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Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high-resolution remote sensing data

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We report in this communication the length fluctuation and frontal area changes at the snout of Gangotri Glacier based on high-resolution satellite data from 1965 to 2006. Glacial outlines were mapped from de-

classified imageries from Corona (1965, 1968), Hexagon (1980) and Indian satellites IRS PAN (2001) and Cartosat-1 (2006). The results show that Gangotri Glacier exhibited retreat up to 819 ± 14 m and lost 0.41 ± 0.03 sq. km (~ 0.01 sq. km year⁻¹) at its front from 1965 to 2006. The retreat rates are lower than those previously reported using coarse-resolution remote sensing data and the Survey of India topography map. The results of the present study are supported by *in-situ* field survey conducted by the Geological Survey of India.

Keywords: Gangotri Glacier, remote sensing, retreat, satellite data.

GANGOTRI Glacier is the largest glacier (length ~ 30 km) in the Garhwal Himalayas. The Bhagirathi River originates from the snout (Gaumukh; ~ 3950 m asl) of Gangotri Glacier, which is the main source stream of Ganga River (Figure 1). Gangotri Glacier originates from the Chaukhamba group of peaks (~ 6853 – 7138 m asl) and flows northwest towards Gaumukh. About 29% of its total area is covered by debris¹. Gangotri Glacier is one of the well-documented and monitored glaciers in the Indian Himalayas as regards to its snout position. Auden² first systematically mapped the snout and geomorphic features of Gangotri Glacier in 1935 using a plane-table survey at a scale of 1 : 4800. Several scientists from GSI have resurveyed Gangotri Glacier and marked the position of the snout on Auden's plane-table map and measured its length in terms of retreat^{3–6}. Length records though are not the most significant parameter for glacier

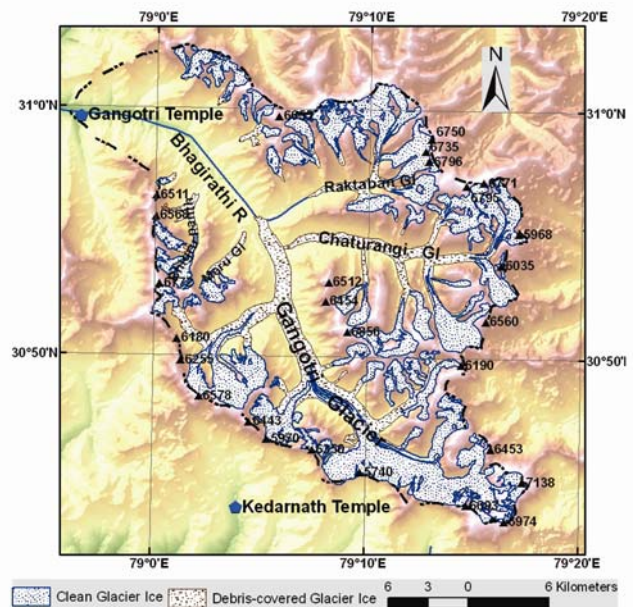


Figure 1. Gangotri Glacier with its tributary glaciers. Clean and debris-cover glacier outlines of Gangotri Glacier and tributary glaciers derived from Bhambri *et al.*¹.

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changes, are easy to measure, and are available for many glaciers around the world⁷. These records are useful to reconstruct glacier mass balance^{8,9}; estimate the glacier contribution to sea-level rise^{10,11}; historical equilibrium-line altitudes¹²; response times of glaciers^{13,14}, and global and hemispheric temperature¹⁵. In addition, several remote sensing-based studies have mapped Gangotri Glacier using various multi-temporal and multi-spectral satellite data and measured its linear retreat^{16–21} (Table 1). Among these studies, few have used Survey of India (SOI) topography maps^{17,18,20} or coarse-resolution satellite data¹⁹ (e.g. Landsat MSS with a spatial resolution of 79 m) to acquire older glacier extents (1960s and 1970s) for quantifying variability records of Gangotri Glacier. However, studies have shown examples of inaccuracies in SOI topographical maps^{22–26}. In addition, interpretation of debris-cover, shadow area and seasonal snow on satellite images is known to be one of the major challenges in glacier inventories and glacier change studies^{26–31}.

Declassified imagery (e.g. Corona and Hexagon) or aerial images from the 1960s and 1970s are ideal to map historic extents of glaciers^{30–35}, and can also be used for comparison with glacier outlines derived from old topography maps^{26,30}. These images are accessible from United States Geological Survey website (USGS; <http://edcns17.cr.usgs.gov/NewEarthExplorer/>). The Corona satellite orbit was near-polar and circular. However, the orbit inclination and equator crossing time were different for different missions³⁴. Therefore, there is no systematic coverage of the earth's surface. Generally, the inclination angle varied from 60° to 100° (measured from the equator)³⁴. However, to the best of our knowledge there have been no attempts earlier to measure length records of Gangotri Glacier from historic high-resolution Corona and Hexagon imageries. Thus, the main goals of the present study are: (1) to generate length records and area vacated by Gangotri Glacier at the snout from declassified imageries, and (2) to compare our results with the SOI topography map (1962) and previous remote sensing and field records.

We used two high-resolution Corona KH4A imageries for 24 September 1965 and 27 September 1968, and KH-9 Hexagon imagery for 8 September 1980 with minimal

snow to extract the historic extent of Gangotri Glacier (Table 2). In addition, orthorectified 2006 high-resolution Cartosat-1 and 2001 IRS-1C PAN images and 2006 ASTER DTM, generated for a previous study³¹ were used for the extraction of recent glacier outlines. The Cartosat-1 imagery was used as base image for rectification of older Corona and Hexagon imageries. These older imageries were co-registered based on a two-step approach: (i) a projective transformation was performed based on ground control points (GCPs) and the ASTER DTM using ERDAS Imagine 9.3, followed by (ii) a spline adjustment using ESRI ArcGIS 9.3 (refs 1, 30). For older declassified imageries between 30 and 50, GCPs were acquired from Cartosat-1 imagery for co-registration.

The glacier extents were manually delineated from panchromatic data of Corona, Hexagon, IRS PAN and Cartosat-1 imagery. For the calculation of length changes, stripes with 50 m distance were drawn parallel to the main flow direction of the glacier (Figure 2). Length change was calculated as the average length from the intersection of the stripes with the glacier outlines³⁶. Based on the outlines of the different years, the area vacated near the snout was also calculated. We also calculated length changes in terms of its retreat along the central flow line to be compared with results derived from average length from the intersection of the stripes with the glacier outlines. Geomorphic features such as gully talus and moraines presented by GSI studies^{2,37} in large-scale map were also mapped from 1968 Corona imagery (Figure 3). These moraines were dated using lichenometry³⁷.

Glacier outlines derived from various satellite datasets with different spatial resolutions, obtained at different times with varying snow cover, cloud and shadow conditions have different levels of accuracy. Thus, estimation of the uncertainty is crucial to know about the accuracy and significance of the results. The Spline method

Table 1. Retreat of Gangotri Glacier measured by various authors

Period	Retreat		Reference
	Total (m)	Mean rate per year (m)	
1935–1996	1220	20	6
1962–1999	1250	34	42
1935–1997	2500	40	45
1962–2000	1600	42	17
1985–2001	368	23	21
1962–2000	1510	40	18
1962–2006	1651	38	20

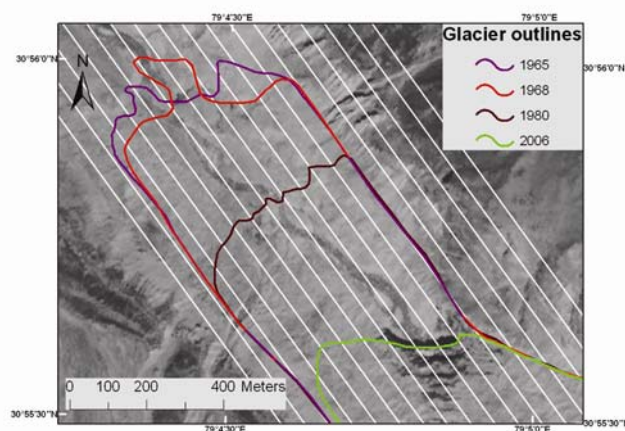
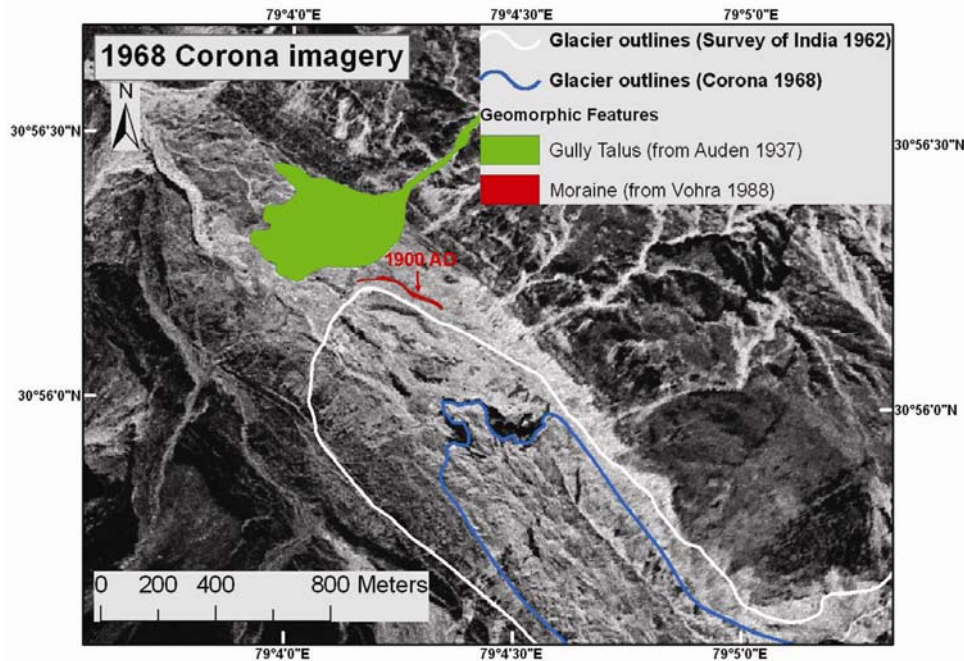


Figure 2. Glacier outlines derived from different satellite imageries and overlaid stripes with 50 m distance. The average retreat rates are derived from the intersection of the glacier outlines with the band of stripes.

Table 2. Details of satellite data used in the present study

Satellite data	Date of acquisition	Spatial resolution (m)	Scene/product ID	Planimetric accuracy
Corona KHA	24 September 1965	4	DS1024-1023DF117	± 5.2
Corona KHA	27 September 1968	4	DS1048-1134DF107	± 3.2
KH-9 Hexagon	08 September 1980	7	DZB1216-500329L007001	± 12.7
IRS PAN	26 October 2001	5.8	IRS1CDPSR1V4D090002600101	± 10.7
Cartosat-1	28 September 2006	2.5	097001100102	± 10

**Figure 3.** Geomorphic features demarcation on Corona imagery according to Auden² and Vohra³⁷ large-scale map.

provides a precise registration with a minor error¹. To assess the positional accuracy, 11 common geomorphic location points were identified on the base of Cartosat-1 and other Corona KH4A, KH-9 Hexagon and IRS-1C PAN satellite imageries²⁶. The horizontal shift between base Cartosat-1 and corresponding Corona (1965, 1968), Hexagon (1980) and IRS PAN (2001) imageries was found to be 5.2, 3.2, 12.7 and 10.7 m respectively (Table 2). The uncertainty was calculated from the following formula for multi-temporal measures of the glacier front position using satellite images³⁸.

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

where $a1$ is the pixel resolution of imagery 1, $a2$ the pixel resolution of imagery 2 and E_{reg} is the registration error.

Hence, the uncertainty can be estimated in case of the 1965 Corona imagery as follows:

$$e = \sqrt{[(4)^2 + (2.5)^2]} + 5.2 = 10 \text{ m.}$$

The uncertainty was 8 m for Corona (1968), 20 m for Hexagon (1980) and 17 m for IRS PAN imagery

(2001). The uncertainty for glacial area was estimated by multiplication of the uncertainty of length with glacier width.

Our results show that Gangotri Glacier retreated 819 ± 14 m from 1965 to 2006 (Table 3). On an average, Gangotri Glacier retreated at the rate of 5.9 ± 4.2 m/year from 1965 to 1968 and 26.9 ± 1.8 m/year from 1968 to 1980, and it retreated 21.0 ± 1.2 m/year between 1980 and 2001. The recession rate declined during 2001–2006 and it receded at a rate of 7.0 ± 4.0 m/year. Earlier studies on the recession of Gangotri Glacier using topography map and satellite data show higher estimation of recession than our assessments. For instance, one study²⁰ estimated 1651 m or an average 38 m/year retreat rate of Gangotri Glacier based on the 1962 topography map and 2006 ASTER imagery. Similarly, other studies^{17,18} reported about 1600 and 1510 m recession of Gangotri Glacier at its front from 1962 to 2000 respectively. All these estimations are almost twice as high as our results (1965–2006). However various studies^{18,20} show that the glacier outline derived from the SOI topography map (1962) covers an area near the moraine dated AD 1900 by Vohra³⁷ up to the gully talus^{2,37} (Figure 3). This indicates that higher retreat of Gangotri Glacier is probably

Table 3. Total and average recession of Gangotri Glacier length

Period	Total retreat (m)	Rate of retreat (m/year)	Total length change (m) along the central flow line
1965–1968	-17.7 ± 12.8	-5.9 ± 4.2	+77 ± 12.8
1968–1980	-323.2 ± 21.5	-26.9 ± 1.8	-465 ± 21.5
1980–2001	-441.0 ± 26.2	-21.0 ± 1.2	-537 ± 26.2
2001–2006	-37.0 ± 20	-7.4 ± 4	-6 ± 20
Total	-818.9 ± 14	-19.9 ± 0.3	-1085 ± 14

Table 4. Total and average area vacated near Gangotri Glacier snout

Year	Total area vacated at snout (10 ³ m ²)	Average area vacated at snout (10 ³ m ² /year)
1965–1968	22.9 ± 6.0	7.6 ± 2.0
1968–1980	163.9 ± 10.1	13.7 ± 0.8
1980–2001	215.4 ± 12.3	10.2 ± 0.5
2001–2006	16.39 ± 9.4	3.2 ± 1.8
Total (1965–2006)	418.5 ± 37.8	10.2 ± 0.9

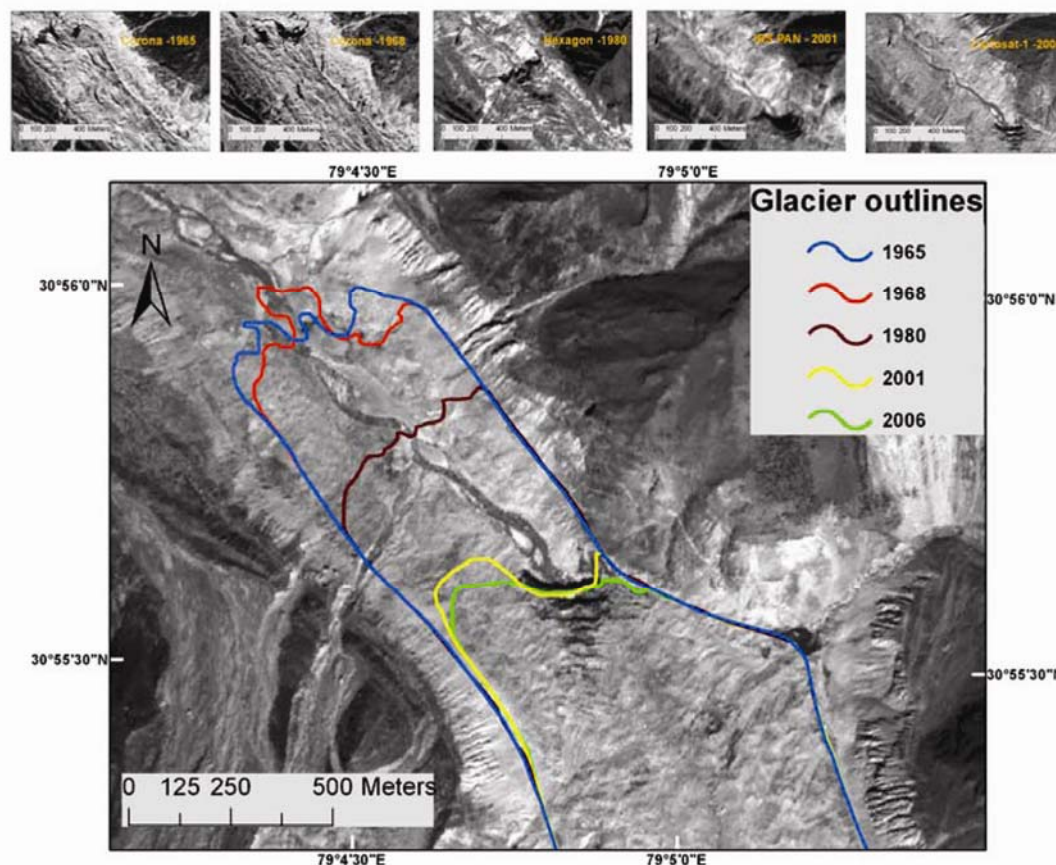


Figure 4. Glacier outlines derived from different high-resolution satellite data overlaid on Cartosat 1 (2006) imagery.

associated with the overestimated delineation of the glacier outline on SOI map. We also calculated the recession of Gangotri Glacier as shown in the satellite imagery by Kargel *et al.*³⁹. The older terminus positions shown by Kargel *et al.*³⁹ in satellite imagery are based on

lichnometry^{37,40}. A retreat of ~ 1444 m from 1935 to 2006 (~ 20.3 m/year) was calculated by Kargel *et al.*³⁹ along the Bhagirathi River, whereas a GSI study⁶ suggests that Gangotri Glacier retreated by ~ 1220 m between 1935 and 1996, which amounts to an average rate of ~ 20 m/year.

We found that Gangotri Glacier receded about 764 ± 19 m between 1968 and 2001 (23.2 ± 0.6 m/year), whereas the field-based GSI study⁶ showed that its lost about 720 m length from 1971 to 1996 (~ 28.8 m/year). Previous remote-sensing studies^{17,18,20} calculated the retreat along the central flow line or more or less along the Bhagirathi River. Our results based on the average length from the intersection of the stripes with the glacier outlines reveal that Gangotri Glacier receded 819 ± 14 m from 1965 to 2006, whereas recession along the central flow line would be 1085 ± 14 m. These results show similar tendencies, but the measure based on one point of the glacier only may overestimate the recession and is more susceptible to outliers. The averaging along the front is a more robust method and provides more reliable estimations, especially in the situation of a change in location of the ice caves (Table 3).

The present study shows that Gangotri Glacier lost 0.41 ± 0.03 sq. km (~ 0.01 sq. km year⁻¹) area between 1965 and 2006 from its front (Table 4). These results are supported by *in-situ* field surveys conducted by GSI⁶. The GSI results indicate that Gangotri Glacier reduced its area at its terminus by 0.58 sq. km (~ 0.01 sq. km year⁻¹) between 1935 and 1996 (ref. 6). In addition, Auden² noticed a single ice cave at the left side of Gangotri Glacier snout. Another GSI study³ reported two caves one small and one large, on the terminus of Gangotri Glacier in 1956. Furthermore, one more field-based photographic evidence shows that the ice near and between the two tunnels of Gangotri Glacier was vertically banded as a result of the flow structure imposed on the glacier where it had reunited after its bifurcation immediately upstream by a rock barrier⁴¹. Another study⁴ noticed only a single large cave on the right fringe of the snout during 1967. However, after 1956, the larger and prominent ice cave had been considered for the recession studies^{4,6}. Shadows of ice caves on the 1965 and 1968 Corona satellite image-ries suggest the existence of two caves at the terminus of Gangotri Glacier (Figure 4). This indicates that high-resolution satellite data provide more reliable results in comparison with previous studies^{17,18,20} based on coarser-resolution satellite data such as Landsat MSS and TM, and/or topography maps. We found slight advancement of the middle part at the terminus of Gangotri Glacier during 1968, which is probably concerned with deposition of ice block of the snout after its disintegration. This natural process was reported by an earlier study⁴². Our results suggest that in recent times (2001–2006) Gangotri Glacier has lost few square metres of the area, which has also been reported by prior field-based studies²⁵. Frontal recession of Gangotri Glacier has shown variability in the amount, rate and time of occurrence during the study period. From 2001 to 2006, the recession of Gangotri Glacier has declined compared to the previous observation during the study period. However, it does not imply that Gangotri Glacier recession has ceased as length changes

show only the indirect and delayed response of a glacier to climate change, in contrast to glacier mass balance. The response time of the large debris-covered Gangotri Glacier is likely to be much longer than that of smaller glaciers in the Garhwal region⁴³. Thus the study of mass balance is needed for precise knowledge of glacier health. However, *in situ* measurements over the entire glacier are logistically difficult and hence not feasible owing to its size and characteristics. The geodetic approach using the presented Corona data⁴⁴ could be a more suitable substitute as well as cost-effective method. Moreover, topographic parameters such as elevation range, aspect as well as glacier size, shape, motion, thickness and distribution of debris-covered area, contribution of tributary glaciers to the accumulation and the local topography influence glacier response, which need to be addressed in further studies.

The main challenges with the Corona data are the complex image geometry and the absence of satellite camera specifications. The positional accuracy of the rectified Corona imagery can be evaluated based on common unchanged location points. We have only addressed the length and frontal glacial area changes measured through the snout position on satellite image-ries for different years. The uncertainty is negligible for the small area, but is usually higher when addressing a larger area. The Corona data are useful for providing insight into glacier changes since the 1960s, and the above mentioned field studies^{5,6} corroborate our results for Gangotri Glacier. Suitable declassified images are also available for many glaciers of other remote mountain areas where no aerial images are available or accessible.

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