Morphometric control on glacier area changes in the Great Himalayan Range, Jammu and Kashmir, India

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We have utilized satellite images of 1975 and 2001 to reveal the slow response of glaciers to climatic warming in the Great Himalayan Range, Jammu and Kashmir, India. Correlation of various glacier morphometric parameters with reference to glacier area change and shift in the snout position revealed that morphometric parameters exert prime control on area changes over glaciers, but do not have much control on the snout retreat or advancement of glaciers. The snout of glaciers which possess low relief may witness more retreat and vice versa. Percentage of area loss was higher over smaller glaciers indicating significant sensitivity of smaller glaciers to area changes.

Keywords: Glaciers, morphometric parameters, remote sensing, snout retreat.

HIMALAYA, the youngest mountain system in the earth, has 17% of its area covered by glaciers and influences the climate, regional hydrology and environment of our subcontinent[1]. Most glaciers in the Himalayan region are retreating due to accelerated global warming during the last century causing long-term loss of natural freshwater storage[2–4]. In contrast, a decrease in summer run-off by 20% in the Hunza and Shyock rivers in the Karakoram and Hindukush mountains was linked to 1°C fall in mean summer temperature since 1961. This was also related with the observed thickening and expansion of the Karakoram glacier (western Himalaya), in contrast to widespread decay and retreat of glaciers in the eastern Himalaya[5]. The contrasting response of the glaciers to climate change in the Zanskar valley, Jammu and Kashmir (J&K), India has been evaluated in a few studies[6–9]. Glacier change studies attempted on 13 select glaciers in parts of the Zanskar valley using Survey of India (SOI) topographic maps of 1962 and satellite images of IRS-1C LISS-III of 2001 indicated 18.16% glacier area loss during this period, with retreat rate varying from 6 to 33 m/yr (ref. 10). Glacier changes examined over 35 glaciers in parts of the Great Himalayan Range (GHR), Ladakh, J&K using multi-temporal satellite images of 1975, 1989, 2001 and 2007 indicated maximum glacier area loss percentage as well as increase in retreat rate during 1989–2001 (ref. 8). A glacier system is influenced by many factors such as climatic, topographic and glacier supplying conditions[11–13]. In order to quantify glacier changes, it is necessary to collect information in terms of glacier size, elevation distribution, exposition and other properties[14]. Wang *et al.*[13] attempted an inventory of 44 glacier systems in China and classified them according to their sensitivities to climate warming. Snout retreats are commonly associated with short to medium length glaciers (< 30 km), whereas snout advances are related to flow direction[15]. Susceptibility of 1105 glaciers to deglaciation processes in the Indian Himalaya was discussed under the present climate change based on morphometric characteristics[16]. Less retreat of the Gangotri glacier (19 m/yr) in the Garhwal Himalaya was attributed to its wider snout (1.50 km)[17], whereas advancement of the Chota Shigri glacier, Himachal Himalaya during 1987–89, was related to prolonged snow periods[18]. Many researchers have attempted the computation of glacier retreat in different parts of the Himalaya based on topographical maps and satellite images[19–21]. Glacier retreat computations attempted in the Himalaya utilizing SOI topographic maps are not precise in some instances[22]. Therefore, in the present work we have utilized satellite imageries for mapping 34 selected glaciers in GHR for computation of area change and snout retreat during the period from 1975 to 2001. Attempts were also made to assess the control of morphometric parameters of each glacier on its retreat/advancement and area shrinkage/growth. Various glacier morphometric parameters like length, snout width, area, perimeter, snout altitude and altitudinal range were derived based on glacier mapping using IRS-1C LISS-III satellite image of 2001.

The study area covers 5000 sq. km in a part of GHR. The area extends between 32°59′N and 33°55′N lat. and 76°15′E and 77°15′E long., with elevation ranging from 3070 to 6400 m asl (Figure 1). Glaciers of various dimensions are present on both the northern and southern aspects in the study area. Satellite data of IRS-1C LISS III (acquired in August 2001) and LANDSAT MSS (acquired in October 1975) along with elevation data from ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer), GDEM (Global Digital Elevation Map) with spatial resolution of 30 m were used in the present study.

Satellite images of the area were registered with reference to the SOI topographic map to bring the satellite image to real-world coordinates using Erdas Imagine, 8.6. UTM projection system was followed using WGS-84 datum. For proper registration, 30 well-distributed ground control points (GCPs; Figure 1) such as bends, junctions of rivers, etc. were selected. Additional GCPs were collected using DGPS during the field study. The study area was extracted from IRS-1C LISS III and LANDSAT MSS satellite data for mapping glacier boundaries during the periods of their acquisition. The adequate spatial

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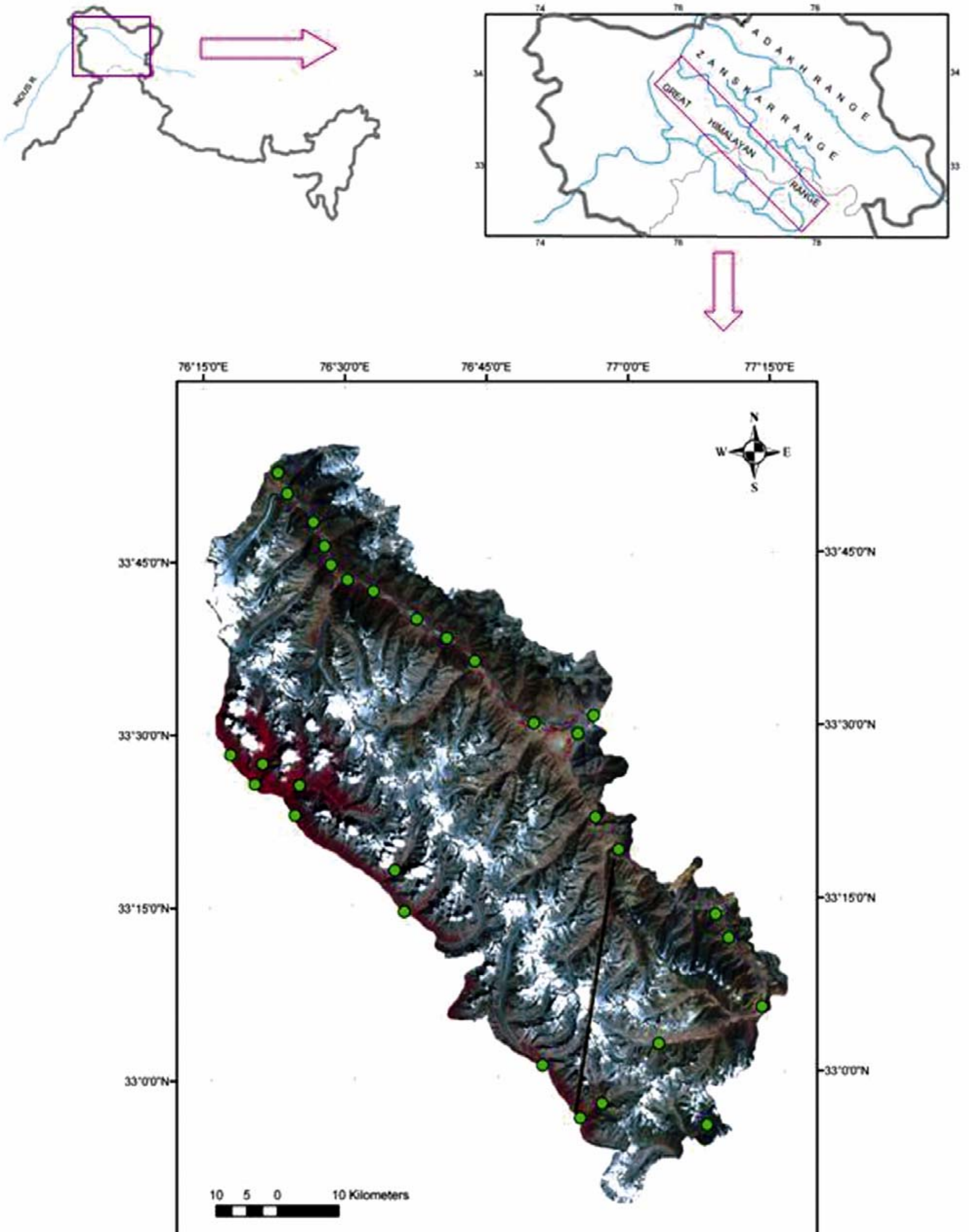

Figure 1. Location map of the study area showing a large number of glaciers over the Great Himalayan Range (as viewed using the IRS-1C LISSIII satellite image of 2001 with ground control points used for registration).

Table 1. Morphometric parameters of the glaciers

Glacier code	Length (km)	Snout width (m)	Area (sq. km)	Perimeter (km)	Snout altitude (m)	Relief (m)
1	21.92	341	74.09	110.81	4570	1040
2	12.93	334	29.49	58.18	4200	1110
3	14.56	287	39.61	81.28	4010	1180
4	13.39	454	64.12	147.35	3950	1710
5	10.19	486	23.76	61.86	4480	1220
6	5.09	293	3.89	12.88	4830	670
7	7.20	284	8.11	27.07	4480	990
8	7.09	264	24.29	54.29	4170	1210
9	5.41	317	9.27	27.38	4610	760
10	5.58	308	8.80	19.42	4530	770
11	3.60	487	6.11	14.76	4670	660
12	5.61	246	7.41	22.66	4820	890
13	6.58	182	24.17	45.62	4480	1330
14	8.77	167	22.87	42.61	4130	1170
15	8.94	297	15.77	35.94	4590	950
16	6.81	254	20.61	70.47	4480	780
17	7.35	182	8.88	23.02	4630	1150
18	5.89	245	7.24	29.35	4680	1090
19	7.20	590	37.90	89.70	4440	910
20	9.75	330	26.24	68.35	4500	1100
21	4.62	190	5.40	16.87	4980	860
22	7.66	235	11.52	24.23	4820	990
23	6.99	496	26.54	72.42	4490	1430
24	2.92	223	3.72	14.52	4750	910
25	9.07	464	21.53	41.73	3930	1650
26	6.42	323	18.69	49.70	4390	1120
27	13.02	398	32.06	78.11	4130	1470
28	10.06	486	13.36	52.86	4230	1230
29	11.30	539	45.78	89.19	4080	1390
30	14.62	566	78.03	147.14	4030	1480
31	10.41	275	10.96	33.72	4500	1010
32	7.38	497	24.31	76.87	4610	650
33	3.85	112	9.16	23.37	4770	430
34	9.98	388	16.01	44.29	4570	1130

resolution of 23.5 m of LISS III satellite data allowed accurate mapping of glacier boundaries using False Colour Composite (FCC) image with standard combination of bands, 432 as RGB. Different glacial parameters like length (measured along the central line from the snout to the highest point in the accumulation zone along maximum length), snout width and area were calculated using mapped glacier boundaries in the GIS platform (Table 1). Field validation was done for select glaciers in 2008 and 2011 (Figure 2). Using ASTER GDEM, the contour map of the study area was generated, which was used for locating the altitude of the glacier snout. The contour data were also used for computing the relief of the glaciers by subtracting their minimum altitude from maximum altitude[23]. The glacier area change of 34 glaciers was analysed by comparing glacier areas mapped in the satellite images of 1975 and 2001. Glacier retreat was measured along the centerline using snout positions delineated on both the satellite datasets. The measured glacier morphometric parameters were examined with reference to glacier area change and snout retreat. A flow chart of the methodology is shown in Figure 3.

Categorization of morphometric parameters in various classes revealed that majority of the glaciers in the area have length of 5–10 km, snout width of 150–350 m, area of 10–30 sq. km, perimeter of 20–60 km, snout altitude of 4500–4800 m and relative relief of 1000–1500 m. In terms of categorization of percentage of area loss during 1975–2001 it was estimated that majority of the glaciers (20) exhibited area loss in the medium (20–30%) and low (10–20%) categories in nearly equal proportions (Table 2). Only three glaciers exhibited very high glacier area loss (> 40%) and five glaciers exhibited high area loss (30–40%). Based on multi-temporal satellite datasets, Pandey *et al.*[8] found that during the period 1975–89/92, all the glaciers exhibited area loss up to 1.5%, whereas during the later period of 1989/92–2001, all the glaciers exhibited area loss up to 4%. The present study clearly indicates that prominent area loss over the glaciers took place during 1989/92–2001 (Figure 4). In the same region retreat rate of 23 m/yr and 10–55 m/yr was reported during 1975–2003 and 2003–2008 respectively[7]. Similar observations indicate high area loss (0.25%/yr) during 1992–2001 in Khumbu Himal, Nepal[19]. Large shrinkage

(0.77 sq. km/yr) of glaciers during 1999–2003 occurred in the Naimonańyi region of western Himalaya[24]. To envisage the gravity of glacier area loss in the study area during 1975–2001, absolute area loss in each glacier was estimated, which indicates that majority of the glaciers (33) witnessed area loss in the medium (5–15 sq. km) and low (< 5 sq. km) categories in nearly equal proportions (Table 3).

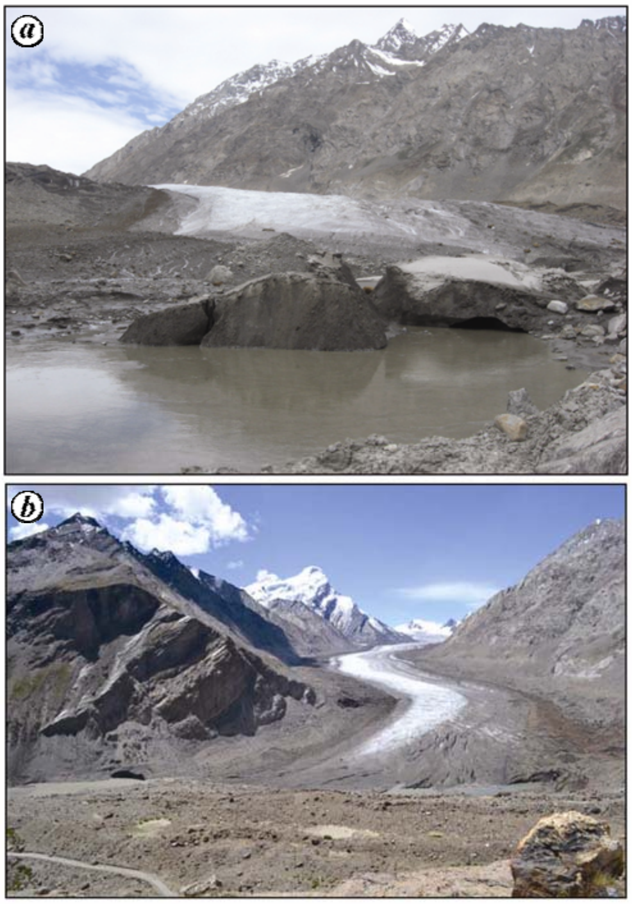

Figure 2. The snout of Drung-drang glacier during field work in (***a***) 2008 and (***b***) 2011.

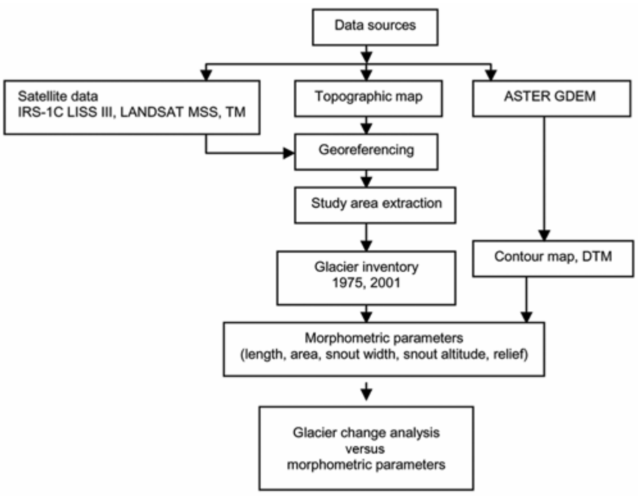

Figure 3. Flow chart of the methodology used.

Glacier terminus retreat analysis was performed only for 26 among the 34 studied glaciers where snout could be determined accurately in both the satellite datasets. It has been estimated that during 1975–2001, all glaciers in the area were in a retreating phase. Categorization of retreat rate revealed that majority (23) of the glaciers belonged to low (< 15 m/yr; nine glaciers), medium (15–25 m/yr; seven glaciers) and high (25–35 m/yr; seven

Table 2. Categorization of glacier area loss percentage into various types

Glacier area loss (%)	Number of glaciers	Area loss type
> 40	3	Very high
30–40	5	High
20–30	10	Medium
10–20	10	Low
< 10	6	Very low

Table 3. Categorization of glacier area loss into various types

Glacier area loss (sq. km)	Number of glaciers	Area loss type
> 15	1	High
5–15	16	Medium
< 5	17	Low

Table 4. Categorization of glacier retreat into various types

Retreat range (m)	Number of glaciers	Retreat type
> 35	3	Very high
25–35	7	High
15–25	7	Medium
< 15	9	Low

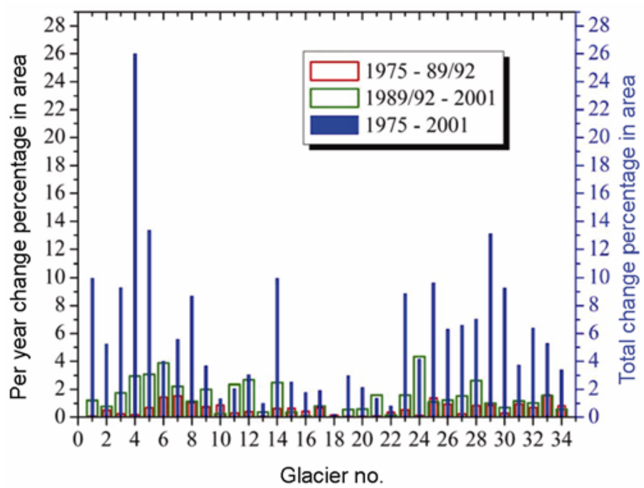

Figure 4. Graphical representation of glacier area loss statistics during different periods.

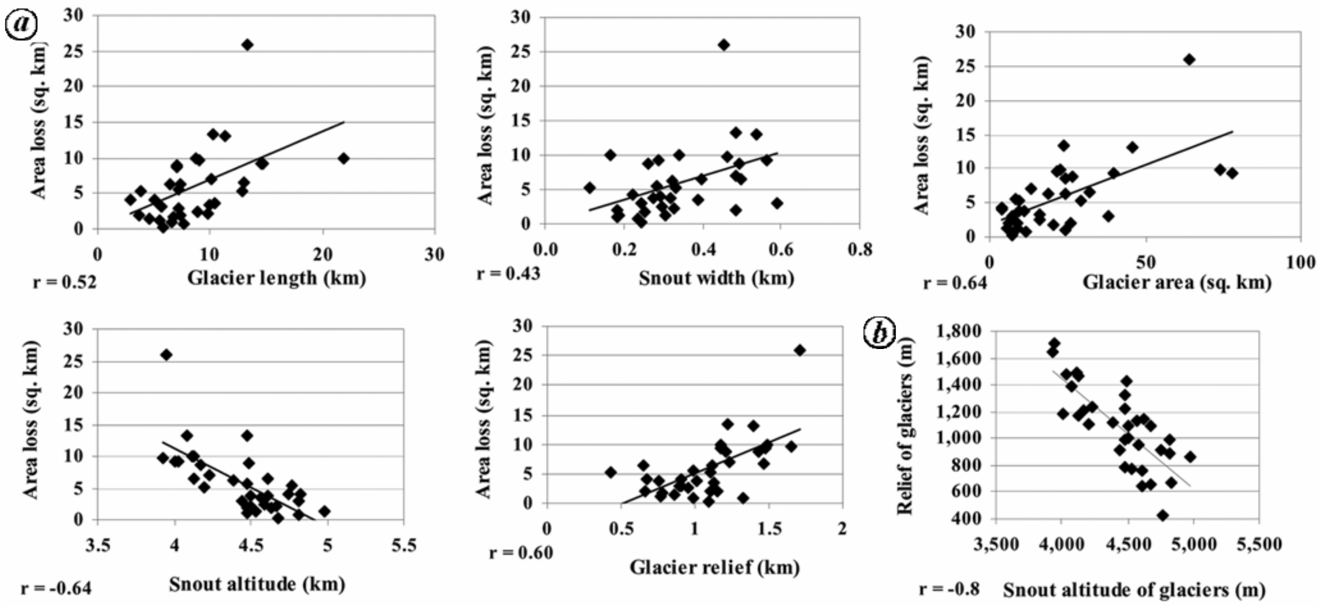

Figure 5. Correlation between (***a***) various morphometric parameters and area loss, and (***b***) various snout altitudes and glacial relief.

glaciers) retreat rate categories and only three glaciers exhibited very high retreat rate (>35 m/yr; Table 4).

With reference to glacier area change and glacier snout retreat, majority (22) of the glaciers in the region were slow in their response to climatic warming during 1975–2001, as there were only a few glaciers (six) which were changing at a very fast rate. This could be attributed to the fact that individual glaciers have their own response towards climate fluctuation even in similar climatic setting[25,26]. This also suggests that each glacier, due to its individual morphometric characteristics influences its response to climate forcing, thereby exerting prime control on its area changes and snout retreat or advancement. It is still difficult to generalize inferences about all glaciers on the earth, as the differences in individual glacier responses to climate change are large[27].

The correlation between the morphometric parameters and snout retreat and glacier area loss was studied. Snout retreat of glaciers does not exhibit definite correlation with any of the glacier morphometric parameters. Therefore, it can be stated that snout retreat of the glaciers to a larger extent is not controlled by glacier morphometry. The irregular recession of the snout of most of the glaciers in the Himalayan region was attributed partly to the large annual fluctuations in the rates of snowfall[17].

Evaluating the control of glacier morphometric parameters on glacier area loss revealed that absolute area loss during the period 1975–2001 in each glacier exhibited a positive relationship with the glacier length and glacier area (Figure 5 *a*). The analysis indicates that glacier area exhibited significant and positive correlation with glacier area loss at 90% significance level. On the contrary, percentage area loss during the same period maintained a negative relationship with these parameters. This possibly signifies that very long and big glaciers lost more in terms of their absolute area in comparison to very short and small glaciers. But this area loss comprises a very small percentage of their total area. Even smaller area loss in the case of short and smaller glaciers can result in large percentage loss of their total area. Therefore, it can be concluded that there is significant sensitivity of the smaller glaciers to changes in the climatic conditions in the area under study. In an adjacent basin, Kulkarni *et al.*[21] also showed significant loss in glacier area over the smaller glaciers (38%) in comparison to minor loss over the larger glaciers (12%). The larger percentage change (36) in glacier area was also estimated over smaller glaciers in the Su-lo Mountain in the Northeastern Tibetan Plateau, China[26].

More accumulation of snow and ice may occur over glaciers with high relief, which may result in down forcing of the glacier snout to lower height. There was a negative relationship between relief and terminus altitude with varying degree of correlation coefficient in different parts of the Himalaya[16]. The relief of the glaciers and their snout altitude in the study area also exhibited a negative correlation ($r = -0.8$), which possibly indicates that glaciers with low relief may witness more snout retreat and vice versa (Figure 5 *b*). Based on hypsometric analysis we found that glaciers having very low (< 10 m/yr) retreat rate possessed lesser percentage (less than 40) of area in low altitude (below 5200 m) and vice versa[6].

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The Younger Dryas cold event in NW Himalaya based on pollen record from the Chandra Tal area in Himachal Pradesh, India

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Pollen record of an AMS radiocarbon dated lacustrine sediment profile underlying the Chandra peat deposit in Himachal Pradesh, yielded signatures of the globally reported Younger Dryas (YD) cold event. This report of the YD event in NW Himalaya, substantiated by mineral magnetic variations, also records significant wet and warm conditions prior to 12,880 cal yrs BP, depicting the Ållerød interstadial preceding YD. The notable decrease in local (meadow) and regional (desert steppe) vegetation indicates major climate shift towards cold and dry conditions marking the onset of YD that intensified progressively till 11,640 cal yrs BP. The YD terminates with gradual reappearance of local and regional flora, indicating initiation of the Holocene wet and warm conditions. The pollen-inferred floristic changes and mineral magnetic variations

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