Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India

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Dokriani glacier is one of the well-developed, medium-sized (7.0 km^2) valley glaciers of Gangotri group of glaciers in the Garhwal Himalaya. The glacier was originally mapped in 1962–63 and was remapped in 1995 by the Survey of India. The snout, surface area and elevation changes were determined by a comparison of these two topographic maps and fieldwork. The glacier shows rapid frontal recession, substantial thinning at the lower elevation and reduction of glacier area and volume. Between 1962 and 1995, glacier volume is estimated to have been reduce by about 20% and frontal area had vacated by 10%. The study revealed that during the period 1962–1995 the glacier has receded by 550 m with an average rate of 16.6 m/yr. However, the yearly monitoring of snout position of the glacier during 1991–1995 revealed an average rate of recession of 17.4 m/yr and has vacated an area of 3957 m^2.

GLACIERS are dynamic and fragile ice bodies on the landscape and are products of the climate and climatic changes. Change in climate is clearly reflected in mass and temperature changes of glaciers. Hence the perennial land ice bodies are considered the key for climate system studies[1,2]. Glacier advancement and recession are the most significant evidences of change in glacier geometry. Shifting of snout position of glacier as a response to climatic changes is the best indicator of glacier advancement and recession over a period of a few years or decades. The change in snout position varies for different glaciers and processes are rather irregular in amount, rate and time of occurrence. It is important to monitor the glaciers routinely to evaluate the changes that occurred in the ice mass, surface area and its geometry. Mass balance and snout fluctuation are often determined by traditional stake method over a period of a few years or decades. In the Himalaya there are only a few glaciers, which are being symmetrically monitored for snout recession. The earlier geometrical records of these glaciers are available only in the Survey of India toposheets. A comparison of an earlier map and a recent map gives the average changes that occurred in the glacier during the period. The fluctuation records of Himalayan glaciers are only 150 years old. Mayeswki and Jeschke[3] studied 122 glaciers of the Himalaya and Karakoram regions and concluded that most of them are retreating. Many significant studies on the recession of the Himalayan glaciers have also been made[4–9]. In the present study an attempt has been made to evaluate the changes in glacier snout position, surface area, elevation and ice mass of Dokriani glacier during the period of 1962–95.

Dokriani glacier (30°49′ to 30°52′N and 78°47′ to 78°51′E) is one of the well-developed, medium-sized glaciers of the Bhagirathi river basin in Garhwal Himalaya. It originates from Draupadi ka Danda group of peaks at an elevation of 6000 m amsl and is formed by two cirque glaciers. The glacier follows NNW direction for about 2 km before it turns towards WSW and terminates at an altitude of 3886 m (Figure 1). The length of the glacier is 5.5 km with a width varying from 0.08 to 2.5 km. The total catchment area is 15.7 km^2, with the glacier ice covering an area of 7.0 km^2. The thickness of glacier ice varies from 25 to 120 m between snout and accumulation zone; its average thickness is 50 m[10]. The

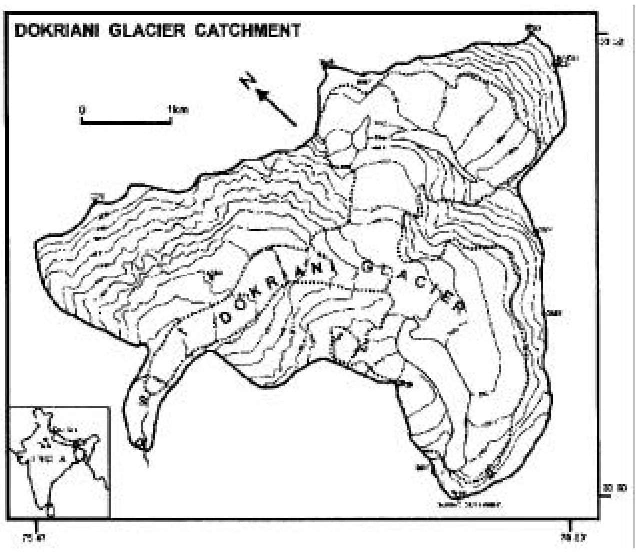

Figure 1. Location map of Dokriani glacier.

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lower reaches of the ablation zone are covered by debris, while the lateral moraines exist all the way along the glacier up to the accumulation zone. The glacier valley is deep bounded by freestanding morainic ridge, which suggests shrinkage in the glacier size from the past. The melt-water stream emerging from the glacier is known as Din Gad and joins river Bhagirathi at Bhukki.

Methodology

The earlier record of Dokriani glacier is available in the Survey of India map (1962 edn.) on a scale of 1 : 50,000. The glacier has been remapped by the Survey of India in 1995 on a scale of 1 : 10000 and 1 : 25,000 under the Himalayan glaciology programme coordinated by Department of Science and Technology, Govt. of India. The co-ordinates (grid value) snout position obtained from the Survey of India toposheet (1962–63) was subtracted from the value obtained from the 1995 survey map to calculate the total retreat of the snout during the period. The area vacated by the glacier due to recession is estimated by superimposing the earlier map on the recent map. The change in glacier geometry, surface elevation and volume during the period was obtained by a comparison of the topographic map of 1962 and 1995. The surface elevation was calculated by profiling the distance between the pair of contours along the centreline. Volume change during the period was calculated by preparing area-average thickness map of both the survey years. The average thickness and volume of the glacier in 1962 was determined from the surface slopes[11]. The volume calculation in 1995 is aided by GPR thickness profiling of the glacier[10]. For regular monitoring of the glacier snout position and frontal area vacated by the glacier, a network of stakes at the centre, left and right margins of the snout has been made in 1991. These stakes were measured yearly (fixed date) by Electronic Distant Meter (EDM) survey techniques to calculate the annual snout recession.

Results

Snout retreat

In order to study the total snout recession of Dokriani glacier during the period of investigation, three sets of data were obtained: (i) total recession between 1962 and 1991 was obtained as 480 m, with an average rate of 16.5m/yr; (ii) comparison of snout position from the maps of 1962 and 1995 showed that the snout retreated by 550 m during the period calculated with an average rate of 16.6 m/yr; (iii) field observation carried out during the period 1991–95 showed that the glacier has receded by about 69.9 m with an average rate of 17.4 m/yr (Figure 2, Table 1). The study reveals that the snout of the glacier is continuously retreating and the annual rate increased slightly. Overall average rate calculated during the period 1962–95 (Table 1) is 16.6 m/yr; however, the present study (1991–95) reveals that the snout recession rate has increased by 1 m/yr. This increasing recession rate is probably attributed to the effect of global warming. The progressive recession of Dokriani glacier snout indicates that it has undergone marked changes in shape and position.

Area vacated

The area vacated by the glacier was estimated from the Survey of India maps of 1962 and 1995. The total area vacated by the glacier is nearly 0.78 km^2; out of this 77561.3 m^2 was frontal recession during the last 33 years at an average rate of 2350.34 m^2/yr, and the remaining

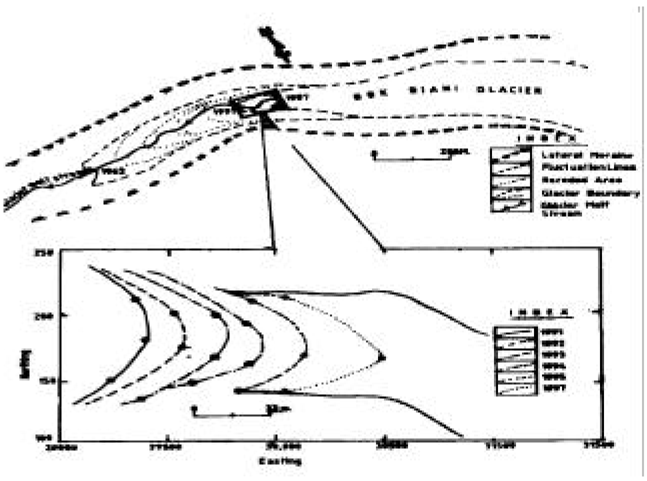

Figure 2. Snout recession of Dokriani glacier during 1962–95.

Table 1. Snout recession of Dokriani glacier during the period 1962–95

Period	Recession (m)	No. of years	Average recession (m)	Frontal area vacant (m^2)	Altitude (m)
1962–91	480.1	29	16.5	73604.3	3868.2
1962–95	550.0	33	16.6	77561.3	3882.0
1991–92	016.2	01	16.2	968.0	3870.0
1992–93	016.5	01	16.5	1187.0	3877.4
1993–94	018.5	01	18.5	818.0	3879.0
1994–95	018.7	01	18.7	984.0	3882.2
1991–95	69.9	04	17.4	3957.0	–

area vacated in the main glacier ice body and adjoining areas of the glaciated region. During 1991–1995, the glacier snout has vacated an area of 3957 m^2 with an average rate of 998.25 m^2/yr. The area vacated by the glacier in its proglacial region during each period has been computed (Table 1). The relationship between the two parameters, viz. ice snout retreat and frontal area vacated by the glacier, clearly indicates that the area vacated by the glacier has not always similar to rise and fall in the rate of snout retreat. This phenomenon may be due geometrical readjustment of snout position after its recession. Such a phenomenon is also observed in others glaciers of the adjoining areas[8,9,12,13].

Surface elevation changes

The surface elevation changes between 1962 and 1995 have been determined by elevation profiling along the centerline of the glacier (Figure 3). The glacier surface shows significant elevation changes with a maximum of 90 m in the lower reaches (3900–4200 m), while in the accumulation zone (5200–5400 m) the glacier has increased surface elevation by 20 m. However, between 4400 and 4600 m, significant elevation changes and area vacation were observed, which resulted in steep surface slope and reduced width of the glacier. Due to the continuous lowering of glacier surface and rapid rate of lateral recession drastic increase in the surface slope occurred in the lower reaches, while in the accumulation zone the surface slope decreased and the area became more flattened (Figure 4). The snout elevation has also changed its position from 3810 m (1962) to 3882.2 m (1995).

Mass/volume changes

The calculated average ice thickness of Dokriani glacier was 55 m in 1962 and 50 m in 1995, and the corresponding glacier ice volume was 385.11×10^6 m^3 and 315.0×10^6 m^3 of water equivalent respectively. The approximate reduction of the glacier ice volume between the period 1962 and 1995 is estimated as (–) 70.11×10^6 m^3 (water equivalent). The annual mass balance study during 1992–95 shows negative mass balance, which is (–) 1.54×10^6 m^3 (1992–93); (–) 1.58×10^6 m^3 (1993–94) and (–) 2.17×10^6 m^3 (1994–95) of water equivalent with an average rate of (–) 0.28 ma^{-1} (ref. 14). The results show that the present trend of mass balance is moderately negative and increased from the previous years.

The overall geometrical changes that occurred during the period 1962–95 show the significant evolution in the Dokriani glacier (Table 2).

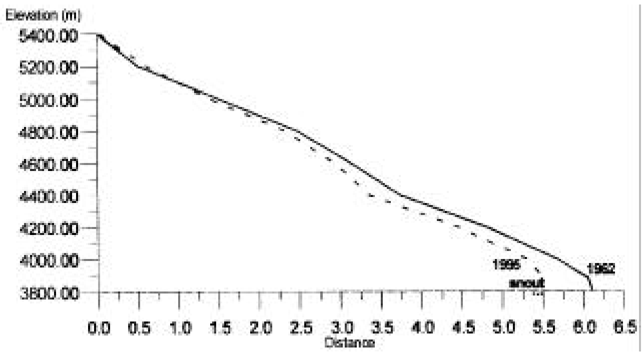

Figure 3. Surface elevation profiles along the centreline of Dokriani glacier in 1962 (solid line) and 1995 (broken line).

Discussion

It is a well-established fact that glaciers are in recessional phase worldwide. However, enhanced recession rates of glaciers during the recent past initiated widespread discussions on global warming and its effects on the cryosphere. Himalayan glaciers also follow the same trend. However, the rate of recession and amount of volume change are irregular for glaciers across the Himalayan arc mainly because of climatological and topographic factors. Out of 917 glaciers in the Garhwal Himalaya, only a few of them were monitored for recession (Table 3). A comprehensive understanding of morphogeometrical changes is needed.

Recession of Dokriani glacier during 1962–95 (33 years) was 550 m (Figure 5). Yearly observation of glacier recession during 1991–95 (Figures 2, 6 *a* and *b*) clearly shows that the rate was accelerated during the

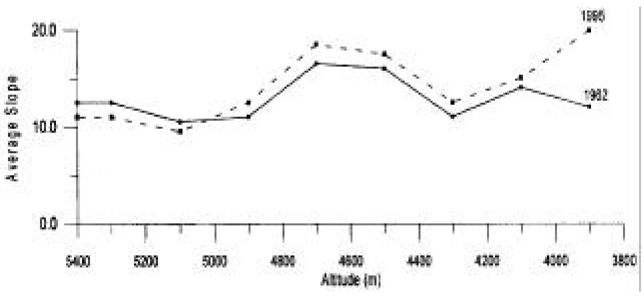

Figure 4. Average slope changes between 1962 and 1995 along the central line.

Table 2. Morphogeometrical changes in Dokriani Bamak glacier from 1962 to 1995

Parameter	1962	1995
Glacierized area (km^2)	11.17	10.20
Glacier area (km^2)	7.78	7.00
Accumulation area (km^2)	–	04.84
Ablation area (km^2)	–	02.16
Glacier length (km)	6.0	5.5
Snout position (m)	3810	3882
ELA (m)	–	4995
Elevation range (m)	3800–6000	3900–6000
Average thickness (m)	55	50
Surface slope (°)	11	12
Ice volume (water equivalent) (m^3)	$385.11.8 \times 10^6$	315.0×10^6

period. This four-year period witnessed a recession of 69.9 m with an average rate of 17.4 m/yr compared to 16.5 m/yr during 1962–91 (Table 1). Snout recession studies are capable of providing only partial information regarding the volumetric and geometrical changes happening to the glacier during a recessional phase. Moreover, studying horizontal and vertical shrinkage of valley glaciers can derive a comprehensive understanding of glacier behaviour. Area vacated by glacier along its frontal and lateral margins plays a major role in sediment transfer from glacierized basins due to its potential for enhancing the erosion. During the last 33 years, Dokriani glacier has vacated a total of 0.78 km^2 along its frontal and lateral margins. Out of which total area vacated 0.077 km^2 is its frontal portion, which amounts to only 10% of the total vacated area of the glacier and the remaining vacated area is occupied by lateral margin of the glacier valley. This reveals that the lateral recession plays a more important role in depletion of glacier than the frontal recession. Frontal area recession between 1991 and 1995 alone accounted for 3957 m^2, however, lateral

Table 3. Recession of glaciers in Garhwal–Kumaon Himalaya (after refs 5, 16 and 17)

Glacier	Period of measurement	Period (years)	Recession (m)	Average rate (m/yr)
Milam glacier	1849–1957	108	1350	12.50
Pindari glacier	1845–1966	121	2840	23.40
Arwa glacier	1932–56	24	198	8.30
Gangotri glacier	1962–91	29	580	20.00
	1990–99	10	190	19.00
Tipra bank glacier	1960–86	26	325	12.50
Dokriani glacier*	1962–95	33	550	16.67

area recession of the glacier has not been calculated for the period 1991–95, as it needs detailed mapping of the glacier.

The vertical shrinkage of the glacier is a major factor contributing to the reduction of glacier ice volume. Average ice thickness of Dokriani glacier in 1962 was ca. 55 m and the total volume of water storage in the form of glacier ice was 385.11×10^6 m^3. It was found that in 1995 the average ice thickness had reduced to 50 m and storage volume was calculated to be 315.0×10^6 m^3. The total loss in glacier ice volume was (–) 70.11×10^6 m^3 during the period of 33 years. Observation by stakes measurement over the glacier surface established for mass balance studies during 1992–95 (ref. 14) showed that the glacier has continuous negative balance on an average of (–) 1.62×106 m^3/yr (w.eqn). A recent study on ablation accumulation pattern shows that the annual ablation rate recorded 3 to 3.5 m/yr, while average accumulation rate is 0.45 m/yr. The radioisotopic study of shallow ice core of Dokriani glacier also supports the low rate of accumulation and has been calculated as 0.43 ma^{-1} (ref. 15). The low accumulation rate over the Dokriani glacier during the period may be one of the factors of negative balance. The present enhanced rate of ice mass depletion by 0.28 ma^{-1} indicates more discharge, more suspended load and changes in ice volume will also result in changing in the length, width, surface slope of the glacier in the coming years.

The profound melting observed at the glacier surface resulted in significant elevation changes all over the glacier. As expected, a high degree of variability is observed in the elevation changes, which is directly related to the altitude. Maximum changes in elevation of 90 m was

Figure 5. Panoramic view of Dokriani glacier showing the recession between 1962 and 1995. A snow/ice melt stream emerges from the glacier snout called Dingad. In the background, glacier ablation area is covered with debris and bounded by standing lateral moraines. Further back a snow/ice blanket with horn, pyramidal peaks and small snow avalanch paths feeding to glacier.

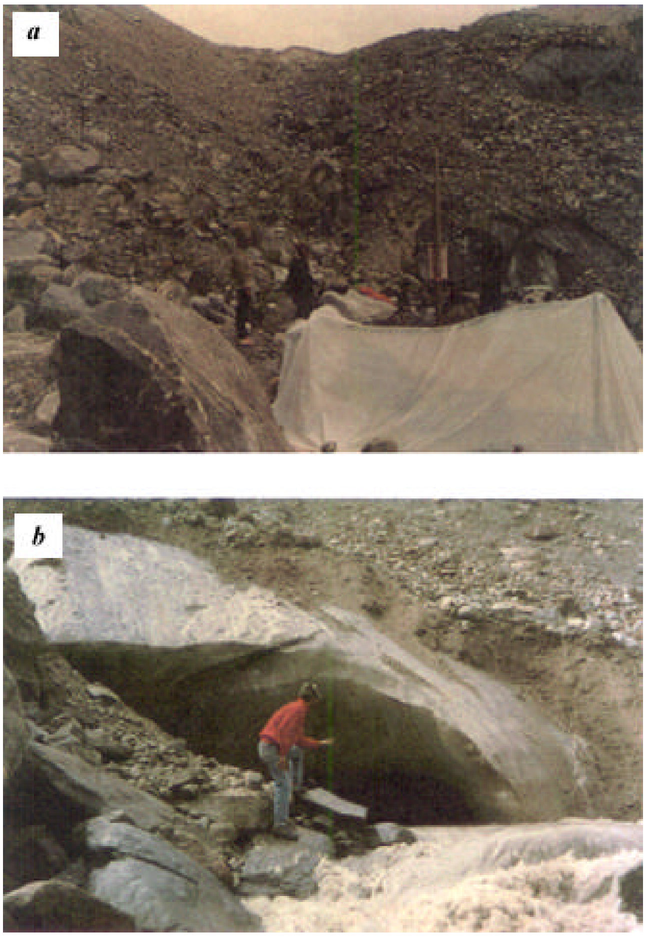

Figure 6. View of snout positions of Dokriani glacier in 1991 (***a***) and 1995 (***b***).

observed at the lower reaches (4400–4600 m), while the upper reaches (5200–5400 m) comprising the accumulation zone, experienced 20 m increase in surface elevation (Figure 3). Significantly, average surface slope of the glacier increased from 11° in 1962 to 12° in 1995. The snout of the glacier elevated from its position of 3810 m in 1962 to 3882 m in 1995. Such types of study can be done in other glaciers of the Himalayas for a comprehensive understanding of glacier ice mass behaviours, changes in geometry and effect of global warming on the glaciers.

Conclusion

Snout recession of the Dokriani glacier from 1962 to 1995 was 550 m, with an enhanced recession rate of 17.4 m/yr during 1991–95. Shrinkage of glacier is more pronounced on the lateral margin. During the period 1962–95, the area vacated by the frontal recession of the glacier was only 10% of the total area vacated by the glacier. Average glacier ice thickness reduced to 50 m in 1995 from 55 m in 1962 and glacier ice volume reduced by 70.11×10^6 m^3 during the period. Considerable increase in water loss was noticed during the 1992–95 ablation period. Lower reaches of the glacier experienced 90 m reduction in surface elevation, while 20 m increase was recorded at the accumulation zone.

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