Differential recession of glaciers in Nanda Devi Biosphere Reserve, Garhwal Himalaya, India

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Abstract This study compares past toposheets (1955 and 1962) and ASTER satellite images (2004 and 2005) to examine the changing state and causes of varying retreat rates of glaciers in Nanda Devi Biosphere Reserve of Garhwal Himalaya. The Dunagiri, Milam and Tipra glaciers were surveyed in 2008, 2009 and 2010, respectively. The study reveals that the Milam, Tipra and Dunagiri glaciers retreated at the rates of 29.4, 12.5 and 1.3 m year^{-1}, respectively. Such differential retreat rates can be explained by altitudes of their snouts and local physiographic conditions. The change of mean width of the Tipra, Dunagiri and Milam glacier was estimated to be –0.01, –0.005 and 0.29 km. The Tipra, Dunagiri and Milam glaciers have vacated areas of about 0.54, 0.03 and 1.66 km^2, respectively. The glaciers show negative mass balance. The net mass change of the Tipra and Dunagiri glaciers was about –470 and –107 × 10^6 m^3 water equivalent (WE), respectively.

Key words glacial retreat; mass balance; glacial geometry; Tipra; Milam and Dunagiri glaciers; climate change; Indian Himalaya

INTRODUCTION

Recently, the glaciers are retreating worldwide (Li *et al.*, 1998; Oerlemans, 2005; IPCC, 2007; Kulkarni *et al.*, 2007). The global mean specific mass balance was negative and estimated at about –283 ± 102 kg m^{-2} year^{-1} during 1960–1961 to 2003–2004. The negative mean specific mass balance increased from –219 ± 92 kg m^{-2} year^{-1} during 1960–1961 to 1989–1990 to –420 ± 121 kg m^{-2} year^{-1} during 1990–1991 to 2003–2004 (Dyurgerov & Meier, 2005). Studies suggest that further shrinkage of glaciers will occur with warmer climate and many mountain glaciers will disappear in the near future (Haeberli & Hoelzle, 1995; Zemp, 2006). The glaciers are considered as a signal of climate change (Khalsa *et al.*, 2004; Oerlemans, 2005; Bajracharya *et al.*, 2007). Measurement of glaciers over a period of time serves as the best proxy to understand climate change over highly remote regions, where meteorological measurements are difficult and rare (Berthier *et al.*, 2007; Bhambri *et al.*, 2011). The changes in extent, geometry and mass balance of glaciers clearly reflect the changes in climatic conditions.

In Indian Himalaya, the glaciers (more than 4200) cover an area of approx. 8797 km^2 and this is one of the largest concentrations other than the polar regions (Mool & Bajracharya, 2003; Bhagat *et al.*, 2004; Sah *et al.*, 2005). In recent decades, the Himalayan glaciers have been reported to retreat with an accelerated rate (Raina, 2010). However, their retreat rate significantly varies across the Himalayan region and even within a single valley. The glacial retreat in general has been attributed to climate change (WWF, 2005; Mehta *et al.*, 2011). However, there are other not obvious factors that determine the retreat rate, e.g. physiography of a region including bedrock topography, slopes, orientation/aspect, snout altitude of glaciers, etc. The driving forces of such differential retreat rate are not properly understood because the glaciers are poorly sampled and studied in the field (Berthier *et al.,* 2007) and systematic and regular monitoring is rather rare. No more than 35 glaciers have been studied in the field in Indian Himalaya. Considering the above stated issues, regular and long-term monitoring of Himalayan glaciers has become essential. Therefore, our research was undertaken to study: (1) the changing state of Tipra, Dunagiri and Milam glaciers, and (2) the driving forces of varying retreat rate in Nanda Devi Biosphere Reserve (NDBR), Uttarakhand Himalaya, India. The NDBR is an important high altitude Himalayan protected area. It is located in the districts of Chamoli, Pithoragarh and Bageshwar of Uttarakhand State and lies between the geographic coordinates of 79°13′E to 80°17′E longitude and 31°04′N to 30°06′N latitude.

DATA SOURCES AND METHODOLOGY

The toposheets of 1954 (1:250 000) and 1962 (Survey of India (SOI) – 1:50 000), ASTER ortho-rectified satellite images and ASTER DEMs have been used to study the changes in length, mean width, vacated area, elevation range and glacial mass. Three field visits were made to conduct GPS aided survey (snout positions, glacial lakes, moraines, tributary glaciers, etc.) of Dunagiri, Milam and Tipra glacier in October 2008, October 2009, and June 2010, respectively. The toposheets were co-registered to already geo-registered (UTM projection) ASTER satellite images using ERDAS Imagine 9.2. The Tipra and Dunagiri glaciers were mapped on toposheets of 1962 and Milam on toposheet of 1954 using ArcGIS 9.3. The ASTER satellite images of 29 September 2005 for Milam and Dunagiri, and 19 October 2004 for Tipra glacier were used for mapping their current state. Present snout positions were marked and verified on satellite images by GPS locations recorded in the field.

The earlier maps of glaciers (1955 and 1962) were subtracted from the latest maps (2004 and 2005) to calculate changes in length, mean width, surface and vacated area of glaciers. The length of glaciers along the centre line was compared to estimate snout retreat. The mean width of individual glaciers was calculated by dividing their areas by their length. The change of glacial mass was estimated by comparing the DEM generated from contours of SOI toposheets and ASTER DEMs and multiplying the difference image by their area. The cut and fill function of Spatial Analysis of ArcGIS 9.3 works on the same principle and was therefore used. Further, the images of mass change were multiplied by value of ice density (900 kg m^{-3}) to convert them into water equivalent (we). All the pixels of mass balance images were summed up to calculate net mass change. Change in elevation range of glacier surface was estimated along the central line using the interpolate line and create profile graph function of 3D analysis of ArcGIS 9.3.

RESULTS AND DISCUSSION

Snout retreat

The snouts of Tipra, Dunagiri and Milam glaciers retreated about 600, 60 and 1590 m with varying average retreat rates of approx. 12.5 (1962 to 2010), 1.3 (1962 to 2008), and 29.4 m $year^{-1}$ (1962 to 2009), respectively. Total altitudinal retreat of snouts of Tipra, Dunagiri and Milam were estimated at 60, 53 and 114 m, with the average of 1.58, 1.67 and 3 m $year^{-1}$, respectively (Table 1). The retreat rate was considerably higher for the Milam than the Tipra and Dunagiri glaciers. Varying retreat rates of glaciers can be directly correlated with the altitudes of their snout positions. The temperature remains relatively low at higher altitudes leading to lower ice melting rate. In contrast, temperature is recorded relatively higher at lower altitudes that leads to higher melting rates. Consequently, snouts located at lower altitudes have retreated at higher rates, e.g. Milam (29.4 m $year^{-1}$), than those located at higher altitudes, e.g. Tipra (12.5 m $year^{-1}$) and Dunagiri (1.3 m $year^{-1}$). However, field survey suggests that other factors such as bedrock topography, slope, orientation/aspect, debris cover, etc. also affect the retreat rate.

Field observations suggest that a low retreat rate of Tipra glacier may be attributed to the following forces: (1) The snout and ablation zone of Tipra is heavily debris covered (Fig. 1(a)). Therefore, the glacier surface is not fully exposed to atmospheric influences. It reduces melting of ice leading to lower retreat rate, and (2) the slope of the lower ablation zone (about 1.5 km) is gentle and almost the entire ablation zone is at the same altitude. It also restricts the downslope ice movement to the snout position (Fig. 1(a); Gautam & Mukherjee, 1992). Consequently, the entire lower ablation zone (1.5 km) is undergoing melting at almost the same rate, unlike the other glaciers where considerable melting takes place only near snout positions. This, coupled with debris cover, leads to lowered snout retreat rates. The lower ablation zone has become dead and considerable sub-surface melting is taking place. As a result, the glacier is now empty from beneath, leading to the collapse of the upper glacier surface in many places (Fig. 1(b)). It indicates the very poor state of Tipra glacier. Its many tributary glaciers have recently detached from it. It is expected that in future, the lower ablation zone (about 1.5 km) will also detach from main glacier in a considerably shorter duration and the snout will retreat with the accelerated rate, if temperature rise continues at the present pace and there is no significant increase of snowfall.

Table 1 Changes of glaciological parameters of glaciers under study.

Parameters/ Glaciers	Years/ Change	Area (km^2)	Length (m)/snout retreat	Mean width (kms)	Altitude of snout (m)	Elevation range (m)
Tipra	1962	9.09	7.58	1.19	3760	3760–5739
	2010	8.53	7.18	1.18	3820	3820–5532[1]
	Change	–0.54	–288/404/600	–0.01	60	––
Dunagiri	1962	2.48	5.35	0.46	4212	4212–4930
	2008	2.45	5.29	0.46	4265	4265–5213[2]
	Change	–0.03	–60	–0.005	53	––
Milam	1955	75.77	18.48	4.10	3508	––
	2009	74.11	16.89	4.38	3622	––
	Change	–1.66	–1590	0.29	114	––

Source: Calculated from topographical maps and satellite images. 2004[1] 2005[2].

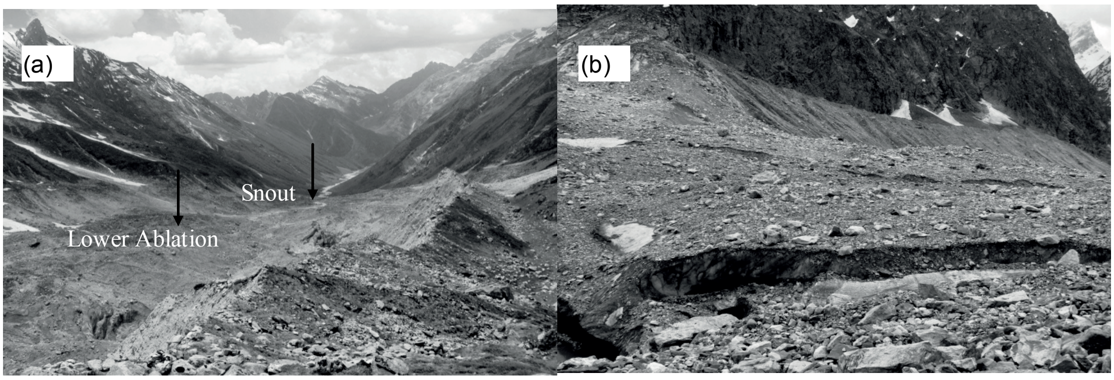

Fig. 1 (a) Debris covered lower ablation zone, snout and moraines of Tipra glacier indicating glacial retreat, (b) dead glacial zone and sub-surface melting of Tipra glacier making the surface vulnerable to collapse: an indication of accelerated glacial melting.

The very low retreat rate of Dunagiri glacier, in addition to its higher altitude snout position (4265 m), may be attributed to the low altitudinal range of glacier (4265–5213 m), its gentle slope, heavily debris covered snout and local topography. The lower ablation zone of Dunagiri glacier has a steep slope (Srivastava & Swaroop, 1997) and is protected by narrow ridges and moraines on both sides (Fig. 2(a)). The steep slope of the lower ablation leads to a continuous supply of ice to the snout position. Consequently, the snout maintains its original position. Besides, heavy debris cover on the snout and narrow ridges on both sides of the glaciers towards the snout position reduces its exposure to the atmosphere, leading to a very low retreat rate. In the middle parts of the glacier, significant thinning has taken place due to very low feeding of ice from the accumulation zone (Fig. 2(b)).

The high retreat rate (29.4 m $year^{-1}$) of the snout of Milam can be correlated to its lower altitude (3622 m). The upper reaches of Milam could not be visited due to poor weather conditions. Therefore, understanding other reasons for its high retreat rate requires further field investigations. The thinning and fragmentation of the lower ablation zone is quite visible. The terrace-like layering of lateral moraines and well-developed recessional moraines confirm periodical recession.

Mean width change

The mean width of the Tipra (1962), Dunagiri (1962) and Milam (1955) glaciers was 1.19, 0.46 and 4.10 kms, respectively. Total change in mean width of Tipra, Dunagiri and Milam over the year was estimated to be –0.01, –0.05 and 0.29 km (Table 1, Fig. 3).

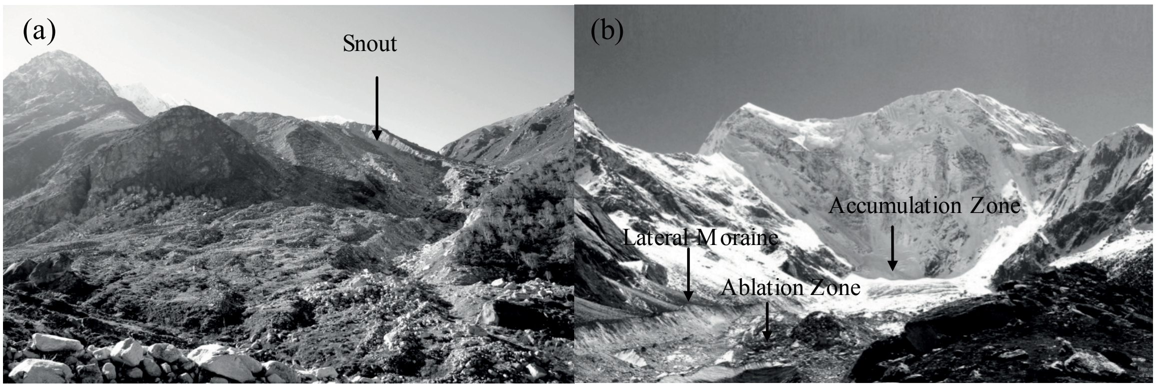

Fig. 2 (a) Debris covered snout of Dunagiri glacier, (b) small accumulation zone feeding very low ice to ablation zone. Well-established right and left lateral moraines indicate glacier retreat.

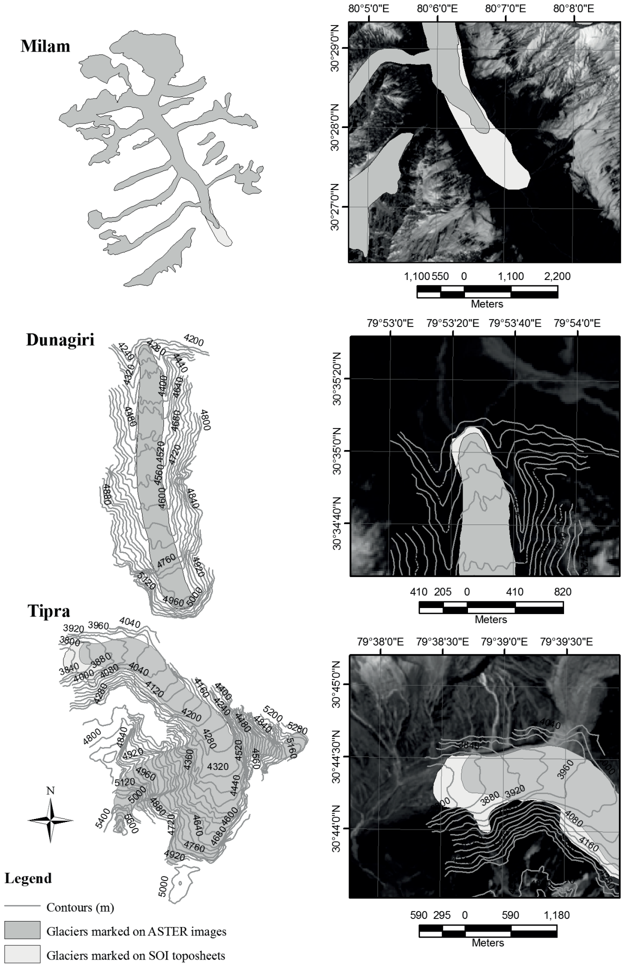

Fig. 3 Retreating snouts of the Milam, Dunagiri and Tipra glaciers.

Vacated area

Glacier thinning and retreating snouts have vacated large areas along lateral moraines and in front of the glacier snout (Fig. 3). The Tipra, Dunagiri and Milam glaciers have vacated areas of 0.54, 0.03 and 1.66 km^2, respectively. Varying vacated areas by these glaciers can be correlated with the differential retreat rate of snout positions. Glaciers with higher retreat rates (e.g. Milam 29.4 m year^{-1}) have vacated more areas in their foreland and along moraines than those retreating at lower rates (e.g. Dunagiri 1.3 m year^{-1}).

Change in elevation range

The elevation range of Tipra glacier decreased to 3820–5532 m in 2004. The upper slope de-elevated significantly by about 200 m. Considerable thinning has taken place on the sun facing side of the accumulation zone. However, the accumulation zone of Dunagiri gained the height of about 190 m and the lower ablation zone experienced significant melting. The elevation range of Dunagiri was 4212–4930 m in 1962, which altered to 4265–5213 m in 2005.

Change in net ice mass

The total ice loss of Tipra glacier over the period of 1962–2004 was estimated to be about –1092 × 10^6 m^3 of we, whereas the ice accumulation was about 622 × 10^6 m^3 of we. Thus, net mass change was about –470 × 10^6 m^3 of we. However, total ice loss for Dunagiri over the period 1962–2005 was estimated at –159 × 10^6 m^3 of we, whereas the ice accumulation was about 51 × 10^6 m^3 of we. Thus, the net mass change was about –107 × 10^6 m^3 of we (Table 2).

In the case of Tipra glacier, the ice loss is prominent in all parts, even though the loss of ice decreases with increasing altitude (Fig. 4). Aspects of slopes seem to have significant influence on

Table 2 Mass balance of Tipra and Dunagiri glaciers in water equivalent (10^6 m^3).

Glaciers	Ablation (ice loss)	Accumulation (ice gain)	Net Mass Balance*
Tipra	–1092	622	–470
Dunagiri	–159	51	–107

Source: Calculated from SOI and ASTER DEMs.

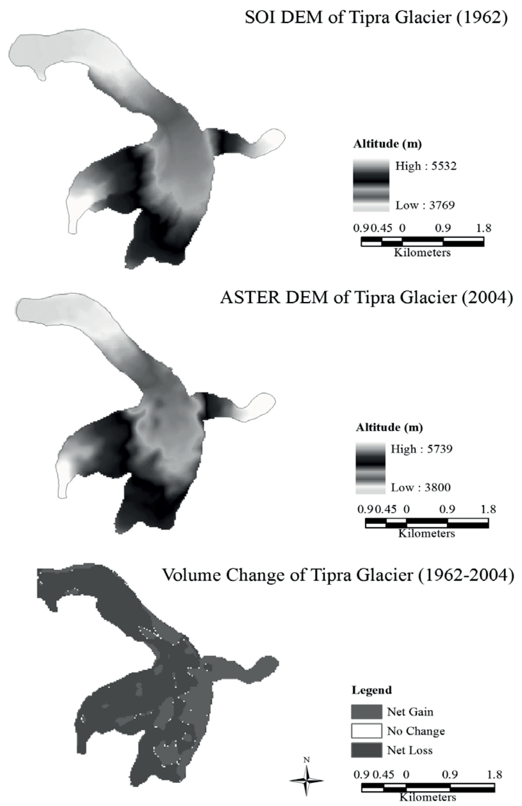

Fig. 4 Net mass balance of Tipra glacier (1962–2004).

mass change due to the varied exposure to sunshine. The south facing slopes of glaciers show more ice loss than other aspects, as these are exposed to direct sunshine. The north facing slopes experienced less ice loss, as these are in the shadow zone.

Dunagiri is a north facing glacier and the patterns of change in ice mass are influenced by altitude. The ice loss decreases with increasing altitude. The ice and snow accumulate in the upper parts of glacier whereas the lower parts experience ice loss.

CONCLUSION

Glaciers have retreated across the world. Most scientists have correlated glacial recession with global warming. The retreat rate of glaciers varies even within the same valley. Many local factors such as physiography, orientation, slope of bedrock, altitudes, climatic zone, etc. have significant influence. High altitude glaciers retreat at lower rate than low altitude glaciers. In the same way, debris-covered glaciers retreat with lower recession rates than those with debris cover. Given these results, it is necessary and important to carry out more regional investigations of glacier changes over various climatic and physical regimes around the mountain regions.

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