glacier (1891-2010)

Based on these toposheets, it was observed that the glacier retreated with an average rate of 3.56m/year between 1935 and 1962. Thus the retreat rate was very less as compared to the average retreat of about eight decades. Further snout was marked using satellite data of Landsat MSS for 1976, Landsat TM for 1990, Landsat ETM+ for 1999, and Landsat ETM+ for 2001. The recession rate increased to 23.1m/year during the years 1962-1976 and to 26.27m/y from 1976-1990 and remained high as 25.32m/y and 30.9m/y for the years 1990-1999 and 1999-2001 respectively. However for the years 2001-2010, the retreat rate showed a decline to 8.11 m/year (Figure 7). Earlier studies on the recession of Gangotri glacier using topography map and satellite data have shown similar estimation of recession (Table 5).

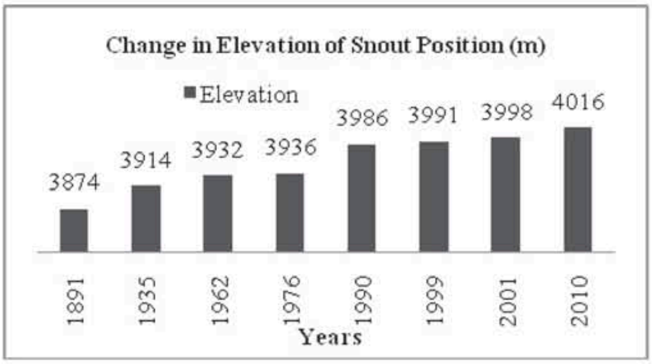

Figure 8: Change in elevation of Snout (1891-2010)

Table 6: Retreat obtained using OCGM

Year	Length (m)	Rate of Recession (m/y)
2001	29069.04	—
2002	29065.14	03.89
2003	29060.90	04.24
2004	29046.96	13.93
2005	29038.54	08.42
2006	29029.86	08.69
2007	29025.90	03.96
2008	29023.81	02.09
2009	29020.28	03.53
2010	29015.24	05.04

Table 7: Comparison of results obtained from OCGM with previous years' works

Years	Retreat rate (m/year)	Source
2001-2010	6	OCGM
2000-2008	10	Milap Sharma (2010)
2005-2008	6	K. Kumar (2008)
2001-2006	7+ - 4	Bhambri (2011)

Thus frontal recession of Gangotri glacier has shown variability in the amount, rate and time of occurrence during the study period. This could be due to several factors like flow, input parameters, climate factors and other factors which are yet to be investigated. On an average the glacier is receding at the rate of about 18 to 19 m per year. The glacier snout also shows significant elevation change of 142m from 1891-2010 due to the continuous recession in the lower reaches of the glacier. The snout elevation has changed its position from 3874 m (1891) to 4016 m (2010) (Figure 8). Since we had snow-meteorological data from 2001-2010, we applied OCGM to measure the retreat during this period (Table 6). Using AWS meteorological data, the recession and rate of recession (m/yr) were calculated for the changing snout position from the year 2001 to 2010. The average rate of recession for this duration was calculated to be 6 m/yr. The derived length from the model clearly shows that Gangotri glacier has retreated from 29069.04 m (length derived in 2001 using satellite data) to 29015.24 m within a span of ten years. The result is close to the recession (72 m) and retreat rate (8 m/yr) during this period observed using Landsat images. The difference was less than 20 m (less than a pixel of Landsat image) thus supporting the usefulness of remote sensing observations for monitoring rough and hard to access terrain. Table 7 shows the comparison of results obtained from OCGM and other studies for the same years. The classification was performed on temporal LISS-III images to demarcate the wet snow line.

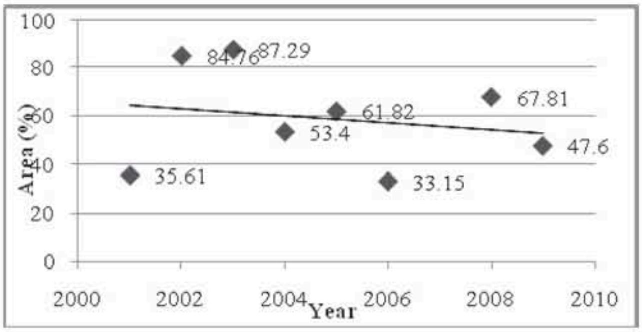

Figure 9: Snow cover for summer months (2001-2009)

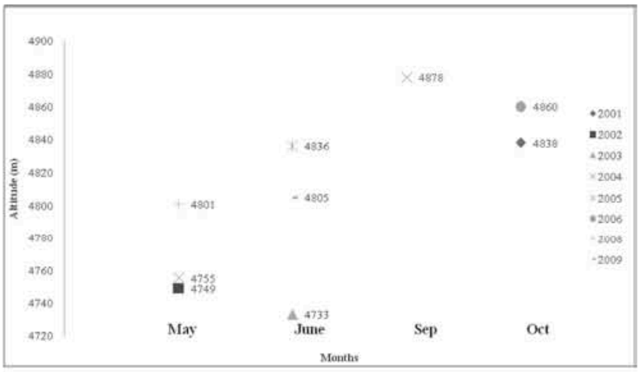

Figure 10: Variation in wet snow line altitude

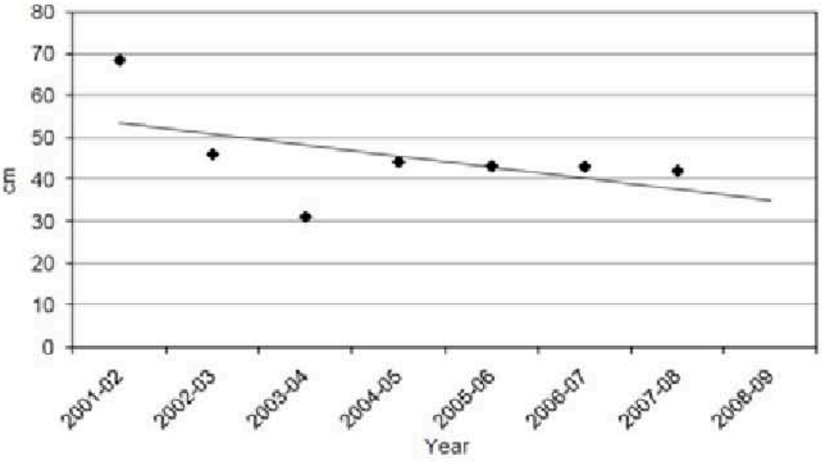

Figure 11: Average fresh snowfall amount of winter season (November-April) from ground observations data

The seasonal snow cover area analysis on these images showed an overall decreasing trend for summer months (May, June) with some points of higher snow cover area not following the trend (Figure 9). When compared with AWS data, it was found that such irregularity was because of either snowfall in the corresponding summer months or because of very high and late snowfall in previous winter months.

The variation in wet snow line with respect to altitude showed an overall ascending trend from May to September (Figure 10). Further September onwards, wet snow line altitude starts descending could be due to early snowfall at high altitudes (Figure 10). The observations of changing wet snow line and snow cover areas are in accordance with the recorded meteorological parameters.

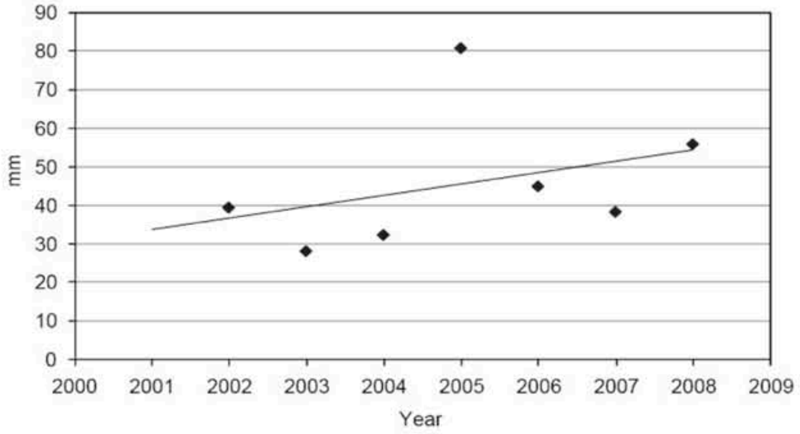

Figure 12: Average rainfall amount of summer and rainy seasons (May-October) from ground observations data

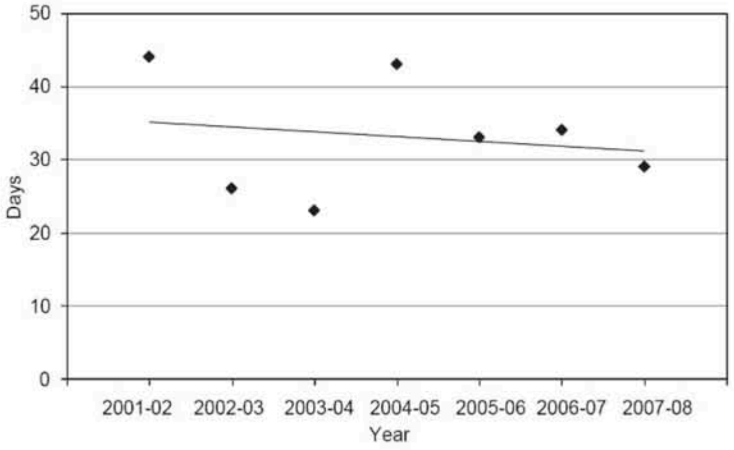

Figure 13: Number of fresh snowfall days during winter season (where snowfall day is considered if any amount of fresh snowfall occurred in one day)

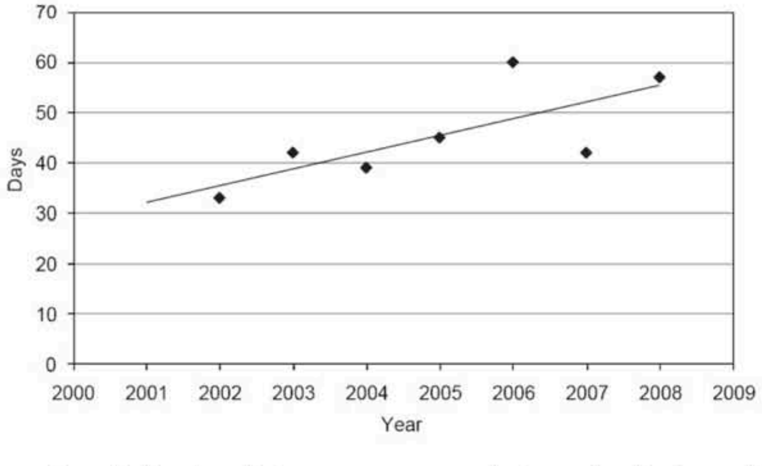

Figure 14: Number of rainy days during summer season (where rainy day is considered if any amount of rain occurred in one day)

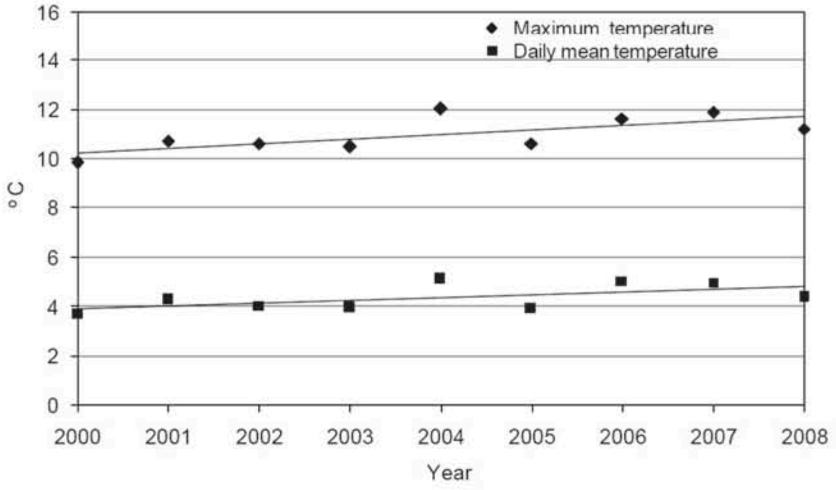

Figure 15: Maximum and daily mean temperatures pattern between year 2000 and 2008

Similar observations were also reported by Mohite et al., (2007) for a period of two year. The precipitation data (fresh snowfall and rainfall) recorded between years 2001 and 2009 showed a decreasing trend of average fresh snowfall during winter (Figure 11) and an increasing trend for average rainfall during summer and rainy seasons (Figure 12). This supported the decreasing trend of SCA (Snow Covered Area) retrieved using satellite data. The increased average rainfall amount also suggests increased wet snow cover condition. Further decreasing trend in number of fresh snowfall days was observed during winter season (Figure 13) and increasing trend in number of rainy days was observed during summer and rainy seasons (Figure 14). The temperatures data recorded for 9 years also showed an overall rising trend in the daily mean and maximum temperatures observed between years 2000 and 2008 (Figure 15). This rising trend of daily mean and maximum temperature within study area also supported the snow cover conditions and causes of fast melting.

5. Conclusions

The prospective of satellite remote sensing and meteorological observatory data was examined for snout position and wsl monitoring of the Gangotri glacier. The observed changes in snow cover area and snow characteristics were correlated with field collected snow-meteorological data and field visits. Further, the comparison of the results of this study matches closely with the previous studies carried out by different researchers for same study area. Apart from the continuously retreating glacier mass, a number of recently formed glacial lakes were also observed during field survey indicating the adverse effects of climate change. For examining the glaciers with debris cover (as is the case with most of the Himalayan glaciers), a high resolution, time series collection of thermal images can prove to be effective as it can give the extent of glacier under debris. Also microwave data can be very effective as all time all weather phenomenon with additionally enabling us for snow parameters estimation. The glacier specific modifications in OCGM can be more accurate if we have detailed knowledge about upper reaches and accumulation zone of the glacier.

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