Are the Himalayan glaciers retreating?

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The Himalayan mountain system to the north of the Indian land mass with arcuate strike of NW–SE for about 2400 km holds one of the largest concentration of glaciers outside the polar regions in its high-altitude regions. Perennial snow and ice-melt from these frozen reservoirs is used in catchments and alluvial plains of the three major Himalayan river systems, i.e. the Indus, Ganga and Brahmaputra for irrigation, hydropower generation, production of bio-resources and fulfilling the domestic water demand. Also, variations in the extent of these glaciers are understood to be a sensitive indicator of climatic variations of the earth system and might have implications on the availability of water resources in the river systems. Therefore, mapping and monitoring of these freshwater resources is required for the planning of water resources and understanding the impact of climatic variations. Thus a study has been carried out to find the change in the extent of Himalayan glaciers during the last decade using IRS LISS III images of 2000/01/02 and 2010/11. Two thousand and eighteen glaciers representing climatically diverse terrains in the Himalaya were mapped and monitored. It includes glaciers of Karakoram, Himachal, Zanskar, Uttarakhand, Nepal and Sikkim regions. Among these, 1752 glaciers (86.8%) were observed having stable fronts (no change in the snout position and area of ablation zone), 248 (12.3%) exhibited retreat and 18 (0.9%) of them exhibited advancement of snout. The net loss in 10,250.68 sq. km area of the 2018 glaciers put together was found to be 20.94 sq. km or 0.2% (± 2.5% of 20.94 sq. km).

Keywords: Ablation, glacier, Himalaya, retreat, snout.

GLACIERS occur in the high-altitude regions of the mountains and in the polar regions of the earth. They are vital to mankind as they control the global hydrological cycle, maintain the global sea levels and perennially supply freshwater to the rivers. In the wake of climatic variations arising due to increasing concentration of greenhouse gases in the atmosphere resulting in global warming and its implications on various resources, glaciers are increasingly being monitored worldwide. The Himalayan mountain system to the north of the Indian land mass with arcuate strike of NW–SE for about 2400 km holds one of the largest concentration of glaciers outside the polar regions in its high-altitude regions. Perennial snow and ice-melt from these frozen reservoirs is used in catchments and alluvial plains of the three major Himalayan river systems, i.e. Indus, Ganga and Brahmaputra for irrigation, hydropower generation, production of bio-resources and fulfilling the domestic water demand. Also, variations in the extent of these glaciers are understood to be a sensitive indicator of climatic variations of the earth system and might have implications on the availability of water resources in the river systems. Therefore, mapping and monitoring of these natural, frozen freshwater resources is required for the planning of water resources and understanding the impact of climatic variations. However, ground-based studies on monitoring of the Himalayan glaciers require enormous effort in terms of time and logistics due to lack of atmospheric oxygen in high altitudes, trekking in rough terrain and cold climatic regimes. Despite these difficulties, the efforts made by many expedition teams have led to the generation of vital information on the fluctuations of Himalayan glaciers in terms of mass balance or simply snout monitoring[1–9]. Remote sensing having the capability of providing synoptic view, multi-temporal coverage and multispectral characterization of earth surface features has demonstrated its utility for glacier monitoring in different mountain regions of the world, including the Himalaya[10–20]. The satellite data available in the public domain such as Landsat TM[21], topographic maps prepared in the past, aerial photographs and recently released CORONA photographs along with data from other earth observation satellites such as IRS series, ASTER, etc. have been the main sources for generating this information. However, it is seen that very few studies compare the changes in glaciers from data of similar sources. The present study uses mainly data from LISS III sensor of IRS satellites for an interval of about one decade between 2000/01/02 and 2010/11 for monitoring of 2018 glaciers taken from different parts of the Himalaya.

Snowfall in the Himalayan mountain ranges is nourished by two climatic systems: the mid-latitude westerlies and South Asian monsoon. A significant inter-annual climatic variability in the region is also associated with El Nino Southern Oscillation (ENSO)[22]. The monsoonal influence is greatest on the southern slopes of the Himalaya and eastern Tibet, which experience a pronounced summer maximum in precipitation occurring at high

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altitude as snow. In contrast, the more northern and western ranges receive heavy snowfall during winter with moisture supplied by mid-latitude westerlies[23]. So the glaciers monitored in this study represent different climatic and orographic settings. It includes 149 glaciers of Karakoram (glaciers of mainly the Nubra basin and north of it), 560 glaciers of Himachal (glaciers of the Chenab and the Sutlej basins), 729 glaciers of Zanskar (glaciers of the Zanskar, the Spiti and the Suru river basins), 353 glaciers of Uttarakhand (glaciers of the Ganga basin), 195 glaciers of Nepal (the Kosi basin) and 32 glaciers of Sikkim region (glaciers of the Tista River basin and north of it) (Figure 1). These include typical valley-type glaciers, ice aprons and glaciers occurring on mountain slopes. In terms of debris cover on their ablation zones, the selected glaciers include all types, i.e. fully debris covered, partially debris covered and debris-free.

Satellite data of end of the ablation period are normally used for mapping of glacier extent. End of ablation period varies across the Himalaya from west to east. End of ablation for western Himalaya corresponds mainly to September to mid-October period, whereas the corresponding period for the eastern Himalayan region (Tista region in Sikkim) is from December to early January. Accordingly, IRS LISS III images (spatial resolution 23.5 m) corresponding to the end of the ablation period for the year 2000/01/02 and 2010/11 were used for mapping of glacier extent. As IRS LISS III data were not available for 2001 in the case of Nepal, a Landsat scene (spatial resolution 30 m) of 2000 was used. Details of the data used for each of the six regions are given in Table 1.

Visual interpretation techniques were used to delineate the extent of the glaciers. Digital False Colour Composites (FCCs) of LISS III images were interpreted on-screen in different combinations of green, red and NIR, or green, red and SWIR bands. The first combination is used to distinguish vegetated areas around snouts of the glaciers, whereas SWIR band helps in the distinction of snow and clouds and glaciated region from the surrounding rocky areas. Mapping of glaciers with bare ice surface is relatively simpler because ice has a distinct signature than the other surrounding features. However, many Himalayan glaciers do not have clean surfaces as they are covered with varying amounts of moraine, consisting of dust, silt, sand, gravel, cobbles and boulders. Though identification of snout position and delineation of glacier boundaries is difficult for debris-covered glaciers, certain interpretation techniques are used to identify snout position and glacial extents accurately in the above conditions as has been done by several authors[11,24,25]. Moreover, debris cover on the glacier tongue normally shows distinct texture in contrast to the texture of the surrounding rocks. Additional use of DEM also helps in the interpretation of glacier extent. Therefore, ASTER and SRTM DEMs were used as additional data to confirm the snout position. In many cases, the snout positions of glaciers were confirmed by locating the point of emergence of stream from the glaciers. Sometimes the snouts of the debris-covered glaciers are characterized by unique morphological shape and steep slope, which help in identifying their position on the image. When old and inactive lateral moraines in the form of ridges were seen along the glacier valleys, the extents were delineated excluding the lateral moraines.

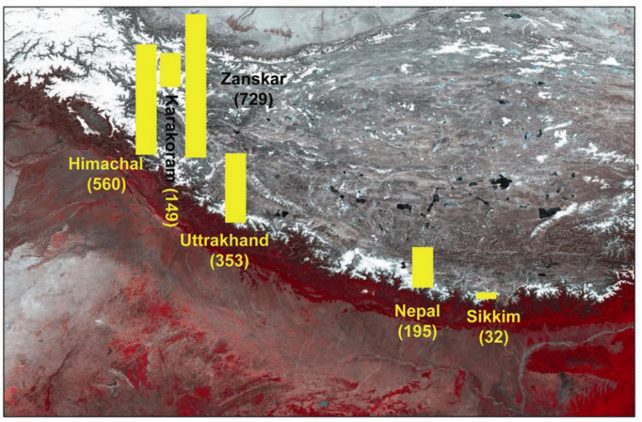

Figure 1. Study regions with the number of glaciers monitored (2018): Karakoram–149, Himachal–560, Zanskar–729, Uttarakhand–353, East Nepal–195 and Sikkim–32.

Table 1. Satellite data used in glacier monitoring

Region	2001	2010–11
Karakoram	LISS-III_July & Oct-2001	LISS-III_Oct-2010
Zanskar	LISS-III_Aug-2001	LISS-III_Aug-2010
	LISS-III_Aug-2001	LISS-III_Sep-2010
	LISS-III_Aug-2001	LISS-III_Aug-2011
Himachal	LISS-III_Aug-2001	LISS-III_Oct-2010
	LISS-III_Aug-2001	LISS-III_Oct-2011
	LISS-III_Aug-2001	LISS-III_Oct-2011
	LISS-III_Sep-2001	LISS-III_Sep-2010
	LISS-III_Aug-2002	LISS-III_Sep-2010
Nepal	Landsat ETM+_Oct. and DEC_2000	LISS III_Dec-2010
Uttarakhand	LISS-III_Sept-2001	LISS-III_Oct-2010
	LISS-III_Oct-2001	LISS-III_Sep-2011
	LISS-III_Oct-2001	LISS-III_Oct-2011
	LISS-III_Oct-2001	LISS-III_Oct-2011

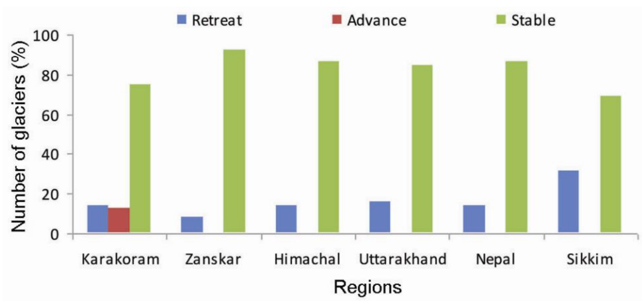

Figure 2. Number of glaciers showing retreat, advance or stability during 2000/01/02–2010/11.

Table 2. The size–frequency distribution of glaciers considered for monitoring

Area (sq. km)	Karakoram	Zanskar	Himachal	Uttarakhand	Nepal	Sikkim	Total
<1	8	436	261	184	21	4	914
1 to 3	46	197	139	90	59	8	539
3 to 5	30	43	54	23	32	7	189
5 to 10	17	31	51	26	37	8	170
10 to 20	21	9	33	18	25	3	109
> 20	27	13	22	12	21	2	97
	149	729	560	353	195	32	2018

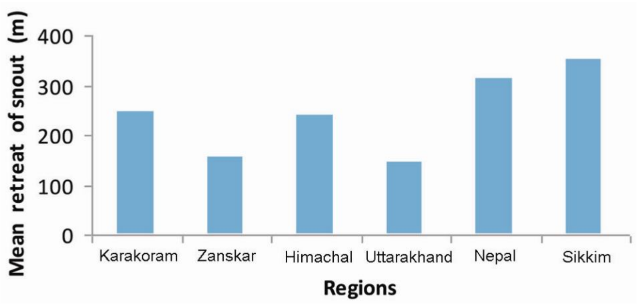

Figure 3. Mean retreat of snout (total retreat /no. of retreating glaciers) in six regions during 2000/01/02–2010/11 for 248 glaciers.

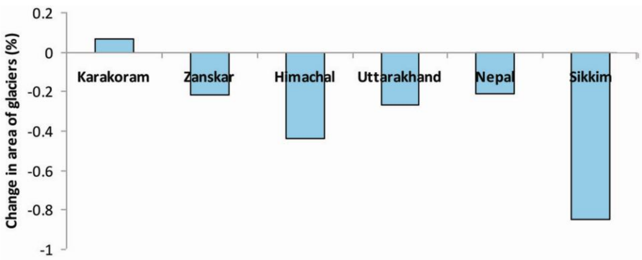

Figure 4. Changes in area of ablation zone during 2000/01–2010/11 shown for six regions.

The method adopted for change detection in many earlier studies was based on finding the change in the total area of the glacier over an interval of time[14,26], which includes zones of accumulation and ablation. Images of the end of ablation season when snow line reaches the maximum altitude are used for delineating accumulation and ablation zones. The upper limit is delineated on the ridges or ice-divides at the head of the glaciers. The accumulation zones of the glaciers remain dynamic in terms of snow cover and so the area of accumulation zones keeps on changing in the scale of days and months. The area of accumulation normally differs on two different dates and different years. The net effect of mass change is seen on the variation in ablation zone, including the snout. Therefore, change only in the ablation zone of glaciers, which is a relatively stable zone, and shifting of the snout, have been considered as the criteria for monitoring stability, retreat or advance of glaciers. Extents of glaciers were finalized using data of 2000/01 and superimposed on a second set of data to observe the shift in the position of snout and changes in the area of each glacier. LISS III images for both the timeframes were co-registered with an accuracy of better than 0.5 pixel (11.5 m) for finding out the shift in snout position as well as change in glacial area.

Area–frequency distribution of the monitored glaciers in the six regions is given in Table 2. Glaciers having area less than 1 sq. km constitute 45% of the number monitored. Ninety-seven glaciers occupy area larger than 20 sq km. Most of the glaciers of Karakoram region are larger in area than in other regions. Smaller glaciers are more in Zanskar region followed by Himachal and Uttarakhand regions.

Monitoring of 2018 glacier snouts from the satellite data of 2000/01/02 and 2010/11 shows that 1752 glaciers (86.8%) have been observed to be stable (no change in the snout position), 248 glaciers (12.3%) have exhibited retreat and 18 of them (0.9%) have experienced advancement (Figure 2). Region-wise mean shift in snout position for the retreating glaciers is shown in Figure 3. It varies from 145 to 313 m for the 2000/01/02–2010/11 period with a positional uncertainty of 11.5 m. Average movement of 300 m of snout was observed for advancing glaciers (18 glaciers) of Karakoram. Maximum retreat was observed in Sikkim region followed by Karakoram and Himachal region. The mean retreat of snout for 248 retreating glaciers was found to be 170 m (17 m annually approx.). But by considering all the 2018 glaciers monitored, the mean retreat was found to be 21 m (2.1 m annually). No detachment of glaciers in the ablation zones in the study area was observed during the period of monitoring.

Changes in area of glaciers were mapped and monitored in the ablation zones. The glaciers with stable snouts (1752 glaciers) have not exhibited any change in area of ablation zones. Glaciers with retreat of snout (248 glaciers covering 34% of total area in 2001) exhibited loss in area, whereas the glaciers having advancement (18 glaciers covering 6% of total area in 2001) exhibited increase in area. This gives a net loss of 20.94 sq. km (0.2 ± 2.5% uncertainty) in the total area of 10,250.68 sq. km for all the monitored glaciers mapped in the year 2000/01. Net change in glaciated area varies from one region to another (Figure 4). The uncertainty in the interpretation of mixed pixels at the margins of the extents of glaciers in the two datasets get nullified. However, there could be an uncertainty of about 2.5% in area due to half pixel error at the periphery of changed extents of glaciers[25].

The advancement of glaciers in Karakoram region is in conformity with the results presented in the literature[27–30]. These results differ from other parts of the Himalayan region probably because the Karakoram region is also fed by mid-westerlies besides being influenced by the southwest monsoon. However, exceptionally high advance movement has not been noted in the glaciers of Karakoram. Figures 5–9 show a few examples of glaciers showing advancement, retreat and stable fronts as seen on IRS LISS III images. Field verifications were also carried out by visiting 15 glaciers during 2001–2011 to validate the snout positions. Field photographs are shown in Figure 10. Overall, the results of the present study indicate that most of the glaciers show stable front or little loss in area during 2000/01/02/11.

A few other studies on the monitoring of Himalayan glaciers relevant in this context are worth mentioning. A loss of 15% in glacier extent in 25 years (1970–1996) has been reported in Peru[20]. In another study, change in glacier cover was mapped in Peruvian mountains and a loss of 1.4 sq. km per year or 54% in 48 years (11% per decade) was recorded during 1955–2003 (ref. 25) based on topographical maps and Landsat images[26]. Glaciers in western Canada were mapped using Landsat images of 1985 and 2005 and a loss of 24 ± 4.6% in glacier area of Alberta and 10.8 ± 3.8% in British Columbia was

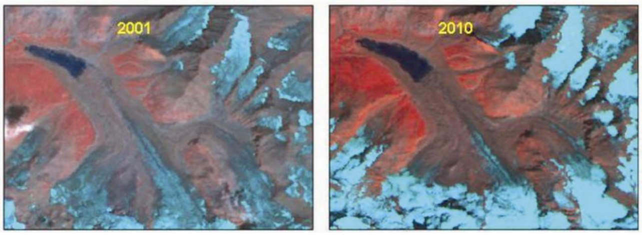

Figure 5. Snout of a glacier in Bhaga basin (Himachal region) showing retreat during 2001–2010.

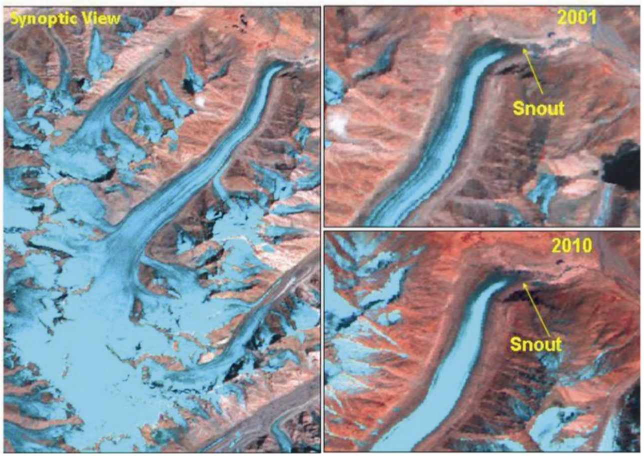

Figure 6. Snout of Durung Drung in Zanskar basin showing stability during 2001–2010.

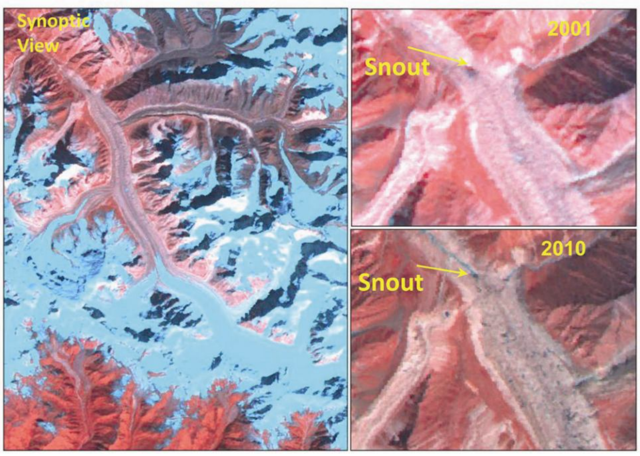

Figure 7. Snout of Gangotri glacier in Uttarakhand region showing stability during 2001–2010.

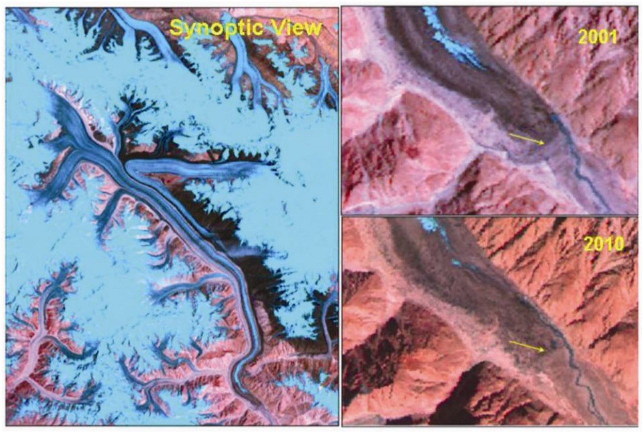

Figure 8. Snout of Siachin glacier in Karakoram region showing stability during 2001–2010.

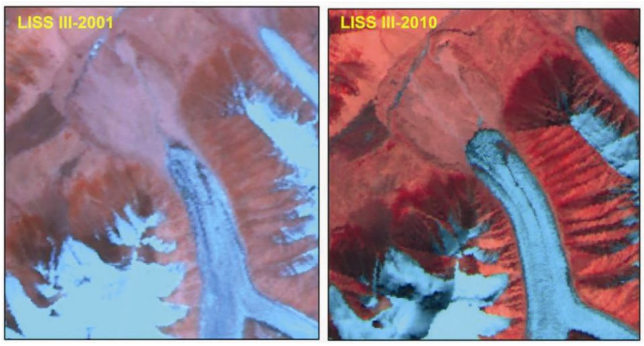

Figure 9. IRS LISS III images showing snout of a glacier in Karakoram region advancing during 2001–2010.

Figure 10. Field photographs showing snout of Panchinala glacier (Bhaga basin), Miyar glacier (Miyar basin), Durung Drung glacier (Zanskar basin) and Satopanth glacier (Alaknanda basin).

found[14]. The uncertainty mentioned in this study[14] was attributed to difference in snow cover. In the Himalayan region, mean loss of 16% in area of glaciers was reported using topographical maps of 1962 and satellite images of 2001 (ref. 17). Retreat and advance varying from 50 to 150 m/yr was reported in the Tibetan plateau for a period from 1973 to 1993 (ref. 18). Another study states that 65% of monsoon-influenced Himalayan glaciers are retreating and those which are heavily debris covered have stable fronts between 2000 and 2008 (ref. 19). The study also found that the maximum rate of retreat of the glaciers was 80 m/yr. Rate of length, area and mass changes for glaciers for the Himalayan–Karakoram region have been reviewed[31]. The study[31] reveals that there is 0.4%/yr loss in area from 1969 to 2010 for small glaciers of the Trans-Himalayan region 0.2% to 0.7%/yr from 1960s to 2001 in the Indian Himalaya and 0.12%/yr from 1968 to 2007 in Garhwal Himalaya.

From the aforementioned discussion and the results of the present study it can be inferred that the number and rate of glacier retreat have come down in the last decade compared to the results of other studies carried out for a period prior to 2001.

The results of the present study indicate that most of the glaciers were in a steady state compared to the results of other studies carried out for the period prior to 2001. This period of monitoring almost corresponds to hiatus in global warming in the last decade[32]. It may happen that an interval of one decade could be smaller than the response time of glaciers to be reflected in terms of any significant change with 23.5 m spatial resolution of data. This point requires further studies using high-resolution data for a longer interval of time.

1. Dobhal, D. P., Gergan, J. T. and Thayyen, R. J., Recession and morphogeometrical changes of Dokriani glacier (1962–1995), Uttarakhand Himalaya, India. *Curr. Sci.*, 2004, **86**(5), 692–696.
2. Dobhal, D. P., Gergan, J. T. and Thayyen, R. J., Mass balance studies of Dokriani glacier from 1992–2000, Uttarakhand Himalaya, India. *Bull. Glaciol. Res.*, 2008, **25**, 9–17.
3. Raina, V. K., Kaul, M. K. and Sing, S., Mass budget of the Gara glacier. *J. Glaciol.*, 1977, **18**(80), 415–423.
4. Raina, V. K., Status of glacier studies in India. *Himalayan Geol.*, 2005, **26**(1), 285–293.
5. Naithani, A. K., Nainwal, H. C., Sati, K. K. and Prasad, C., Geomorphological evidences of retreat of Gangotri glacier and its characteristics. *Curr. Sci.*, 2001, **80**, 87–94.
6. Nainwal, H. C., Chaudhary, M., Rana, N., Negi, B. D. S., Negi, R. S., Juyal, N. and Singhvi, A. K., Chronology of the late Quaternary glaciation around Badrinath (Upper Alaknanda basin): preliminary observations. *Curr. Sci.*, 2007, **93**(1), 90–96.
7. Singh, R. K. and Sangewar, C. V., Mass balance variation and its impact on glacier flow movement at Shaune Garang glacier Kinnaur, H.P. In Proceeding of National Meet on Himalayan Glaciology, New Delhi, 1989, pp. 149–152.
8. Yamada, T. *et al.*, Fluctuations of the glaciers from 1970s to 1989 in the Khumbu, Shorong and Langtang regions, Nepal Himalaya. *Bull. Glaciers Res.*, 1992, **10**, 11–19.
9. Wagnon, P. *et al.*, Four years of mass balance on Chota Shigri glacier, Himachal Pradesh, India. A new benchmark glacier in the western Himalaya. *J. Glaciol.*, 2007, **53**(183), 603–611.
10. Ajai *et al.*, Snow and glaciers of the Himalayas. Report of Space Applications Centre, Ahmedabad, 2011, ISBN 13 978-81-909978-7-4.

11. Bahuguna, I. M., Kulkarni, A. V. and Nayak, S., DEM from IRS 1C PAN stereo coverages over Himalayan glaciated region–accuracy and its utility. *Int. J. Remote Sensing*, 2004, **25**(19), 4029–4041.
12. Bahuguna, I. M., Kulkarni, A. V., Nayak, S., Rathore, B. P., Negi, H. S. and Mathur, P., Himalayan glacier retreat using IRS 1C PAN stereo data. *Int. J. Remote Sensing*, 2007, **28**(2), 437–442.
13. Bhambri, R., Bolch, T., Chaujar, R. K. and Kulshreshtha, S. C., Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. *J. Glaciol.*, 2011, **57**, 543.
14. Bolch, T., Menounos, B. and Wheate, R., Landsat-based inventory of glaciers in Western Canada, 1985–2005. *Remote Sensing Environ.*, 2010, **114**, 127–137.
15. Donghui, S. *et al.*, Monitoring the glacier changes in the Muztag Ata and Konggur mountains, east Pamir, based on Chinese glacier inventory and recent satellite imagery. *Ann. Glaciol.*, 2006, **43**, 79–85.
16. Khromova, T. E., Osipova, G. B., Tsvetkov, D. G., Dyurgerov, M. B. and Barry, R. G., Changes in glacier extents in the eastern Pamir, central Asia, determined from historical data and Aster imagery. *Remote Sensing Environ.*, 2006, **102**, 24–32.
17. Kulkarni, A. V., Rathore, B. P., Singh, S. K. and Bahuguna, I. M., Understanding changes in the Himalayan cryosphere using remote sensing techniques. *Int. J. Remote Sensing*, 2011, **32**(3), 601–615.
18. Li, Z., Sun, W. and Zeng, Q., Measurements of glacier variation in the Tibetan plateau using Landsat data. *Remote Sensing Environ.*, 1998, **63**, 258–264.
19. Scherler, D., Bookhagen, B. and Strecker, M. R., Spatial variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.*, 2011, **4**, 156–160.
20. Silverio, W. and Jaquet, J., Glacier cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery. *Remote Sensing Environ.*, 2005, **95**, 342–350.
21. GLCF Landsat data; http://glcf.umd.edu/data/landsat/
22. Benn, D. I. and Evans, D. J. A., *Glaciers and Glaciation*, Hodder Education, London, 2010, p. 802.
23. Owen, L. A. and Benn, D. I., Equilibrium line altitude of the last glacial maxima for the Himalaya and Tibet: an assessment and evaluation of results. *Quaternary Int.*, 2005, **138–139**, 55–78.
24. Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S. and Dhar, S., Glacier retreat in Himalaya using Indian Remote Sensing Satellite data. *Curr. Sci.*, 2007, **92**(1), 69–74.
25. Brahmbhatt, Rupal, M., Bahuguna, I. M., Rathore, B. P., Kulkarni, A. V., Nainwal, H. C., Shah, R. D. and Ajai, A comparative study of deglaciation in two neighbouring basins (Warwan and Bhut) of Western Himalaya. *Curr. Sci.*, 2012, **103**(3), 298–304.
26. Silverio, W. and Jaquet, J., Multi-temporal and multi source cartography of the glacier cover of Nevado Corpuna (Arequipa, Peru) between 1955 and 2003. *Int. J. Remote Sensing*, 2012, **33**(18), pp. 5876–5888.
27. Hewitt, K., The Karakoram Anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. *Mt. Res. Dev.*, 2005, **25**(4), 332–340.
28. Mayer, C., Fowler, A. C., Lambrecht, A. and Scharrer, K., A surge of North Gasherbrum Glacier, Karakoram, China. *J. Glaciol.*, 2011, **57**(204), 904–916.
29. Gardelle, J., Berthier, E. and Arnaud, Y., Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geosci.*, 2012, **5**, 322–325; doi: 10.1038/NGEO1450.
30. Kaab, A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y., Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, 2012, **488**, 495–498.
31. Bolch, T. *et al.*, The state and fate of Himalayan glaciers. *Science*, 2012, **336**, 310–314.
32. Bala, G., Why the hiatus in global warming in the last decade? *Curr. Sci.*, 2013, **105**(8), 1031–1032.

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