Monitoring of great Himalayan glaciers in Patsio region, India using remote sensing and climatic observations

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Three glaciers, namely Panchi-Nala, Zing-Zing-Bar and Baralacha-La in the Patsio region, Great Himalaya, India were monitored between 1971 and 2011 using satellite data. These glaciers were selected based on their terminus altitude, slope variations and debris cover. The Landsat, Corona, LISS-IV and Cartosat-1 satellite data were analysed to monitor variations in the area of glacier, terminus and annual snow line. Glacier outlines from the satellite imageries were generated using hybrid technique consisting of visual interpretation, band ratio, NDSII and thermal band (TM and ETM+) data. Glacier outline was also verified by GPS survey on Zing-Zing-Bar in 2011. The total loss in the area of a glacier was observed to be maximum (16.35 ± 3.74%) for the smallest glacier, i.e. Baralacha-La glacier between 1971 and 2011. A maximum average retreat in glacier terminus of 22.5 ma^{-1} was observed for the Zing-Zing-Bar glacier, whereas for Panchi-Nala and Baralacha-La glaciers, the average retreat rate was observed to be 9.2 and 10 ma^{-1} respectively. An upward shift in Equilibrium Line Altitude was observed for all the glaciers between 1971 and 2011. The climate data collected at SASE meteorological station, Patsio (3800 m) between 1983 and 2011 suggests an increasing trend in the mean annual temperature and a decreasing winter precipitation. These observations support the effect of climate variability on spatial variation of glaciers in the Patsio region. Non-climatic factors such as size of the glacier, slope variation and debris cover were found to influence variable responses of different glaciers in the same climatic zone.

Keywords: Climate change, glaciers, remote sensing, snow line.

THE Himalayas possess large area of glaciers covering approximately 33,000 sq. km, which act as an important source of water for the rivers originating in the Himalaya[1,2]. Therefore, it is important to regularly monitor the spatial and temporal changes in the area and length of these glaciers. Recent studies on the Himalayan glaciers, using ground- and satellite-based observations, indicate a long-term trend of climate variability and change that may accelerate melting of the Himalayan glaciers[3–5]. Studies also suggest a decreasing trend in snowfall[6], which acts as the main source of precipitation for sustaining the glaciers and freshwater resources in the Himalayan region. Thayyen and Gergan[7] reported that the runoff variation in Himalayan catchments that experiences snowfall in winter and monsoon precipitation in summer is linked with precipitation rather than mass balance changes in the glacier. Short-term studies of terminus and mass balance of the Himalayan glaciers, based on *in situ* observations, show an accelerated rate of melting[8–10]. Recent trends of glacier retreat may be attributed to 20th century climate fluctuations. The response of glaciers to such climate fluctuations is complex and may also depend on non-climatic factors such as topography, glacier geomorphology, debris cover and ice dynamics[11,12].

A glacier does not respond only to the immediate climatic changes, for if it is the case then all glaciers within the same climatic zone should have been advancing or retreating at the same time[13]. Snow lines at the end of the ablation season serve as a good proxy for Equilibrium Line Altitudes (ELAs) and therefore for mass balance and climate reconstructions[14]. In the present study, we have monitored variations in area, length and ELA of three glaciers in a single climatic zone of the Patsio region in middle Himalayan snow climatic zone[15], to understand the effect of climate change over a period of past 40 years. The middle Himalayan zone is characterized by fairly cold temperatures, heavy and dry snowfall with strong wind action[15]. The possible drivers for variable rates of glaciers response have been analysed. These possible factors can be useful to model the response of climate change on Himalayan glaciers. Climate data observed at Snow and Avalanche Study Establishment (SASE) observatory located in the Patsio station were analysed for temperature and snowfall trends. Kulkarni *et al.*[16] have reported that Zing-Zing-Bar glacier (which they named as Patsio glacier) is a rapidly retreating glacier due to climate change; but their studies are more qualitative and lack climatic observations in the region. In addition, their study was not specific to a single climatic zone of the Himalaya.

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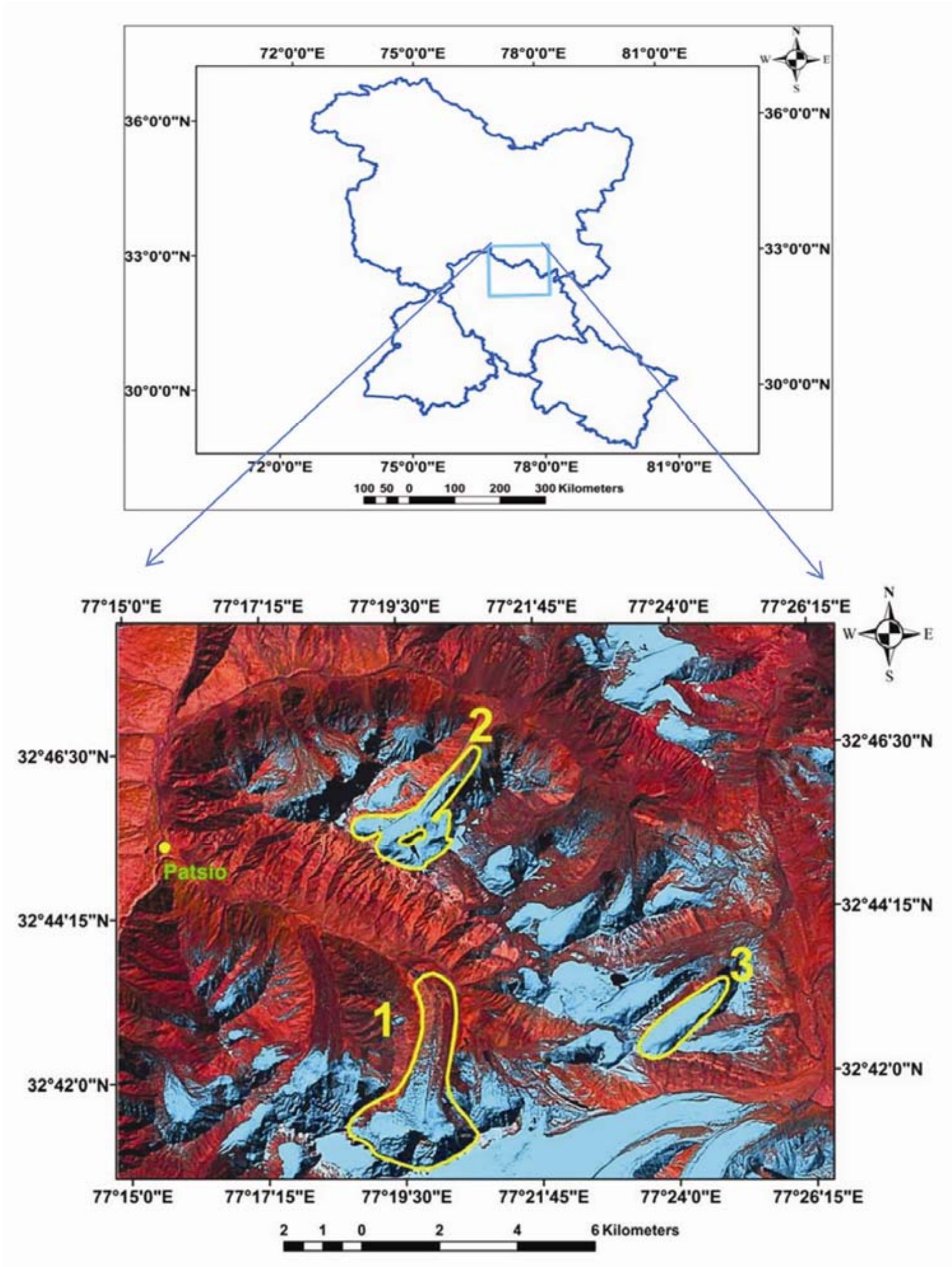

Figure 1. Study area of Patsio region (Great Himalayan range). 1, Panchi-Nala glacier; 2, Zing-Zing-Bar glacier; 3, Baralacha-La glacier.

Study area

The study area in the Patsio region, lies between lat. 32°40′22″–32°48′29″N and long. 77°14′57″–77°26′32″E in the Himalaya (Figure 1). Three glaciers, i.e. Panchi-Nala (77°18′07″E, 32°42′12″N), Zing-Zing-Bar (77°20′26″E, 32°46′02″N) and Baralacha-La (77°24′38″E, 32°43′07″N) were selected for monitoring from this region. These glaciers were selected because one glacier from one climatic zone may not be the true representative due to variations in topographic parameters (elevation, slope, aspect/orientation), glaciers sizes (area) and debris cover. Therefore, based on different topographic characteristics such as terminus altitude, slope variations, size and debris cover, three different glaciers were selected from the same snow climatic zone (Figure 2 and Table 1). This can provide the overall glacier variations in the study area as well as the different rate of spatial variations due to local factors.

From Table 1, it can be seen that while Panchi-Nala terminates at lowest elevation (4544 m), the Zing-Zing-Bar and Baralacha-La terminate at higher elevations of 4607 m and 5190 m respectively. Panchi-Nala has thick debris cover in the ablation zone, the Zing-Zing-Bar has few medial moraines and Baralacha-La is free of debris cover.

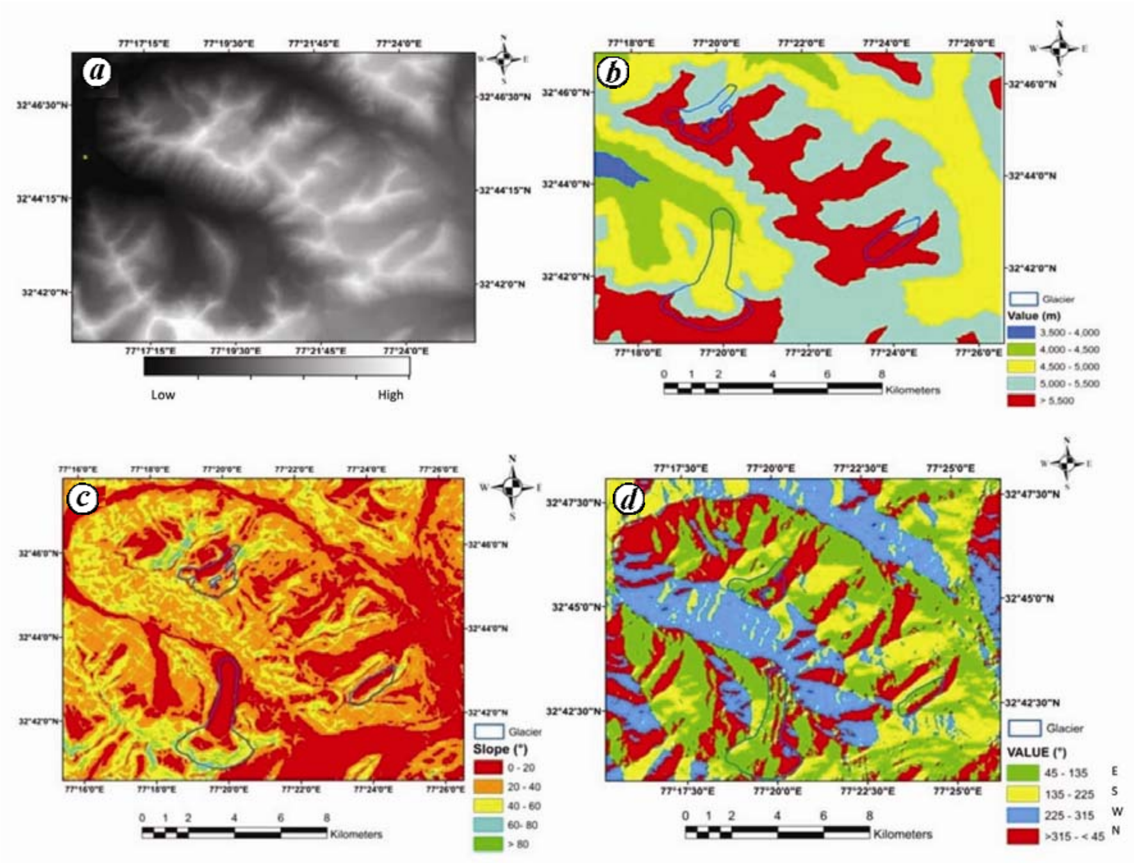

Figure 2. Different topographic thematic maps generated using DEM; ***a***, DEM; ***b***, Elevation map; ***c***, Slope map; ***d***, Aspect map.

Table 1. Studied glaciers in Patsio region, Great Himalaya

Glacier	Basin	SoI toposheet number (1 : 50,000)	Altitude range	Aspect	Mean slope (°)	Debris cover
Panchi-Nala	Bhaga	52 H6	4544–5450	N	12	Heavy
Zing-Zing-Bar	Bhaga	52 H5	4607–5531	NE	15	Light
Baralacha-La	Zaskar	52 H6	5190–5625	NE	11	Clean

Data sources

The Survey of India (SoI) map sheets at a scale of 1 : 50,000 surveyed in 1979 were used for generating database for glaciers. In addition, a Corona (KH-4B) declassified image of 28 September 1971 with minimum cloud cover was used for the generation of base maps of the glaciers. The multi-spectral Landsat satellite data of MSS/TM/ETM+ sensors were downloaded from USGS (United States Geological Survey, http://glovis.usgs.gov/) web-server and used for the spatio-temporal monitoring of the glaciers. Scenes at the end of the ablation season were preferentially selected to extract the annual snow lines. The ablation season begins during May and gradually ends through September. A total 13 cloud-free Landsat scenes were found suitable and the details of scenes are given in Table 2. Eleven out of thirteen images were selected from August to September and two images of October were included to fill the gap in the years 1979 and 1989. The high-resolution satellite images of Cartosat-1 (2.5 m) and LISS-IV (5.8 m) were used to evaluate the uncertainty in glacier outline analysis. The study area using these images can be observed in Figure 3. The digital elevation model (DEM) generated at SASE, using SoI map sheet at 6 m resolution was used for topographic analysis.

Field visits were conducted in June and September in 2011 and 2012. The ground control points (GCPs) of snout position, geomorphology features and snow line were collected at the approachable glacier Zing-Zing-Bar (Figure 4). To understand better the possible relation of glacier behaviour with regional climate, meteorological data such as maximum temperature, minimum temperature and precipitation (snowfall/rainfall) of the past 28 years

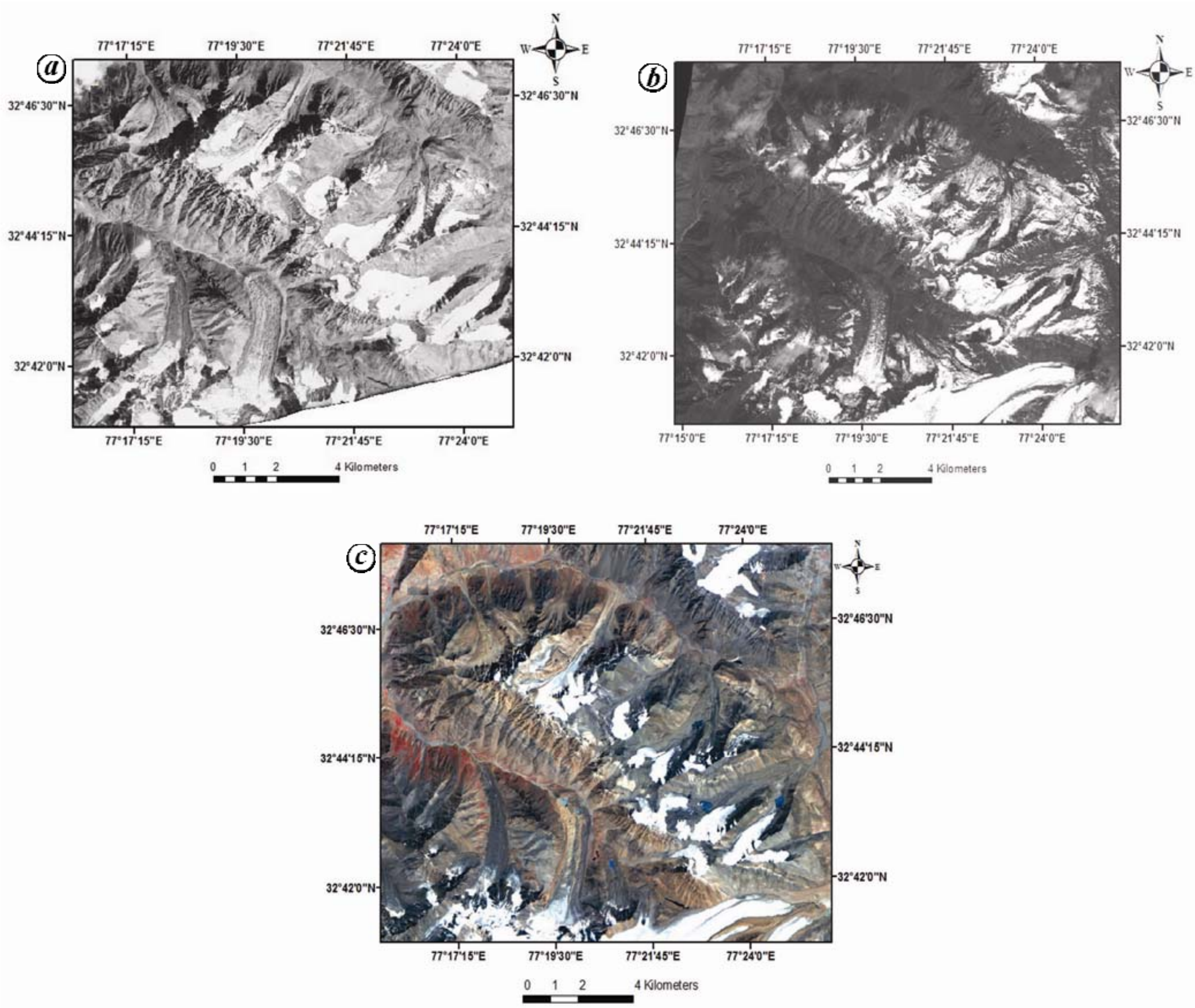

Figure 3. High resolution images of the study area. ***a***, Corona; ***b***, Cartosat-1; ***c***, LISS-IV.

Table 2. Satellite data used for spatio-temporal monitoring of glaciers

Date of pass	Satellite/sensor	Spatial resolution (m)	No. of bands
28 September 1971	Corona (KH-4B)	1.83	1
10 September 1976	Landsat-2 MSS	80	4
28 October 1979	Landsat-3 MSS	80	4
16 September 1980	Landsat-3 MSS	80	4
09 October 1989	Landsat-5 TM	30	7
31 August 1998	Landsat-5 TM	30	7
29 September 2000	Landsat-7 ETM+	30	8
22 September 2003	Landsat-7 ETM+	30	8
08 September 2004	Landsat-7 ETM+	30	8
26 August 2005	Landsat-7 ETM+	30	8
30 September 2006	Landsat-7 ETM+	30	8
16 August 2007	Landsat-7 ETM+	30	8
13 August 2009	Landsat-5 TM	30	7
28 September 2011	Landsat-7 ETM+	30	8
06 September 2004	LISS-IV	5.8	3
15 October 2009	Cartosat-1	2.5	1

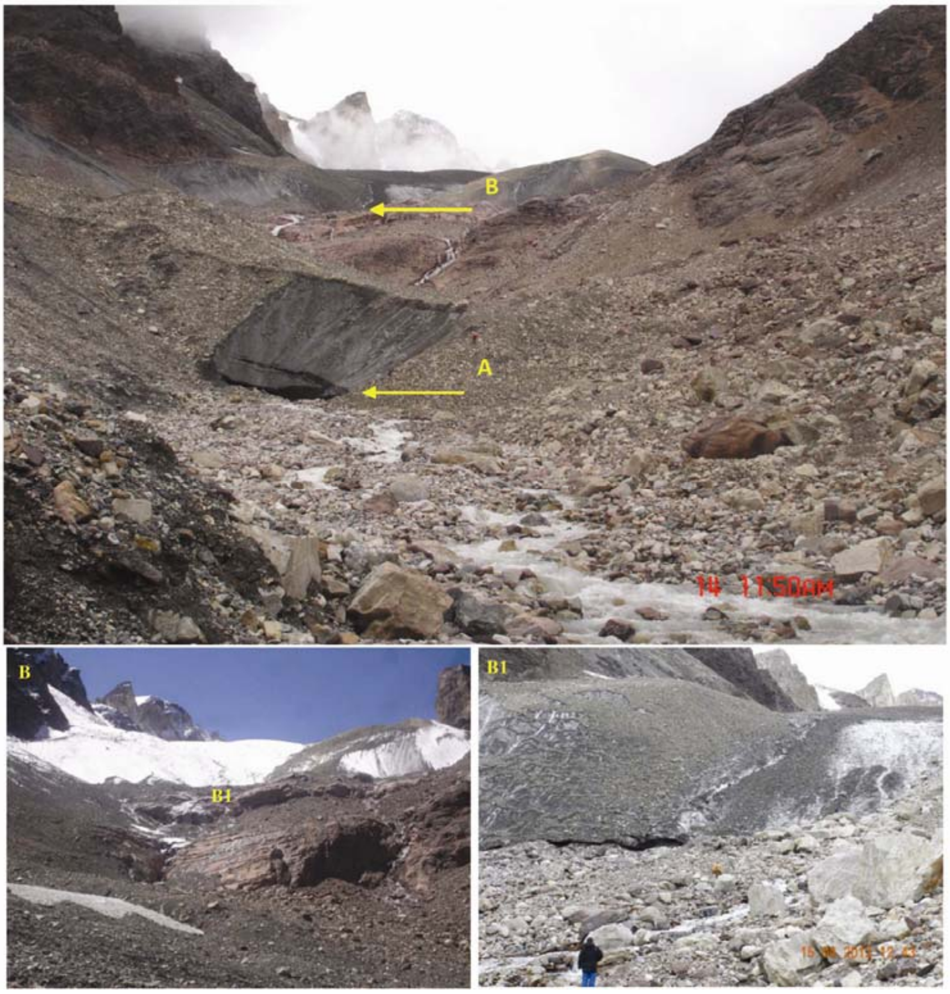

Figure 4. Field photographs of Zing-Zing-Bar glacier, point 'A' represents the position of terminus during 1971, and location 'B' and photograph 'B1' (zoomed area of location 'B' in 2012) represent current terminus position.

(1983 to 2011) collected at SASE meteorological station, Patsio (3800 m) were analysed. During the accumulation season, the glaciers of this region gain mass due to western disturbances in winter.

Methodology

The digital database generation, pre-processing and analysis of satellite data were carried out using ERDAS Imagine (ver. 2011) and ARC GIS (ver. 9.3) software. The GCPs in the field were used for pre-processing and identifying the different features in the study area using satellite data. The reference basemaps of the glaciers were generated using SoI mapsheet (surveyed 1979), Corona data (1971) and GCPs collected in the study area. The projected Landsat scenes matched well with our GPS-data where horizontal shifts were found to be less than a pixel (i.e. < 30 m). The availability of DEM allows one to obtain topographic characteristics of the glaciers, e.g. elevation, slope, aspect[17,18]. Different topographic thematic maps such as elevation, slope and aspect/orientation maps were generated.

In this study, remote sensing was employed to measure the snow line as an approximation of ELA. Snow lines mapped at the end of ablation with minimal snow cover should reasonably approximate the ELA position in the absence of superimposed ice[19]. In order to identify glacier boundary accurately, use of any one method is not sufficient due to highly rugged topography of the Himalaya, presence of shadow and debris cover. Therefore, hybrid analysis was carried out using visual and digital image processing techniques on Landsat scenes for the estimation of annual snow line/ELA and area and length of glaciers. This technique helps in confirmation in the generation of snow line and glacier boundary. Contours were generated using topographic DEM at 100 m intervals for demarcation of snow line altitude and terminus position. The visual interpretation of false colour composite (FCC) images overlaid with contours and normalized difference snow index (NDSI)[20,21] was used for the

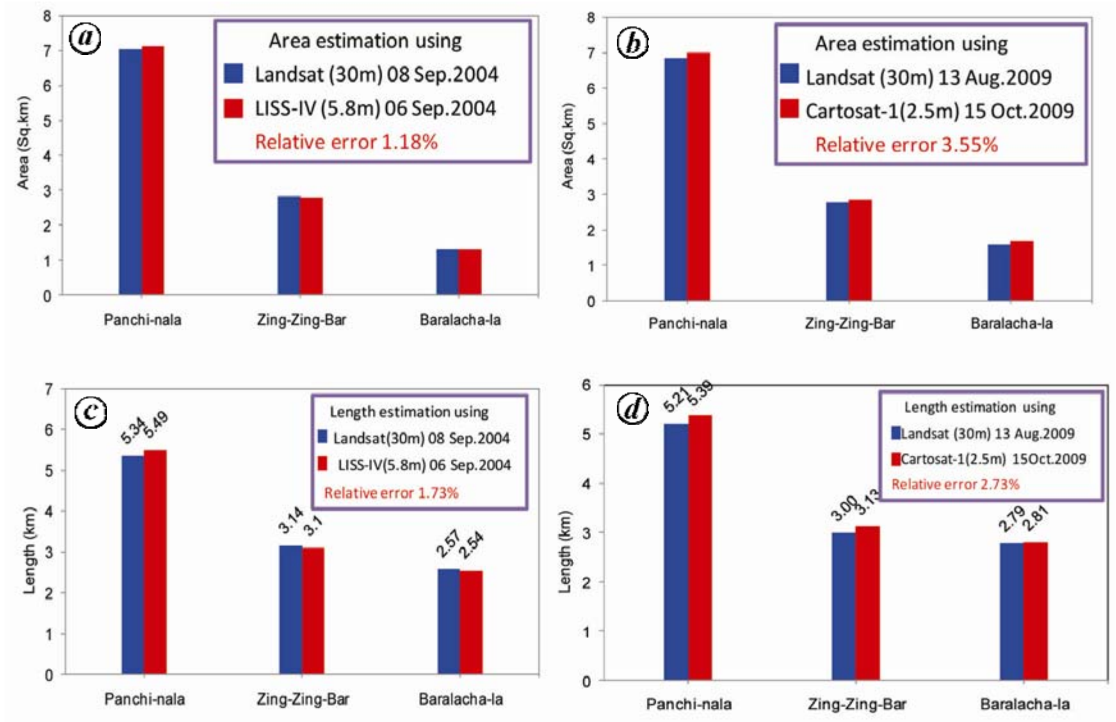

Figure 5. Estimation of uncertainty in area and length calculation using Landsat data.

estimation of ELA. The hybrid analysis used for the estimation of glacier area and length, includes unsupervised classification using ISODATA, application of ratio images using one visible or near-infrared and one shortwave infrared band[22,23], topographic thematic map information, use of thermal band data from TM and ETM+ sensor [24,25], normalized difference snow and ice index (NDSII; NDSII = (RED – SWIR)/(RED + SWIR)) and FCC images. Further, the glacier outline was verified by GPS survey data in 2011 for Zing-Zing-Bar glacier. The planimetric accuracy of GPS was observed to be approx. 2.5 to 3.0 m. After defining the glaciers, their outlines were manually digitized and the areas calculated.

Uncertainty in the estimation of area and length of glaciers is crucial in determining the accuracy and significance of the data obtained by the multi-temporal satellite data. Therefore, the area and length of the glaciers were also estimated using different high-resolution datasets of LISS-IV and Cartosat-1 on the same or nearby dates. The comparison of areas and lengths obtained from Landsat (8 September 2004) and those derived from LISS-IV (6 September 2004) for all the three glaciers showed an uncertainty of ±1.18% and ±1.73% respectively (Figure 5). In addition, the comparison of area and length obtained from Landsat imagery of 13 August 2009, with Cartosat-1 imagery of 15 October 2009, suggested an uncertainty of ±3.55% and ±2.73% respectively (Figure 5). The mapping uncertainty in the area for individual glaciers, i.e. Panchi-Nala, Zing-Zing-Bar and Baralacha-La was found to be ±1.78%, ±1.58% and ±3.74% respectively and mapping uncertainty of their length was found to be ±3.03%, ±2.72% and ±0.95% respectively. Thus the overall mapping uncertainty can be considered as ±3.74%. These uncertainties are within the range of previous accuracy estimates which were less than 4% for glacier area[22,23].

The climate data recorded at field observatory station located at Patsio (3800 m) from 1983 to 2011 were analysed for the period start from November to October next year. The mean annual temperature and winter snowfall of the Patsio observatory were analysed and the average trend was established. Mann-Kendall test was performed for significance of the linear trends. The estimated annual snow line altitude/ELA for all the three glaciers was compared with climatic parameters. To find out if any fresh snowfall had occurred just before the satellite date of pass, the fresh snowfall data collected at SASE Patsio location was used.

The terminus location of Zing-Zing-Bar glacier was observed during field visits on 23 September 2011 and 15 September 2012. Figure 4 shows the overall view of the terminus location, where approximate position of terminus in 1971 can be observed (point A) and location B represents the current terminus position. A large vacated area and steep bedrock were observed near the present terminus. The annual snow line altitude was recorded during the field visit in 2011 (Figure 4, location B) and debris cover is relatively less on this glacier (in 2012, Figure 4, 'B1'). Down the present terminus, dead ice mounds suggest the presence of glacier in the recent past (few decades). The changes in area and length of all the three glaciers were monitored on decadal basis and the causes of variable spatial responses of glaciers were analysed.

Results and discussion

Change in glacier area

In order to find the spatial changes in glaciers on decadal basis, five hybrid classified output maps having approximately equal temporal variation, i.e. of years 1971, 1979, 1989, 1998 and 2009 were selected. A continuous decreasing trend was observed in the area of glaciers (Figure 6). The total loss in glacier area between 1971 and 2011 was observed to be maximum for Baralacha-La glacier (16.35 ± 3.74%) as compared to Zing-Zing-Bar and Panchi Nala glaciers. In general, the higher rate of glacier loss may be due to the small size of Zing-Zing-Bar glacier. It has been reported that small Himalayan glaciers have lost significantly more area than larger glaciers[26,27]. On the other hand, for large glaciers like Gangotri, the reduction in the area of glacier was reported to be about 4–6% in the last 3–4 decades[26,28]. Based on the decadal analysis, the loss in the area of glaciers was observed to be maximum between 1979 and 1989. This loss was found to be maximum for Zing-Zing-Bar glacier (8.87 ± 1.58%) between 1979 and 1989 (Figure 6). This retreat and glacier loss trends in all the studied glaciers indicate the effect of climate change on glaciers lying in this geographic region. Generally in the Great Himalaya, Central Himalaya and Eastern Himalaya, glaciers are retreating due to climate change[1,16,27,29]. This statement is well applicable to glaciers of Great Himalaya studied here. Further, the decrease in the area was observed to vary for different glaciers. The variable response of glacier loss in similar climatic zone may be due to non-climatic factors as discussed under the section 'Non-climatic factors'.

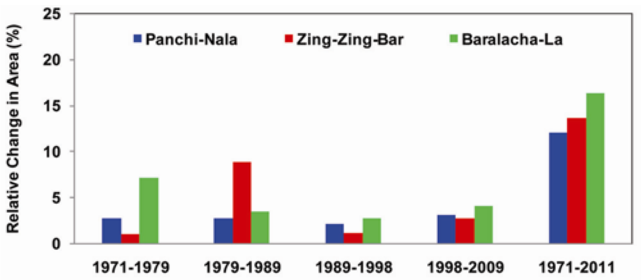

Figure 6. Relative change in area of different glaciers estimated using satellite data on decadal basis and loss in glacier area between 1971 and 2011.

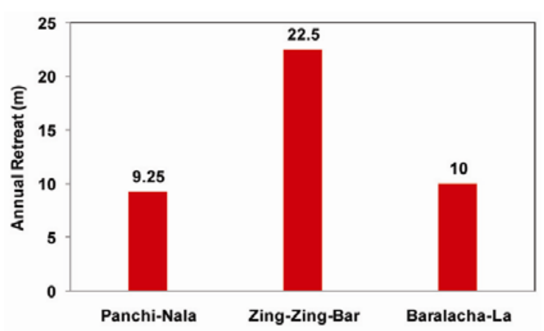

Figure 7. Annual rate of retreat for different glaciers estimated using satellite data.

Change in glacier length

The longitudinal variation of the glaciers was estimated using the length of glacier between 1971 and 2011. Overall, all the glaciers terminuses were found to be in the retreating phase. Of the selected glaciers, a high rate of average retreat ~22 ma^{-1} was observed for Zing-Zing-Bar, whereas it was 9.25 and 10 ma^{-1} for Panchi-Nala and Baralacha-La respectively (Figure 7). This observation is in agreement with the spatial variation and confirms that all the glaciers of Patsio region are in the retreating phase, where the Zing-Zing-Bar glacier has retreated with higher rate. The possible reason for high rate of retreat in Zing-Zing-bar glacier between 1979 and 1989 is discussed under the section 'Non-climatic factors'. After 1989 the retreat rate was not observed to be high for any selected glacier in the study area. Field photograph (Figure 4) also supports the glacier retreat between 1971 and 2012.

Change in equilibrium line altitude

Based on multi-temporal satellite records from all the three glaciers between 1976 and 2011, significant variation was observed in annual snow line/ELA though glaciers which are in close proximity. Figure 8 shows these fluctuations in ELA of individual glaciers generated from temporal images between 1971 and 2011. Overall an increasing trend was observed of annual ELA for all the selected glaciers (Figure 9). The variation in ELA was observed to be 400 m for Panchi-Nala and Baralacha-La glaciers. However, this variation was 750 m for Zing-Zing-Bar glacier. This shows more gradient in temporal rising ELA for Zing-Zing-Bar glacier and indicates more negative mass balance in comparison to other two glaciers (Figure 9). The average ELA was observed at approximately 4900 m (Panchi-Nala), 5000 m (Zing-Zing-Bar) and 5200 m (Baralacha-La). Such long-term average ELA is the altitude for which the glacier as a whole has a mass balance of zero, and is said to be in equilibrium with climate[12]. The annual ELA above or below the average ELA indicates a negative or positive mass balance respectively, for that particular year. The annual ELA for the year 2011 shows positive mass balance for Zing-Zing-Bar glacier and steady state for other two selected glaciers.

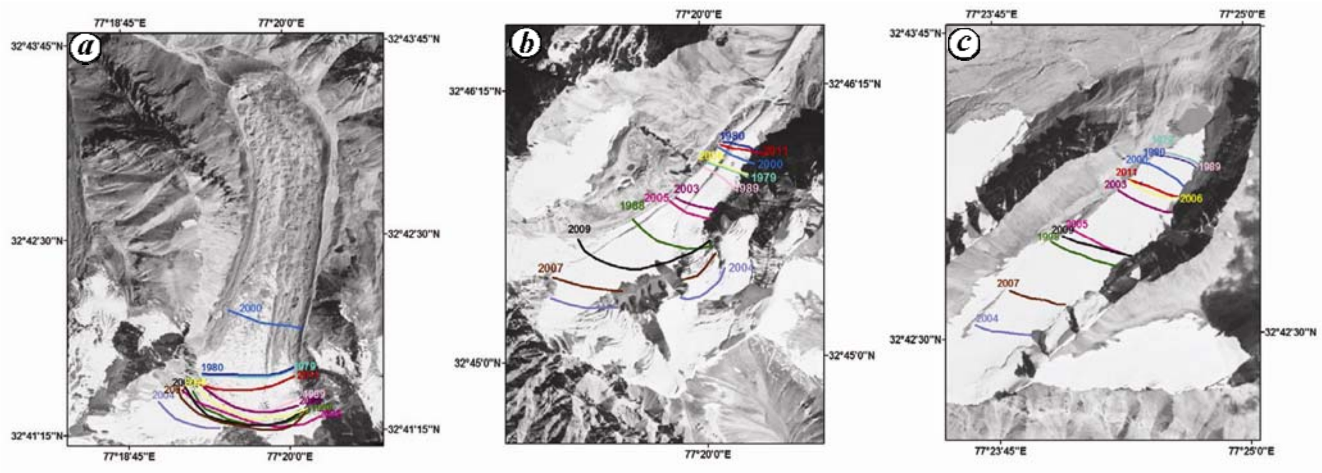

Figure 8. Fluctuations in ELA generated from temporal images between 1971 and 2011 and overlaid on Corona image of (***a***) Panchi-Nala; (***b***) Zing-Zing-Bar and (***c***) Baralacha-La.

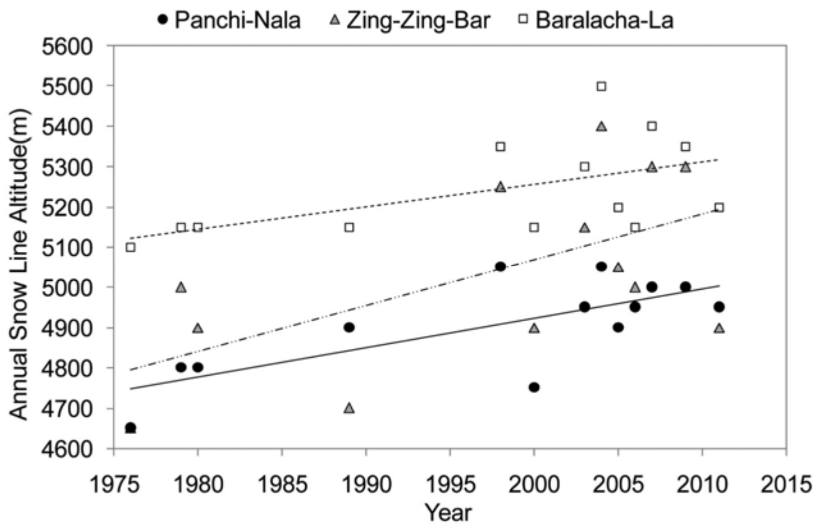

Figure 9. Annual snow-line altitude trend between the years 1976 and 2011 estimated using multi-temporal Landsat data.

The potential regional causes for ELA variations are precipitation due to westerly disturbances, i.e. snowfall during winters and monsoon rainfall during summers. The monsoon rain will also enhance the melting and hence the variation in ELA[7]. Temperature in the region is the other major parameter for ELA variations. These observations are discussed below.

Climatic consideration

The climate data of the Patsio region shows an overall increasing trend in the mean annual temperature and a decreasing winter snowfall (November to April) in the area (Figure 10). The annual snowfall trend was found significant with Mann-Kendall test for significance of the linear trends, whereas the trend for mean annual temperature was not significant for the Patsio region. The rate of change in mean annual temperature and winter snowfall trends are +0.07 deg/yr and –8.3 cm/yr respectively. These climatic observations in the region, in general, support the results of increasing trend of annual snow line altitude and retreat of glaciers. This confirms that the Great Himalayan glaciers in the Patsio region are responding to climate variability.

Non-climatic factors

Different non-climatic factors were analysed for the variable response of the selected glaciers. Figure 11 suggests that altitude-wise terminus position of Panchi-Nala is at the lowest elevation zone than the other two glaciers, where more melting is expected. This glacier is heavily debris covered. The debris covered ice was mapped using the thermal band data of Landsat TM/ETM+ imageries[24,25] and it was found that Panchi-Nala glacier is approximately 42% covered by debris. Such thick debris

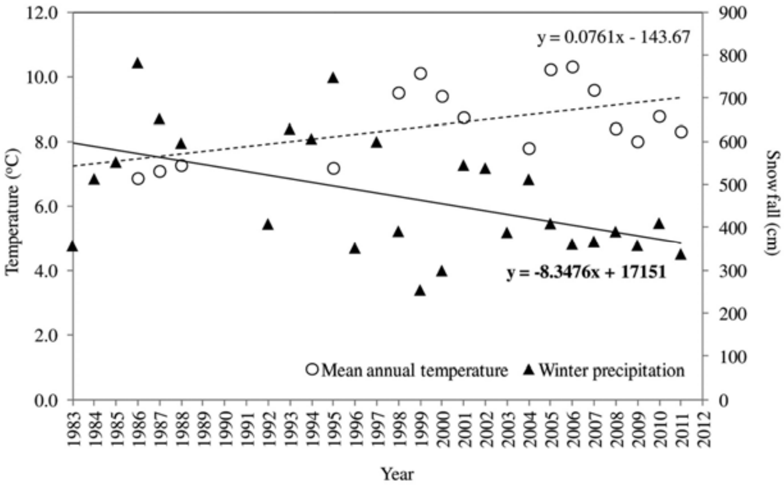

Figure 10. Climatic observations collected at SASE observatory located at Patsio between 1983 and 2011.

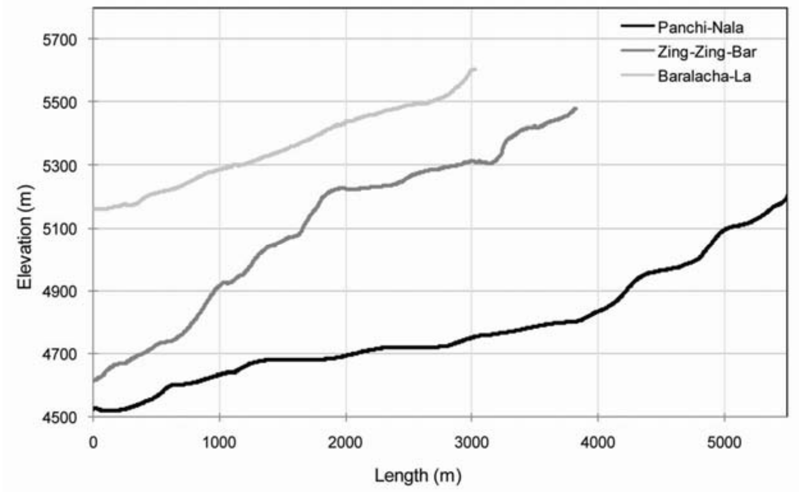

Figure 11. Longitudinal profiles along different glaciers representing slope variations along the glacier path. Note steep middle segment for the Zing-Zing-Bar glacier.

cover can protect underlying ice from melting by shielding it from incoming radiation or atmospheric heat and thus reducing the ablation[1,11]. Thus the rate of retreat of Panchi-Nala glacier was found to be less than that of Zing-Zing-Bar glacier. The longitudinal profiles of glaciers are shown in Figure 11. Zing-Zing-Bar glacier has a steep irregular gradient with a significant hump in the middle part of the profile, where presently the terminus of the glacier exists. The steep slope with bedrock near the terminus of Zing-Zing-Bar glacier was observed on ground (Figure 4). This bump in the bedrock acts as sliding surface for glacier[30]. However, gradual slope variations are observed for Baralacha-La and Panchi-Nala glaciers. The observation indicates that slope variation along the glacier path may be a driving factor for faster retreat of Zing-Zing-Bar glacier than the other glaciers. Kulkarni *et al.*[16] have also suggested that the response of the Himalayan glaciers to climate change is different for different glaciers selected, depending upon their size, area–altitude distribution, orientation and moraine cover.

Conclusions

The spatio-temporal variations in the Great Himalayan glaciers of Patsio region were studied combining remote sensing and field observations. The study revealed that the overall outline and length of the glaciers in this region are retreating. Climate data of the region support the retreating trend of glaciers. The rates of retreat vary for different glaciers. Zing-Zing-Bar glacier in the study region was found to be faster retreating glacier compared to others. The loss in glacier area was found to be maximum for smallest glacier, i.e. Baralacha-La. However, such loss in glacier area, at an average of 0.4% per year, was also reported in different glaciers of the Himalayan region[1,31].

The variable responses were of glaciers from the same climatic zone are influenced by non-climatic factors such as slope variation, glacier size and debris cover. There may be other non-climatic factors such as monsoon rain, etc. In climate observations, other meteorological parameters are also important to study the variable responses of the glaciers in the same climatic zone. For this, SASE has recently installed an automatic weather station near the terminus of Zing-Zing-Bar glacier, which can be useful to derive a better understanding of the glacier health.

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