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Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh

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The Himalayas has one of the largest concentrations of glaciers outside the Polar regions. Various reports suggest that a significant number of mountain glaciers are shrinking due to climatic variations. In this communication, unusual retreat of the Parbati glacier in the Parbati river basin, Kullu district, Himachal Pradesh is reported. This is one of the largest glaciers in the valley. Satellite data of 1990, 1998, 2000 and 2001 are used in the investigation. The study has shown that the glacier had retreated 578 m between 1990 and 2001, almost 52 m per year. This rate of retreat was confirmed by field observations of glacier terminus in October 2003. Position of glacier snout was estimated by comparing its relative position with other features in field and in satellite images. In addition, position of the snout was also estimated using Global Positioning System. Compared to other glaciers in the Himalayas, this glacier is retreating at a high rate. This is possibly because the glacier is located in the lower altitude range. About 90% of the glacier is located in the altitude range lower than 5200 m; this is almost equal to the average altitude of the snow line at the end of the ablation season. The specific mass balance of the glacier is estimated using Accumulation Area Ratio method for a year 2001 as – 86 cm. The amount of retreat along with maximum length was predicted as 1461 m between 2001 and 2022, more than the present rate of retreat. This suggests that the Parbati glacier will continue to retreat at an unusual rate and it will profoundly affect the availability of water in the basin.

THE Parbati glacier is one of the largest glaciers in the Parbati river basin, a major tributary of Beas river and fed by almost thirty-six glaciers, covering an areal extent[1] of 188 km^2. Melt water from these glaciers forms an important source of run-off in the Parbati basin. In terms of economics, the Parbati basin is important because an 800 MW power project is under construction and another 520 MW power project is being planned. In addition, many micro and mini hydroelectric projects are being planned in the basin. Therefore, knowledge of the changes in glacial extent is important to assess future changes in stream run-off.

In the Himalayas as well as in other parts of world, mountain glaciers are retreating in response to climatic

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Table 1. Retreat of glaciers in the Himalaya

Glacier	Basin	Glacier area (km^2)	Year of observation	Retreat (m) Total	Retreat (m) Rate/yr	Reference
Bilare Bange	Satluj	2.8	1962–97	90	2.6	8
Shaune Garang	Satluj	8.8	1962–97	923	26.4	8
Janapa Garang	Satluj	12.3	1962–97	696	19.9	8
Milan	Ganga		1966–97	940	30.3	17
Dokariani Bamak	Ganga	5.8	1962–97	585	16.7	18
Gangotri	Ganga	143	1977–96	535	28.1	19
Chipa	Dhauliganga	5.0	1961–2000	1050	26.92	20
Meola	Dhauliganga	14.0	1961–2000	1350	34.62	20
Jhulang	Dhauliganga	3.3	1962–2000	400	10.53	20
Miyar	Chenab	87.8	1961–96	575	16.43	21
Meru Bamak	Ganga	4.7	1977–2000	395	17.2	22

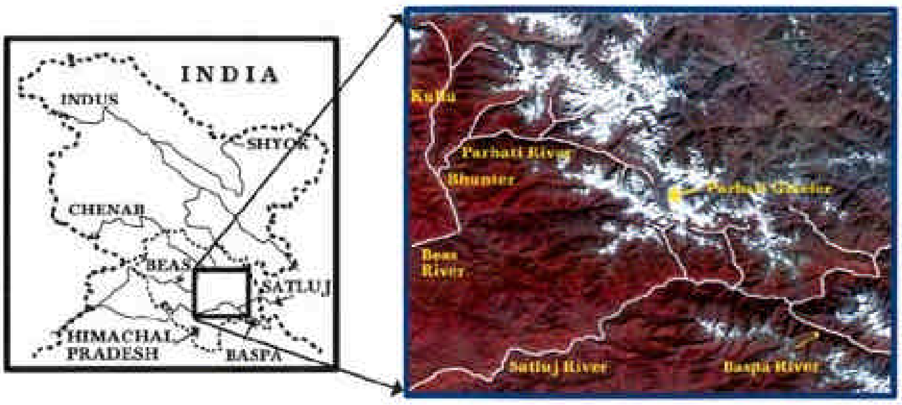

Figure 1. Location map of Parbati glacier.

warming[2,3]. Investigations[4] in the Baspa basin have shown an overall 19% deglaciation from 1962 to 2001. Glacial retreat was estimated in the Baspa basin using stereo images of Indian remote sensing satellite. The retreat varied[2] from 90 to 923 m between 1962 and 1998. The amount of retreat for Himalayan glaciers is compiled from various sources (Table 1). It suggests that the Himalayan glaciers are retreating at varying rates and maximum retreat of 34.62 m per year has been observed at Meola glacier in Dhauliganga river basin. The amount of glacial retreat depends upon overall mass balance and rate of melting at the terminus[5]. Debris cover can influence rate of melting at the terminus. Excessive debris retards melting and protects a glacier from retreat[6]. Heavy debris cover makes small glaciers in the Himalayas less sensitive to climate change, in contrast to the Alps and Trans-Himalayas, where small glaciers react more quickly to changes in mass balance and climate change[7]. In this investigation, unusual retreat of the Parbati glacier is reported. The location map of the glacier is given in Figure 1.

The boundary of the Parbati glacier was delineated from the topographic maps of the Survey of India (1 : 50,000 scale). This region was surveyed using vertical air photograph taken in 1962. The boundary was superimposed on satellite images of 1990, 1998, 2000 and 2001 obtained using Landsat and Indian remote sensing satellite (IRS) images (Table 2; Figure 2). Images of August–September season were selected, because during this period snow cover is minimum and glaciers are fully exposed. Delineation of glacial boundary was carried out using standard band combination as 2 (0.52–0.59 m), 3 (0.62–0.68 m) and 4 (0.77–0.86 m). Debris cover on the glacier was estimated using band combination as 2 (0.52–0.59 m), 4 (0.77–0.86 m) and 5 (1.55–1.75 μm). Reflectance of rock in band 5 is higher than that of ice; therefore, debris cover on glacier gives a red tone[8]. In the year 1998, IRS PAN and LISS-III data were available. Therefore, these data were merged to improve interpretation capability. Various types of techniques can be used to merge data. However, Bovey technique was found more suitable for glaciated region[9]. The glacial retreat is estimated along the maximum length as given in Figure 3. Geographic Information System (GIS) technique was used to analyse changes in glacial parameters. In order to verify the position of the glacier snout, an expedition was organized to Parbati glacier in October 2003. Snout position was obtained using GPS and by comparing relative position of the snout in comparison with other geomorphological features. In order

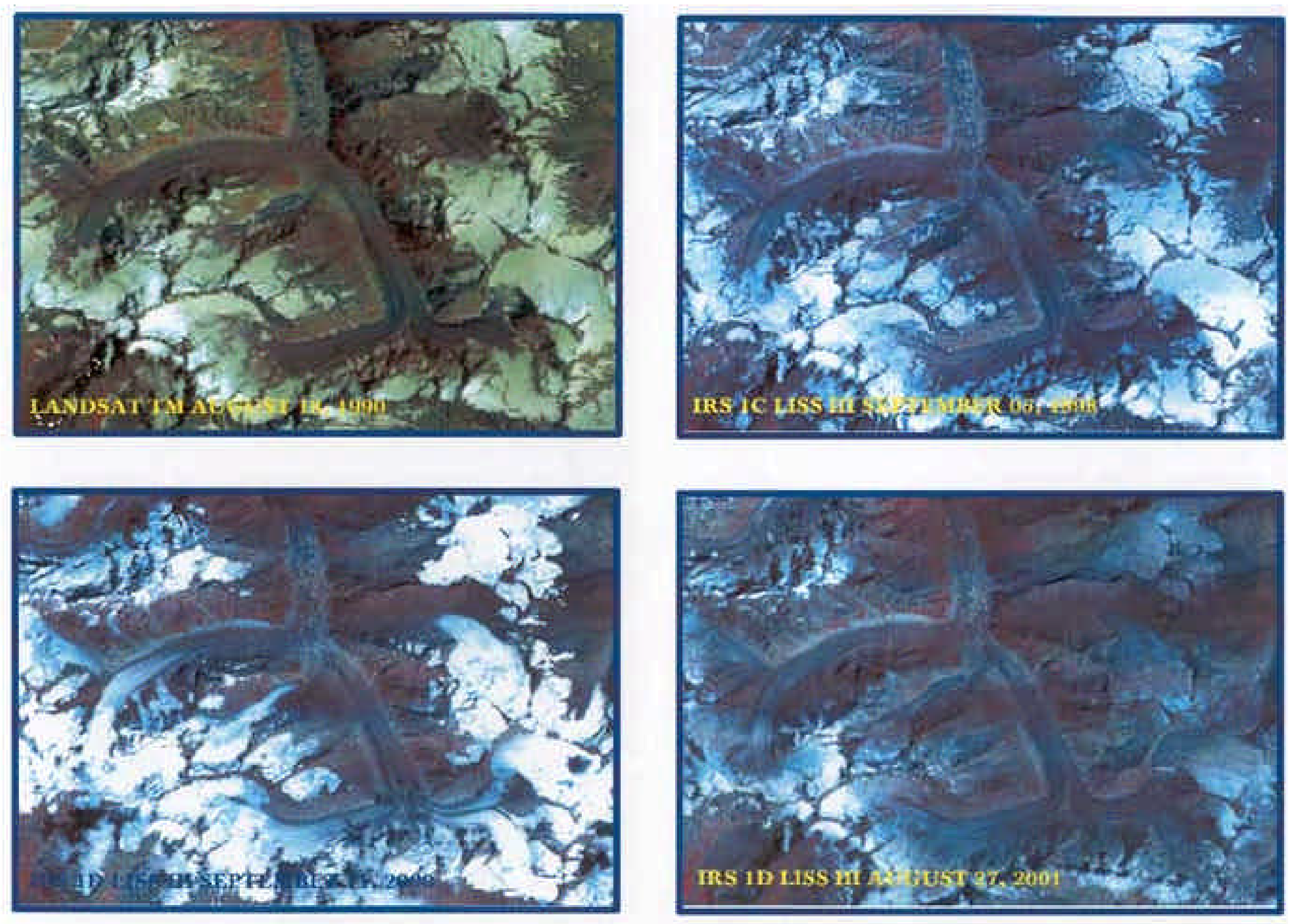

Figure 2. Satellite images showing Parbati glacier in 1990, 1998, 2000 and 2001.

Table 2. Satellite data used in the analysis

Satellite	Sensor	Spatial resolution (m)	Date of acquisition
Landsat	TM	30	18 September 1990
IRS	LISS-II	36.25	18 August 1993
IRS	PAN and LISS-III	5.8 and 23	5 September 1998
IRS	PAN and LISS-III	5.8 and 23	11 September 2000
IRS	LISS-III	23	27 August 2001

to estimate future changes in the glacial snout, information about glacial depth, mass balance and ablation rate at snout is needed. This information was estimated using following relationships.

Changes in glacial length were estimated using the following relationship[10]:

$$L_1 = L_o * db/b_t,$$

where L_1 is the change in glacial length, L_o the present length of glacier, db the change in glacial mass balance and b_t the annual ablation at glacier terminus.

The dynamic response time to change in glacial length is estimated using the following relationship[11]:

$$T = h_{max}/b_t,$$

where T is the response time, and h_{max} the maximum glacial depth.

Glacial depth was estimated using the following relationship with area developed for the Himalayan glaciers[12]:

$$H = -11.32 + 53.21\ F^{0.3},$$

where H is the mean glacier thickness (m) and F the glacier area (km^2).

Glacial mass balance was estimated using Accumulation Area Ratio (AAR). Accumulation area was measured using systematic analysis of weekly data of WiFS sensor (Figure 4). The following relationship was used to estimate mass balance from AAR[13,14].

$$b = 243.01 * X - 120.187,$$

where b is the specific mass balance in water equivalent (cm) and X the Accumulation Area Ratio.

Initially, a map of the Parbati glacier was prepared using topographic map of Survey of India. In 1962, the glacial areal extent was 48.44 km^2 and it was fed by two major tributary glaciers. The main and tributary glaciers are facing northwest and northeast respectively. In the period between 1962 and 1990, the glacier has experienced large retreat. Therefore, the main and tributary glaciers got completely detached from each other, forming two independent glaciers. The areal extent of the Parbati glacier was estimated from a large number of satellite data, starting from the year 1990 to 2001. Four datasets were collected and analysed. The changes in areal extent from 1962 onwards are given in Table 3. Satellite data are available for five years from 1990 to 2001. However, data are of different spatial resolution. Therefore, glacial retreat for purpose of analysis is taken from data 1962, 1990, 1998 and 2001. The total loss in glacial extent of 8.3 km^2 was observed from 1962 to 1990. In addition, 1.93 and 1.32 km^2 loss in extent was observed for a period between 1990–98 and 1998–2001 respectively. This suggests a total loss of 11.55 km^2 between 1962 and 2001. The loss in glacial length is also estimated and overall glacial retreat was estimated as 5991 m from 1962 to 1990 and 578 m from 1990 to 2001. This suggests a total loss of 6569 m from 1962 to 2001 (Table 2). The loss in glacial length is plotted in Figure 5, indicating overall reduction in rate of retreat at the end of the 20th century. The amount of retreat is high in the period between 1962 and 1990, possibly because of gentle topography of the deglaciated region (Figure 6). From 1990 to 2001, systematic satellite data suggest large variations

Figure 3. Retreat of Parbati glacier from 1962 to 2001. Maximum glacial length is also shown. Glacial retreat was measured along this length.

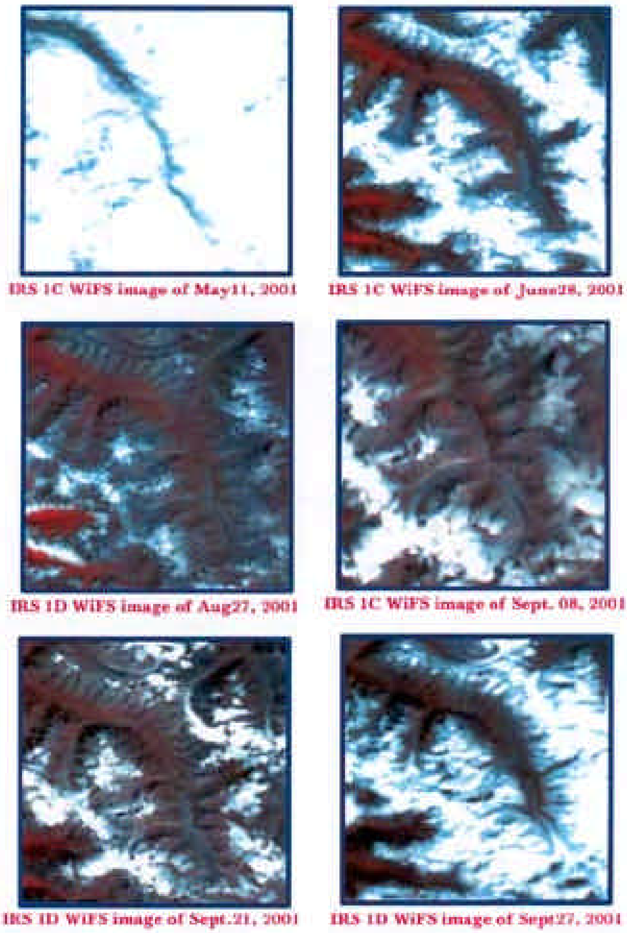

Figure 4. WiFS images showing snow line at the end of ablation season.

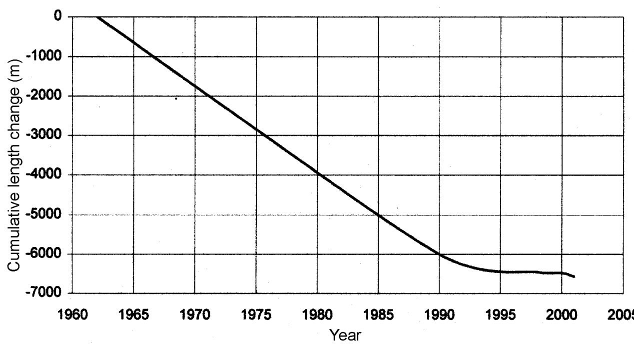

Figure 5. Cumulative change in length of glacier snout from 1962 to 2001. Satellite observations are available for 1990, 1998, 2000 and 2001. Note that rate of glacial retreat is changing between 1990 and 2001. Total loss in glacial length from 1962 and 2001 is 6569 m.

Table 3. Changes in Parbati glacier between 1962 and 2001

Year	Areal extent (km^2)	Loss in area from 1962 (km^2)	Loss in area from Previous observation	Maximum length (m)	Loss in length from (m) 1962	Loss in length from (m) Previous observation Total	Loss in length from (m) Previous observation Rate/yr	Snout altitude (m)
1962	48.44	–	–	16689	–	–		4042
1990	40.14	8.3	8.3	10698	5991	5991	214	4297
1998	38.21	10.23	1.93	10239	6450	459	57	4324
2000	37.73	10.71	0.48	10217	6472	22	11	4326
2001	36.87	11.55	0.84	10120	6569	97	97	4331

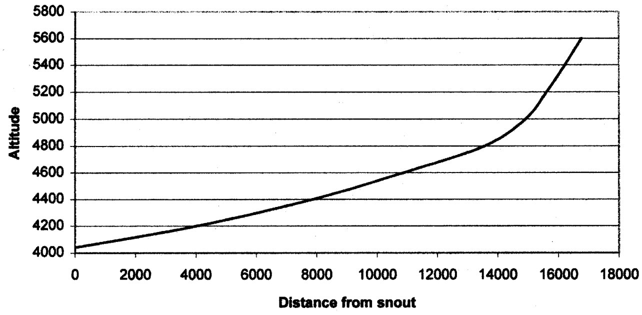

Figure 6. Slope of glacial surface from snout upwards. Slope near glacial snout and lower altitude areas is gentle compared to higher altitude areas.

in amount of retreat from year to year. For example, for the period between 1998 and 2000, the glacier had retreated by only 22 m, while it has retreated by 97 m between 2000 and 2001 (Table 3).

In order to verify satellite observations, field investigation was carried out to assess position of glacier terminus. Position of glacier snout was estimated by comparing its relative position with other geomorphological features in field and satellite images. In addition, position of snout was also estimated using GPS. Figure 7 *a* shows glacial ice and GPS. Field investigation suggests that the lower portion of the glacier tongue is broken into independent ice mounds. These are covered by fine sand and separated from each other by valleys. These ice mounds are not attached with active glaciers and therefore, can be considered as dead ice. Dead ice mounds will slowly convert into ice-cored moraines and ice will melt independently of main glacier body. Transition of ice mound into ice-cored moraine can be clearly seen in the field. Figure 7 *b* and *c* shows ice-cored moraine and ice mound. The zone of ice mounds and ice-cored moraines can be easily identified on high-resolution satellite images (Figure 7 *d*). This is because each ice mound is separated by a valley and this topographic variation causes mountain shadow (Figure 7 *d*).

In the Himalayas, glaciers were retreated[2] in the range 90–923 m between 1962 and 1997. For the Parbati glacier, the amount of retreat from 1962 to 1990 and from 1990 to 2001 was 5991 and 578 m respectively. This rate of retreat is high and alarming in nature. In order to assess possible reasons for the unusual retreat, area altitude distribution of glacier was studied (Figure 8). The investigation suggests that the entire glacier is located in the low altitude zone. In Figure 9, cumulative per cent area below each altitude zone is given. It suggests that almost 96% of the glacier is located in the altitude range lower than 5200 m. This is almost equal to the average altitude of snow line at the end of the ablation season[14] of year 2001. In addition, mid-altitude of the glacier in 1962 was 4800 m (Figure 9). This is low compared to mid-altitude of 5500 and 5300 m in Beas and Satluj basins respectively[15]. This shows that the Parbati glacier has been experiencing negative mass balance for a long period.

In order to assess glacier mass balance, a technique base upon AAR is used. AAR is a ratio between accumulation area and total glacier area[16]. Accumulation area is the area of the glacier above equilibrium line. This technique has been extensively used in the Himalayas for estimation of glacial mass balance[13,14]. The maximum retreat of snow line was observed on 27 August 2001 (Figure 4). Mass balance for the year 2001 was estimated as – 86 cm.

In order to understand future changes in glacial extent, models based upon various parameters, as mentioned earlier are used. Results are given in Table 4. Investigation has shown that response cycle for the main glacier is 21 years. During this period, glacier will retreat by 1461 m. This means the main glacier body will continue to retreat with almost the same rate till 2022.

The present and future rate of retreat is large compared to many other glaciers in the Himalaya. The amount of retreat depends upon glacier mass balance, annual ablation at terminus and present length of glacier[10]. The snout of the Parbati glacier is covered by debris, therefore, the amount of melting at the snout may not change significantly. Thus, mass balance is a more dynamic and important parameter to understand this large retreat. One of the methods to estimate glacial mass balance is AAR, which depends upon altitude of snow line at the end of ablation season and amount of glacial area below snow line. One of the parameters which can influence snow line is orientation and topography of glacial valley. The Parbati glacial valley is gentle and wide (Figure 6), causing more solar radiation to be

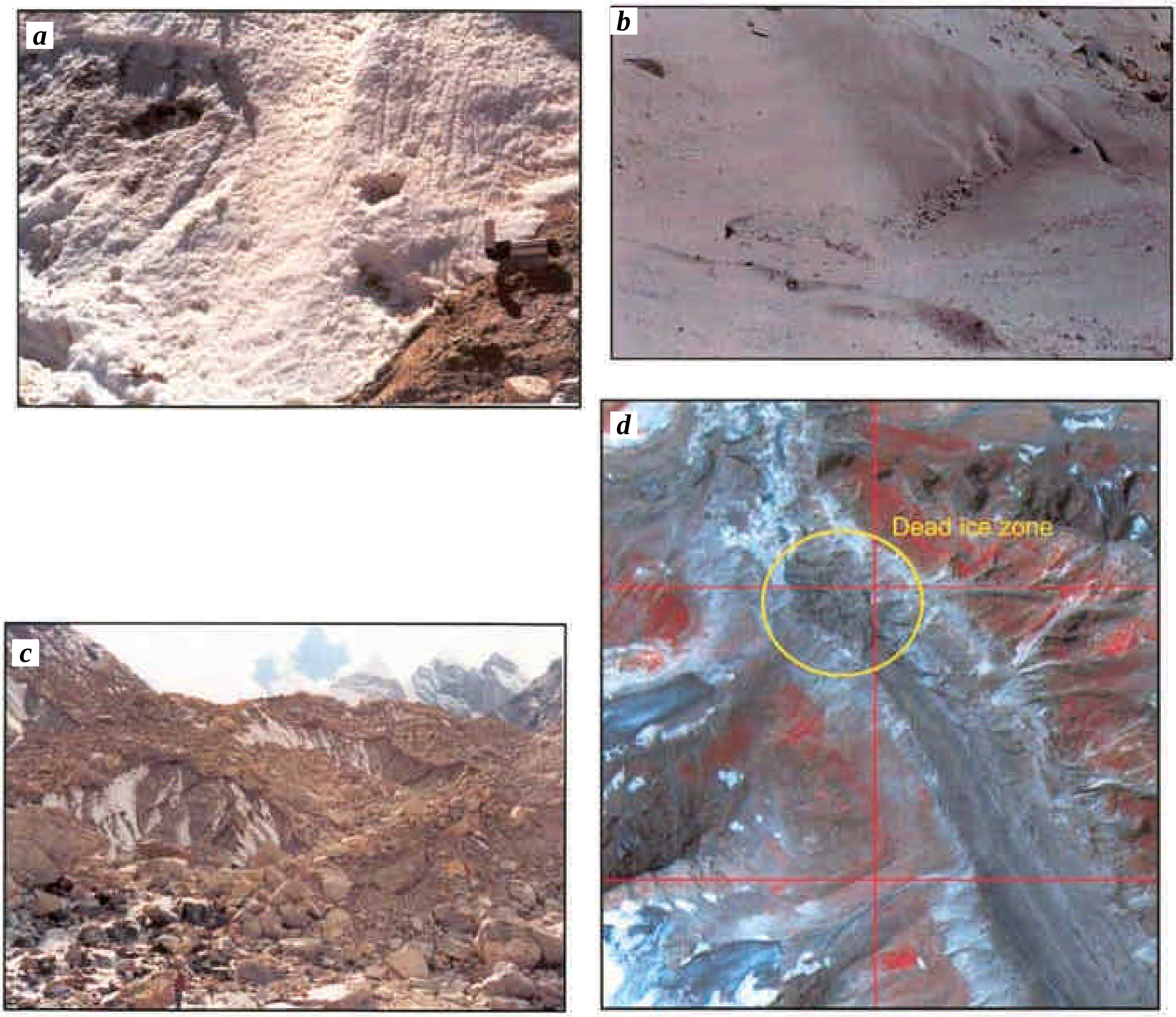

Figure 7. Field photograph showing glacial ice and GPS (***a***), ice-cored moraine (***b***) and dead ice mound (***c***). ***d***, Satellite imagery showing dead ice mounds.

Table 4. Measured and estimated characteristics of Parbati glacier. Parameters are estimated to assess future changes in glacial extent. Parameters are estimated for part of the main glacial body

Parameter	Main glacial body
Areal extent of glacier in 2001	23.7 km^2
Accumulation area in 2001	3.56 km^2
Accumulation Area Ratio in 2001	0.138
Estimated glacial mass balance 2001	–86 cm
Estimated depth of glacier in 2001	126 m
Measured rate of melting at snout (Chhota Shigri glacier 1988–89)	–6 m/yr
Measured glacier length in 2001	10,120 m
Estimated response time for loss in length from 2001	21 yrs
Estimated loss in glacial length from 2001 to 2022	1461 m

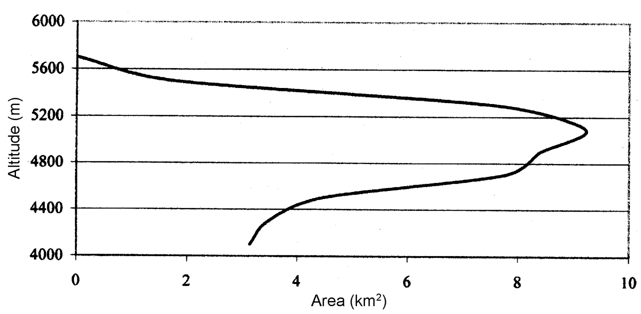

Figure 8. Distribution of glacier area in altitude zone between 4100 and 5800 m.

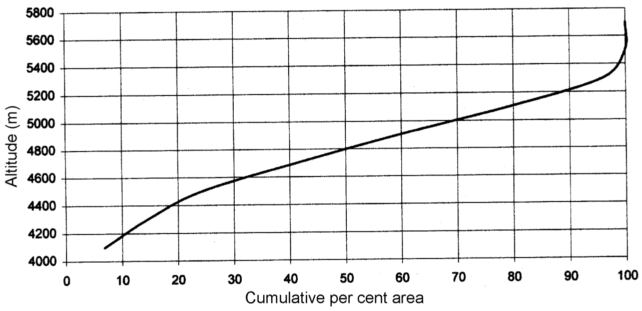

Figure 9. Distribution of glacier in per cent below various altitude zones. For example, below 4800 m altitude 50% of glacier is located.

received on the glacial surface. In addition, gentle slopes causes less accumulation of avalanche snow. If snow pack is shallow, it can expose glacial ice for longer duration. Low albedo of ice compared to snow can cause further absorption of solar radiation and lead to more negative mass balance. Another factor which can influence AAR is glacial area below snow line at the end of the ablation season. The altitude of snow line at the end of the ablation season in the region is around 5200 m and almost 96% of the glacier is located in altitude range lower than 5200 m. Therefore, it appears that wide valley, gentle slope and low altitude are the major cause for rapid retreat of the Parbati glacier. This massive retreat will continue in future and it will have profound effect on stream run-off of the Parbati river.

In addition, satellite data indicate that the amount of retreat is different from year to year. For example, the Parbati glacier had retreated by only 22 m from 1998 to 2000, but retreated by 97 m from 2000 to 2001. Similar pattern of retreat is observed in many valley glaciers in the world. Therefore, to understand the proper pattern of glacial retreat, it needs to be monitored annually.

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