Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing

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ABSTRACT. Glacier outlines are mapped for the upper Bhagirathi and Saraswati/Alaknanda basins of the Garhwal Himalaya using Corona and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images acquired in 1968 and 2006, respectively. A subset of glaciers was also mapped using Landsat TM images acquired in 1990. Glacier area decreased from 599.9 $\pm$ 15.6 km^2 (1968) to 572.5 $\pm$ 18.0 km^2 (2006), a loss of 4.6 $\pm$ 2.8%. Glaciers in the Saraswati/Alaknanda basin and upper Bhagirathi basin lost 18.4 $\pm$ 9.0 km^2 (5.7 $\pm$ 2.7%) and 9.0 $\pm$ 7.7 km^2 (3.3 $\pm$ 2.8%), respectively, from 1968 to 2006. Garhwal Himalayan glacier retreat rates are lower than previously reported. More recently (1990–2006), recession rates have increased. The number of glaciers in the study region increased from 82 in 1968 to 88 in 2006 due to fragmentation of glaciers. Smaller glaciers (<1 km^2) lost 19.4 $\pm$ 2.5% (0.51 $\pm$ 0.07% a^{-1}) of their ice, significantly more than for larger glaciers (>50 km^2) which lost 2.8 $\pm$ 2.7% (0.074 $\pm$ 0.071% a^{-1}). From 1968 to 2006, the debris-covered glacier area increased by 17.8 $\pm$ 3.1% (0.46 $\pm$ 0.08% a^{-1}) in the Saraswati/Alaknanda basin and 11.8 $\pm$ 3.0% (0.31 $\pm$ 0.08% a^{-1}) in the upper Bhagirathi basin. Climate records from Mukhim (~1900 m a.s.l.) and Bhojbasa (~3780 m a.s.l.) meteorological stations were used to analyze climate conditions and trends, but the data are too limited to make firm conclusions regarding glacier–climate interactions.

INTRODUCTION

The Himalaya comprise one of the largest collections of glaciers outside the polar regions, with a total glacier cover of ~33 000 km^2 (Dyurgerov and Meier, 1997) and a total number of ~9600 glaciers in the Indian Himalaya (Raina and Srivastava, 2008). Himalayan glaciers are of interest for several reasons. Seasonal and monsoon precipitation along with snow and ice melt concomitantly governs flow regimes of Himalayan rivers. Water discharge from Himalayan glaciers contributes to the overall river runoff (Immerzeel and others, 2010). For instance, on average the annual snow and glacier melt contribution in the Ganga basin is estimated to be 97% at Bhojbasa (~3780 m a.s.l.) near the terminus of Gangotri Glacier (Singh and others, 2008), ~71% at Loharinag-Pala (~2100 m a.s.l.; Arora and others, 2010) and 29% at Devprayag (~830 m a.s.l.; Singh and others, 1993, 2009) (Fig. 1). One recent field study (Thayyen and Gergan, 2010) indicates that observed flow variations in the Din Gad catchment (Bhagirathi basin, Garhwal Himalaya) is correlated with precipitation rather than glacier melt. Nevertheless, water discharge from Himalayan glaciers is important for irrigation and hydropower generation (Singh and others, 2009). In addition, Himalayan glacier change is likely to contribute significantly to sea-level change (Dyurgerov and Meier, 2005).

Historic instrumental weather records from the northwestern Himalayan region have shown an increase in temperature of ~1.6°C over the past century, accompanied by a decreasing trend in monsoon precipitation (Bhutiyani and others, 2007, 2009). Himalayan glaciers have been in a general state of recession since the 1850s (Mayewski and Jeschke, 1979; Bhambri and Bolch, 2009). Existing studies of Himalayan glaciers indicate that many have exhibited an increased receding trend over the past few decades (Kulkarni and others, 2005, 2007; Bolch and others, 2008; Chaujar, 2009). However, some glaciers (e.g. Raikot Glacier in Nanga Parbat, Punjab Himalaya) have been stable during recent decades (Schmidt and Nüsser, 2009) and others have advanced (e.g. tributaries of Panmah and Liligo Glaciers in the Karakoram region of Pakistan) (Hewitt, 2005; Belò and others, 2008). Individual local glacier advances have also been reported in the Greater Himalayan Range of Ladakh (Kamp and others, 2011). This advance could be attributed to surging (Hewitt, 2005, 2007). Advances may also be associated with a climate trend to increased precipitation in accumulation areas in recent decades (Fowler and Archer, 2006). Generally, the regional irregularity of Himalayan glacier variability could be explained by differences in monsoonal intensity (Kargel and others, 2005), characteristics and thickness of supraglacial debris cover (Bolch and others, 2008; Scherler and others, in press), altitude of accumulation zone and size of glaciers (Kulkarni and others, 2007) and contributions from tributary glaciers in accumulation zones (Nainwal and others, 2008b).

Thus, regular monitoring of a large number of Himalayan glaciers is important for improving our knowledge of glacier response to climate change. Although field investigations are highly recommended, only a limited number of glaciers can be investigated owing to time and logistical constraints in remote mountain regions. Hence, glacier mass-balance

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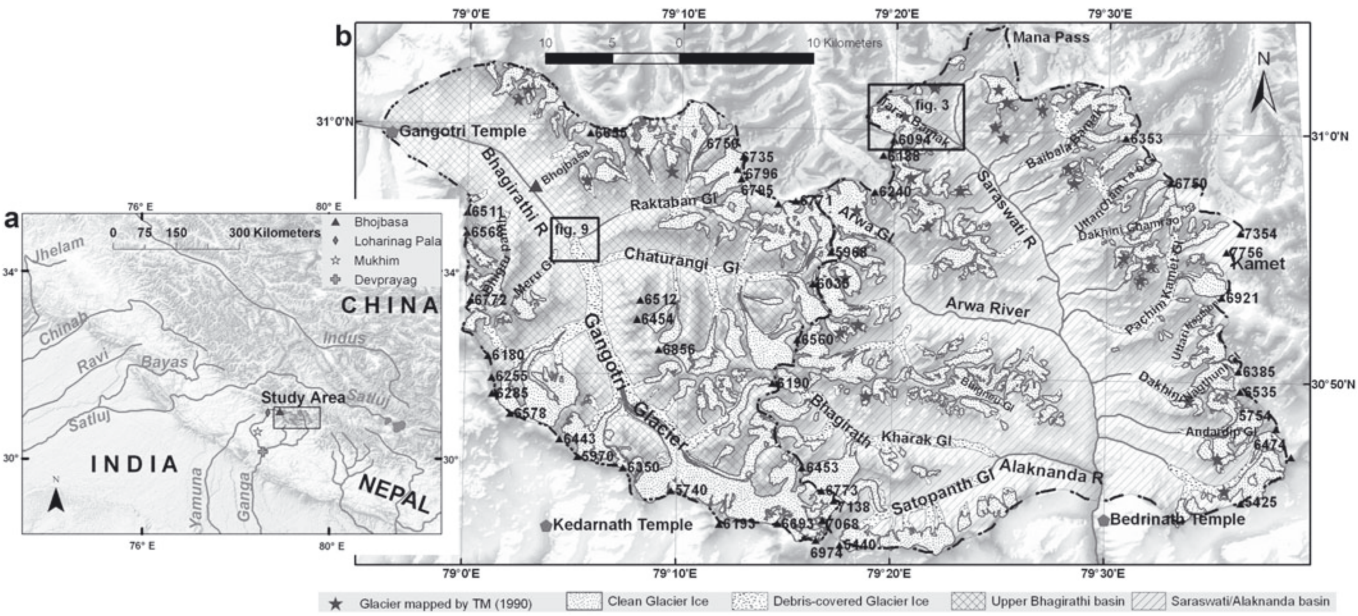

Fig. 1. (a) Location of study area in the Himalaya with major river systems of the Indian subcontinent. (b) Glacier coverage in the upper Bhagirathi and Saraswati/Alaknanda basins, based on ASTER (11 October 2006) imagery; stars represent glaciers mapped from Landsat Thematic Mapper (TM) (15 November 1990)

studies including field measurements have been reported for only a few glaciers, such as Dokriani Glacier (1992–1995, 1997–2000 and 2007–present) and Chorabari Glacier (2003–present) in the Garhwal Himalaya (Dobhal, 2009; Dobhal and Mehta, 2010) and Chhota Shigri Glacier in Himachal Himalaya (Wagnon and others, 2007).

Multitemporal and multispectral satellite data provide abundant potential for mapping and monitoring the large spatial coverage of glaciers at regular temporal intervals, as they allow automated/semi-automated glacier mapping (Paul and others, 2009; Racoviteanu and others, 2009; Bolch and others, 2010b). Most of the glacier change studies from the Indian Himalaya are based on a comparison of satellite data with 1960s topographic maps. However, several studies have reported that mapping of glacier areas on Survey of India (SOI) topographical maps has serious accuracy issues (Vohra, 1980; Raina and Srivastava, 2008; Bhambri and Bolch, 2009; Raina, 2009). Declassified imagery from the 1960s and 1970s (e.g. Corona and Hexagon) is ideal for mapping historic extents of glaciers (Bolch and others, 2008; Narama and others, 2010) and can be used for comparison with glacier outlines derived from old topographic maps (Bhambri and Bolch, 2009; Bolch and others, 2010a).

Several mapping and monitoring studies exist for Gangotri Glacier, the largest glacier in the Garhwal Himalaya (Chaujar and others, 1993; Srivastava, 2004; Bahuguna and others, 2007; Kumar and others, 2008; Bhambri and Chaujar, 2009) and a few studies have been published on mapping and variability of selected glaciers of the adjacent Saraswati/Alaknanda basin (e.g. Nainwal and others, 2008a,b). However, to our knowledge there are no published studies addressing glacier changes and influencing variables, such as debris cover, topography and climate parameters, for the larger glaciated region of the Garhwal Himalaya. In addition, no studies exist that use declassified imagery. Thus, the main goals of this study are to: (1) generate a current glacier inventory for the Garhwal Himalaya using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery and provide information on the general glacier characteristics; (2) analyze recent glacier area changes in the upper Bhagirathi and Saraswati/Alaknanda sub-basins; and (3) evaluate air temperature and precipitation tendency.

STUDY AREA

The Garhwal Himalaya are part of the Uttarakhand state of India, close to China. Based on the glacier atlas of India, 968 glaciers exist in the Garhwal Himalaya, covering ~2885 km^2 or ~5.3% of the state (Srivastava, 2008). Our research area covers two sub-basins of the Ganga River in the Garhwal Himalaya: the upper Bhagirathi basin and the Saraswati/Alaknanda basin. The Bhagirathi River is the main source stream of the Ganga River, which originates from the snout (Gaumukh; ~3950 m a.s.l.) of Gangotri Glacier, the largest valley glacier (~30 km) in the Garhwal Himalaya. The headwater of the Alaknanda River originates from the snouts of Bhagirath Kharak and Satopanth Glaciers. The Alaknanda basin has ~407 glaciers covering ~1229 km^2, whereas the Bhagirathi basin contains ~238 glaciers covering ~755 km^2 (Raina and Srivastava, 2008). The study area of the upper Bhagirathi basin covers ~700 km^2 and an elevation range ~3000–7000 m a.s.l. (Fig. 1). Gangotri Glacier originates in the Chaukhamba massif (~6853–7138 m a.s.l.) and flows northwest towards Gaumukh. The equilibrium-line altitude (ELA) of Gangotri Glacier is ~4875 m a.s.l. (Ahmad and Hasnain, 2004). The study area of the Saraswati/Alaknanda basin extends from Mana Pass to Badrinath Temple including Arwa Valley and the Western Kamet Group. It occupies ~970 km^2 with an elevation range of ~3100–7756 m a.s.l. at Mount Kamet (Fig. 1). The Pawegarh Ridge (5288–6165 m a.s.l.) is a divide between the Alaknanda and Saraswati catchments (Nainwal and others, 2008b).

Garhwal Himalayan glaciers are fed by summer monsoon and winter snow regimes (Thayyen and Gergan, 2010). However, maximum snowfall occurs from December to

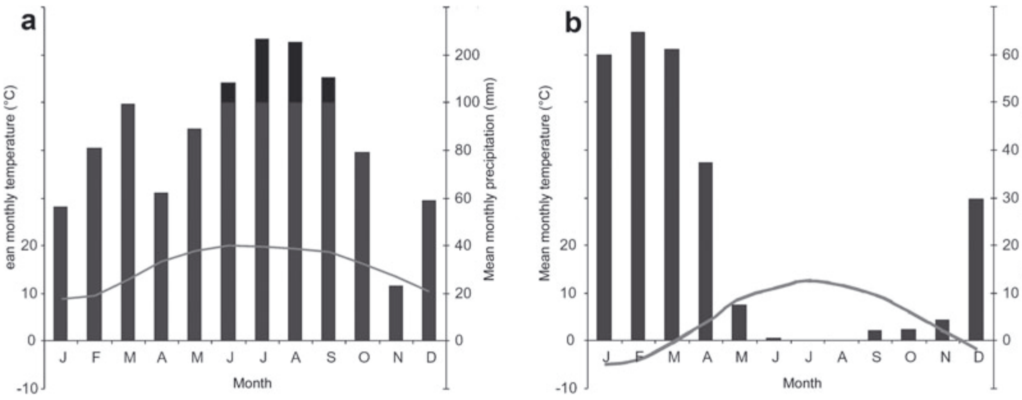

Fig. 2. Climate data for (a) Mukhim (~1900 m a.s.l.; MAAT 15.4°C, annual precipitation 1648 mm, 1971–2000) and (b) Bhojbasa stations (~3780 m a.s.l., 4.4°C; 2001–09) (see Fig. 1 for location). Data sources: Indian Meteorological Department (IMD) and Snow and Avalanche Study Establishment (SASE).

March, mostly due to western disturbances (Dobhal and others, 2008). At Mukhim station (~1900 m a.s.l.; ~70 km from the snout of Gangotri Glacier) the mean annual air temperature (MAAT) is 15.4°C and the annual precipitation is 1648 mm (Fig. 2). In December 1999, the Snow and Avalanche Study Establishment (SASE) established a manned meteorological observatory at Bhojbasa (~3780 m a.s.l.) and an automatic weather station (AWS) ~4 km from the snout of Gangotri Glacier (http://www.dst.gov.in/about_us/ar04–05himalayan.htm). From 2000 to 2008, average annual maximum (T_{MAX}) and minimum (T_{MIN}) temperatures at Bhojbasa were 11.0°C and –2.3°C, respectively, and average winter (DJF) snowfall was 546 mm.

Field surveys and assessment of satellite images indicate that most glaciers in the study area are covered with debris in the ablation zone (e.g. Gangotri Glacier). The debris in upper Bhagirathi basin consists mainly of granite, granitic gneiss and sheared granitic gneiss (Chaujar and others, 1993). Knowledge of glacier changes and debris cover in the neighboring Bhagirathi and Saraswati/Alaknanda basins is limited.

METHODS

Data sources

Three Corona KH-4A images (footprint ~17 km × 233 km) from 27 September 1968, with minimal snow and cloud cover, were used to extract the historic extent of glaciers in the study area. A digital terrain model (DTM) was constructed from ASTER stereo images (2006) at horizontal grid spacing of 30 m. The DTM had a vertical accuracy of ±21 m (Bhambri and Bolch, 2009; Bhambri and others, in press), similar to that of ASTER DTMs in other rugged terrain such as the Swiss Alps and the Andes (Kääb, 2002; Racoviteanu and others, 2007).

Orthorectified 2006 high-resolution Cartosat-1 and multi-spectral Resourcesat-1 (IRS-P6) Linear Imaging Self-Scanning sensor (LISS) IV images, generated for a previous study (Bhambri and others, in press), were used to extract and evaluate recent glacier outlines (Table 1). Cartosat-1 data with 10 bit radiometric resolution covered the entire debris-covered area of Gangotri Glacier but only parts of Raktavan and Chaturangi Glaciers due to their limited swath (~27 km); the data allowed for the interpretation of complex polygenetic glacier landscapes. 1976 Landsat multispectral scanner (MSS) and 1990 Landsat thematic mapper (TM) images were used to obtain additional information for glacier mapping and glacier change analysis (Table 1).

Monthly average T_{MAX} and T_{MIN} and precipitation data for Mukhim station from 1957 to 2005 (missing years: 1962, 1963, 1967, 1983 and 1984) were acquired from the Indian Meteorological Department (IMD; Fig. 2a). Monthly data were used to obtain average indices for annual and seasonal (December, January, February: DJF; June, July, August: JJA) values of temperature (T_{MIN} and T_{MAX}) and precipitation. Data from Tehri and Mukhim stations have an overlap of 22 years. Mean monthly climate data (temperature and

Table 1. Details of satellite data

	Date of acquisition	Spatial resolution m	Scene/Product ID	Accuracy RMS*x,y*
Corona	27 September 1968	8	70MM X DS1048–1134DF107 70MM X DS1048–1134DA108 70MM X DS1048–1134DF109	<15 m
Landsat MSS	19 November 1976	79	EMP156R39_2M19761119	<40 m
Landsat TM	15 November 1990	30	ETP145R39_5T19901115	<20 m
ASTER	11 October 2006	15, 30, 90	AST_L1A_00310092006053458_20070823104834_7280	<15 m
IRS-P6 LISS IV	1 October 2006	5.8	090007100101	<15 m
Cartosat-1	28 September 2006	2.5	097001100102	<10 m

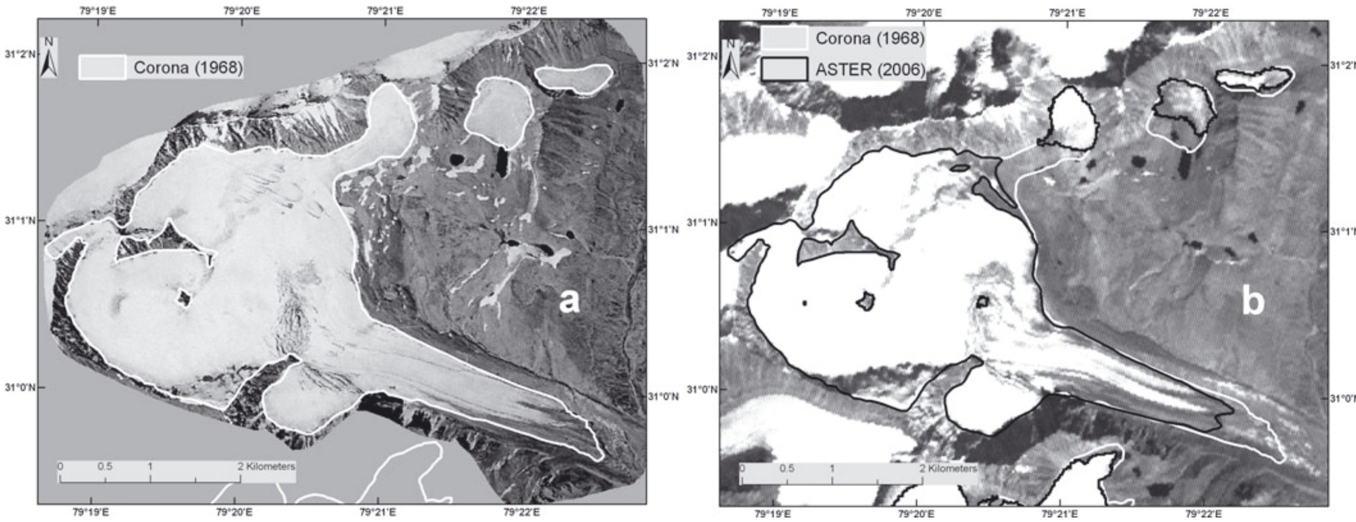

Fig. 3. Satellite images of Tara Bamak Glacier, Saraswati/Alaknanda basin (see Fig. 1 for location). (a) Rectified subset of Corona image (27 September 1968) based on spline method with similar-year glacier outline. (b) ASTER image (11 October 2006) with ASTER and Corona glacier outlines.

snowfall) for Bhojbasa station from 1999 to 2008 were acquired from SASE. A nonparametric Mann–Kendall test was used to determine statistical significance trend, and magnitudes of the trend were obtained by linear regression analysis (Racoviteanu and others, 2008; Sansigolo and Kayano, 2010). A correlation analysis was carried out to verify trend results from Mukhim station and to determine whether it is possible to transfer data from Mukhim station (longer time series) to Bhojbasa station (shorter time series).

Rectification of Corona satellite images

Individual Corona strips were merged using the unregistered mosaic module of PCI Geomatica 10.1. Owing to difficult geometry of the Corona imagery, we generated 26 Corona subsets for the Saraswati/Alaknanda basin and eight subsets for the upper Bhagirathi basin. All subsets were co-registered based on a two-step approach: (1) a projective transformation was performed based on ground-control points (GCPs) and the ASTER digital elevation model (DEM) using ERDAS Imagine 9.3; followed by (2) a spline adjustment using ESRI ArcGIS 9.3. Stable river junctions and road stream junctions were used to collect GCPs assuming no changes occurred on the ground. For each Corona subset, 30–255 GCPs were acquired from ASTER imagery for co-registration (Fig. 3). We focused on the adjustment of the area around the glaciers on Corona images in respect of ASTER imagery for consistency of results during rectification of Corona imagery. It was assumed that no change occurred at the upper glacier boundaries during the time covered by the study. To assess positional accuracy, 20 common location points such as river junctions were identified in both ASTER images and Corona subsets; the horizontal shift between both images was 11 m (1.4 pixels). Landsat MSS and TM images were co-registered with the ASTER DEM and ASTER imagery using the projective transformation algorithm. Horizontal shifts of $\sim$40 m and $\sim$20 m, respectively, were found.

Glacier mapping

We used the modified classification of the Global Land Ice Measurements from Space (GLIMS) initiative (www.glims.org/MapsAndDocs/guides.html) to define glacierized areas, and excluded ice parts above the bergschrund because they only occasionally and indirectly contribute snow and ice to the glacier mass through avalanches and creep flow. Previous studies have shown that normalized-difference snow index (NDSI) and band ratio methods could not differentiate debris-covered glacier ice from surrounding moraines/rocky surface due to similar spectral signatures (Bolch and others, 2007). However, when compared with manual delineation, thresholding of NDSI and band ratio methods are time-efficient and robust approaches for mapping clean glacier ice (Rott, 1994; Hall and others, 1995; Paul and others, 2002; Bolch and Kamp, 2006; Racoviteanu and others, 2008, 2009). It has been reported that for shaded areas with thin debris cover the band ratio near-infrared/shortwave infrared (NIR/SWIR) performs better than red/SWIR and NDSI (Paul and Kääb, 2005; Andreassen and others, 2008). In our study, several image band ratios (1/3; 3/4), NDSI (1–4/1+4) and classifications were tested using ASTER imagery. Band ratio NIR/SWIR was most suitable for mapping clean glacier ice. The clean glacier-ice mask was generated in a binary image using threshold values of 1.0 for ASTER and 2.0 for TM imagery, and the binary image was then converted into vector format. Misclassified glacier areas such as water bodies, shadows and isolated rocks were eliminated manually. Morphometric and thermal band information was used for mapping debris-covered glaciers (Bhambri and others, in press) to assist the manual delineation based on ASTER imagery and the ASTER DTM (Racoviteanu and others, 2008; Bolch and others, 2010b). We found that the separation of stagnant glacier ice from active debris-covered ice is an enormous challenge in glacier terminus mapping. Therefore, Cartosat-1 and LISS IV band combination 2–3–4 were used to improve the debris-covered glacier outlines derived from ASTER imagery. Several characteristics such as supraglacial ponds or creeks were used to determine the most likely position of the termini. Cartosat-1 and LISS IV data were also used to evaluate the clean-ice glacier polygons derived from ASTER imagery (Table 2). The 1968 glacier extents were manually delineated from Corona images. Small high-altitude glaciers that were mapped from Corona images were not included in

Table 2. Comparison between glacier areas derived from ASTER (11 October 2006) and LISS IV sensor (1 October 2006)

	Glacier area (LISS IV) km^2	Glacier area (ASTER) km^2	Deviation km^2	Deviation %
1	0.2692	0.2686	0.0006	0.2
2	3.7673	3.7108	0.0565	1.5
3	0.6553	0.6399	0.0153	2.3
4	0.3692	0.3605	0.0087	2.3
5	1.3109	1.2731	0.0378	2.8
6	0.1535	0.1570	–0.0035	–2.3
Total	6.5253	6.4099	0.1154	1.7

Table 3. Derived glacier parameters (2006) for the upper Bhagirathi and Saraswati/Alaknanda basins

	Study area	
	Upper Bhagirathi basin	Saraswati/ Alaknanda basin
Average elevation minimum (m)	4963	5105
Average elevation maximum (m)	6315	5896
Average elevation mean (m)	5629	5490
Average elevation median (m)	5636	5494
Average elevation range (m)	1352	791
Mean slope (°)	24.8	23.3
Debris-covered glacier area (km^2)	72.6 (26.4%)	76.7 (24.6%)
Clean-ice glacier area (km^2)	201.3 (73.4%)	234.8 (75.3%)
Area by glacier size (km^2)		
<1 km^2	2.8	20.8
1–5 km^2	20.8	45.3
5–10 km^2	1.9	68.6
>10 km^2	228.3	176.7
Total glacierized area (km^2)	274	311.4

the comparison with glacier outlines derived from the ASTER imagery, because close to mountain ridges significant errors occurred during co-registration. The minimum glacier size we took into account for comparison was 0.17 km^2 in 1968. The ice divides were visually identified using the shaded ASTER DTM and ASTER bands 3–2–1 and then manually digitized (Bhambri and others, in press). It was assumed that the divides were fixed over the time under investigation. This approach avoids errors that may occur due to different delineation of the upper glacier boundary, for example different snow conditions (Fig. 3). Landsat MSS and TM scenes were only partially suitable for glacier mapping due to large shadows and fresh snow cover. Hence, from Landsat TM imagery we could only map 29 glaciers in the upper Bhagirathi and Saraswati/Alaknanda basins (Fig. 1). MSS data were mainly used to assist in identifying glacier terminus positions from Corona images.

Topographic information was computed from the ASTER DTM using Geographic Information System (GIS) tools as suggested by Paul and others (2009). We investigated the characteristics of glacier distribution in the study region by statistically analyzing the relations between topographic parameters and glacier polygons. Glacier changes between 1968 and 2006 could be compared for 69 glaciers in the Saraswati/Alaknanda basin and for 13 glaciers in the upper Bhagirathi basin.

Mapping uncertainty

Glacier outlines derived from various satellite datasets with different resolutions, obtained at different times with varying snow, cloud and shadow conditions, have different levels of accuracy. Thus, estimation of the uncertainty is crucial in determining the accuracy and significance of the results. Previous studies report a mapping uncertainty of ±2–3% for clean-ice glaciers (Paul and others, 2002; Bolch and Kamp, 2006). Comparison between the glacier boundaries derived from ASTER (2006) and those derived from high-resolution LISS IV images (2006) for six selected glaciers suggested an uncertainty of ±1.76% (Table 2). Similarly, we estimated an additional uncertainty of ±0.2% for debris-covered glaciers based on comparison between the ASTER outline of the debris-covered area of Gangotri Glacier and the outline derived from the Cartosat-1 image. Thus, the mapping uncertainty is about ±2% for glacier delineation from ASTER imagery. In addition, we estimated the uncertainty for each glacier based on a buffer method suggested by Granshaw and Fountain (2006) and Bolch and others (2010b). The final mapping error, a combination of the mapping uncertainty and the uncertainty of the misregistration, was estimated to be ±3.15%, ±4.0% and ±2.6% for ASTER, Landsat TM and Corona images, respectively. The total error was estimated to be ±4.0% when comparing the data from the ASTER and Corona images. These mapping uncertainties are within the range of previous estimates (Paul and others, 2003; Racoviteanu and others, 2008; Bolch and others, 2010a,b).

RESULTS

Glacier characteristics

We identified 83 glaciers in the Saraswati/Alaknanda basin from ASTER images (2006), covering an area of 311.4 ±9.8 km^2 (Table 3). Of the 83 glaciers, 51 had debris-covered tongues, which have an area of 76.7 ± 2.4 km^2 (~24.6% of the total glacierized area). Glacier size ranges from 0.11 to 32.9 km^2, with a mean size of 3.7 km^2. Some topographic parameters clearly show regional characteristics of glacier distribution. For instance, larger compound basin glaciers tend to extend down to lower elevations, while smaller glaciers have higher termini. On average, glaciers <1 km^2 in area terminate at 5308 m and glaciers >5 km^2 in area at 4706 m in the Saraswati/Alaknanda basin. There are 43 glaciers with an area less than 1.0 km^2, which cover 20.8 ± 0.65 km^2 in this basin (Table 3). Median elevation of the glaciers, widely used for the estimation of long-term ELA based on topographic data (Braithwaite and Raper, 2009), ranges from 4749 to 5896 m, with an average of 5494 m. We found no significant correlation between glacier size and mean/median elevation or aspect in the Saraswati/Alaknanda basin.

The 20 glaciers identified in the upper Bhagirathi basin in 2006 cover an area of 274 ± 8.6 km^2. The overall debris-covered area is about 72.6 ± 2.3 km^2 (~26.4% of the whole ice cover). This shows that the upper Bhagirathi basin has a slightly higher debris-covered glacier area than the Saraswati/Alaknanda basin. Glaciers <1 km^2 in area terminate at 5178 m, and glaciers >5 km^2 in area at 4613 m, on average

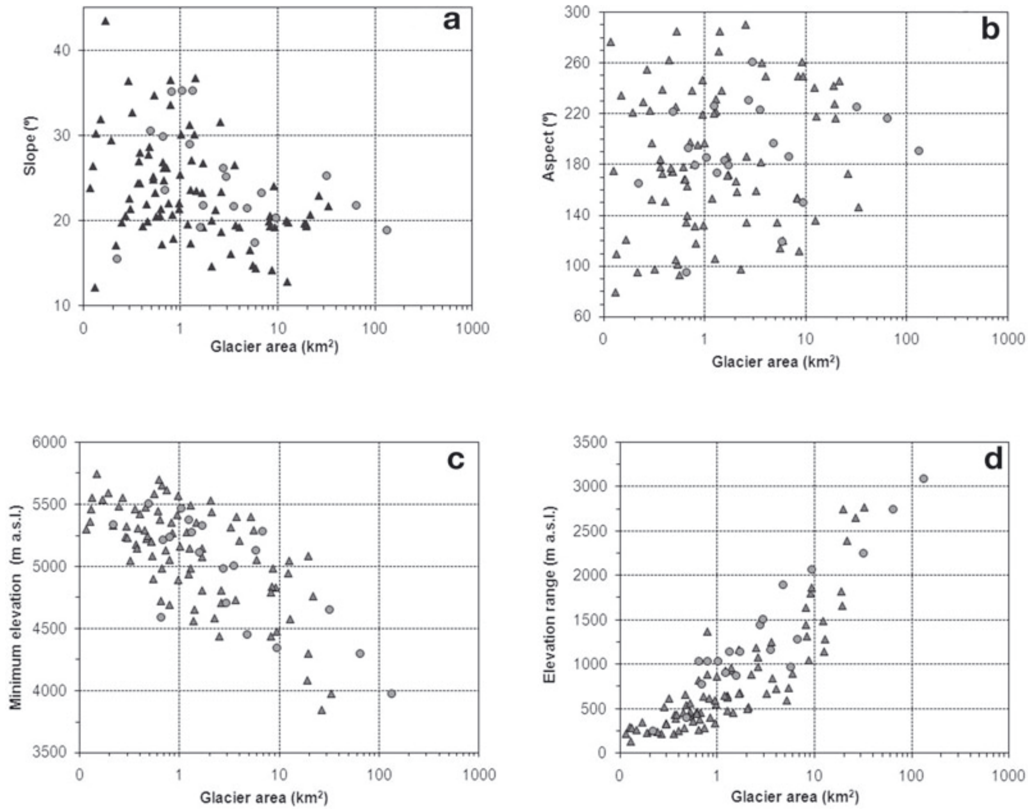

Fig. 4. Scatter plots of (a) glacier area vs slope, (b) glacier area vs aspect, (c) glacier area vs minimum elevation and (d) glacier area vs elevation range. Triangles are for the Saraswati/Alaknanda basin and circles are for the Bhagirathi basin. Glacier area and inventory data derived from ASTER (11 October 2006) image and DEM.

in the upper Bhagirathi basin. Five glaciers that are <1.0 km^2 cover a total area of 2.8 km^2. The median elevation of the glaciers ranges from 4712 to 6214 m, with an average of 5636 m (Table 3). Glaciers range in size from 0.21 to 132.7 km^2, with a mean of 13.7 km^2 in the upper Bhagirathi basin.

On average, glacier termini are 142 m higher in the Saraswati/Alaknanda basin (5105 m) than in the upper Bhagirathi basin (4963 m) (Table 3). Large glaciers (>10 km^2) cover ~83% of the glacial area in the upper Bhagirathi basin and ~57% in the Saraswati/Alaknanda basin. Small glaciers tend to have smaller altitudinal ranges while larger glaciers have higher altitudinal ranges in both the Saraswati/Alaknanda and upper Bhagirathi basins ($r^2 = 0.51$) (Fig. 4). The maximum number of glaciers is in the <0.5 km^2 class (Fig. 5).

The 29 glaciers mapped from Landsat TM can be seen as a representative subset of all glaciers as they cover different size classes and elevation ranges (Fig. 1). There are 12 glaciers <1.0 km^2 in area, covering 7.3 km^2 in both the Saraswati/Alaknanda and upper Bhagirathi basins, while the two glaciers >10 km^2 in area cover 25.7 km^2.

Glacier and climate change

Glaciers have fluctuated noticeably within the study area since 1968 (Table 4). In the Saraswati/Alaknanda basin, the area of the glaciers investigated changed from 324.7 ± 8.4 km^2 (1968) to 306.3 ± 9.5 km^2 (2006), a decrease of 18.42 ± 9.0 km^2 or 5.7 ± 2.7%. The number of glaciers increased from 69 (1968) to 75 (2006) due to the disintegration of ice bodies. The loss in glacier area of individual glaciers ranged from 0.9% to 42.5%. On average, small glaciers (<1 km^2) lost ~19% of their area between 1968 and 2006 in the Saraswati/Alaknanda basin. South-facing glaciers lost ~19.4% of their area, about four times more than for north-facing glaciers (~4.7%).

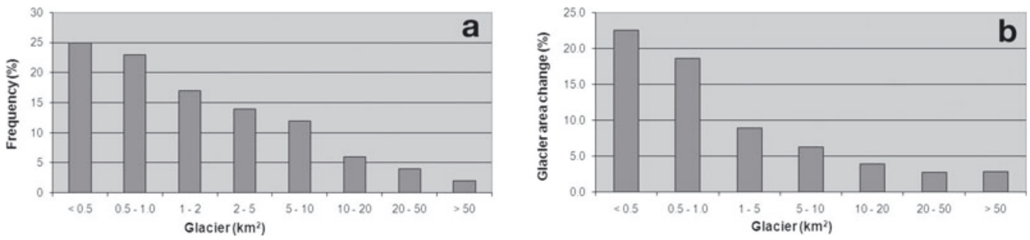

Fig. 5. (a) Area frequency distribution of glaciers for both the Saraswati/Alaknanda and upper Bhagirathi basins derived from analysis of ASTER (11 October 2006) image. (b) Glacier area change and area measurements (%) based on Corona (27 September 1968) and ASTER (11 October 2006) images in both the Saraswati/Alaknanda and upper Bhagirathi basins.

Table 4. Changes in total ice area, clean-ice area and debris-covered ice area in the Garhwal Himalaya between 1968, 1990 and 2006 based on spaceborne imagery

Year (sensor)	Ice extent						Period	Change rate			% change rate			Basin
	Total area		Clean ice		Debris cover ice			Total area	Clean ice	Debris cover ice	Total area	Clean ice	Debris cover ice	
	km^2	No. of glaciers	km^2	No. of glaciers	km^2	No. of glaciers		km^2	km^2	km^2	% and % a^{-1}	% and % a^{-1}	% and % a^{-1}	
1968 (Corona)	599.93	82	472.13	82	127.80	45	1968–2006	–27.40	–46.40	+19.00	–4.56, –0.12	–9.82, –0.25	+14.80, +0.39	Both Alaknanda and Bhagirathi
2006 (ASTER)	572.53	88	425.73	88	146.80	56								
1968 (Corona)	324.77	69	260.26	69	64.51	34	1968–2006	–18.42	–29.92	+11.50	–5.67, –0.14	–11.49, –0.30	+17.82, +0.46	Alaknanda
2006 (ASTER)	306.35	75	230.34	75	76.01	45								
1968 (Corona)	275.15	13	211.86	13	63.29	11	1968–2006	–8.98	–16.47	+7.49	–3.26, –0.08	–7.77, –0.20	+11.83, +0.31	Bhagirathi
2006 (ASTER)	266.17	13	195.39	13	70.78	11								
1968 (Corona)	99.60	29	94.43	29	5.17	7	1968–2006	–9.15	–10.55	+1.40	–9.18, –0.24	–11.17, –0.29	+27.07, +0.71	Both Alaknanda and Bhagirathi
1990 (Landsat TM)	96.12	29	90.81	29	5.31	7	1968–90	–3.48	–3.62	+0.14	–3.49, –0.15	–3.83, –0.17	+2.70, +0.12	
2006 (ASTER)	90.45	29	83.88	29	6.57	7	1990–2006	–5.67	–6.93	+1.26	–5.89, –0.36	–7.62, –0.47	+23.72, +1.48	
1968 (Corona)	86.97	24	82.53	24	4.44	4	1968–2006	–8.07	–9.36	+1.29	–9.27, –0.24	–11.34, –0.29	+29.05, +0.76	Alaknanda
1990 (Landsat TM)	83.74	24	78.99	24	4.75	4	1968–90	–3.23	–3.54	+0.31	–3.71, –0.16	–4.28, –0.19	+6.98, +0.31	
2006 (ASTER)	78.90	24	73.17	24	5.73	4	1990– 2006	–4.84	–5.82	+0.98	–5.80, –0.36	–7.36, –0.45	+20.63, +1.28	
1968 (Corona)	12.63	5	11.90	5	0.73	3	1968–2006	–1.09	–1.19	+0.10	–8.63, –0.22	–10.00, –0.26	+13.69, +0.36	Bhagirathi
1990 (Landsat TM)	12.37	5	11.82	5	0.55	3	1968–90	–0.26	–0.08	–0.18	–2.05, –0.09	–0.67, –0.03	–24.65, –1.12	
2006 (ASTER)	11.54	5	10.71	5	0.83	3	1990–2006	–0.83	–1.11	+0.28	–6.70, –0.41	–9.39, –0.58	+50.90, +3.18	

In the upper Bhagirathi basin, the glacierized area changed from $275.1 \pm 7.5\,km^2$ (1968) to $266.1 \pm 8.3\,km^2$ (2006), a decrease of $8.9 \pm 7.9\,km^2$ or $3.3 \pm 2.8\%$. The loss in glacier area ranged from 2% to ~28% in this basin.

The glacierized area across both basins decreased from $599.9 \pm 15.6\,km^2$ (1968) to $572.5 \pm 18.0\,km^2$ (2006), a decrease of $27.4 \pm 16.8\,km^2$ or $4.6 \pm 2.8\%$ (Fig. 6). In both basins, on average over the study period, glaciers with areas $<1.0\,km^2$ lost a larger percentage of their area ($19.4 \pm 2.5\%$ or $0.51 \pm 0.07\%\,a^{-1}$), than glaciers with areas $>50\,km^2$ ($2.8 \pm 2.7\%$ or $0.074 \pm 0.068\%\,a^{-1}$) (Fig. 5). For all glaciers, we found strong positive correlation between absolute area change of glaciers and glacier area ($r^2 = 0.89$) (Fig. 7). This indicates that smaller glaciers are more sensitive to climate change than larger glaciers.

The 29 mapped glaciers lost $3.48 \pm 3.1\,km^2$ (~$3.49 \pm 3.1\%$ or $0.15 \pm 0.13\%\,a^{-1}$) of their area from 1968 to 1990, and $5.67 \pm 3.3\,km^2$ ($5.89 \pm 3.3\%$ or $0.36 \pm 0.21\%\,a^{-1}$) from 1990 to 2006, in both the upper Bhagirathi and Saraswati/Alaknanda basins; that is, the rate of glacier recession has increased over the past 16 years compared with the previous 22 years. The debris-covered glacier area increased by $17.8 \pm 3.1\%$ ($0.46 \pm 0.08\%\,a^{-1}$) in the Saraswati/Alaknanda basin and $11.8\% \pm 3.0\%$ ($0.3 \pm 0.08\%\,a^{-1}$) in the upper Bhagirathi basin from 1968 to 2006. In total, 45 glaciers were covered with debris in 1968. The number of debris-covered glaciers increased to 56 in 2006.

The annual and JJA T_{MIN} indices from Mukhim station show significant trends (correlation coefficient = –0.50) of $-0.072°C\,a^{-1}$ and $-0.19°C\,a^{-1}$ between 1957 and 2005, while T_{MIN} for DJF shows no trend. In contrast, the annual ($+0.05°C\,a^{-1}$), DJF ($+0.1°C\,a^{-1}$) and JJA ($+0.06°C\,a^{-1}$) T_{MAX} values display a significant warming trend. There is a slight but not significant decrease in annual precipitation between 1957 and 2005, mainly due to summer precipitation (Fig. 8; Table 5). The mean annual temperature at Mukhim station shows an insignificant decreasing trend ($-0.006°C\,a^{-1}$) over the study period. The JJA T_{MIN} indices for Mukhim and Tehri stations show, for the overlapping 22 years of data, trends of $-0.109°C\,a^{-1}$ and $-0.088°C\,a^{-1}$, respectively, during 1957–2005. There is no correlation between Bhojbasa and Mukhim climate data for 5 years of overlapping data (2000–05). Meteorological data from Bhojbasa indicate that annual T_{MIN}, T_{MAX}, DJF T_{MIN} and JJA T_{MAX} increased, whereas DJF T_{MAX} and JJA T_{MIN} decreased from 1999 to 2008. Solid precipitation (snowfall) increased during the same period. However, results from Bhojbasa are not statistically significant due to the short time series.

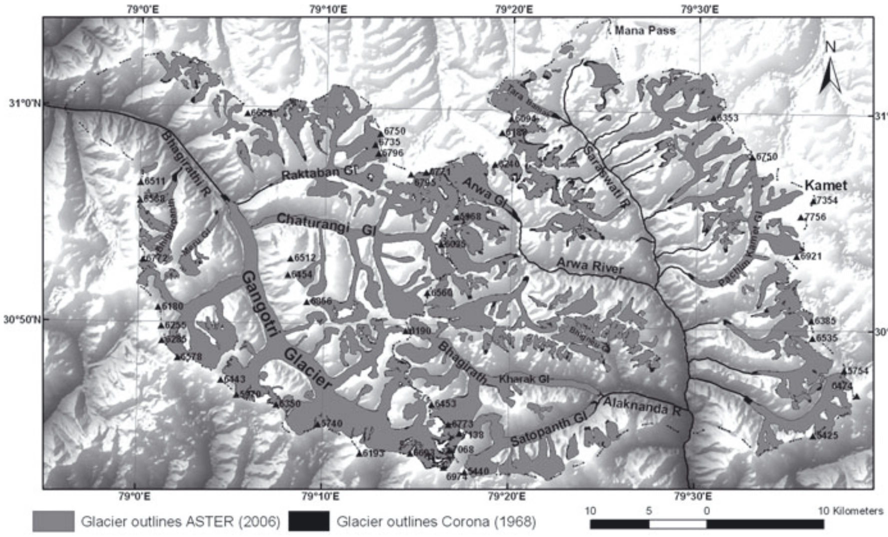

Fig. 6. Glacier change in the Garhwal Himalaya from 1968 to 2006.

DISCUSSION

Glacier inventory and changes in the Garhwal Himalaya

We have generated a glacier inventory for 2006 for parts of the Garhwal Himalaya based on digital sources that are time-efficient and largely reproducible (Manley, 2008; Paul and Svoboda, 2009; Paul and others, 2009; Bolch and others, 2010b). The Geological Survey of India (GSI) has compiled a glacier inventory for the selected basins of the Indian Himalaya, including Jhelum, part of Satluj, Bhagirathi, Tista and the entire eastern Himalaya, based on SOI topographic maps, vertical aerial photographs and satellite images, wherever possible with field checks (Kaul, 1999). Recent work of the GSI on a comprehensive glacier inventory for entire basins of the Indian Himalaya is relevant and provides a good overview (Raina and Srivastava, 2008; Sangewar and Shukla, 2009). The glaciological community will benefit greatly when these data, which are currently assembled in statistical records only (Kulkarni, 2007; Braithwaite 2009), are made available in digital GIS format. Information is included concerning topographic parameters (e.g. mean slope, aspect, median and mean elevation) and the percentage of debris cover, which are not available in the Indian glacier inventory in digital GIS format, but are valuable for glaciological and hydrological modeling (Braithwaite, 2009).

The areal changes of the glaciers investigated in the Garhwal Himalaya confirm an expected and widely published trend of glacier retreat. However, the rate of retreat is less than previously estimated by remote sensing. For example, the present study suggests that Gangotri Glacier shrank by $4.4 \pm 2.7\,km^2$ ($0.11 \pm 0.07\,km^2\,a^{-1}$) between 1968 and 2006, whereas Kumar and others (2009) claimed that it reduced by $15.5\,km^2$ ($\sim 0.51\,km^2\,a^{-1}$)

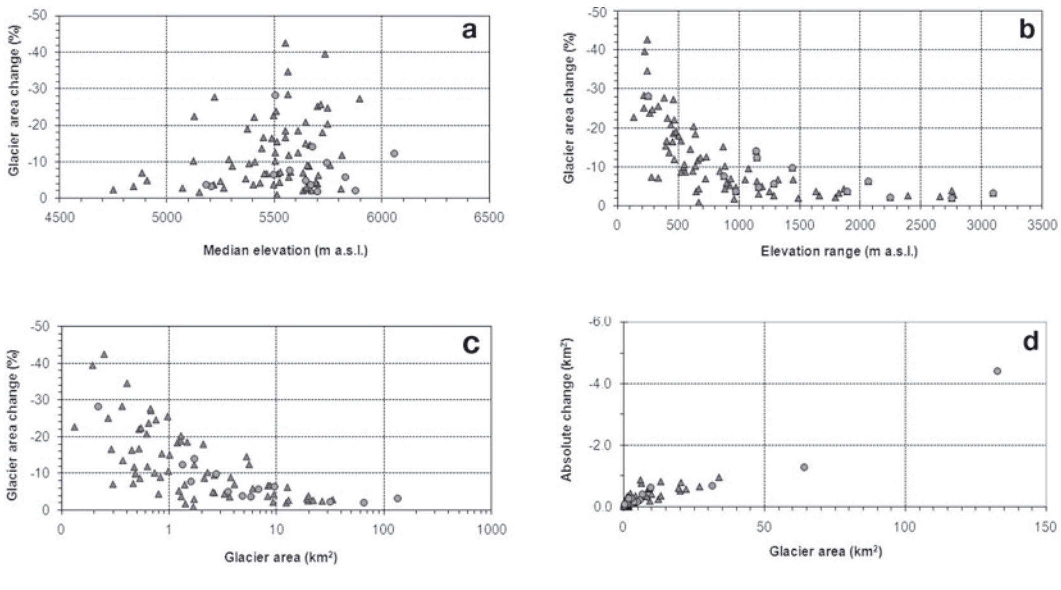

Fig. 7. Scatter plots of (a) median elevation vs glacier area change (%), (b) elevation range vs glacier area change (%), (c) glacier area (km^2) vs glacier area change (%) and (d) glacier area (km^2) vs absolute glacier area change (km^2). Triangles are for the Saraswati/Alaknanda basin and circles are for the Bhagirathi basin. Glacier area change (%) derived from analysis of Corona (27 September 1968) and ASTER (11 October 2006) images.

Table 5. Temperature and precipitation trends for the period 1957–2005 for Mukhim station, based on the Mann–Kendall non-parametric test

	Correlation coefficient	*Z*	*p*	Mann–Kendall results	
				ΔT	ΔP
				$^{\circ}\mathrm{C\,a^{-1}}$	$\mathrm{mm\,a^{-1}}$
Annual T_{MIN}	–0.499	–4.824	0.0000	–0.072	–
Annual T_{MAX}	0.460	4.441	0.0000	0.057	–
DJF T_{MIN}	–0.012	–0.104	0.9170	0.003	–
DJF T_{MAX}	0.441	4.309	0.0000	0.10	–
JJA T_{MAX}	0.473	4.513	0.0000	0.06	–
JJA T_{MIN}	–0.590	–5.636	0.0000	–0.19	–
Annual precipitation	–0.029	–0.263	0.7926	–	–0.108
DJF precipitation	0.094	0.909	0.3634	–	0.064
JJA precipitation	–0.097	–0.920	0.3574	–	–0.85

Note: DJF: December, January, February; JJA: June, July, August.

between 1976 and 2006, and Ahmad and Hasnain (2004) found that it reduced by 10 km^2 ($\sim$0.62 km^2 a^{-1}) between 1985 and 2001. The main reason for the discrepancy could be that the debris-covered terminus of this glacier is not distinct and snout retreat is obscured. An additional explanation may concern interpretation of debris cover, shadow area and seasonal snow on the coarse satellite images (e.g. Landsat MSS as used by Kumar and others (2009); personal communication from R. Kumar, 2010) and topographic maps (used by Ahmad and Hasnain, 2004), which is known to be one of the major challenges in glacier inventories (Bhambri and Bolch, 2009; Paul and others, 2009; Racoviteanu and others, 2009; Bolch and others, 2010a). Kumar and others (2009) reported that Gangotri Glacier area decreased from all sides, a fact that could not be confirmed from our study based on high-resolution Corona and Cartosat-1 data. Our results suggest that Gangotri Glacier lost 0.38 ± 0.03 km^2 (0.01 km^2 a^{-1}) from its front between 1968 and 2006, based on high-resolution Corona and Cartosat-1 images (Fig. 9). These results are supported by the ground-based plane-table survey by Srivastava (2004). This study indicates that between 1935 and 1996 the area of Gangotri Glacier reduced by 0.58 km^2 ($\sim$0.01 km^2 a^{-1}) at its terminus. In addition, Auden (1937) reported a single ice cave at the left side of Gangotri Glacier snout. Jangpangi (1958) noticed two caves, one small and one large, on the terminus of Gangotri Glacier in 1956. However, after 1956 the larger and prominent ice cave had been considered for the recession studies (Tiwari, 1972; Srivastava, 2004). Shadows of ice caves on the 1968 Corona satellite image suggest two caves at the terminus of Gangotri Glacier (Fig. 9). This indicates that high-resolution satellite data possibly provide more reliable results than coarse-resolution satellite data such as Landsat MSS and TM and/or topographic maps, and thus constitute a valuable resource for glacier monitoring.

However, inconsistencies in the rectification of Corona images probably are the main source of uncertainty in our

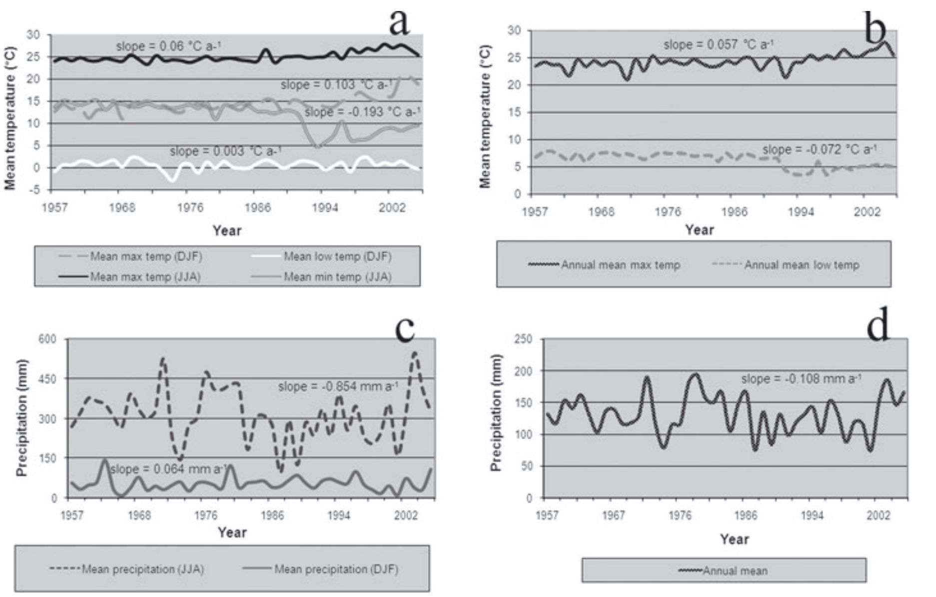

Fig. 8. Climate parameters for Mukhim station: (a) mean T_{MAX} and T_{MIN} for DJF and JJA from 1957 to 2005; (b) mean annual T_{MAX} and T_{MIN}; (c) mean minimum and maximum precipitation for DJF and JJA; and (d) annual mean precipitation. DJF: December, January, February; JJA: June, July, August.

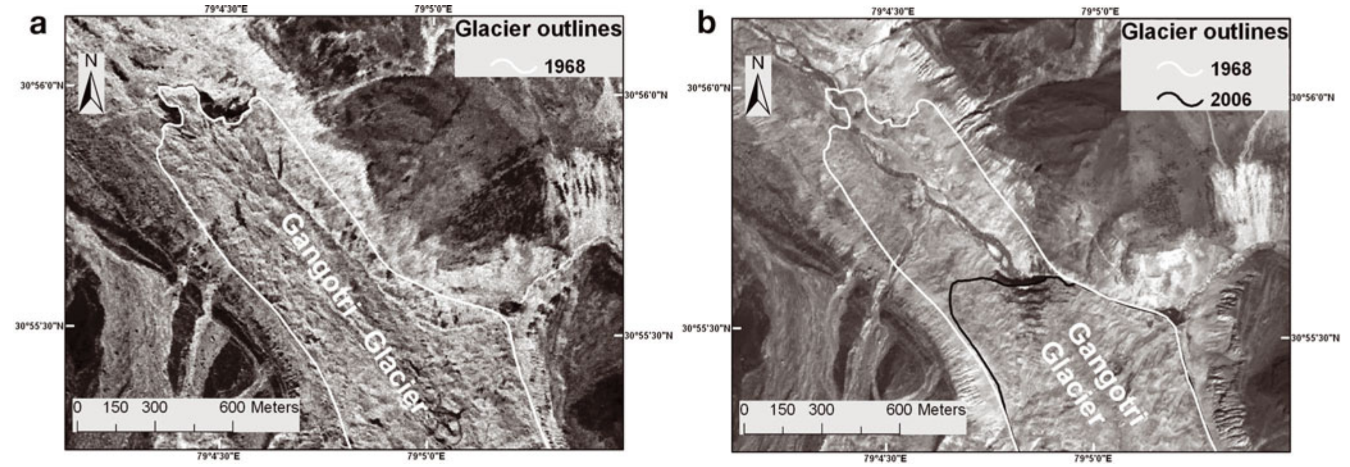

Fig. 9. Frontal area images of Gangotri Glacier. (a) Corona image (27 September 1968) with same-year glacier outline, (b) Cartosat-1 image (11 October 2006) with glacier outline of 1968 and 2006.

estimations of glacier change. The main challenges with Corona data are the complex image geometry and the absence of satellite camera specifications. The adopted spline method for rectification of the imagery in the present study is time-consuming, depends on local knowledge of topography and requires interpreter expertise for collection of GCPs. However, the data are very useful for providing insight into glacier changes since the 1960s, and the above-mentioned field studies (e.g. Srivastava, 2004) support our results for Garhwal Himalayan glaciers. These data are also available for other remote mountain areas where no aerial images are available or accessible. However, existing suitable aerial photographs from the early 1960s from the Indian authorities may provide better insight into glacier change as derived from Corona images in the Garhwal Himalaya.

In other parts of the Garhwal Himalaya, such as the Alaknanda basin, the glacier ice area of Satopanth Glacier shrank by 0.314 km^2 (1.5%; 0.007 $km^2\,a^{-1}$) near the snout between 1962 and 2006. During a similar period, Bhagirathi Kharak Glacier lost 0.129 km^2 (0.4%; 0.002 $km^2\,a^{-1}$) (Nainwal and others, 2008b). Our results, based on Corona and ASTER imagery, suggest that from 1968 to 2006 Satopanth Glacier lost 0.280 km^2 (0.007 $km^2\,a^{-1}$) near the snout, whereas Bhagirathi Kharak Glacier lost only 0.083 km^2 (0.002 $km^2\,a^{-1}$). The reason for the minor difference could be the use of the SOI topographic map by Nainwal and others (2008b). Dokriani Glacier (area ~7 km^2), in the Bhagirathi basin, lost ~9.5% (0.2% a^{-1}) between 1962 and 2007 (Dobhal and Mehta, 2010). In addition, the GSI has monitored several glaciers based on plane-table survey in Uttarakhand; for example, Pindari Glacier lost 0.111 km^2 (0.0026 $km^2\,a^{-1}$) at its front from 1958 to 2001 (Oberoi and others, 2001). These field-based studies also support our results.

Comparison between the upper Bhagirathi and Saraswati/Alaknanda basins

The present study gives insight into the differences in the debris-covered and clean-ice areas from 1968 to 2006 in the upper Bhagirathi and Saraswati/Alaknanda basins. Glacier shrinkage in the Saraswati/Alaknanda basin was found to be high compared with the upper Bhagirathi basin. The difference in recession patterns of each glacier may be explained by regional relief (e.g. altitudinal range), quantity and distribution of debris load, orientation or aspect, which vary considerably from glacier to glacier in the upper reaches of these basins. The slower rate of area loss in the upper Bhagirathi basin (-3.3 ± 2.8%) compared with the Saraswati/Alaknanda basin (-5.7 ± 2.7%) from 1968 to 2006 can be explained by: (1) the higher altitudinal range (1352 m) of the glaciers in the upper Bhagirathi basin than in the Saraswati/Alaknanda basin (791 m); (2) the mean glacier size, which is approximately four times higher in the upper Bhagirathi basin (13.7 km^2) than in the Saraswati/Alaknanda basin (3.7 km^2); and (3) the three large compound debris-covered glaciers, Gangotri, Raktavan and Chaturangi glaciers, ~83% of the upper Bhagirathi basin area. Generally, larger compound debris-covered glaciers respond more slowly than small glaciers to perturbations in climate (Bahr and others, 1998).

Several studies have reported that debris cover has increased over time in the Himalaya (e.g. Iwata and others, 2000; Bolch and others, 2008; Kamp and others, 2011). We find that debris-covered glacier area increased significantly by 17.8 ± 3.1% (0.46 ± 0.08% a^{-1}) in the Saraswati/Alaknanda basin and by 11.8 ± 3.0% (0.31 ± 0.08% a^{-1}) in the upper Bhagirathi basin between 1968 and 2006. This supports the assumption that, concomitantly with the higher rate of glacier retreat, the debris-covered area increased more in the Saraswati/Alaknanda basin than in the upper Bhagirathi basin. The reason for the increase needs further investigation as debris cover depends on debris supply and debris transport. However, study of englacial transport can be addressed only marginally using remote-sensing data.

Comparison with other Himalayan regions

The present study indicates that the recession rate of Saraswati/Alaknanda basin glaciers (0.15 ± 0.07% a^{-1}) from 1968 to 2006 is less than reported for other Himalayan regions. For instance, from 1962 to 2001 in the Himachal Himalaya, glaciers in the Chenab basin retreated at ~0.53% a^{-1}, in Parbati at ~0.56% a^{-1} and in Baspa at ~0.48% a^{-1} (Kulkarni and others, 2007). However, an apparent higher rate of glacier retreat in the Himachal Himalaya could be the result of overestimation of glacier cover in the old datasets due to the use of SOI topographic maps. Previous studies have found some inaccuracies in these maps (Vohra, 1980; Agarwal, 2001; Raina and Srivastava, 2008; Raina, 2009). This is most likely in the case of Himachal Himalaya glaciers (e.g. Parbati basin) where aerial photographs were acquired during March–June when snow is not fully melted (Bhambri and Bolch, 2009). In this condition, differentiation between snow cover and glacier ice is very difficult and will make glacier delineation on topographic maps problematic.

In the Khumbu Himalaya, Bolch and others (2008) estimated glacier area loss at 5.2% (~0.12% a^{-1}) based on space imagery from 1962 to 2005. Based on topographic maps, Salerno and others (2008) reported 4.9% (~0.12% a^{-1}) of the glacier area was lost between the 1950s and 1990s in Sagarmatha National Park, Nepal. Problems encountered in comparing maps, however, were also highlighted. Ye and others (2009) reported ~10.41% (~0.3% a^{-1}) glacier area loss from 1974 to 2008 at the northern slope of Mount Everest. In contrast, 34 surges have been reported in the Karakoram since the 1860s (Hewitt, 2007). Similarly, Raina and Sangewar (2007) and Ganjoo and Koul (2009) reported, on the basis of field observation, that Siachen Glacier had shown hardly any retreat in the past 50 years. Raikot Glacier, Nanga Parbat, Punjab Himalaya, showed similar behavior (Schmidt and Nüsser, 2009). This suggests that the Karakoram area is showing a different response to climate change than other parts of the Himalaya. High reductions in glacier area of the Himachal Himalaya and surging effects of glaciers of the Karakoram do not appear in the central Himalayan glaciers such as those in the Garhwal and Khumbu Himalaya. Garhwal Himalayan glacier recession rate (~0.12% a^{-1}) matched that of the Khumbu Himalayan glaciers (~0.12% a^{-1}; Bolch and others, 2008).

We found that the number of glaciers increased during 1968–2006 due to glacier fragmentation. Similar fragmentation trends have been reported in other glacierized areas of the Himalaya such as in the Himachal region (Kulkarni, 2007; Kulkarni and others, 2007). The number of debris-covered glaciers increased in 2006, possibly due to melting of clean-ice surfaces resulting in the exposure of debris-covered areas. Since 1990, the rate of recession has increased in selected glaciers of the Garhwal Himalaya. Similar acceleration in glacier recession has been reported in the Khumbu Himalaya (Bolch and others, 2008).

Our results indicate that glaciers <1 km^2 in area lost 19.4 ± 2.5% (~0.51% a^{-1}) of their area from 1968 to 2006 in both the Bhagirathi and Saraswati/Alaknanda basins, whereas in the Himachal Himalaya glaciers <1 km^2 in area lost 38% (~0.97% a^{-1}) of their area from 1962 to 2001–04 (Kulkarni and others, 2007). The combined influence of altitudinal distribution and little or no accumulation zone is likely to be the major cause of the rapid recession of the small glaciers. Larger compound basin glaciers are less sensitive to climate change due to contributions from tributary glaciers in accumulation zones and high supraglacial debris cover in the Garhwal Himalaya. North-facing glaciers in the Saraswati/Alaknanda basin were found to recede less than glaciers with other aspects. Generally, northern slopes receive less radiation than the south-facing Himalayan slopes (Ahmad and Rais, 1999). Thus north-facing glaciers are expected to react more slowly to climate change than the south-facing glaciers of the Saraswati/Alaknanda basin. Similar patterns have been reported in previous studies, for example in the Alaknanda basin (Nainwal and others, 2008b)

Climate set-up and consideration

The Garhwal Himalaya obtain precipitation from the southwest monsoon in summer and from westerlies during the winter season. This climatic regime distinguishes this region from the eastern and Karakoram Himalaya. Our study area (Bhagirathi and Alaknanda catchments) has few climate observatories at higher altitude (e.g. Mukhim and Tehri stations) with breaks in long-term climate data series. The observation of weather conditions near the Gaumukh is limited to the summer period in previous studies (Singh and others, 2005, 2007). Our study shows a significant increasing trend in the annual T_{MAX}, but a decreasing trend in the annual T_{MIN}, during the study period. Shekhar and others (2010) also report an increase (of 2.8°C) in annual T_{MAX} between 1984/85 and 2007/08 in the western Himalaya, while annual T_{MIN} increased by about 1°C during a similar period in the western Himalaya. Dash and others (2007) described decreasing trends (1.9°C) in T_{MIN} over the western Himalaya during 1955–72, followed by an increasing trend in recent years. The present study notes a significant decreasing trend in T_{MIN} in JJA at Mukhim station. The Tehri station data support these findings. Similarly, summer cooling has been reported in some parts of the western Himalaya and upper Indus basin during the latter part of the 20th century (Yadav and others, 2004; Fowler and Archer, 2006). We report a significant increasing trend in T_{MAX} during the winter at Mukhim station (Table 5). Bhutiyani and others (2007) also found that winter mean T_{MAX} for the northwestern Himalaya had increased significantly, by ~3.2°C, during the past two decades.

The present study shows an insignificant decreasing trend in the monsoon precipitation, whereas no trend was found in the winter precipitation at Mukhim station. Basistha and others (2009) also reported a precipitation decrease in the Uttarakhand Himalaya during 1965–80. Additionally, in the northwestern Himalaya, a significant decreasing trend has been reported in the monsoon precipitation during the period 1866–2006 (Bhutiyani and others, 2009). We did not find any correlation between precipitation and temperature at Mukhim or Bhojbasa stations. This may be due to the short overlapping period of only 5 years of observations. It may also indicate that climate at the higher altitudes is influenced by local factors that suppress the general synoptic situation. This is the subject of further investigation.

Annual T_{MAX} values show a significant increasing trend in the northwestern Himalaya as well as in the Garhwal Himalaya. However, to date, we are not able to determine the significance of effects of particular climate elements on glacier variability because: (1) availability of climate data in the study area near the glaciers (e.g. >4000 m a.s.l.) is insufficient; (2) analysis of T_{MAX} and T_{MIN} data for Mukhim station suggests diverse characteristics and results of T_{MIN} data for Mukhim station and the western Himalaya do not show similar tendencies; (3) some climate parameters from Mukhim and Bhojbasa stations do not show similar tendencies; and (4) glacier changes in the Garhwal Himalaya show irregularities in amount, rate and time of occurrence during the study period which mainly depend on glacier response times. Sufficient knowledge on the response of Garhwal glaciers (fed by both winter and summer accumulation) to climate changes at different timescales is still not available. In addition, topographic parameters such as glacier size, shape, motion, thickness and distribution of debris-covered area, contribution of tributary glaciers to the accumulation and the local topography also influence glacier response. The summer-accumulation-type glaciers are more susceptible to temperature increase than winter-accumulation-type glaciers (Fujita and Ageta, 2000; Fujita, 2008). Nevertheless current analysis of direct mass-balance measurements and meteorological measurements near Chorabari, Dokriani and Gangotri glaciers in the Garhwal Himalaya and geodetic estimates of glacier mass changes by DTM differencing will provide a valuable database in the near future, and will help to adjust existing glacier models to the specific situation in the Garhwal Himalaya.

CONCLUSION

This study provides a comprehensive multitemporal glacier fluctuation record for the upper Bhagirathi and Saraswati/Alaknanda basins of the Garhwal Himalaya from 1968 to 2006. Declassified Corona images are efficient for mapping glacier terrain in the absence of historical aerial images. Glacier area decreased from $599.9 \pm 15.6\,\mathrm{km}^2$ (1968) to $572.5 \pm 18.0\,\mathrm{km}^2$ (2006), i.e. $4.6 \pm 2.8\%$. In contrast to the basin-wide ice loss, the absolute area loss in the Saraswati/Alaknanda basin ($18.4 \pm 9.0\,\mathrm{km}^2$; $5.7 \pm 2.7\%$) was almost two times higher than in the Bhagirathi basin ($9.0 \pm 7.7\,\mathrm{km}^2$; $3.3 \pm 2.8\%$). This difference can be attributed mainly to the differences in mean glacier size. Smaller glaciers ($<1\,\mathrm{km}^2$) lost $19.4 \pm 2.5\%$ ($0.51 \pm 0.07\%\,\mathrm{a}^{-1}$) of their ice, which is a higher rate than that of larger glaciers: for example, glaciers $>50\,\mathrm{km}^2$ in area lost $2.8\% \pm 2.7\%$ ($0.074 \pm 0.071\%\,\mathrm{a}^{-1}$) of their ice. This indicates that the average shrinkage rate is influenced by glacier size. Overall, south- and southwest-facing glaciers shrank at higher rates. Debris-covered glacier area increased by $17.8 \pm 3.1\%$ ($0.46\%\,\mathrm{a}^{-1}$) from 1968 to 2006 in the Saraswati/Alaknanda basin and by $11.8 \pm 3.0\%$ ($0.31 \pm 0.08\%\,\mathrm{a}^{-1}$) in the upper Bhagirathi basin. Mean annual T_{MAX} for Mukhim station increased significantly during 1957–2005, while precipitation during monsoon months decreased. However, the current availability of climate data in the study area is insufficient to conclude complex glacier–climate interactions, and thus further climatological investigations are needed.

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