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ORIGINAL ARTICLE

# Estimation of the recession rate of Gangotri glacier, Garhwal Himalaya (India) through kinematic GPS survey and satellite data

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## Abstract

Snout monitoring of the Gangotri glacier (Uttarakhand, India) during the ablation season (May to September) in years 2005 and 2015 by using rapid static and kinematic GPS survey reveals that the retreating rate has been comparatively more declined than shown by the earlier studies. Our study is based on the individual measurement by the remote sensing, added by the ground observations by using Differential global positioning system (DGPS) to determine the precise recession rate of the glacier at sub-centimeter level of accuracy. The GPS dataset show that the total average retreat along the snout has been 102.57 ± 0.05 m from 2005 to 2015 with an average rate as 10.26 ± 0.05 m/yr. Additionally, the shift in snout position was also measured through multi-temporal satellite data from 1989 to 2016. The results indicate that the Gangotri glacier snout has retreated by 585.62 ± 38.30 m during this period with an average retreat of 26.75 ± 4.36 m/yr from 1989 to 1999, 21.58 ± 3.77 m/yr from 1999 to 2009 and 14.60 ± 4.81 m/yr from 2009 to 2016. Such a decline in retreat is further confirmed by the satellite data set. A close examination of meltwater discharge and retreating rate ($r^2 = 0.95$) show that both parameters are strongly correlated. Therefore, we suggest that a consistent decrease in meltwater discharge from 1999 to 2015 is in agreement with decreasing trend of retreating rate during the recent years. To determine the possible causes of decreased retreating rate, a relationship between debris thickness and melt rate was also established by ablation stakes. Further, we infer that the declining trend in the glacier retreat is not only controlled by prevailing weather conditions (rainfall and air temperature) but is also governed by increased debris cover on the glacier surface which prevents the ice to melt.

**Keywords** Gangotri glacier · GPS survey · Retreating rate · Debris cover · Glacier snout

## Introduction

The Himalaya contains a number of glaciers, which are mostly valley type, covering an area of about 33,000 km$^2$ (Bahuguna 2003). Himalayan glaciers have always been an issue of debate in perspective of global warming and majority of these are dying due to global warming and climate change (Negi et al. 2012). During the 20th century, a persistent retreat of glaciers along the Himalayan arc has been reported (Vohra 1981) and this process still continues. When mass gain in the receiving zone leads to a significant advance of the terminus, the calving flux is amplified (Kochtitzky et al. 2019). Most of the Himalayan glaciers are partially or fully covered with debris, hence are divided into two categories, clean-ice type (C type) and debris covered ice type (D type) (Shroder et al. 2000). In the cold mountainous environment, debris covered glacier is the main agent of sediment transport (Kirkbride 1995). The debris

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above the glacier surface is generally deposited from the rock fall in the adjacent valley walls and erosion of lateral moraines and avalanches (Benn et al. 2012). Usually, the debris cover is important for determining ice melt rate as well as glacier mass balance (Zhang et al. 2011). Thin debris covered glaciers respond faster to the climatic changes than thick debris covered glaciers (Scherler et al. 2011). Since the glaciers are very sensitive to the climate change, a regular glacier monitoring is required to understand the role of climate change in the glacier dynamics. Apart from climatic conditions, the glacier dynamics also depends on glacier characteristics. Recent studies on Himalayan glaciers point to wide-ranging variability in the retreating rate and mass balance (Dobhal et al. 2013). This is mainly due to morpho-geometrical changes, behavior of winter and summer monsoons and incoherent climatic changes in the Himalayan region (Dumka et al. 2013). As the change in snout position varies from year to year, it is important to regularly monitor the glacier snout to estimate the impact of local factors on glacial retreat.

Hydrological investigations of mountain glaciers are equally important as they are the major source of fresh water for the community living in the downstream region (Bisht et al. 2018). Variability in rainfall, air temperature pattern and solar insolation mainly influence the meltwater discharge, which is one of the major controlling factors of the glacier melt (Young 1981; Bisht et al. 2017). The Himalayan rivers receive significant runoff from snow and glacier melts (Singh et al. 2008), therefore, the meltwater discharge measurements are significant to assess the melting rate of the glaciers (Srivastava et al. 2012).

Past positions of the glacier snout can also be reconstructed using satellite imageries and examination of the terminal moraines (Kaser et al. 2003). The remote sensing method can provide useful information in monitoring the glacier tongue position, length area, equilibrium line altitude (ELA) and volume (Negi et al. 2012). This technique is a bird eye view of the whole glacial body through which one can effortlessly determine the area, retreating trend and delineate the glacial catchment boundaries (Bhambri et al. 2011). For the last few decades, the method has been widely used to estimate ice extent, terminus position, volume and surface elevation of glaciers by using various multi-spectral and multi-temporal data and has a capability to recognize past retreating trends (Negi et al. 2012). However, this approach also faces inadequacy because even the Cartosat, 2.5 m resolution has uncertainty of 10 m (Bhambri et al. 2011). The ground based method is another way to estimate the glacial retreat in which the GPS survey method (static and kinematic surveys) and geomorphological evidences are used to determine the glacier retreat (Kaser et al. 2003).

In the present study, we have selected the Gangotri glacier (Fig. 1) as it has initiated widespread discussions because of its more dynamic nature and varying rate of retreat. Several studies have been conducted on this glacier to estimate the recession rate using remote sensing data (Srivastava 2004; Tangri 2004; Thayyen 2008; Bhambri et al. 2011) as well as geomorphological evidences (Naithani et al. 2001; Singh et al. 2017), whereas, a few studies have been based on the GPS survey (Kumar et al. 2008). However, the aim of our study is to understand the dynamic nature (retreating rate) of Gangotri glacier using DGPS and the relationship between meltwater discharge and rate of glacier retreat. In addition, the emphasis is given on the impact of debris cover in terminus retreat of the Gangotri glacier.

## Study area

Gangotri glacier (30°43′10″ to 30°55′50″ N, 79°4′55″ to 79°17′18″ E) is situated in the Uttarkashi district of Uttarakhand (Fig. 1). Geologically, the area lies above the Main Central Thrust (MCT), a key structure in the Indian Himalaya as basal contact between the Greater Himalayan sequence and the underlying Lesser Himalayan sequence) (Metcalfe 1993; Bisht et al. 2020). The regional climate is mainly influenced by the Indian Summer Monsoon (ISM) as well as Indian Winter Monsoon (IWM) (Dimri et al. 2016; Kotlia et al. 2018) and the microclimate is affected by both the altitude and valley aspects (Naithani et al. 2001). At present, the glacier comprises mainly two inactive glacier tributaries (Raktavarna and Chaturangi) and four active tributary glaciers (Kirti, Swachhand, Maiandi and Ghanohlm). The Gangotri glacier is NW flowing valley type glacier, about 30.2 km long and 0.5 to 2.5 km wide (Kaul 1999). The longitudinal U shaped valley occupies 39.18 $km^3$ of ice volume with 258.56 $km^2$ glaciated area (Naithani et al. 2001). Evidence of neotectonic activity (e.g., deep gorges, triangular fault facets and tectonic depressions) observed in this region are mainly responsible for modification of the present landform. The occurrence and distribution of various landforms including snout positions of the tributary glaciers appear to be controlled by the neotectonic activity and partially by the glacial movement (Bali et al. 2003). The depositional features (e.g., lateral and terminal moraines, talus cones and dead ice mounds) and erosional features (e.g., gorges, truncated spurs, glacier striations, cirques, glacial horns, glacial lakes etc.) are characteristics of the glacier landforms and are well exposed all along the glacier valley. Throughout the glacier surface, transverse and longitudinal crevasses are formed mainly due to unequal surface velocity of the glacier at marginal and central parts, ranging in length from 4–10 m and 1–2 m in width. Besides this, the glacier abrades the valley walls, depositing highly unsorted, angular and unconsolidated sediments on and along its sides.

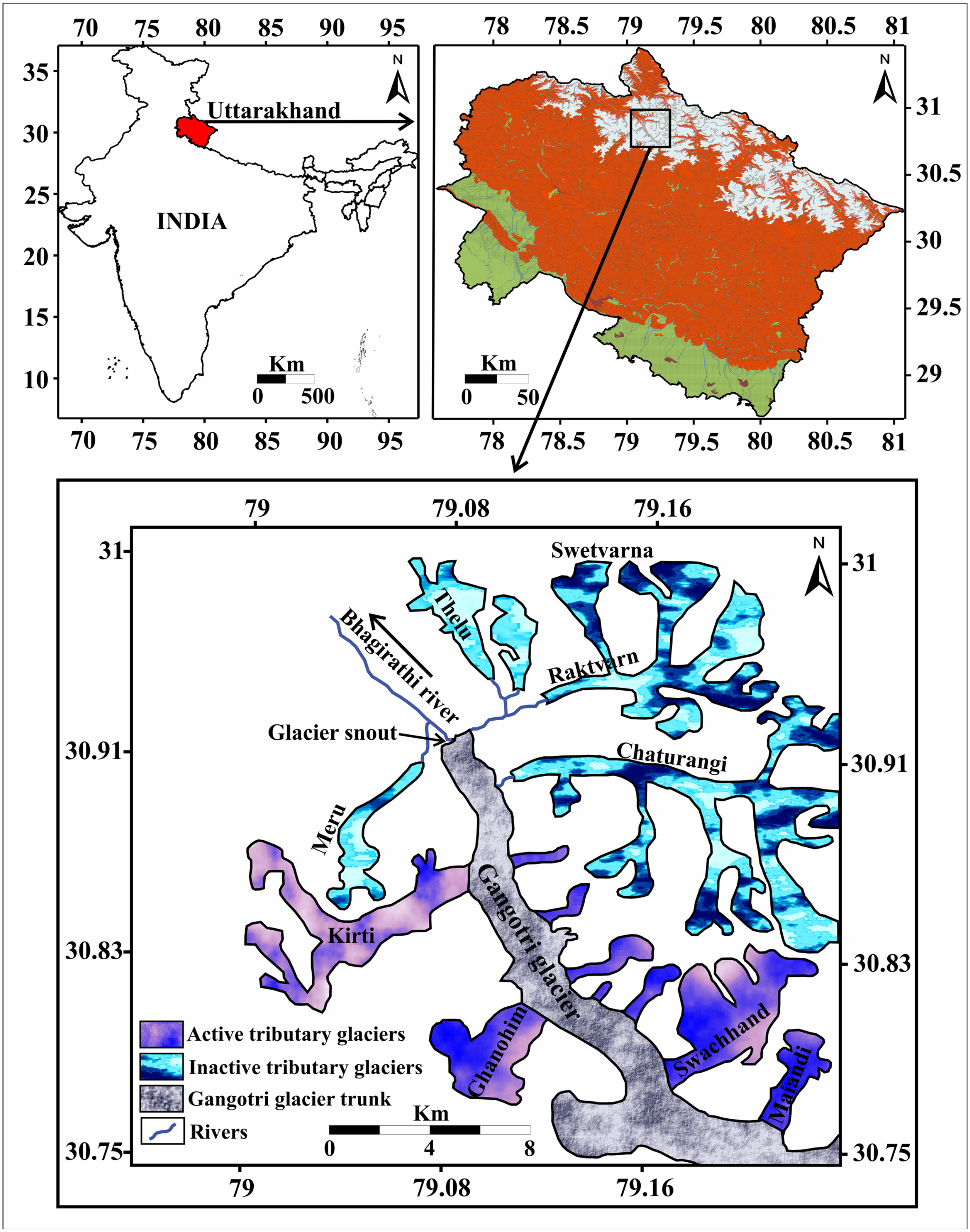

**Fig. 1** Location map of the study area, showing Gangotri glacier system with its tributary glaciers

## Materials and methods

### DGPS survey for retreat measurements

The snout of the Gangotri glacier was monitored using Differential Global Positioning System (DGPS) survey with high level of accuracy for annual retrieval rate of the glacier. The survey was carried out all along the snout in year 2005 (May) and 2015 (June) by using a pair of Leica SR520 GPS receivers and AT502 antenna in rapid static and kinematic modes in which one antenna, attached with receiver was mounted on a solid bedrock with 1 mm hole located off the glacier (Fig. 2a), and another receiver was used as a rover (Fig. 2b) which takes observation at an interval of 5 s, lasting for 5 min to obtain precise position of coordinates with accuracy of sub-centimeter. We started the reference station 24 h before the kinematic survey for instrument calibration and to get a precise location of the reference point. The roving antenna was fixed to the top of an iron rod, attached to the backpack, nearly 2 m above the ground level (Fig. 2b). The survey was carried out along the closest possible tracks, 1–4 m distance from the glacier snout to avoid mishap from ice, rock and debris fall. The GPS derived raw data were processed by using Leica SKI-PRO 3.0 software and position coordinates were presented in form of the WGS 84 coordinate system. The position quality was also calculated, defined as Root Mean Square (RMS) error of standard deviations of $X$ and $Y$ coordinates (Kumar et al. 2008). The accuracy of results is also affected by large Geometric Dilution of Precession (GDOP), which may introduce a large error in the GPS derived positions. To minimize this error, all GPS observations having GDOP > 6 were not considered in the final analysis.

### Area velocity method for discharge measurements

Area velocity method (Eq. 1) was used to calculate channel discharge as a product of water flow velocity ($\text{ms}^{-1}$) and the channel cross sectional area ($\text{m}^2$) in years 2005 and 2015. A suitable gauging site was selected ~1.6 km downstream (30°56′15″ N and 79°3′53″ E) from present position of the Gangotri glacier snout. The channel cross section area was measured by standard survey technique using ruler and a tape measure (Fig. 2c). Here, a transect across the stream at 50 cm interval was taken as the height from bed to the water surface. The channel flow velocity was measured by wooden floats over a stream flow length. Since channelized water flow velocity decreases exponentially towards the bed and banks of channel, the correction factor ($k = 0.8$) was applied to obtain mean channel velocity (Hubbard and Glassar 2005). Variation in water level was recorded 6–8 times at a regular interval to draw a rating curve for daily discharge measurement by using following formula (Hubbard and Glassar 2005).

$$Q = k(A \times V) \tag{1}$$

Where $Q$ is discharge, $k$ is correction factor (0.8), $A$ is channel cross sectional area and $V$ is surface velocity of the channel.

### Measurements of debris thickness for glacier melt

The study was conducted during the ablation season (May to September) in 2015 to determine the surface melt rate and varying thickness of debris cover. The ablation measurements were undertaken with the glaciological stake network method (Østrem and Brugman 1991). To measure the ablation and debris thickness, 10 ablation stakes were emplaced up to 2 m depth into the glacier surface by ice drill machine (AR 502, Fig. 2d). The ablation stakes were labeled as 1–10 from one valley side to other side near the tongue and were divided into two categories, e.g., thin debris covered stakes (≤ 5 cm) and thick debris covered stakes (5–55 cm). The height of the ablation stakes from the glacier surface (Fig. 2e) was taken at an interval of one month during the entire ablation period of 5 months (May to September) to determine monthly melting of the glacier surface. The snout of the glacier was also photographed at the same place with high resolution camera in 2005 and 2015 (Fig. 3) to compare observed changes in its position and shape.

### Remote sensing method for retreat measurements

Average annual retreating rate of Gangotri glacier snout was also computed from 1989 to 2016 through remote sensing method. To achieve past positions and retreating rate of glacier tongue, multi-temporal satellite imageries (Landsat Sentinel 2016, IRS LISS III 2009, Landsat ETM + PAN 1999 and Landsat TM 1989) (https://earthexplorer.usgs.gov/; https://bhuvan.nrsc.gov.in/) were processed and georectified using Arc GIS (ver. 10.2) and ERDAS imagine (ver. 14) software. A comprehensive set of multi-spectral and multi-temporal satellite data were acquired in cloudless condition (see Table 1). The registration error was calculated by registering the images 1989 (Landsat TM), 1999 (Landsat ETM + PAN) and 2009 (LISS III) to base image 2016 (Landsat Sentinel), which were 0.6 pixel or 6 m, 0.4 pixel or 4 m and 0.5 pixel or 5 m, respectively. To assess positional accuracy of results, the uncertainty was calculated by using the formula, as proposed by Hall et al. (2003).

**Fig. 2** **a** Reference antenna mounted on solid bedrock, **b** GPS survey along the snout of Gangotri glacier, **c** measurements of cross section area across the Bhagirathi stream draining from Gangotri glacier, **d** photograph showing drilling on the glacier surface through ice drill (AR502), **e** measurement of stake height to determine the debris thickness on the glacier surface

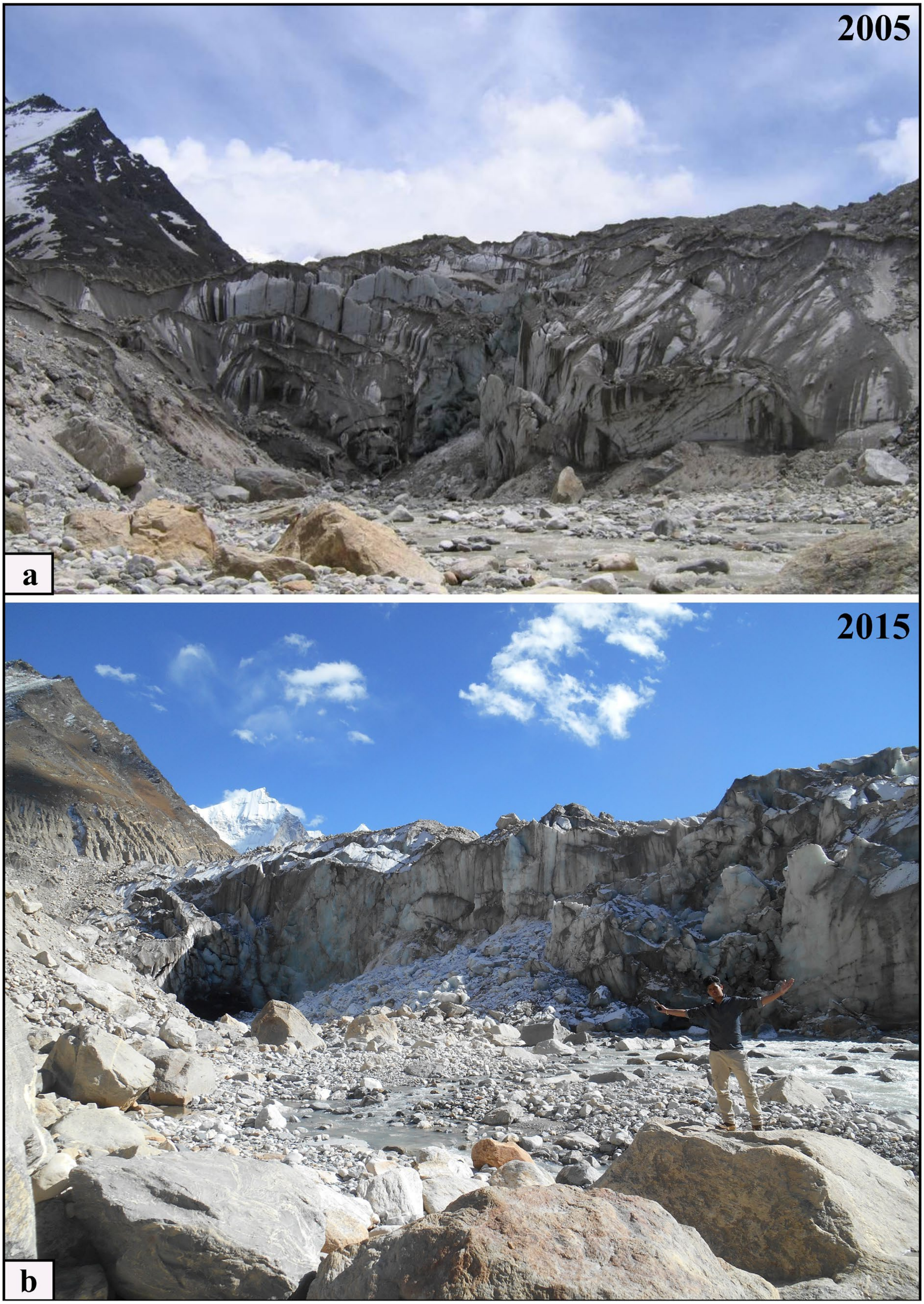

**Fig. 3** Photographs showing change in the position of glacier snout from 2005 (**a**) to 2015 (**b**)

**Table 1** Comprehensive details of multi-spectral and multi-temporal satellite data from 1989 to 2016

| Satellite/sensor | Date of acquisition | Spatial resolution (m) | Spectral resolution |
|---|---|---|---|
| Landsat TM | 15/11/1989 | 30 | G = 0.52–0.60 μm<br>R = 0.63–0.69 μm<br>NIR = 0.76–0.90 μm |
| Landsat ETM + Pan | 15/10/1999 | 15 | G = 0.52–0.60 μm<br>R = 0.63–0.69 μm<br>NIR = 0.76–0.90 μm |
| Liss III | 23/10/2009 | 23.5 | G = 0.52–0.59 μm<br>R = 0.62–0.68 μm<br>NIR = 0.77–0.86 μm |
| Sentinel | 09/10/2016 | 10 | G = 0.56 μm<br>R = 0.66 μm<br>NIR = 0.84 μm |

$$e = \sqrt{(a1)^2 + (a2)^2} + E_{\mathrm{reg}} \tag{2}$$

where a1 is spatial resolution of image 1; $a2$ is spatial resolution of image 2 (base image) and $E_{\mathrm{reg}}$ is registration error of the image.

Therefore, the uncertainty for 1989 Landsat TM data can be estimated as follows;

$$e = \sqrt{(30)^2 + (10)^2} + 6 = 37.62\,\mathrm{m}$$

Similarly, the uncertainty was found as 22.03 m for Landsat ETM + PAN and 30.54 m for LISS III.

## Results and discussion

### Variation in retreating rate of the glacier

Monitoring changes in the snout terminus provides useful information for understanding the impact of various factors on glacial retreat (Kaser et al. 2003). Kinematic GPS survey along the glacier snout is an effective method for monitoring changes in the position of glacier terminus (Karpilo 2009). Comparison of mapped terminus positions of glacier tongue over different time periods provides a record of change in glacier length and area by processing the data, derived from the DGPS. Detailed analysis through the kinematic GPS survey indicates that the recession was maximum in frontal part of the glacier towards the northern side (129.57 ± 0.09 m) and minimum towards the southern side (88.56 ± 0.06 m) (see Fig. 4). This may be attributed to melting of the ice through tributary glacier meltwater (e.g., Raktavarna) at northern side of the snout. A similar retreating trend has also been reported by previous workers on the Gangotri and its tributary glacier (e.g., Chaturangi) (Kumar et al. 2008; Bisht et al. 2019). Based on the DGPS studies at different locations along the snout, we infer that the glacier was retreated by 102.57 ± 0.05 m from 2005 to 2015 (Table 2), and estimate that the frontal part of the glacier has been retreating at an average rate of 10.26 m/yr after 2005. Previous studies have revealed that the terminus area of glacier was reduced by 0.58 $\mathrm{km}^2$ (~ 0.01 $\mathrm{km}^2$/yr) between 1935 and 1996 (Srivastava 2004). The preceding observations on the recession of the glacier show varying rates in the last century (see Table 3). The wide variability in terminus retreat rate and mass balance of different glaciers in the Himalayan region are mainly due to topography and climate of the region (Dobhal et al. 2013). Venkatesh et al. (2012) and Pudelko et al. (2018) also suggested that the reduction in glacier extent vary with time depending on the dynamics of ice movement (controlled by length and slope of the glacier), size and type of the glacier. In the Gangotri glacier, a higher recession rate (38 m/yr) was recorded during 1975–1976 (Puri 1984), while the lower rate (10.16 m/yr) was observed during 1935–1956 (Jangpangi 1958). The Sonapani glacier in the Himachal Himalaya also show variable retreat rate during different time intervals from 1906 to 2016 (Majeed et al. 2020). Such variations

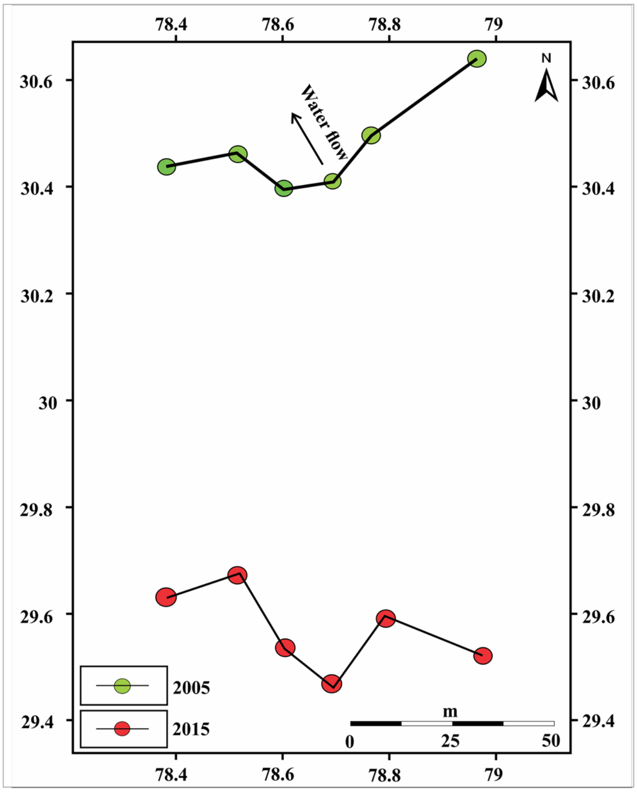

**Fig. 4** Retreating trend and total displacement of Gangotri glacier snout from 2005 to 2015 as obtained from DGPS derived coordinates

**Table 2** Position coordinates of GPS derived snout points in 2005 and 2015 for comparative study of average retreat rate of the glacier

| Year/points | X (North) (m) | Y (East) (m) | Position quality (cm) | Change in N (dX) (m) | Change in E (dY) (m) | Resultant change in position (m) |
|---|---|---|---|---|---|---|
| 2005-1 | 1038066.32 | 5380262.49 | 5.3 | − 34.86 | 84.03 | 90.97 ± 0.05 |
| 2015-1 | 1038031.46 | 5380346.52 | 0.94 | | | |
| 2005-2 | 1038054.9 | 5380266.2 | 6 | − 38.72 | 80.59 | 89.41 ± 0.06 |
| 2015-2 | 1038016.18 | 5380346.79 | 0.91 | | | |
| 2005-3 | 1038049.1 | 5380274.67 | 5.8 | − 39.55 | 88.3 | 96.75 ± 0.05 |
| 2015-3 | 1038009.55 | 5380362.97 | 1.23 | | | |
| 2005-4 | 1038055.6 | 5380279.14 | 1.4 | − 54.65 | 91.9 | 106.92 ± 0.01 |
| 2015-4 | 1038000.95 | 5380371.04 | 0.81 | | | |
| 2005-5 | 1038060.8 | 5380282.54 | 1.4 | − 68.66 | 75.19 | 101.82 ± 0.07 |
| 2015-5 | 1037992.14 | 5380357.73 | 7.24 | | | |
| 2005-6 | 1038072.3 | 5380289.3 | 9.1 | − 103.43 | 78.05 | 129.57 ± 0.09 |
| 2015-6 | 1037968.87 | 5380367.35 | 4.05 | | | |
| Mean | | | | − 56.64 | 83.01 | 102.57 ± 0.05 |

**Table 3** Recession rate in the Gangotri glacier as estimated by present study and earlier workers

| Period | Annual snout retreat (m) | References |
|---|---|---|
| 1935–1956 | 10.16 | Jangpangi (1958) |
| 1956–1971 | 27.33 | Vohra (1971) |
| 1971–1974 | 27.34 | Puri and Singh (1974) |
| 1974–1975 | 35.00 | Puri (1984) |
| 1975–1976 | 38.00 | Puri (1984) |
| 1976–1977 | 30.00 | Puri (1984) |
| 1977–1990 | 28.08 | Puri (1991) |
| 1990–1996 | 28.33 | Sangewar (1997) |
| 2004–2005 | 12.10 | Kumar et al. (2008) |
| 2005–2015 | 10.26 | Present study |

may correspond to changes in the climatic conditions and behavior of winter and summer monsoons (Thayyen and Gergan 2010; Dumka et al. 2013). In addition, the fluctuation in retreating rate through different time periods may also be due to low response time of large glaciers to the climate variability (Kulkarni 2007).

The results obtained from long term satellite imageries were used to determine the temporal changes in the snout position and retreating trend of the glacier from 1989 to 2016 (Fig. 5). The glacier retreat, computed during three different periods, viz., 1989–1999, 1999–2009 and 2009–2016 was observed as 267.56 ± 43.59 m, 215.84 ± 37.66 m and 102.22 ± 33.65 m respectively with a total recession of 585.62 ± 38.30 m (Table 4). Reconstruction of the past snout position and cumulative retreating trend clearly shows that the recession rate of the glacier was higher (26.75 ± 4.36 m/yr) during 1989–1999, and subsequently, consistently decreased during 1999–2009 (21.58 ± 3.77 m/yr) as well as from 2009 to 2016 (14.60 ± 4.81 m/yr) (Table 4). The snout retreat, measured by satellite data from 2009 to 2016, is more or less similar to the results derived by the DGPS during 2005–2015, indicating that the recession rate of Gangotri has been slowed down during the recent years. Bhattacharya et al. (2016) also reported decreased retreat rate during the recent years, compared to other debris covered glaciers in the Himalayan region. The Pindari glacier in Kumaun Himalaya also shows decreased recession from 1966 to 2007 (Bali et al. 2009). The satellite and ground based study carried out by Ali et al. (2019) also proves that the retreat rate of Pindari glacier has slowed down since 2010. Similarly, the Milam glacier has retreated at a rate of 9.54 m/yr after 2004 (Dumka et al. 2013), significantly slower than 30.32 m/yr from 1966 to 1997 (Shukla and Siddiqui (2001). Similarly, the Satopanth glacier which provides water to the Ganga basin, has receded at a rate of 22.86 m/yr before 2005 but slowed down to 6.5 m/yr in next years (Nainwal et al. 2008). Most evidently, a 70 km long Siachin glacier, too, has been in a steady state for the last several decades, with almost no retreat (Sinha and Shah 2008). Considering all this, we believe that the recession rate of many glaciers has slowed down in different parts of the Himalayan region.

## Relationship between meltwater discharge and glacier melt

The hourly data were used to obtain mean daily variation in meltwater discharge during the ablation season in year 2005 and 2015 (Fig. 6). The hydrograph pattern clearly shows an increasing trend of the meltwater discharge beginning from June, subsequently attains highest value around July and then gets decreased. In early part of the ablation season, the limb

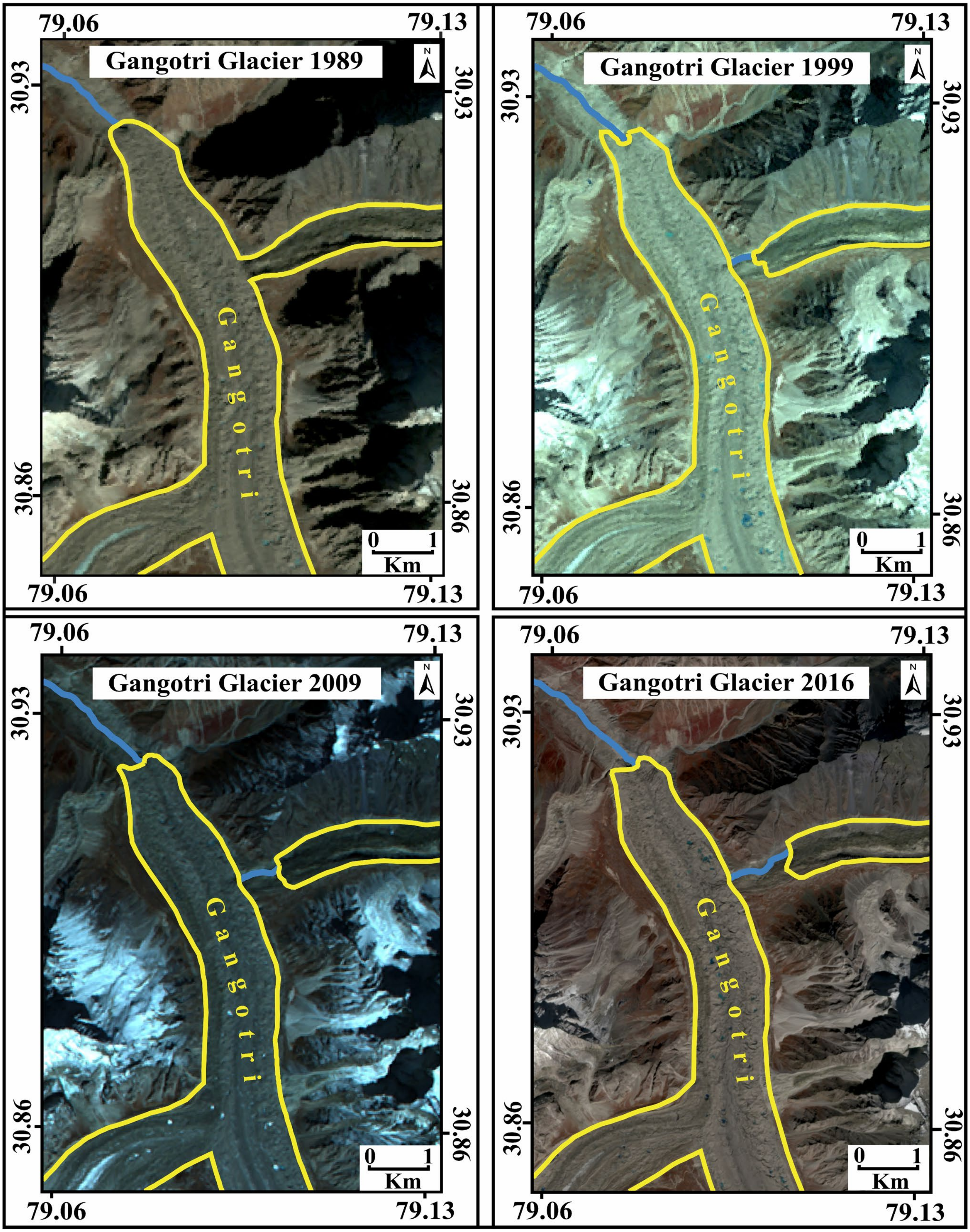

Fig. 5 Satellite images of Gangotri glacier with change in the position of the snout in 1989 **(a),** 1999 **(b),** 2009 **(c)** and 2016 **(d)**

**Table 4** Retreating rate of Gangotri glacier from 1989 to 2016 as estimated from remote sensing technique by using satellite data

| Time duration (years) | Total recession (m) | Retreating rate (m/yr) |
|---|---|---|
| 1989–1999 | 267.56 ± 43.59 | 26.75 ± 4.36 |
| 1999–2009 | 215.84 ± 37.66 | 21.58 ± 3.77 |
| 2009–2016 | 102.22 ± 33.65 | 14.60 ± 4.81 |
| Total | 585.62 ± 38.30 | |

of the hydrograph is almost flat (Fig. 6) showing no significant changes during early part of the ablation season because of less melting due to weak solar insolation (e.g., Singh et al. 2006). The discrepancy in the hydrographs in both the years may perhaps correspond to variation in precipitation pattern and extreme events such as Glacial Lake Outburst Flood (GLOF). The total meltwater discharge volume draining from the Gangotri glacier was calculated for entire ablation periods of 2005 and 2015 (Table 5). To establish a relationship between meltwater discharge and retreat rate, we have compared the discharge values and retreating rate with previous studies (Kumar et al. 2002, 2008; Tangri et al. 2004). The average meltwater discharge and retreating rate in 1999 ($565.87 \times 10^6$ m$^3$ and 25 m/yr) (Kumar et al. 2002; Tangri et al. 2004), 2000 ($479.32 \times 10^6$ m$^3$ and 17.15 m/yr) (Kumar et al. 2002, 2008), 2005 ($423.47 \times 10^6$ m$^3$ and 12.10 m/yr) (Kumar et al. 2008) and 2015 ($354.42 \times 10^6$ m$^3$ and 10.26 m/yr) show positive correlation ($r^2 = 0.95$) (Table 6). Thus we suggest that a consistent decrease in meltwater discharge during 1999, 2000, 2005 and 2015 is in agreement with decreasing trend of retreating rate during recent years.

**Table 5** The meltwater discharge volume draining from Gangotri glacier during entire ablation season in year 2005 and 2015

| Month | Meltwater discharge volume ($\times 10^6$ m$^3$) | |
|---|---|---|
| | 2005 | 2015 |
| May | – | 17.92 |
| June | 73.46 | 36.16 |
| July | 145.32 | 120.98 |
| August | 147.74 | 138.69 |
| September | 56.95 | 40.67 |
| Total | 423.47 | 354.42 |

## Impact of debris thickness variation in glacier melt

Due to vertical thinning, recession and movement of the glacier, enormous sediment load has been deposited on its surface from the valley walls. Also, along the margins of active tributary glacier (connected with the main trunk), the valley sides are scrapped and rock blocks are broken off into the ice and are carried away. This leads to undercutting of the valley sides and pave the ground for sliding, slumping and debris avalanching, bringing large quantity of rock-waste on top of the main glacier trunk. Some inactive tributary glaciers (detached from the main trunk), lying above the main glacier are also responsible for sediment transport on the glacier surface by meltwater streams. The physical weathering of rocks through frost-wedging is another phenomenon, responsible for deposition of the rocks on the glacier surface. To determine the influence of debris cover on surface melting of the glacier, 10 ablation stakes were emplaced on the glacier surface near snout. The results reveal that melting for

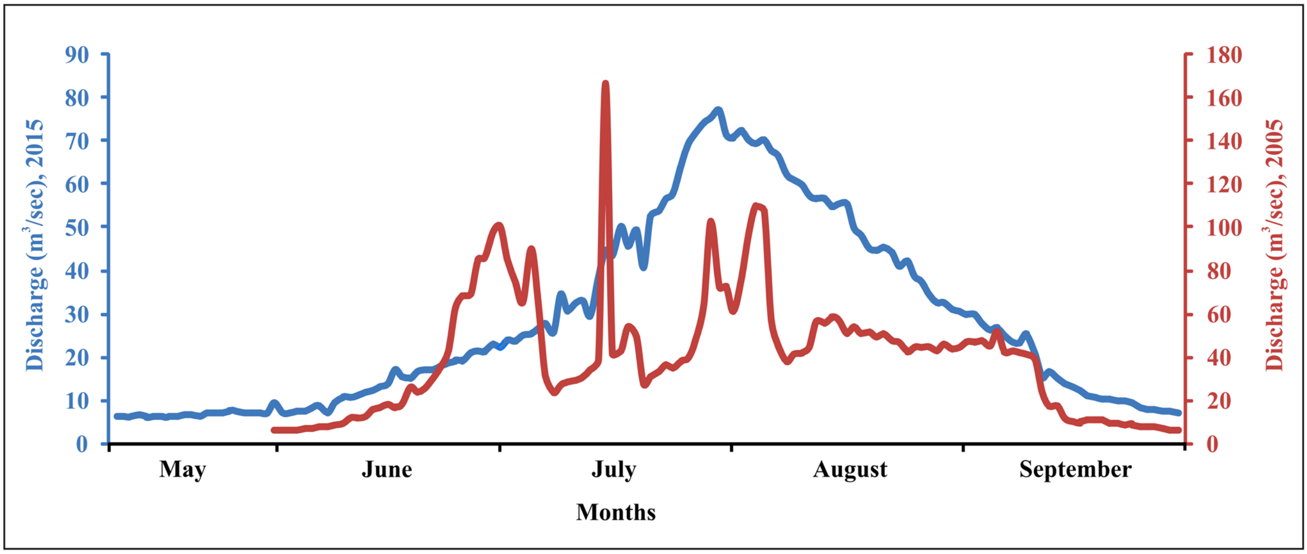

**Fig. 6** Hydrograph showing daily mean meltwater discharge draining from Gangotri glacier during the ablation period (2005 and 2015)

**Table 6** Retreating rate of Gangotri glacier and total discharge volume during ablation season of four different years

| Year | Discharge volume ($\times 10^6$ m$^3$) | Retreating rate (m/yr) | References |
|---|---|---|---|
| 1999 | 565.87 | 25 | Kumar et al. (2002); Tangri et al. (2004) |
| 2000 | 479.32 | 17.15 | Kumar et al. (2002); Kumar et al. (2008) |
| 2005 | 423.47 | 12.10 | Kumar et al. (2008); Present study |
| 2015 | 354.42 | 10.26 | Present study |

thick debris cover (55 cm) was minimum as 11.9 cm/month and maximum for thin debris cover (1 cm) as 20 cm/month (Fig. 7a), thus, the melting appears decreased significantly with increased debris thickness. Further, a strong correlation ($R^2 = 0.96$) was observed between debris thickness and surface melting of the glacier (Fig. 7b), indicating that both the parameters are inversely correlated with each other. A similar pattern between surface melting and debris thickness has been observed in the nearby Chorabari and Dokriani glaciers (Dobhal et al. 2013; Pratap et al. 2015). Dobhal et al. (2013) proposed that the Chorabari glacier has slower retreat compared to other non debris covered glacier, indicating that the influence of debris cover is mainly responsible for terminus retreat of the glacier. Xiang et al. (2018) further suggested that the debris covered glaciers shrink with lower rate than the debris free glaciers in the Central Himalaya. We suggest that high debris cover near tongue is a major factor for reduced recession of the Gangotri glacier. There are several debris covered glaciers, retreating at a relatively slower rate, such as Shankulpa (6.8 m/yr), Dunagiri (3.0 m/yr) and Bhagirathi Kharak (1.5 m/yr) (Swaroop et al. 2001; Raina and Srivastava 2008; Nainwal et al. 2008).

The retreating rate of the Chaturangi glacier (tributary glacier of Gangotri) was measured as 22.85 ± 0.05 m/yr during 2015–2016 (Bisht et al. 2019) and this indicates that the glaciers, although stretching out in the same valley do not respond homogeneously with change in prevailing weather conditions and the retreat also depends on the glacier characteristics and topography of the glacier valley (Singh et al. 2017). The geomorphological evidence (e.g., terminal and lateral moraines) in the study also supports the retreat and shrinking of glacier in the recent past. Therefore, repeated photography of snout is useful tool to document changes in the glacier terminus position (Karpilo 2009). To estimate change in the position of glacier snout, photographs of snout were taken (in year 2005 and 2015) and there seems a considerable change in the height and position of the snout (Fig. 3).

## Conclusion

We conclude that the retreating rate of Gangotri glacier has been comparatively more declined than shown by the previous studies. Our results also prove that the consistent decrease in meltwater discharge during recent years is positively correlated with decreased retreating rate of the glacier snout. Therefore, we conclude that a consistent decrease in meltwater discharge from 1999 to 2015 is in favor of decreasing trend of retreating rate during recent years. In addition, we believe that the high load of debris cover and isolated boulders on the surface of the glacier with passage of time is one of the major factors for reduction in retreating rate of the glacier, as high sediment load prevents the solar insolation that protects the ice to melt. It also has been documented in other glaciers of the Himalayan region (e.g., Swaroop et al. 2001; Raina and Srivastava 2008; Nainwal et al. 2008).

Most of the glacial activities were observed near the tongue and upper reaches and palaeo-glacial marks and other geomorphic evidences indicate the existence of glacier up to several km downstream from the present position of snout. Nevertheless, the retreating rate of Gangotri snout measured by satellite data from 2009 to 2016 is more or less similar with the result derived from the DGPS from 2005 to 2015, which also suggests that the rate of retreat has been slowed down during recent years.

Although the tough terrain and logistic problems hamper detailed glaciological studies on the Gangotri glacier, yet the extensive field surveys seem necessary as they provide more accurate results than the satellite imageries. This is because the rock debris, covering the glacier makes it more difficult to measure through satellite research. It is also felt that all the tributary glacier snouts of Gangotri glacier system may be studied to assess the retreat pattern of the whole Gangotri glacier system.

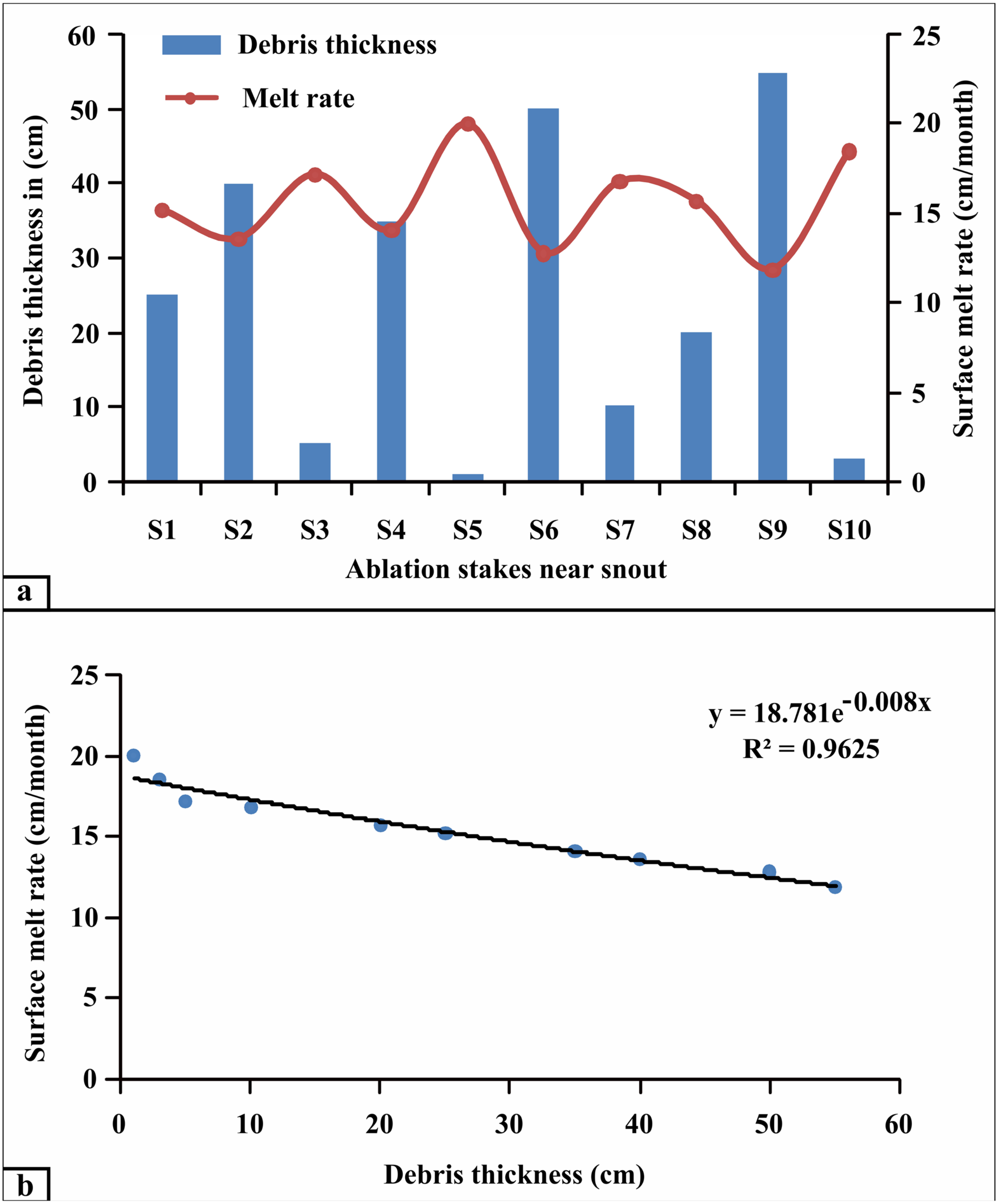

**Fig. 7** **a** Relationship between debris thickness and average surface melt rate of the glacier near snout during ablation season (May to September) in 2015, **b** exponential relationship between debris thickness and average monthly surface melting of the glacier

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