Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India

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ABSTRACT. Recent studies of Himalayan glacier recession indicate that there is wide variability in terminus retreat rate and mass balance in the different sectors of the mountain range, primarily linked to the topography and climate of the region. Variable retreat rates of glacier termini and inadequate supporting field data (e.g. mass balance, ice thickness, velocity, etc.) in the Himalayan glaciers make it difficult to develop a coherent picture of climate change impacts. In this study, the results of a detailed mapping campaign and ground-based measurements of ablation rate, terminus retreat and ice loss are reported for the period 2003–10. In addition, background information from an old glacier map (Survey of India, 1962) was compiled and terminus recession measurements were carried out from 1990 field photographs of Chorabari Glacier, central Himalaya. Our ablation stake network results suggest that the influence of debris cover is significant for Chorabari Glacier mass balance and terminus retreat. The terminus survey finds that the glacier is retreating, but at a lower rate than many other non-debris-covered glaciers in the region. The recession and ablation data (particularly in the upper ablation area at higher altitudes) suggest that the ice volume loss of the glaciers is of greater magnitude than the slow terminus retreat and, if the process continues, the lowermost part of the glacier may reduce to a quasi-stationary position while significant ice loss continues.

INTRODUCTION

The Himalayan mountain range contains thousands of glaciers of widely varying properties, which are spread over nearly 37 000 km^2 with an east–west range >2000 km (Raina and Srivastava, 2008). This large geographic extent, with complex and extreme topography along with variable climatic conditions, results in an inhomogeneous set of glacial recessions. The primary climatic forcing, moving from west to east, is a decreasing influence of the mid-latitude westerlies and an increasing influence of the Indian summer monsoon (Bookhagen and Burbank, 2010). Thus, the distribution of glaciers in the Himalaya is uneven, with a higher concentration of glaciers in the northwest than in the northeast of the mountain range. In general, glaciers in the region have debris-covered ablation areas with debris thickness ranging from millimetres to tens of centimetres. As a consequence of the complex climate system, glacial geometry, glacier surface properties and geology, the recession rates of the glaciers are variable (Scherler and others, 2011).

Various studies, such as mapping of debris-cover extent and its correlation with glacier melting and recession, have been carried out using remote-sensing and field-based data in different parts of the world (Lougeay, 1974; Bishop and others, 2001; Taschner and Ranzi, 2002; Paul and others, 2004; Buchroithner and Bolch, 2007; Stokes and others, 2007; Bolch and others, 2008; Shukla and others, 2009; Kamp and others, 2011; Scherler and others, 2011). Supraglacial debris on glaciers is commonly found to have significant control on the rate of ice ablation (Bozhinsky and others, 1986; Lundstrom and others, 1993). A debris cover influences the terminus dynamics and modifies a glacier's response to climate change (Scherler and others, 2011). Surface ablation rates are generally increased in the presence of a thin (<5 cm) debris cover, but are significantly reduced when a thick (>5 cm) debris cover is present (Østrem, 1965; Lundstrom and others, 1993; Mattson and others, 1993; Reznichenko and others, 2010; Scherler and others, 2011). A thin and patchy debris cover reduces the albedo and elevates shortwave radiation absorption, whereas ablation rates are strongly reduced further down the glacier due to the insulating effect of thicker debris (Mattson and others, 1993; Jackson and Fountain, 2007; Reznichenko and others, 2010). The local mass balance of debris-covered glaciers is distinctly nonlinear and non-monotonic with elevation. Generally ablation takes place below the equilibrium-line altitude (ELA) and ablation rates increase with decreasing elevation; however, at Chorabari Glacier at lower altitudes, where the debris cover thickens to >5 cm, ablation rate decreases.

In the central Himalaya a large number of glaciers are debris-covered, especially in the ablation zone, which can exist over stagnant termini. Over some glacier surfaces, growing meltwater ponds and surface lowering due to internal melting indicate that these glaciers are downwasting on the whole. This paper presents recent results of ablation observations on Chorabari Glacier from 2003 to 2010. Our aim is to quantitatively evaluate the influence of the debris cover on summer ablation and terminus recession and to discuss the effects of debris cover on mass-balance processes.

Study site

Chorabari Glacier (30°46′20.58″ N; 79°2′59.381″ E) is a medium-sized compound valley-type glacier covering an area of ~6.6 km^2. The glacier is located in the Mandakini River basin of the Alaknanda catchment (a tributary of the River Ganga) (Fig. 1a). Chorabari Glacier has its accumulation area below Bhartkhunta peak (6578 m a.s.l.) and Kedarnath peak (6940 m a.s.l.) and flows from north to south between 6400 and 3895 m a.s.l. with an average

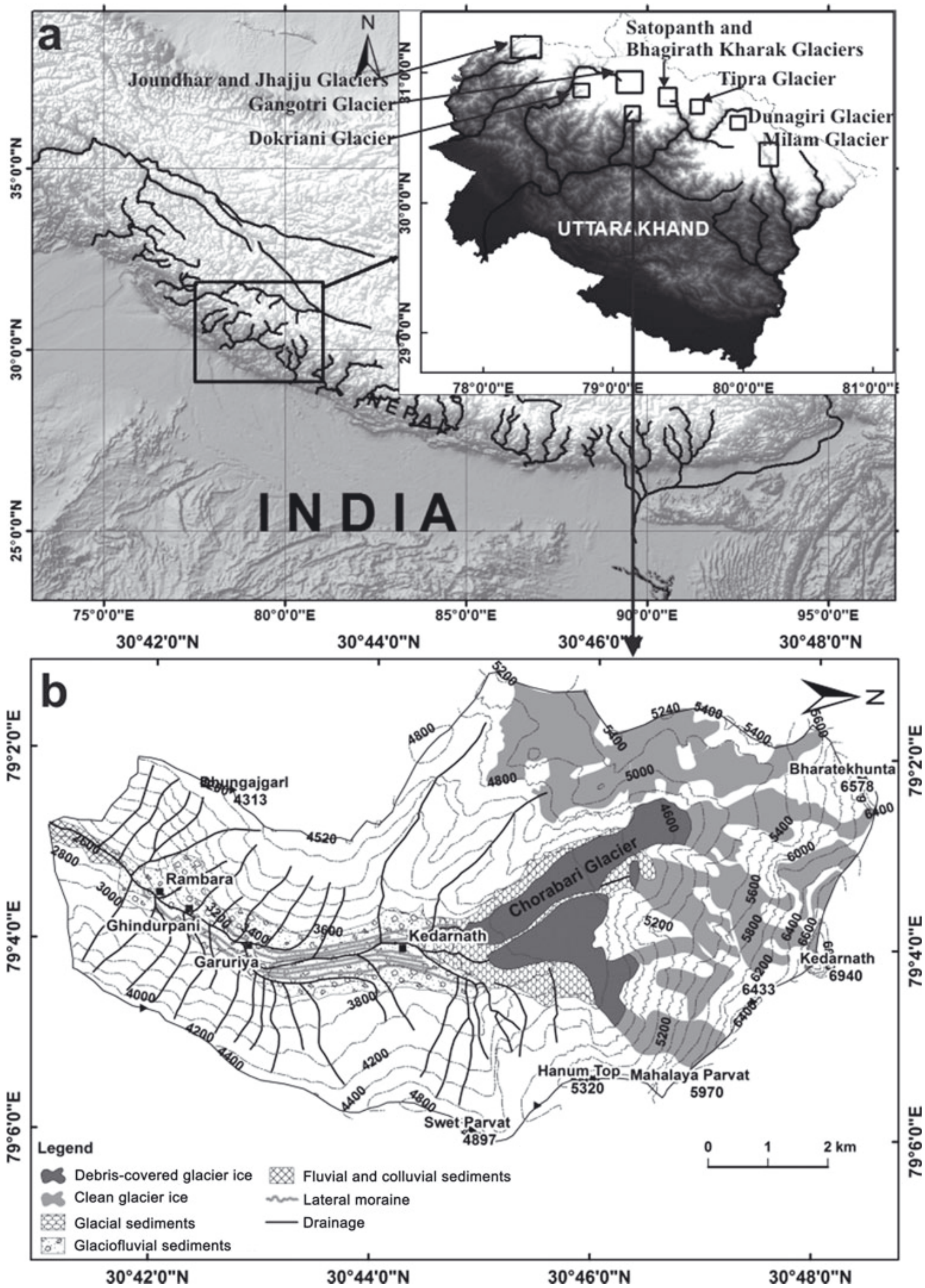

Fig. 1. (a) Location of Chorabari Glacier and adjacent glaciers in the Garhwal Himalaya showing the major river systems of the Indian Himalaya. (b) Geomorphic overview of Chorabari Glacier and the extension of lateral moraine up to Rambara (~2800 m a.s.l.).

surface slope of 20° (Fig. 1b). The key feature of this glacier is its small accumulation area formed by three steep-sloped tributary glaciers, whereas the ablation area is broad with a gentle slope and covered by thick debris. The debris-covered area accounts for ~53% of total glacier area. A number of longitudinal and transverse crevasses and several small supraglacial ponds are present in the ablation zone. Debris thickness increases along the glacier and is >50 cm at the terminus (Fig. 2). A second unnamed glacier (4.5 km long) flows parallel to Chorabari; it ranges from 3810 to 4250 m a.s.l. and its area is ~3.5 km^2. The ablation area has a thick debris layer covering ~80% of the total area of the glacier. It does not have a well-defined accumulation zone and accumulation is received mostly from avalanches. The glacier can be considered quasi-stationary as no terminus retreat was observed during the study period. A huge modified medial moraine (Fig. 2) suggests that the two glaciers may once have been one, now separated by recession. The extension of lateral moraines is observed up to 6 km downstream at Rambara town (2800 m a.s.l.), which is ~13 ± 2 ka old (Mehta and others, 2012). There appear to have been five stages of recession, the records of which are well preserved by traces of the lateral moraine throughout the valley (Fig. 1b; Mehta and others, 2012). In summary, the characteristic features of this glacier are that it is south-facing and has a wide and broad terminus that is thickly debris-covered. Some of the salient properties of the glacier are given in Table 1.

Fig. 2. Chorabari Glacier showing the clean accumulation zone (Acz) and debris-covered ablation zone (Abz). On the right-hand side is an unnamed glacier with thick debris cover (3.5 km^2) flowing parallel to Chorabari.

General climatic setting

The area is precipitated by the Indian summer monsoon in summer and westerly disturbances in winter (Owen and others, 1996). Vohra (1981) suggested that the Ganga basin experiences equal amounts of summer monsoon precipitation and winter westerly precipitation. Therefore these glaciers are also called summer as well as winter accumulation type glaciers (Vohra, 1981; Ageta and Higuchi, 1984; Higuchi and Ohata, 1996).

The general climate of the study area is humid–temperate in summer and dry–cold in winter. There are no long-term instrumental data available for weather parameters. The monitoring of Chorabari Glacier began in 2003 and a manned meteorological observatory (3820 m a.s.l.) was installed to monitor air temperature, wind speed and precipitation during the investigation period. In 2007, an automatic weather station (AWS; Campbell Scientific) was installed near the terminus of the glacier at 3820 m a.s.l. Daily mean temperature was found to fluctuate between +12°C and –1°C (June–October) during the period 2003–10. Maximum air temperature was 16.6°C in June 2009, and the minimum was –18°C in January 2008. Summer precipitation is highly influenced by the monsoon and average rainfall recorded between 2007 and 2010 was 1253 mm (June–October). Winter precipitation generally occurs between December and March (when the westerlies are dominant in the area as they move eastward over northern India) and is the main source of snow accumulation. There are no instrumental data available for winter snowfall; however, residual snow depth fluctuated between 25 and 50 cm in April and early May at 4000 m a.s.l. during the study period from 2003 to 2010. Snow normally melts before the monsoon commences in mid-June. The average wind speed at the AWS was 2.5 m s^{-1} and average daily sunshine duration was 190 min between 2007 and 2010 (Fig. 3a). The measured daily mean temperature and rainfall are shown in Figure 3b.

Table 1. Salient features and geomorphological parameters of Chorabari Glacier

Coordinates	30°46′20.58″ N, 79°2′59.381″ E
Surface area (1962)	~7.37 km^2
Surface area (2010)	~6.66 km^2
Ablation area (2010)	~3.67 km^2
Accumulation area (2010)	~2.99 km^2
Length (2010)	~7.5 km
Orientation	South
Elevation extension	3895–6420 m a.s.l.
Average surface slope	20°
Ablation slope	10°
Accumulation slope	30°
Mean total width	0.43 km
ELA (2010)	5070 m
AAR (2010)	0.44
General climate	Humid temperate in summer and dry cold in winter
Temperature at 3820 m a.s.l. (2007–10)	Annual daily average 3.4°C Daily maximum 16.04°C (Jun 2007) Daily minimum –18°C (Jan 2008)
Geology (rock type)	Crystalline rocks, mainly augen and granitic gneisses

STUDY METHODS

Glacier survey

The earliest record of Chorabari Glacier is available in the Survey of India (1962) topographic map on 1:50 000 scale with 40 m contour interval (planimetric accuracy ±12.5 m and elevation accuracy ±6.5 m; Prasada Raju and Ghosh, 2003). In 1990, the terminus (snout) position was marked and the glacier was photographed. Changes in the terminus position were measured (fixed date) during the field seasons of 2003–10 with handheld GPS (Magellan, Pro Mark-X) with vertical accuracy (z) 1–5 m and horizontal accuracy (x, y)

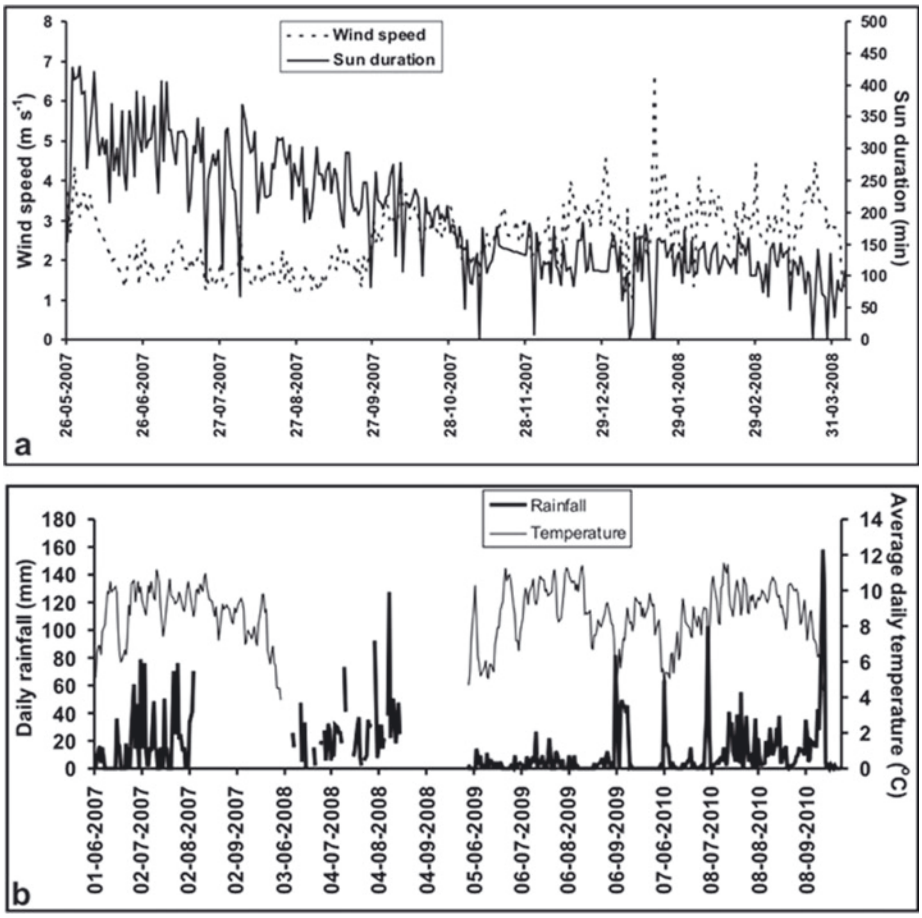

Fig. 3. Meteorological data collected during the study period from an AWS at 3820 m a.s.l.: (a) wind speed and sun duration; (b) average daily temperature and rainfall. Date format is day-month-year.

3 m (0.01′) and survey-grade total station measurements from the fixed stable survey point (see Fig. 5a further below). The area vacated by the glacier due to recession was estimated by comparing the field measurements with the Survey of India (1962) map. The annual monitoring of glacier terminus position, frontal area loss, surface volume loss and elevation change was undertaken following well-established techniques (Østrem and Brugman, 1991; Dobhal and others, 2004, 2008; Wagnon and others, 2007).

Mass-balance and debris thickness measurement

Mass-balance measurements were undertaken by the glaciological stake network method (Østrem and Brugman, 1991). In October 2003 a network of 44 stakes was set up and each stake was fixed to a depth of 10–12 m by stream drill (Heucke ice drill) to measure the accumulation, ablation and debris thickness (Fig. 4a). However, in the upper ablation zone (4400–4600 m a.s.l.) a few stakes were lost in winter. These were replaced as per standard procedure. The process was repeated in each measurement year as the area is steeply sloped, with a bare ice surface in the upper ablation region and thick debris cover in the lower ablation region. These stakes were labelled Nos. 01–44 in sequence from the terminus to the accumulation area. Stake height readings were taken at an interval of 5–10 days during the entire ablation period to determine monthly melting and net ablation. Accumulation measurements were made in snow pits and by probing at different locations. These measurements were made in April–May (early summer) and again in October each year. Snowpack density was measured at various altitudes. The density measured in several pits at different altitudes was used to assess water equivalent measurement. Average densities of 0.56 and 0.85 g cm^{-3} were calculated for snow–firn and ice, respectively. Stake locations, obtained by total station and handheld GPS, were transferred to the map for further analysis. In addition, based on the Survey of India (1962) topographic map, Landsat Enhanced Thematic Mapper Plus (ETM+) imagery (2005) glacier outlines were delineated and a contour map prepared. The outlines of debris cover were manually delineated. The surface area of each elevation band was calculated using a planimeter and multiplied by the calculated value of net accumulation/ablation for each elevation band used for final calculation of net mass balance for a budget year. The standard error, estimated to be 10% of total mass balance, comprises stake height measurement, snow ice density variation and extrapolation for inaccessible crevasse-prone areas (Wagnon and others, 2007; Dobhal and others, 2008).

The distribution of ablation stakes for measurement of melting and debris thickness was divided into three categories: clean ice (stake Nos. 35–40), thin debris cover ≤5 cm (stake Nos. 25–34) and thick debris cover >5 cm (stake Nos. 01–24). Maximum debris thickness measured was ~1.8 m in the lower ablation zone near the glacier terminus (Fig. 4c). In order to study the influence of debris thickness on the ablation process, the area was divided into four different altitude zones (Fig. 4b): (1) below 4300 m a.s.l., (2) between

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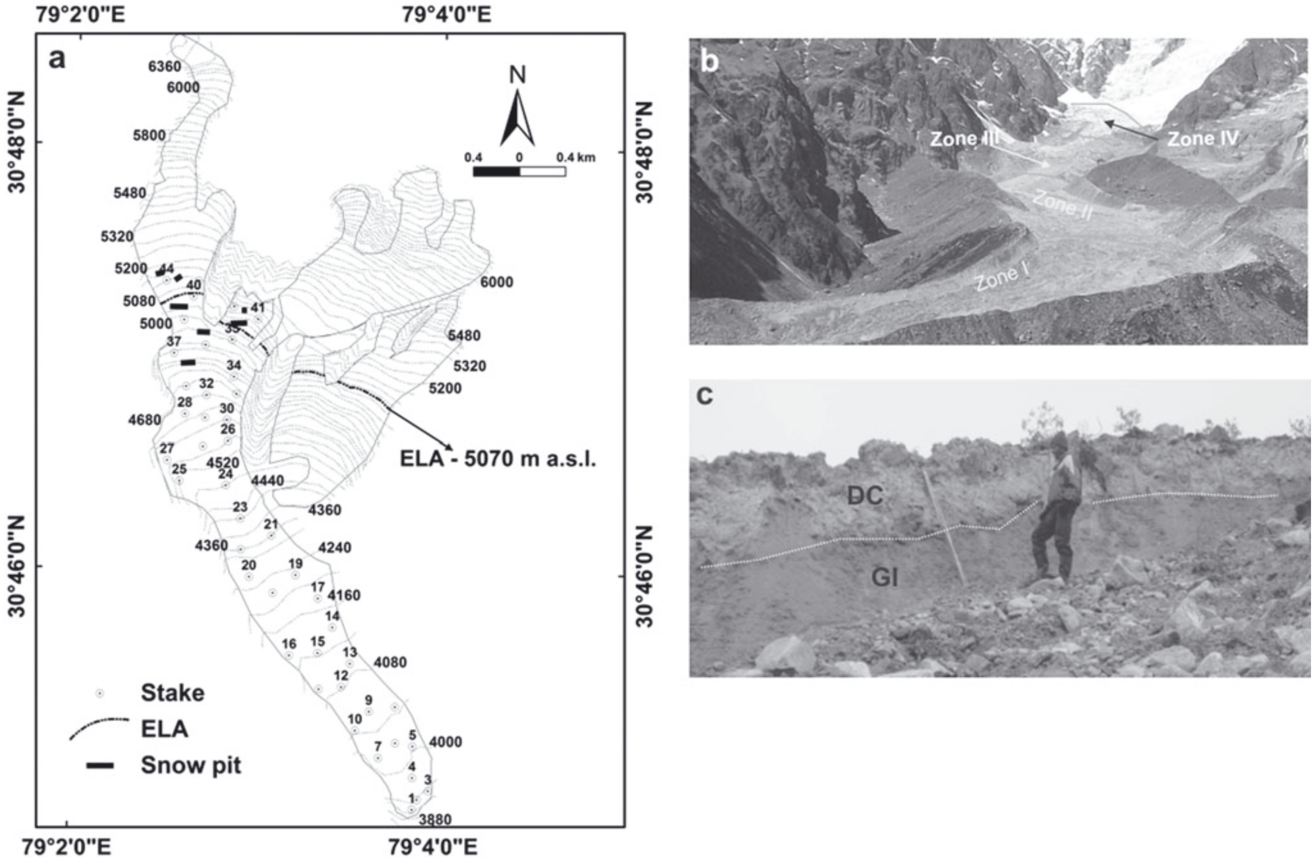

Fig. 4. (a) Contour map and stake network for accumulation/ablation measurement; circles denote stake and snow-pit locations. (b) Photograph showing ablation stake zones. (c) Debris thickness of ~1.3 m near the left margin of the glacier termini (DC: debris cover; GI: glacier ice). Photograph taken on 30 June 2010.

4300 and 4500 m a.s.l., (3) between 4500 and 4800 m a.s.l. and (4) between 4800 and 5100 m a.s.l. These stakes were measured every 5–10 days throughout the summer period (May–October 2003–10) to estimate the net ablation at different altitudes. In addition, the locations of ablation stakes were used to plot the debris thickness on the map.

RESULTS

Terminus retreat and area loss

In order to examine the terminus retreat and area loss of Chorabari Glacier during the period 1962–2010, three sets of data were obtained: (1) total terminus retreat from 1962 to 2003 was ~262 m at an average rate of 6.4 m a^{-1}; (2) field observations from 2003 to 2010 indicate that the glacier receded ~65 m at an average rate of 9.3 m a^{-1} (Table 2); and (3) total cumulative retreat from 1962 to 2010 was 327 m at an average rate of 6.8 m a^{-1}. Thus investigation indicates that the terminus of the glacier is continuously retreating at varying rates (Fig. 5a and b). We find that the long-term average retreat rate has increased significantly from 6.4 (1962–2003) to 9.3 m a^{-1} (2003–10).

Overall, the results reveal that the average recession rate for Chorabari Glacier is lower than that of other glaciers studied in the region, with rates between 15 and 25 m a^{-1} and one exceptional case, Joundhar Glacier, with a retreat rate of 40 m a^{-1} (Fig. 6; Dobhal and others, 2004; Kulkarni and others, 2005, 2007; Raina, 2009; Mehta and others, 2011, 2013). The data show that these Himalayan glaciers are experiencing continuous enhanced retreat rates (Fig. 6).

The area loss from Chorabari Glacier in its proglacial region during the study period has been computed by comparing toposheet maps (Survey of India, 1962) with field measurements. The total area lost by the glacier for the period 1962–2010 was ~0.712 km^2, an average rate of 0.015 km^2 a^{-1}. Approximately 12% of the total loss took place in the past 7 years (0.062 km^2) (Table 3).

Table 2. Snout recession of Chorabari Glacier during the period 1962–2010. The error (σ) is calculated from the total retreat from the left, right and central part of the snout

Period	Number of years	Recession m	Average recession m a^{-1}
1962–90	28	180 ± 8.48	6.43
1990–2003	13	82 ± 5.66	6.31
2003/04	1	8 ± 0.86	8.00
2004/05	1	10 ± 0.77	10.00
2005/06	1	12 ± 0.88	12.00
2006/07	1	10 ± 0.70	10.30
2007/08	1	12 ± 0.50	12.50
2008/09	1	5 ± 0.50	5.00
2009/10	1	8 ± 0.60	8.00
Total	48	327	6.80

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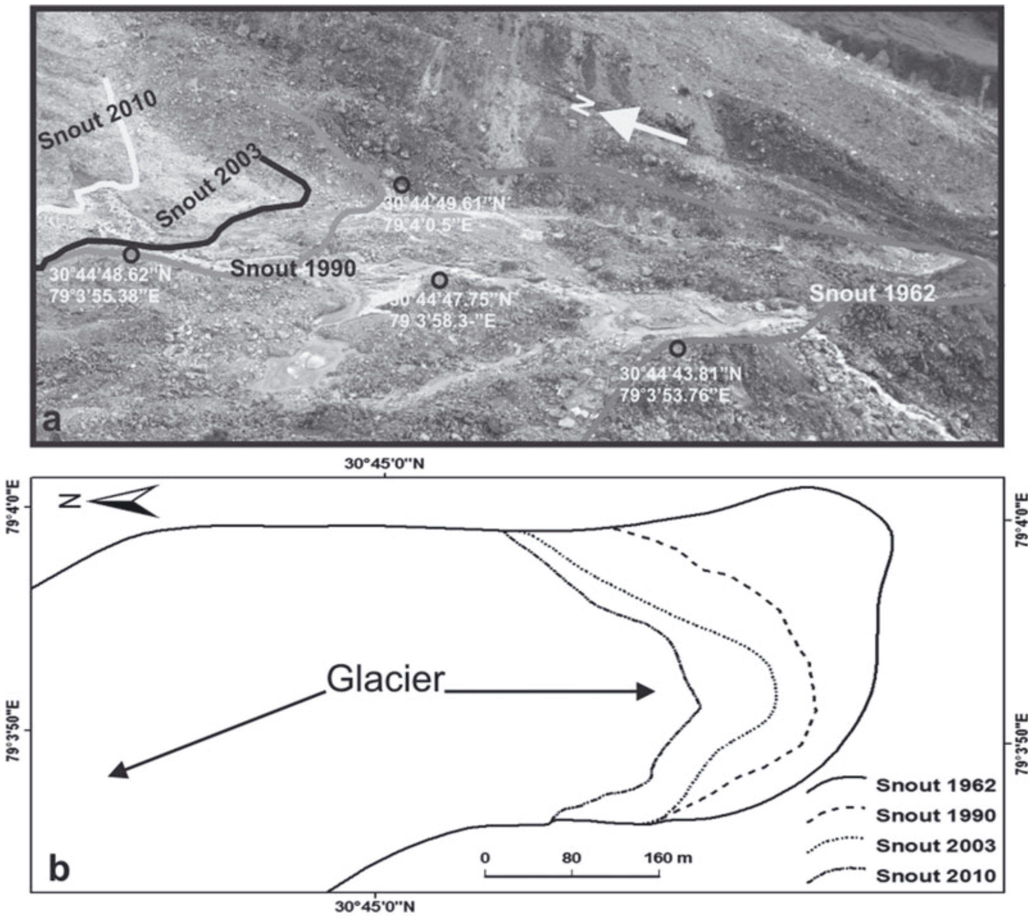

Fig. 5. Frontal retreat of Chorabari Glacier. (a) Photograph showing the different snout positions and benchmarks for termini survey (black circle). (b) Map of terminus positions and retreat of glacier during the period between 1962 (Survey of India, 1962) and 2003–10 (field survey).

Annual mass balance, surface elevation and mass loss

Annual mass balance of the glacier is calculated by integrating values (accumulation and ablation) obtained from field measurements between 2003/04 and 2009/10 (Fig. 7). The result is that the net balance over these 7 years showed a negative trend ranging from -4.97×10^6 m^3 w.e. in 2005/06 to -3.9×10^6 m^3 w.e. in 2007/08 (Table 4). Based on the stake data (accumulation/ablation), we calculate total mass loss to be 30.8×10^6 m^3 w.e. at an average of 4.4×10^6 m^3 w.e. a^{-1} over the 7 year period. We estimate the average specific balance to be –0.73 m w.e. a^{-1}. During the measurement period, specific mass balance of the glacier is strongly negative, reaching –0.82 m w.e. in 2005/06. Subsequently its magnitude decreased to reach ~–0.65 m w.e. in 2009–10 (Table 4). The study also reveals that mass wasting in the ablation zone ranged from –0.46 to –2.97 m w.e. a^{-1}, while the mass gain in the accumulation area ranged from +0.42 to +0.94 m w.e. a^{-1} between 2003/04 and 2009/10. The ELA ascended ~15 m between 2003/04 and 2009/10 (Fig. 7) and the average accumulation–area ratio (AAR) was calculated to be ~0.44 for the period 2003–10 (Table 4).

Surface elevation changes between 2003 and 2010 were measured by monitoring ablation stakes installed along the centre line as well as along a line transverse to flow (Fig. 4a). The surface elevation loss is spatially variable, with a maximum value of 20 m in the ablation zone between 4500 and 4300 m a.s.l. and a minimum of 3 m near the

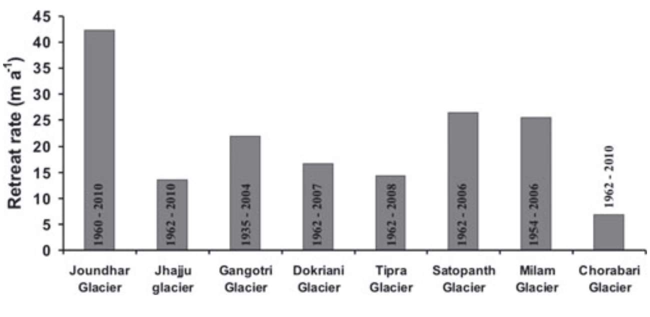

Fig. 6. Histogram showing terminus retreat rates of glaciers near Chorabari Glacier (Fig. 1a).

Table 3. Total and frontal area vacated by Chorabari Glacier (1962–2010). Glacier area loss is ~11% between 1962 and 2010 (48 years)

Period	Years	Total area vacated km^2	Annual average km^2 a^{-1}	Frontal area vacated km^2	Annual average km^2 a^{-1}
1962–2003	41	0.650	0.016	0.058	0.0014
2003–2010	7	0.062	0.009	0.014	0.0020
Total	48	0.712	0.015	0.072	0.0015

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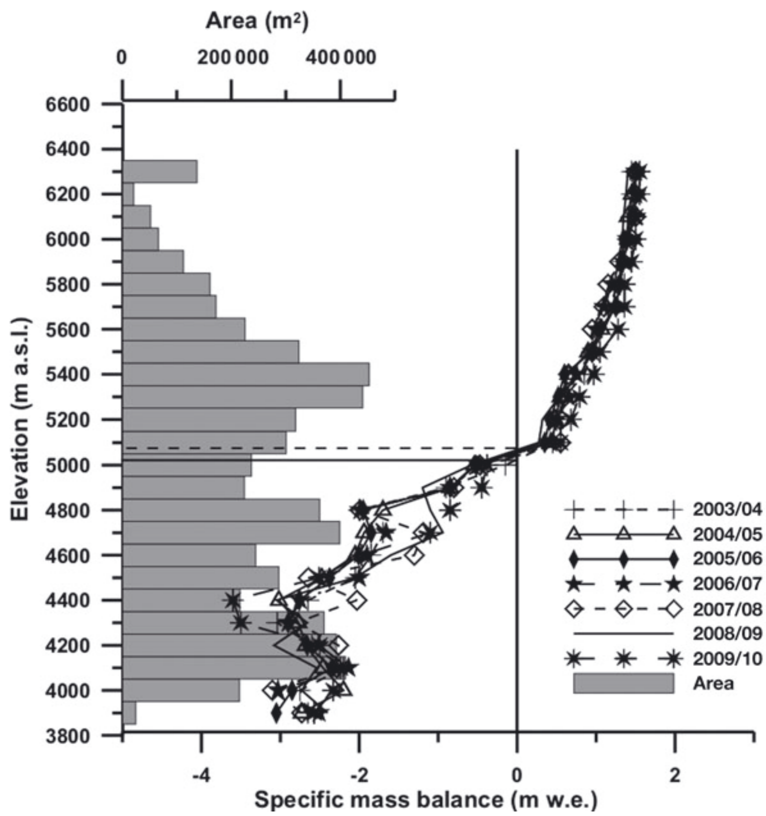

Fig. 7. Specific mass balance versus elevation (2003/04 to 2009/10) and area distribution of Chorabari Glacier derived from field measurements (stakes and pits). Between 4200 and 4500 m a.s.l. the glacier experiences high ablation (less debris cover) compared with lower areas (3800–4200 m a.s.l.; thick debris cover).

equilibrium line (5050–4950 m a.s.l.; Fig. 8). However, in the lower reaches between 4300 and 3895 m a.s.l. the observed elevation changes averaged 15 m (Fig. 8). Generally, melting at lower elevations is higher than in the upper areas; at Chorabari, this is not the case, probably due to the thick debris cover (Fig. 8).

Melt rate and its correlation with debris thickness

The altitudinal distribution of the ablation area of Chorabari Glacier, which is larger than the accumulation area, extends between 3895 and 5070 m. Utilizing 7 years (2003–07) of ablation stake data, the distribution of melting patterns was estimated. Most surface ablation was observed between 4300 and 4500 m, which encompasses areas covered by thin and patchy debris up to 4 cm thick. We suggest that a thin cover reduces albedo without significantly introducing an insulating layer at the surface. The maximum ablation rates occurring at higher altitudes (4500 m) were 2.3 and 3.3 m a^{-1} at 4400 m a.s.l. where debris layer thickness was ~2 cm (Fig. 9a). The melting decreased with greater debris thickness and was 1.6 m a^{-1} at 4120 m a.s.l., where the debris thickness was 20 cm, and 0.75 m a^{-1} at 4000 m a.s.l. with debris thickness of 53 cm (Fig. 9a). In order to evaluate the influence of debris cover on melting, nine stakes (between 4300 and 4400 m a.s.l.) within a 200 m^2 area at locations that were debris-free or had thick (20–50 cm) or thin (1–2 cm) debris cover were monitored from 10 June to 30 July 2010 (50 days). The melting obtained for the thick debris-covered surface was 0.8 cm d^{-1} and for the debris-free surface and thin debris cover was 2.5 and 3.3 cm d^{-1}, respectively. Thus, it is observed that melting reduces substantially with increased

Table 4. Net mass balance, specific balance, ELA and AAR of Chorabari Glacier for the period 2003/04 to 2009/10

Year	Net balance 10^6 m^3 w.e. a^{-1}	Specific balance m w.e. a^{-1}	ELA m	AAR
2003/04	–4.57	–0.74	5055	0.45
2004/05	–4.90	–0.79	5055	0.45
2005/06	–4.97	–0.82	5070	0.44
2006/07	–4.50	–0.75	5070	0.44
2007/08	–3.90	–0.67	5075	0.44
2008/09	–4.00	–0.67	5075	0.44
2009/10	–3.93	–0.65	5070	0.44
Average	–4.40	–0.73	5067	0.44

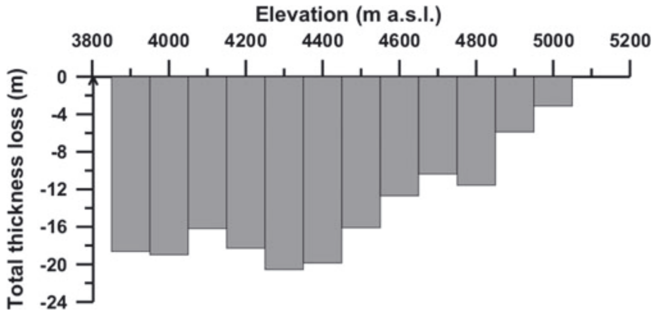

Fig. 8. Total thickness changes at different altitude bands between 2003 and 2010.

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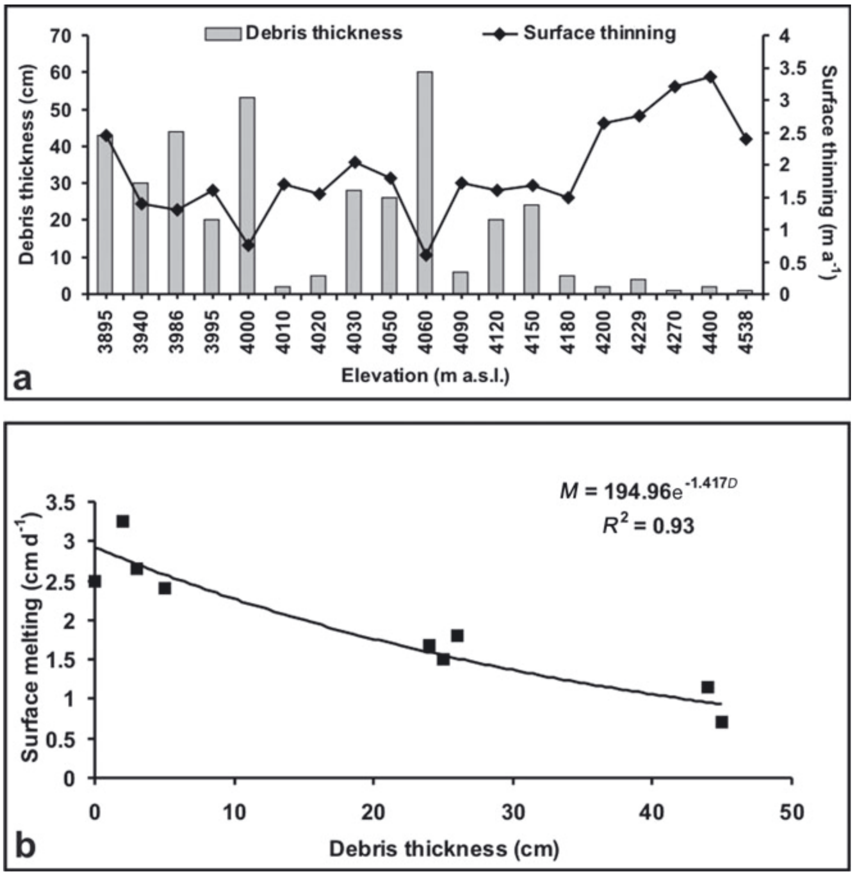

Fig. 9. (a) Relationship between debris thickness and ice melting along the centre line of Chorabari Glacier (4500 m a.s.l.) during observation periods between 2003 and 2010. (b) Relationship between debris thickness and annual melting. Observation made from 10 June to 30 July 2010 (50 days).

debris thickness. Melting in the ablation zone of Chorabari Glacier is greatest in the upper and terminus ablation areas where the glacier surface is thinly covered or is free of debris. An exponential relationship between surface melting and debris thickness shows a good correlation ($R^2 = 0.93$) (Fig. 9b). It is postulated that the presence of supraglacial debris strongly influences glacier ablation, given otherwise similar conditions.

Our study covers an area where the number of debris-covered glaciers is high, yet very little attention has been paid to determining the influence of debris cover on glacier melting or terminus retreat. Our data indicate that a thick debris cover retards melting by shielding and insulating the glacier surface.

DISCUSSION AND CONCLUSION

Glaciers worldwide are excellent climate indicators and are therefore symbols for climate change. It has been speculated that the Himalayan glaciers are retreating faster than glaciers in other regions of the world (Cruz and others, 2007). Owing to the large geographical extent of the Himalayan mountains and regional differences in climate and topography, we cannot generalize about the state of retreat or advance of the whole system. Very few field-based measurements of glacier recession have been carried out in the Himalaya. For instance, of the nearly 10 000 glaciers in the Indian Himalaya, only 11 have been studied in detail for mass balance and little more than 100 glaciers are being monitored for terminus fluctuations (Dobhal and others, 2008; Bhambri and others, 2011). There are many debris-covered glaciers that are retreating relatively slowly, such as Dunagiri (3.0 m a^{-1}), Shankulpa (6.8 m a^{-1}) and Bhagirathi Kharak (1.5 m a^{-1}), but many others are retreating at faster rates of up to 25 m a^{-1} (Vohra, 1981; Swaroop and others, 2001; Nainwal and others, 2008; Raina and Srivastava, 2008). These variations in frontal recession may or may not reflect changes in mass, the critical parameter for long-term glacier health. Lack of data on volume change and ice thickness in studies in the Himalaya has hampered proper evaluation of glacier mass change in the region.

The present study of terminus, area, volume and average thickness changes by field measurement indicates that Chorabari Glacier has retreated at 6.4 m a^{-1} (1962–2003) and 9.3 m a^{-1} (2003–10), leading to a total area loss equivalent to ~11% of its surface area during 1962–2010. However, during the later study period of 2003–10, the glacier surface lowered at ~2 m a^{-1} in the ablation zone. The mass-balance measurement over the 7 year period indicates a negative balance ranging between -4.97×10^6 m^3 w.e. in 2005/06 and -3.9×10^6 m^3 w.e. in 2007/08. The average net mass balance of the glacier over the 7 years (2003/04 to 2009/10) was estimated to be ~-4.4×10^6 m^3 w.e. a^{-1} with specific balance -0.73 m w.e. a^{-1}. The cumulative surface mass loss of 30.8×10^6 m^3 w.e. over the 7 years is significant.

We suggest that the ice volume change due to melting is probably greater than earlier estimated solely from terminus position measurements. The enhanced glacier shrinkage in the higher area of Chorabari Glacier is closely related to climate change. The regional climate is mainly controlled by

Table 5. Annual specific balance and mass loss of Himalayan glaciers in different regions of India

Glacier name	Observation period	Glacier area	Specific balance	Net mass balance	Region	Source
		km^2	m w.e. a^{-1}	10^6 m^3 w.e. a^{-1}		
Neh Nar	1975–84	1.25	–0.54	–0.67	Kashmir	Raina and Srivastava (2008); Raina (2009)
Gara	1974–82	5.19	–0.37	–1.94	Himachal	Raina and Srivastava (2008); Raina (2009)
Gor Gorang	1976–84	2.02	–0.43	–0.87	Himachal	Raina and Srivastava (2008); Raina (2009)
Shaune Gorang	1981–91	4.98	–0.40	–2.00	Himachal	Raina and Srivastava (2008); Raina (2009)
Dunagiri	1984–90	4.39	–0.60	–2.66	Uttarakhand	Raina and Srivastava (2008); Raina (2009)
Dokriani	1992–2000	7.00	–0.32	–2.25	Uttarakhand	Dobhal and others (2008)
Chorabari	2003–10	6.60	–0.73	–4.40	Uttarakhand	Present study
Changme Khangpu	1979–83	5.60	–0.27	–1.50	Sikkim	Raina and Srivastava (2008); Raina (2009)

the south Asian monsoon in summer and westerlies in winter (Vohra, 1981; Owen and others, 1996; Gupta and others, 2003). In general, the terminus recession pattern of Chorabari Glacier shows that there is no uniform frontal retreat observed during the past few decades. However, the right margin of the frontal part of the glacier is almost in a stable condition (Fig. 5) and the central part is gradually retreating. Similarly, the terminus of the adjoining unnamed glacier (Fig. 2) appears to be in a stationary condition, likely due to its thick debris cover. It is observed that no change has occurred in the terminus position of this unnamed glacier since 1962. However different surface features such as meltwater ponds, ice cliffs and an undulating surface (suggesting subsurface melting) indicate shrinking of the glacier (Fig. 2). Thus, we suggest that consideration of the terminus boundary alone can lead to a poor estimate of the net mass loss for debris-covered glaciers.

As noted earlier for Chorabari Glacier, there is significant variability in melt along the length of the glacier. The ablation rate under 10 cm of debris is roughly one-tenth of that for clean ice; for layers >100 cm the ablation becomes negligible (Mattson and others, 1993; Nakawo and others, 1999; Reznichenko and others, 2010). Reznichenko and others (2010) developed a relationship between debris cover and clean ice for surface melting and found that ice melted fastest under a 10 mm debris cover and less as debris thickness (>5 cm) increased. Similarly, Inoue and Yoshida (1980) and Nakawo and others (1999) found that for Khumbu Glacier, a heavily debris-covered glacier in the Nepal Himalaya, the change in terminus position is not a good indicator of mass change.

Across the Himalayan ranges glaciers are wasting at variable rates. The annual mean net mass balance of studied glaciers ranges between –0.67 and -2.66×10^6 m^3 w.e. a^{-1} except for Chorabari Glacier (-4.4×10^6 m^3 w.e. a^{-1}, present study) (Table 5). Nevertheless, various estimations based on in situ and satellite glacier mass balance in the entire Hindu Kush–Karakoram–Himalayan (HKKH) region indicate heterogeneous behaviour (Cogley, 2011; Bolch and others, 2012; Gardelle and others, 2012; Kääb and others, 2012). Kääb and others (2012) reported that the specific balance across the HKKH glaciers as a whole during 2003–08 was -0.21 ± 0.05 m w.e. a^{-1} and that thinning rates were 0.66 ± 0.09 m a^{-1} in the Jammu Kashmir region; Gardelle and others (2012) suggest that the specific mass balance of the central Karakoram glaciers was positive (0.11 ± 0.22 m w.e. a^{-1}) between 1999 and 2008.

The magnitude of the mass change (-4.4×10^6 m^3 w.e. a^{-1}) for Chorabari Glacier is higher than that of other glaciers in the region (Table 5). In addition, because of the gradient in debris cover, the higher-elevation areas (with less debris) have lost significantly more mass than the lower regions. If this process continue, the lower part of the glacier may remain quasi-stagnant while volume loss continues in higher glacier areas. If we assume that the debris-cover profile is relatively constant, with thin debris (and high melt) below the ELA, then a warming climate and a rise in ELA will tend to affect the higher elevations of these glaciers disproportionately. We suggest that current models and estimates based on non-debris-covered glaciers will lead to uncertainty in mass loss in a warming scenario. Although the measured rates are few in number while the number of debris-covered glaciers in the Himalaya is high, we conclude that monitoring of terminus position is not sufficient to estimate the loss and gain of ice mass. Studies need to be enhanced with observations of melt rate at different elevations with the aim of reducing uncertainty in estimates of the future ice resources of this important region.

ACKNOWLEDGEMENTS

We thank Anil K. Gupta, Director, Wadia Institute of Himalayan Geology (WIHG), Dehra Dun, India, for providing facilities to carry out this work. We also thank Robert A. Spicer and Sridhar Anandakrishanan for discussion and valuable suggestions. Rakesh Bhambri, Amit Kumar, Bhanu Thakur and Akshya Verma are acknowledged for help in the field. We also thank the Department of Science and Technology, Ministry of Science, New Delhi, India, for financial support.

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MS received 28 September 2012 and accepted in revised form 10 June 2013