Recent glacier area changes in Himalaya–Karakoram and the impact of latitudinal variation

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We present the observed area changes in 5234 glaciers (out of which 3435 are debris-free) of Himalaya–Karakoram (H–K) region, mapped at a scale of 1 : 25,000 using primarily IRS LISS III data between the years 2001 and 2016/2017/2018. Area change is a direct observable parameter in the monitoring of glaciers. The mapping results have been analysed in different sectors of H–K region. In the Karakoram region, 2143 glacier bodies with an area coverage of 18343.39 km^2 show a gain of 0.026%, whereas in Himalayan region, 3091 glaciers covering an area of 11451.53 km^2 show a loss of 1.44% over a span of 17 years. Loss in glacier area in Himalayan region varies from 0.76% in sub-basins located in the left side of NW flowing Indus River (N–W Himalaya/J&K and Ladakh), 2.2% in Chenab and Sutlej basins (Western Himalaya/Himachal Pradesh), 0.84% in Ganga basin (West-Central Himalaya/Uttarakhand), 2.16% in Ganga basin (Central Himalaya/Nepal and a few glaciers of Tibetan region) and 2.15% in Tista sub-basin (Eastern Himalaya/Sikkim). The mapping uncertainty is less than 0.01%. The results also show that debris free glaciers are more vulnerable to global warming thereby affirming the earlier theories of differential impact of warming on debris free and debris covered glaciers. Overall, the statistics clearly indicate the effect of latitudinal variations on the gain/loss in the area of glaciers from higher to lower latitudes in addition to microclimatic and geomorphological factors.

Keywords: Ablation, accumulation, glacier retreat, snout, latitudinal variation.

REPEATED coverage of the earth's surface using satellites for over half a century has made it possible to map and model changes in area and mass of glaciated regions arising due to global warming[1]. However, the rate at which such changes are happening and their impact on water resources should be known to environmental scientists and policy-makers. Rising global concern on the changes occurring in glacier area or volume is not only because glaciers are one of the most susceptible indicators of climatic variations among all natural land-cover features, but also because such changes might have future implications for freshwater resources[2–5] and sea-level rise[6]. Glaciers, excluding Greenland and Antarctic ice-sheets, cover approximately 706,000 sq. km area globally and contain an estimated total volume of 170,000 km^3 of ice which is equivalent to 0.4 m of potential sea-level rise[7,8]. Between 1961 and 2016, glaciers have contributed 27 ± 22 mm to global mean sea-level rise[9]. An IPCC report mentions that there is a general decline in low-elevation snow cover (high confidence), glaciers (very high confidence) and permafrost (high confidence), and changes in snow and glaciers have changed the amount and seasonality of run-off in snow-dominated and glacier-fed river basins (very high confidence) with local impacts on water resources and agriculture (medium confidence) due to climate change in recent decades[10]. Although the mass of the earth's cryosphere has been fluctuating according to natural climatic variations since the geological past, the present decline has been attributed to recent increase in greenhouse gases (GHGs) concentration in the atmosphere[11] that traps the longwave radiations and increases atmospheric temperature[12]. A considerable part of this entire cryospheric mass is located in High Mountain Asia, which includes two prominent high altitude mountain ranges north of the Indian subcontinent, known as the Himalaya and Karakoram (H–K). This mountain system to the north of the Indian land mass with an arcuate strike of NW–SE for about 2400 km holds one of the largest

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concentrations of glaciers outside the polar regions in its high-altitude areas and has been rightly termed as Asia's 'Water Tower', supporting the economy of millions of people through its drainage system. These mountains have ~17% of their area covered by glaciers, which influence the climate, regional hydrology and environment of the Indian subcontinent[13]. These ice masses are a perennial water source to tributaries and drainages of the Indus, Ganga and Brahmaputra river systems. The water of these rivers is the backbone of Indian economy as many hydropower projects, irrigation in the plains and domestic water needs depend upon the volume of water available in these river basins. The glaciers of the Himalayan region are in a general state of retreat following the global pattern[14]. This attributed to the global rise in temperatures especially in the Himalayan region, which has been reported higher than the global average[15,16]. The retreat can also be confirmed by the occurrence of some palaeo-glacio-morphological features in the vicinity of existing glacier bodies[17–19]. Contrary to the overall retreat, some glaciers of the Karakoram ranges (draining into the Indus basin), further west of the Himalayan ranges, show advancing or stable patterns[20–25]. Surging behaviour in this region remains to be resolved and the mechanism needs to be explained with more understanding of intrinsic and meteorological parameters[26]. In view of these contrasting observations, monitoring of the H–K glaciers is of utmost significance to assess the futuristic changes in glacier-stored water. However, it is challenging to get a holistic view of the plethora of glaciers in a short time interval in the rugged, difficult to access mountainous H–K region by field methods alone. Most of the results of cryospheric changes taking place on earth have come to light due to the utilization of satellite data.

Specially for glaciers of the world, two types of studies have been commonly conducted using satellite data, i.e. changes in area of glaciers and mass changes of glaciers (geodetic methods) using DEM of two different time-frames. While glacier area is a directly observable parameter on images, mass balance needs to be derived through a set of processes involving surface elevation changes and statistical procedures which rely heavily upon the accuracy of empirical models or the errors or deviations involved in DEMs, etc.[1,27–31]. Area changes can also be used for finding mass changes of glaciers, as a pertinent relationship exists between area and volume of glaciers within a given topography[32,33]. Realizing the need to monitor snow and glaciers through spaceborne data, the Space Applications Centre (Indian Space Research Organisation), Ahmedabad, has been monitoring the Himalayan glaciers for the last two decades. One of the first assessments of glacier retreat in the Himalayan region based on the shift in snouts of glaciers was done for eight glaciers of the Baspa sub-basin of Satluj basin using high-resolution IRS 1C PAN orthoimages of ablation season of 1999 and topographical maps of 1962 (ref. 34). This was followed by a series of studies on the retreat of glaciers using loss in the area as a parameter for glaciers of Baspa sub-basin[35]; Parbati glacier[36]; Samudra Tapu glacier[37]; Gangotri glacier[38]; 466 glaciers of the Chenab basin[39] and 2630 glaciers from different sub-basins in the Himalaya[40,41]. These studies were based on two different types of datasets, i.e. topographical maps (orthorectified) and IRS LISS III/Landsat images (unorthorectified), which might have resulted in error in the registration of outlines of glaciers, specially arising due to high relief mountainous terrain of the Himalaya. The complexities of registration were resolved for better estimates when change in the area of glaciers (2018 glaciers) using LISS III (orthorectified using Landsat TM images) and a few Landsat TM orthorectified images (less than 15% of total data) of for 2000–01 and 2010–11 was mapped considering similarity in spatial resolution[42]. This study had a shorter time interval for the change to be reflected spatial resolution of the data used. As a follow-up of this study, area change between 2001 and 2016–18 (longer time interval than the last study) for 5234 glaciers has been mapped at a scale of 1 : 25,000 using IRS LISS III data and partially Landsat TM and OLI data across the H–K region spanning from Kashmir in the west to Sikkim in the east. It includes glaciers of Jammu and Kashmir (J&K), Ladakh, Himachal Pradesh, Uttarakhand and Sikkim in India, and a few glaciers of Nepal and the adjoining Tibetan region in the north. It does not include all the glaciers of the sub-basins but only those glaciers which could be confidently interpreted in both the images. Figure 1 shows the distribution of glaciers in the H–K region. This article presents the results of this exercise along with other associated observations.

Methodology

The satellite data analysis and glacier features interpretation were carried out for the peak ablation period when snow cover over the glaciers was minimum, or most of the glacier ice was exposed on the surface. The highest ablation in glaciers normally occurs between July and September in Western Himalaya, and it shifts to later months as we go towards Central or Eastern Himalaya. The ablation time of glaciers most often coincides with frequent cloud cover over the region produced either locally or due to monsoonal winds during these months, making the task of procuring the ideal datasets for the entire Himalayan belt within one season rather difficult as the repeativity of LISS III or Landsat data is 24 and 16 days respectively, and swath of coverage is less than 200 km, hence, multi-year data are used. In the present study, 2001 was an ideal year for mapping glaciers as most of the scenes were found to be without cloud cover and had minimal snow cover. However, later sets of data had to be chosen from different years and not a single

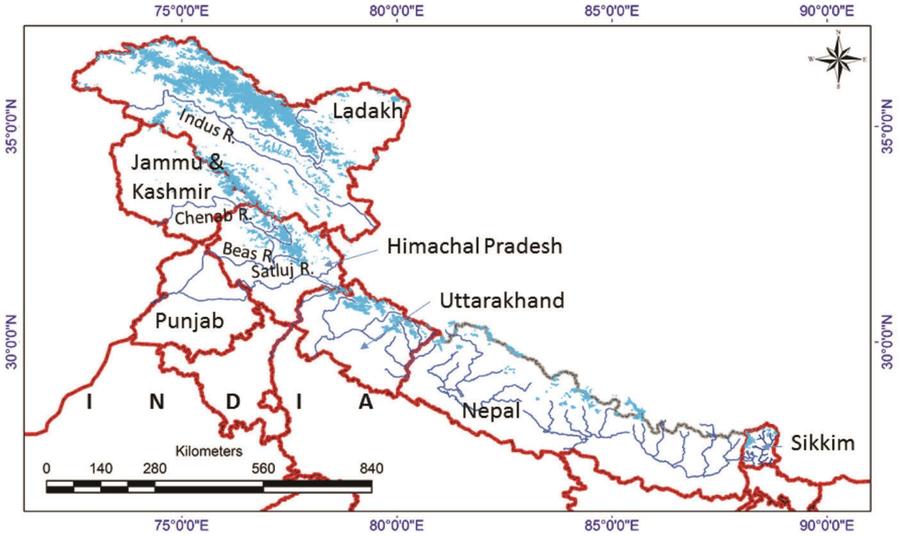

Figure 1. Spatial distribution of the monitored glaciers in Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim (states of India), and parts of Nepal and Tibetan Autonomous Region (N-TAR).

year. Majority of the data used are IRS LISS III but wherever the LISS III scenes were not found suitable for mapping, Landsat data were used. In this study, on-screen interpretation and digitization have been used for the mapping of glaciers as most of the automatic techniques discussed in the literature have not become operational so far. One of the major reasons is the variation in surface properties of materials of glaciers in time and space. In the context of optical images, glacier surface properties include properties of snow, ice and rock debris. It is beyond the scope of this article to discuss the limitations and potential of various techniques of automation. A few approaches include thermal remote sensing[43], segmentation of ratioed images[44], object-based image analysis[45,46], and supervised and unsupervised classification[47,48], etc.

The scale for mapping was fixed at 1 : 25,000 for all the areas so that there remain no discrepancies or digitization errors due to differences in scales. Delineation of glaciers using remote sensing data was done following the methods and procedures given in other similar studies[32–39]. The change in the area of glaciers was visually analysed before mapping. Due to a high degree of subjectivity involved in manual delineation, quality checking of maps was carried out at three levels, i.e. (i) by the mapping team itself, (ii) cross-checking by a second team, and (iii) checking by experts in visual interpretations. Thus, an effort was made to resolve all the ambiguities. Here, we are repeating a few points from previously described methodology, which were taken into consideration while mapping changes in the glaciers.

(a) Debris-free glaciers can be easily distinguished using remote sensing (RS) data as bare ice has distinct reflectance properties in comparison to its surrounding features[49]. In debris-covered glaciers, snouts and outlines of ablation zones were verified using high resolution Google time-series data. Viewing Google images can effectively replace ground validation, especially while dealing with large, inaccessible mountainous terrain. Images were overlaid on SRTM/ASTER DEM to gain more confidence in interpretation of debris-covered glaciers. By inspecting DEM, we can get information on slope of the terrain, its aspect, relative positions of various locations with respect to the source of debris, etc. This helps in better identification of debris-covered glacier features. The chances of errors in interpretation of debris-free glaciers are almost negligible, as the glacial snow and ice have contrasting spectral signatures compared to that of the surrounding landscape, making them conspicuous[50]. Errors can arise on marginal pixels where ice is in the lower ablation zone of the glaciers which experiences change. If the ice is buried beneath debris cover, it is not readily apparent on the images, but indications of a shift in snout can be identified from the texture of debris or exposure of meltwater stream.

(b) Glacier outlines of the accumulation zones were marked along the ridges. Ridges are frequently obscured by shadows; hence multi-date scenes were used to overcome this problem. Snouts were identified by observing the origin of drainage from the glacier. Most of the glaciers have a cave-like morphology at the terminus, which casts a shadow that can be distinctly observed on high-resolution data. In glaciers where lateral moraines are present, outlines remain in the inner side of the moraines. Once the outlines were mapped from one dataset, the layers were overlaid on the second dataset to determine the changes. Such changes have been mapped only in ablation zones or near the terminus. This is because the long-term mass balance changes are reflected in the shift of the snout and change in the area of ablation[51].

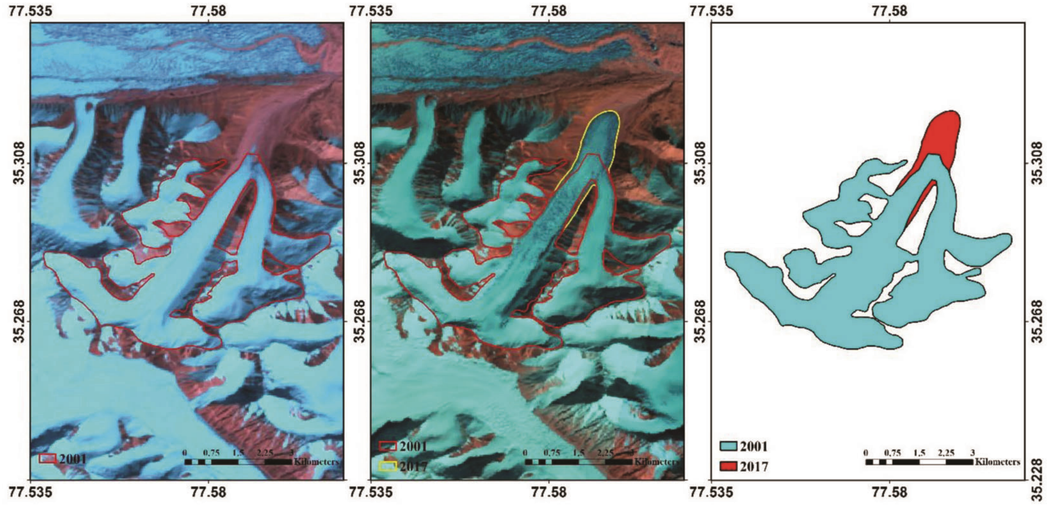

Figure 2. Panel showing two images (2001 (left) and 2017 (middle)) used for mapping changes (right) in the area of a near debris-free valley glacier (advancement/surging).

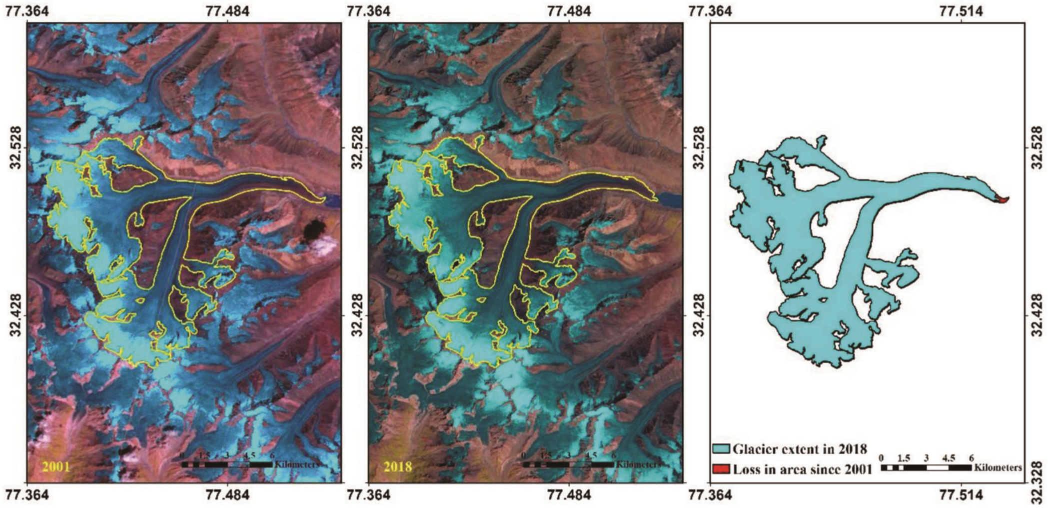

Figure 3. Panel showing two images (2001 (left) and 2018 (middle)) used for mapping changes (right) in the area of a partial debris-covered valley glacier in Chandra sub-basin (Samudra Tapu glacier), Himachal Pradesh.

(c) Considerable snow cover is seen sometimes over glaciers and it is considered that the data are not suitable for mapping. However, it has been observed on several glaciers that snow remains well within the confines of glacier area due to lower temperatures on the glaciers than outside of it, making the glacier outlines distinguishable most of the time. If any exposure of rock was seen in the accumulation zone due to lack of snow, its area was adjusted in the two maps so that there was no disparity in the two polygons due to exposure. Figures 2 and 3 show some examples of glacier maps along with two images of base and reference years. The examples show advancement/surging, and retreat of a debris-covered glacier as well as a debris-free glacier. All the changes in glaciers in this study have been mapped like these examples.

The area change statistics have been analysed with respect to different climatic areas of the H–K region. The glacier change analysis carried out in this study has been substantiated with 20 years of ERA-5 temperature data analysis in the Indus and Ganga basins corresponding to June, July, August and September.

Results, observations and analysis

For spatial analysis of glacier retreat/advance, we have divided the mapped glaciers into the following six regions:

(i) Karakoram region (right of near NW flow of Indus river): Some more glaciers in the adjoining areas are also

Table 1. Sub-basin-wise summary of change in area of glaciers of the Himalaya–Karakoram (H–K) region

Regions of sub-basins	No. of glaciers	Glacier area in 2001 (sq. km)	Glacier area in 2017 (sq. km)	Change in glacier area (sq. km)	% Change in glacier area
Karakoram	2143	18343.39	18348.19	4.80	0.03 ± 0.0004
Jammu and Kashmir and Ladakh	1058	3718.58	3690.44	–28.14	–0.76 ± 0.024
Himachal Pradesh	1265	2597.43	2539.88	–57.55	–2.22 ± 0.148
Uttarakhand	353	2417.59	2397.21	–20.38	–0.84 ± 0.044
Nepal and adjoining Tibetan region	319	2224.11	2175.96	–48.14	–2.16 ± 0.027
Sikkim	96	493.82	483.22	–10.60	–2.15 ± 0.116
Total	5234	29794.90	29634.90	–159.99	–0.54 ± 0.023

Table 2. Sub-basin-wise summary of change in area of debris or partially debris-covered glaciers of the H–K region

Regions of sub-basins	No. of debris-covered glaciers	Glacier area in 2001 (sq. km)	Glacier area in 2017 (sq. km)	Change in glacier area (sq. km)	% Change in glacier area
Karakoram	740	15543.78	15549.75	5.96	0.04
Jammu and Kashmir and Ladakh	626	928.77	912.22	–16.55	–1.78
Himachal Pradesh	321	1326.89	1311.71	–15.18	–1.14
Uttarakhand	200	2119.54	2107.96	–11.57	–0.55
Nepal and adjoining Tibetan region	90	1414.18	1396.94	–17.24	–1.22
Sikkim	16	329.03	325.33	–3.71	–1.13
Total	1993	21662.18	21603.90	–58.29	–0.27

Table 3. Sub-basin-wise summary of change in area of debris-free glaciers of the H–K region

Regions of sub-basins	No. of debris-free glaciers	Glacier area in 2001 (sq. km)	Glacier area in 2017 (sq. km)	Change in glacier area (sq. km)	% Change in glacier area
Karakoram	1403	2799.60	2798.44	–1.16	–0.04
Jammu and Kashmir and Ladakh	432	2789.81	2778.22	–11.59	–0.42
Himachal Pradesh	944	1270.55	1228.19	–42.36	–3.33
Uttarakhand	153	298.06	289.26	–8.80	–2.95
Nepal and adjoining Tibetan region	229	809.93	779.03	–30.90	–3.82
Sikkim	80	164.79	157.89	–6.90	–4.19
Total	3241	8132.74	8031.03	–101.71	–1.25

covered in this region. Other glaciers are found near Pangong lake and N–E of the Shyok river. Most of these glaciers are a part of J&K and Ladakh, India. The sub-basins covered are Gilgit, Hanza, Shigar, Shasgan, Nubra and Shyok.

(ii) NW Himalaya region: Most of these glaciers are part of J&K and Ladakh. The sub-basins covered are Jhelum, Astor, Zanskar, Bhut and Warwan. The last two are tributaries of Chenab river, which later joins the River Indus, and the rest of the sub-basins directly drain into the Indus river.

(iii) Western Himalaya region covering Chenab and Satluj basins in Himachal Pradesh: The glaciers of Chenab and Satluj basins are included in this region. The sub-basins of Chenab are Chandra, Bhaga, Miyar and Ravi. The sub-basins of Satluj are Spiti, Baspa, Beas and Parbati. All these sub-basins are a part of Himachal Pradesh.

(iv) West–Central Himalayan region covering glaciated areas of Uttarakhand: the glaciers of Yamuna, Bhagirathi, Alaknanda, Goriganga, Dhauliganga sub-basins of the Ganga basin in Uttarakhand are covered in this region.

(v) Central Himalayan region covering glaciated parts of Nepal and adjoining areas: The glaciers of Karnali and Gandaki sub-basins and those in the adjoining Tibetan region have been mapped here.

(vi) Eastern Himalaya region covering glaciated parts of Tista basin in Sikkim.

The area change statistics of all the mapped glaciers of the six regions has been summarized and categorized for each region into three groups. One part deals with changes in the total number of glaciers/ice bodies (Table 1). The second part deals with changes in only debris-covered glaciers (Table 2). Third part deals with changes in only debris-free glaciers in each sub-basin (Table 3). This has been done with an explicit objective of expounding our findings vis-à-vis several research publications which claim that debris cover on glaciers protects them from net radiation or turbulent flux of heat[52–56].

The results of area changes of 5234 glaciers clearly indicate the contrast in the changes of glaciers in the Karakoram region and the rest of the Himalayan region. In the Karakoram region, 2143 glacier bodies were

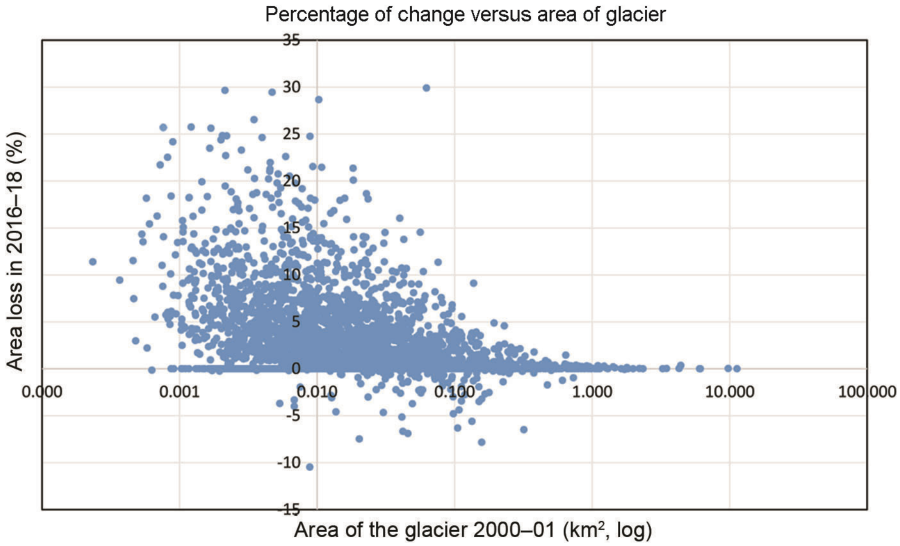

Figure 4. Scatter plot showing area of glaciers (*x*-axis) monitored (2000–01) and the percentage loss (*y*-axis; 2016–18) based on data of 5234 glaciers. The figure shows that loss of area is more in the smaller than large glaciers. Most of the glaciers in the present study are less than 200 sq. km in area. An almost equal number of glaciers show virtually no change in area. The advance and surge are represented in negative percentage change, especially in the Karakoram region.

mapped with a gain in area (0.03%) in the area coverage of 18,343.39 sq. km. The loss was observed only in the Himalayan region, which varied from 0.76% in NW Himalayan region, 2.22% in Chenab and Satluj basins of Himachal Pradesh, 0.84% in Ganga basin of Uttarakhand, 2.16% in parts of Nepal and Tibetan region, to 2.15% in Tista sub-basin of Sikkim. The total 5234 ice bodies include 3241 debris-free glaciers. The loss of debris-free glaciers also varied from higher to lower latitude. It was 0.04% in Karakoram sub-basins, 0.42% in NW Himalayan sub-basins, 3.33% in Chenab and Satluj sub-basins of Himachal Pradesh, 2.95% in sub-basins of Ganga basin in Uttarakhand, 3.82% in the sub-basins of Ganga basin in parts of Nepal–Tibetan region and 4.19% in Tista sub-basin of Sikkim. This affirms the earlier theories of differential impact of warming on debris-free and debris-covered glaciers. Thematic layer of glacier outline of present database is available at visualization of earth observation data and archival system (VEDAS) (https://vedas.sac.gov.in/en/).

From the climate change point of view, monitoring of debris-free masses of ice can become crucial as the effect of warming can be directly observed on these glaciers, thus enabling them as best indicators of global warming. These types of glaciers are typically located at high altitudes. Glaciers of the Spiti sub-basin, parts of Ladakh in the southeast of Pangong-Sho and north of the Alaknanda sub-basin are a few examples of debris-free glaciers. However, a different argument has emerged regarding the role of debris cover on ablation. Recent geodetic mass-balance measurements reveal similar thinning rates on glaciers with or without debris cover in the H–K region[57]. In another study, debris covered or partially debris-covered glaciers in Karakoram have shown almost no retreat in comparison to other parts of the H–K region[58].

Changes in area of glaciers have been checked and compared against initial area of each glacier. Figure 4 shows a scatter plot of the area of all glaciers versus changes in the area in later years. It shows that most of the studied glaciers are less than 200 sq. km in area. The advance and surge are represented in positive percentage change, especially in the Karakoram region. The figure also indicates that a large number of glaciers show virtually no change in the area. Coincidentally, it also reveals that large glaciers do not show any significant change in area (in percentage). The reason for this change in area is related to response time of a glacier to get adjusted with change in its mass balance[51].

Another observation from the data is that the gain or loss in area of glaciers is governed by latitudinal variations in the location of sub-basins (Figure 5 *a*). This latitudinal effect on glacier retreat would not have surfaced if many glaciers of the H–K region were not monitored simultaneously. The area loss increases from higher to lower latitude regions, with exception of Uttrakhand (Figure 5 *b*). This observation has been supported with analysis of regional temperature data.

Uncertainty in the results

The thematic uncertainty in the interpretation of debris-free glaciers could be only due to peripheral pixels of polygons of change in area between two time-frames[55]. The confidence level for finding changes in debris-free glaciers is highest. However, in the case of debris-covered glaciers, the uncertainty could be higher due to complexities involved in interpretation. The changes in glacier extent have been computed while maintaining the consistency of data from the same sensor. The error while registering the 2001 and later images is not more than half a pixel. The following relations have been used to estimate uncertainty in mapping of change in glacier area.

$$\Delta p = \frac{(\text{Perimeter 2001} - \text{perimeter in 2017})}{(\text{Spatial resolution of the pixel})},$$

where Δp is the change in the number of peripheral pixels.

$$\%\ \text{Mapping uncertainty} = \frac{\Delta p * \text{area of one pixel} * 100}{\text{Area of the base year} * 2}.$$

Plausible causes of heterogeneity

Regional driver (temperature): The change in area of glaciers varies from one glacier to another in each sub-basin. Though there is heterogeneity in change in area from west to east, there is near homogeneity within different climatic regions. This is because there are many governing factors, external (micro-climate) or inherent, which control the mass balance of glaciers and indirectly their stability, retreat or advance of glaciers[59]. We analysed the results with respect to two major drivers as possible causes of heterogeneity, i.e. temperature and debris cover. A combined SASE-DRDO and IMD study has shown that more than 80% (from 89 observatories) of the stations under study had a strong negative precipitation tendency rate over Western Himalaya in the winters between 1971 and 2013 (ref. 60). The results confirm the decreasing trends in winter precipitation, indicating the impact of climate change and precipitation variability in Western Himalayan region. In the present study, we also considered the temperature changes in two major basins, i.e. Indus and Ganga using ERA-5 reanalysis data. The data corresponding to the glaciated region were downloaded for June, July, August and September from 2000 to 2020. These months correspond to the ablation season of glaciers when melting is maximum. Data of 1300 and 0100 h UTC were chosen as analysis time as they correspond to maximum and minimum temperatures. Figure 6 *a* shows the average air temperature over Indus basin. Figure 6 *b* shows average air temperature above the surface of Ganga basin. Considering the temperature trends in both the basins, the rise of temperature was more in the Ganga basin (~1°) than in the Indus basin (~0.4°) in 20 years. Therefore, it is expected that the effect of rise in temperature on the glaciers will be more pronounced in the Ganga basin than in the Indus basin. This finding has significance with the results of retreat. Broadly, it matched with the results of retreat or no retreat in the Karakoram region. More analysis is required based on different climatic zones of the H–K region.

From the monthly comparison of average temperature rise in Figure 5, it is clear that the increase in temperature is higher in September than in the earlier months in both the basins. The results suggest that the effect of warming might slowly enter from September to the following months. One study has already indicated that glacier ablation continued in the post-monsoon into the mid-winter period, in some cases[61]. This shows that the duration of the ablation period over glaciers is increasing.

Local drivers (debris cover): Among all local drivers which cause heterogeneity in the mass balance of glaciers directly and retreat of glaciers indirectly, the major ones are micro-climate, morphological characteristics, surrounding geomorphology and lithology of rocks, and the initial energy state of a glacier. Morphological characteristics, and geomorphology and lithology of rocks, besides controlling the energy budget also govern the distribution of debris cover on the ablation zones of glaciers. It comes from broken rock fragments in the adjoining mountains, avalanches or movement of glaciers. Debris cover varies in terms of surface area cover, composition, density, texture, size and thickness of sediments from one glacier to another. Figure 7 provides an example of variation in the reflectance over debris covered glaciers. The ablation zones of these glaciers are partially (Chota Shigri) or fully covered by debris cover (Milam and Miyar). The percentage reflectance which differs from one glacier to another in all the four bands of LISS III indicates variations in composition of debris cover.

Some studies demonstrate a consistent nonlinear relationship between debris thickness and melt rates[62]. When it is thin, debris accumulates heat and transfers it to the ice beneath because it absorbs more heat than snow or ice, but beyond a certain threshold of thickness debris blocks the radiation or heat from directly reaching the ice. There may exist yet another relationship between debris cover and melting of glaciers. The temperature at which ice melts is not constant at 0°C, but decreases as the ice is placed under increasing pressure at a rate of 0.072°C/MPa (ref. 63). For example, the pressure at the base of a glacier 200 m thick is approximately 1.76 MPa, enough to lower the melting to –0.127°C (re-calculated from Negi *et al.*[60]). The lowered melting point of ice is then referred to as the pressure melting point. In the Himalaya, most of the glaciers are located in the high or greater Himalayan region, where rocks are either meta-sedimentary or granitic gneiss or varieties of the same[64]. The average density of such rocks is 2.75 g/cm^3 (compared glacier 0.9 g/cm^3 of ice). Size of sediments of debris cover varies from fine rock fragments of few centimetre in dimension to large-sized boulders. The thickness of debris cover varies from a few centimetres to tens of

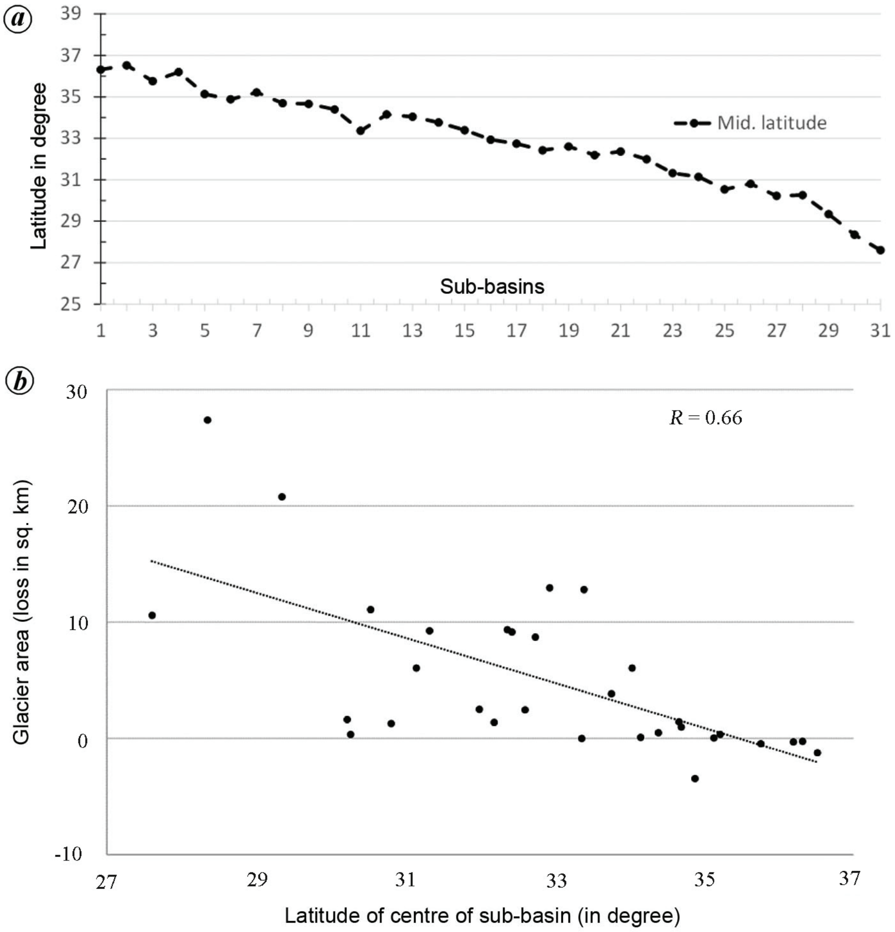

Figure 5. ***a***, Latitudinal distribution of sub-basins across the Himalayan–Karakoram (H–K) region. 1, Gilgit; 2, Hanza; 3, Shigar; 4, Shasgan; 5, Nubra; 6, Shyok; 7, Astor; 8, Kisanganga; 9, Shigo; 10, Dras; 11, Jhelum; 12, Suru; 13, Zaskar; 14, Warwan, 15; Bhut; 16, Miyar; 17, Bhaga; 18, Chandra; 19, Ravi; 20, Beas; 21, Spiti; 22, Parbati; 23, Baspa; 24, Yamuna; 25, Alaknanda; 26, Bhagirathi; 27, Goriganga; 28, Dhauliganga; 29, Karnali; 30, Gandak; 31, Tista. ***b***, Latitudinal variation of loss in glaciated area in the H–K region.

metres. The pressure exerted by debris cover can lower the melting point at the base of the glaciers. Therefore, the role of debris cover is not limited to only blocking heat from reaching the ice, but also in regulating the pressure melting point at the base of glaciers. This component needs to be further explored while analysing the retreat of glaciers and the impact of debris cover on glacial retreat.

Previous studies

A few previous studies on the area loss of Himalayan glaciers are discussed here. The glacial retreat was estimated for 466 glaciers in Chenab, Parbati and Baspa basins between 1962 and 2001. There was an overall reduction in glacier area from 2077 sq. km in 1962 to 1628 sq. km in 2001; overall deglaciation of 21%. Small glacierets and ice fields showed extensive deglaciation. For example, 127 glacierets and ice fields less than 1 sq. km have shown a retreat of 38% from 1962, possibly due to short response time[38].

Using geographical information system (GIS) and remote sensing technologies, quantitative measurements of glacier variations in the Geladandong mountain region of central Tibet from 1969 to 2002 were mapped[65]. Data from Landsat images at three different periods, viz. 1973–76, 1992 and 2002, were compared with glacier areas digitized from a topographic map based on aerial photographs taken in 1969. While some glaciers had advanced during the past 30 years, others had retreated. The area of the retreat was much larger than that of advance. The total glacier area had decreased from 889 sq. km in 1969 to 847 sq. km in 2002, a reduction of almost 43 sq. km (i.e. 4.8% decrease). The variation of glacier area in the Geladandong mountain region was not as significant as in the other areas within the Tibetan Plateau. The increase in summer air temperature is likely the primary reason for glacier shrinkage in the Geladandong mountain region.

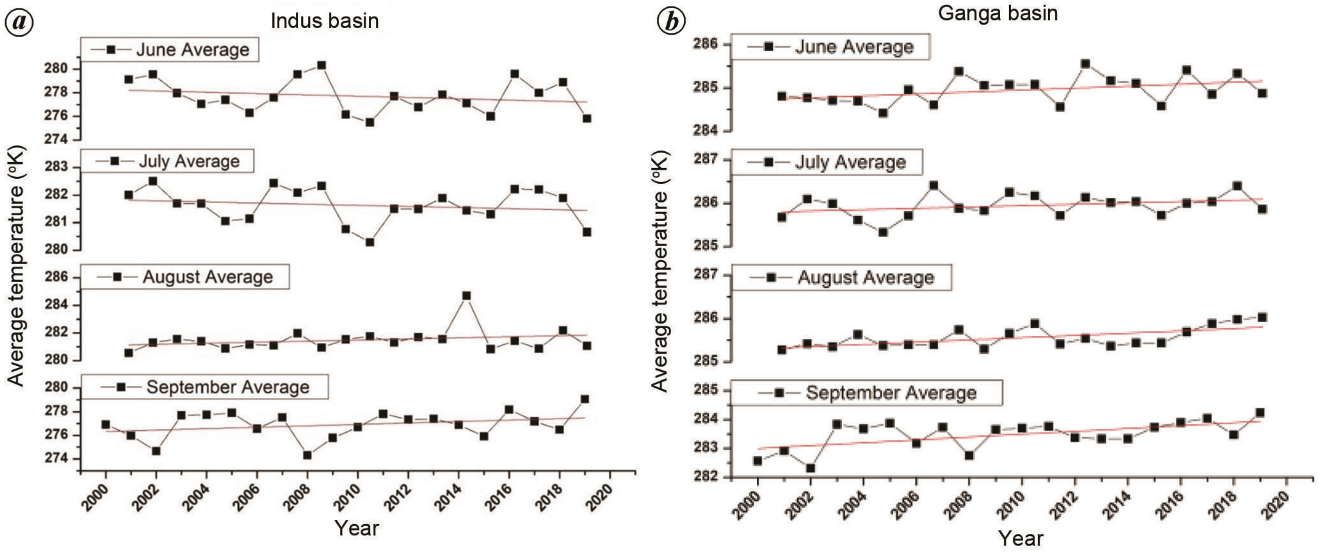

Figure 6. Average daily air temperature observed at 1300 h and 0100 h UTC; data at 2 m above the surface in (***a***) Indus basin and (***b***) Ganga basin during June, July, August, and September from 2000 to 2019 (source: ERA-5 reanalysis data). Note the increasing trend in the Ganga basin and no significant change in the Indus basin.

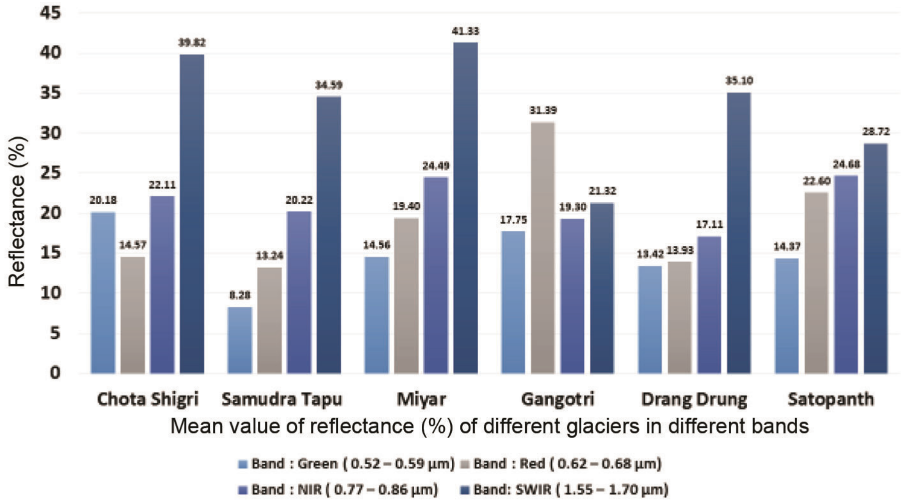

Figure 7. Percentage reflectance from debris cover on some major glaciers. It indicates that different compositions of debris cover respond differently to EMR in the VNIR region.

In another study, 1868 glaciers were monitored in 11 sub-basins distributed in the Indian Himalayas[40,41]. It showed an overall reduction in glacier area from 6332 to 5329 sq. km, or overall deglaciation of 16% from 1962 (based on the outline of glaciers as mapped in Survey of India maps) to 2001–02 (mainly IRS LISS III data of spatial resolution of 23 m).

Changes in different glaciers of the Bhaga basin located in Western Himalaya from 1979 to 2017 were reported[66]. Glacier boundaries were delineated through a semi-automated approach using Landsat satellite imagery. The variation of glacier extent in different elevation zones, snout retreat, and decadal changes were observed. Results show that the total area of glaciers was 238 sq. km in 1979, which reduced to 230.8 sq. km by 2017 (3.025%). Glaciers at low elevation and small in size seem to be faster.

A multi-temporal remote sensing approach based on satellite images (Corona, SPOT and Landsat) was used to detect and analyse area changes of 121 small glaciers, and measure the retreat of 60 cirque and valley glaciers between 1969 and 2010 in Ladakh[67,68]. The region covers about 1000 sq. km and is located in a transitional position between predominantly receding glaciers of the Central Himalaya and some advancing ice masses of the Karakoram. Over the last four decades, the glaciated area has decreased by about 14% (0.3%/year) from 96.4 to 82.6 sq. km, and the average ice front retreat amounts to 125 m (3 m/year). The ice cover loss shows a high decadal variability with maximum shrinkage between 1991 and 2002 (0.6%/year), followed by a slower decrease rate since then (0.2% per year). Due to the high variability of glacier change with a generally decreasing trend and a few stable glaciers, it becomes evident that an extrapolation, even on a regional scale, is problematic. Therefore, considering different responses of various glacier types and glacier sizes is of utmost importance.

Using Corona and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images acquired in 1968 and 2006 respectively, and partially Landsat TM images acquired in 1990, glacier outlines were mapped for the upper Bhagirathi and Saraswati/ Alaknanda basins of the Garhwal Himalaya. Glacier area decreased from 599.9 ± 15.6 (1968) to 572.5 ± sq. km (2006), a loss of 4.6% ± 2.8%. Glaciers in the Saraswati/ Alaknanda basin and upper Bhagirathi basin lost 18.4 ± 9.0 sq. km (5.7% ± 2.7%) and 9.0 ± 7.7 sq. km (3.3% ± 2.8%) area respectively, from 1968 to 2006 (ref. 69).

In one of the earlier studies, 2018 glaciers representing climatically diverse terrain in the Himalaya were mapped and monitored[41]. It included glaciers of Karakoram, Himachal, Zanskar, Uttarakhand, Nepal and Sikkim regions. 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% using data from 2001 and 2010–11.

Thus, these results indicate the effect of global warming on the Himalayan glaciers, but the percentage loss of glacier area does not match among various studies. This is due to differences in time interval, spatial resolution of data used and number of glaciers mapped in a specific study.

Conclusion and future directions

Monitoring of glaciers based on a sample of 5234 glaciers in the H–K region using IRS LISS III images between 2001 and 2016–18 has shown loss of 1.44% and net gain of 0.026% in area of glaciers. The mapping uncertainty is less than 0.01%. The data indicate that the effect of global warming is not universal on glaciers. The debris-free glaciers exhibit more loss in area than partially or fully debris-covered ablation zones of glaciers, though the former are smaller in area, located in relatively higher altitudes and have higher slopes. Data have shown higher rise in temperature in the Ganga basin than the Indus basin. Monthly averages show higher rise in temperature in September indicating lengthening of ablation season. The gain or loss in area of each sub-basin is governed by latitudinal variations regionally at sub-basin scale, besides local controls such as geomorphic characteristics and percentage of debris cover.

It is recommended that mapping at a large scale (~10,000 scale), use of artificial intelligence/deep machine learning-based advanced data processing techniques and algorithms for automation in the mapping of at least debris-free glaciers globally are required to tackle the impact rate of warming on glaciers. The effect of climatic variations should also be gauged through rate of change of precipitation (increasing or decreasing trends) over H–K region, as precipitation might increase due to warming of oceans and northern Eurasian regions. More detailed analysis and arriving at definitive conclusions are possible only when all the grids indicating temperature rise are embedded on change in snow cover or change in glaciers using high computing machines. It is important to mention here that the study of glacier retreat should always be integrated with a study on snow cover or SWE, as the cumulative effect of snow precipitation and change in area or mass of glaciers are mutually dependent. All the studies which are based on geodetic mass balance estimation should be substantiated by data in area loss of the corresponding glaciers to avoid any ambiguity in monitoring.

1. Hugonnet, R. *et al.*, Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 2021, **592**, 726–731.
2. Azam, M. F. *et al.*, Glaciohydrology of the Himalaya–Karakoram. *Science*, 2021; doi:10.1126/science.abf3668.
3. Immerzeel, W. W., van Beek, L. P. H. and Bierkens, M. F. P., Climate change will affect the Asian water towers. *Science*, 2010, **328**, 1382–1385.
4. Huss, M. and Hock, R., Global-scale hydrological response to future glacier mass loss. *Nat. Climate Change*, 2018, **8**, 135–140.
5. Immerzeel, W. W., van Beek, L. P. H., Konz, M., Shrestha, A. B., and Bierkens, M. F. P., Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change*, 2012, 721–736.
6. Gardner, A. S. *et al.*, A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, 2013, **340**, 852–857.
7. RGI, Consortium Randolph Glacier Inventory (v.6.0): a dataset of global glacier outlines. Global land ice measurements from space, RGI Technical Report No. 017, Boulder, Colorado, USA; https://doi.org/10.7265/N5-RGI-60.
8. Huss, M. and Farinotti, D., Distributed ice thickness and volume of all glaciers around the globe. *J. Geophys. Res.*, 2012, **117**, F04010; doi:10.1029/2012JF002523.
9. Zemp, M. *et al.*, Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 2019, **568**, 382–386.
10. Hock, R. *et al.*, High mountain areas. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (eds Pörtner, H.-O. *et al.*), 2019.
11. Marzeion, B., Cogley, J. G., Richter, K. and Parkes, D., Glaciers. Attribution of global glacier mass loss to anthropogenic and natural causes. *Science*, 2014, **345**, 919–921.
12. Ramanathan, V., Trace-gas greenhouse effect and global warming: underlying principles and outstanding issues. Volvo Environmental Prize Lecture – 1997. *Ambio*, 1998, **27**, 187–197.
13. Bajracharya, S. R., Mool, P. K. and Shrestha, B. R., The impact of global warming on the glaciers of the Himalaya. In Proceedings of the International Symposium on Geodisasters, Infrastructure Management and Protection of World Heritage Sites, 2006, pp. 231–242.
14. Racoviteanu, A. E. *et al.*, Himalayan Glaciers (India, Bhutan, Nepal): satellite observations of thinning and retreat. In *Global Land Ice Measurements from Space* (eds Kargel, J. S. *et al.*), Springer Berlin Heidelberg, Berlin, Germany, 2014, pp. 549–582.

15. Shekhar, M. S., Rao, N. N., Paul, S., Bhan, S. C., Singh, G. P. and Singh, A., Winter precipitation climatology over Western Himalaya: altitude and range wise study. *J. Indian Geophys. Union*, 2017, **21**, 148–152.
16. Kulkarni, A. V., Overview of Himalayan cryosphere and emerging issues (Invited talk). In National Workshop on Himalayan Cryosphere, IIRS, Dehradun, 14 February 2020.
17. Naithani, A. K., Nainwal, H. C., Sati, K. K. and Prasad, C., Geomorphological evidences of retreat of the Gangotri glacier and its characteristics. *Curr. Sci.*, 2001, **80**, 87–94.
18. Deota, B. S., Trivedi, Y. N., Kulkarni, A. V., Bahuguna, I. M. and Rathore, B. P., RS and GIS in mapping of geomorphic records and understanding the local controls of glacial retreat from the Baspa Valley, Himachal Pradesh, India. *Curr. Sci.*, 2011, **100**, 1555–1563.
19. Trivedi, Y. N., Deota, B. S., Rathore, B. P., Bahuguna, I. M. and Kulkarni, A. V., IRS images for glacial geomorphological studies of Baspa Valley. *Indian J. Geomorphol.*, 2007, **11**, 12.
20. Hewitt, K., The Karakoram anomaly? Glacier expansion and the ‘elevation effect’, Karakoram Himalaya. *Mt. Res. Dev.*, 2005, **25**, 332–340.
21. 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.
22. Brahmbhatt, R. M. *et al.*, Satellite monitoring of glaciers in the Karakoram from 1977 to 2013: an overall almost stable population of dynamic glaciers, *Cryosphere Discuss.*, 2015, **9**, 1555–1592; doi:10.5194/tcd-9-1555-2015.
23. Bolch, T., Pieczonka, T., Mukherjee, K. and Shea, J., Brief communication: glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1970s. *Cryosphere*, 2017, **11**, 531–539.
24. Ganjoo, R. K., Koul, M. N., Bahuguna, I. M. and Ajai, The complex phenomenon of glaciers of Nubra Valley, Karakorum (Ladakh), India. *Nat. Sci.*, 2014, **6**, 733–740.
25. Koul, M. N., Bahuguna, I. M., Ajai, Rajawat, A. S., Ali, S. and Koul, S., Glacier area change over past 50 years to stable phase in Drass Valley, Ladakh Himalaya (India). *Am. J. Climate Change*, 2016, **5**, 88–102.
26. Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J. and Dehecq, A., Manifestations and mechanisms of the Karakoram glacier anomaly. *Nature Geosci.*, 2020, **13**(1), 8–16.
27. Bahuguna, I. M., Kulkarni, A. V. and Nayak, S., Technical note: DEM from IRS-1C PAN stereo coverages over Himalayan glaciated region – accuracy and its utility. *Int. J. Remote Sensing*, 2004, **25**(19), 4029–4041.
28. Maurer, J. M., Schaefer, J. M., Rupper, S. and Corley, A., Acceleration of ice loss across the Himalayas over the past 40 years. *Sci. Adv.*, 2019, **5**, eaav7266.
29. Nuth, C. and Kääb, A., Co-registration and bias corrections of satellite elevation datasets for quantifying glacier thickness change. *Cryosphere*, 2011, **5**, 271–290.
30. Zhou, Y., Li, Z., Li, J., Zhao, R. and Ding, X., Geodetic glacier mass balance (1975–1999) in the central Pamir using SRTM DEM and KH-9 imagery. *J. Glaciol.*, 2019, **65**(250), 309–320.
31. Brun, F., Berthier, E., Wagnon, P., Kääb, A. and Treichler, D., A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000–2016. *Nature Geosci.*, 2017, **10**, 668–673.
32. Radić, V. and Hock, R., Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *J. Geophys. Res.*, 2010, **115**, F01010.
33. Grinsted, A., An estimate of global glacier volume. *Cryosphere*, 2013, **7**, 141–151.
34. Kulkarni, A. V. and Bahuguna, I. M., Glacial retreat in the Baspa basin, Himalaya, monitored with satellite stereo data. *J. Glaciol.*, 2002, 171–172.
35. Kulkarni, A. V. and Alex, S., Estimation of recent glacial variations in Baspa basin using remote sensing technique. *J. Indian Soc. Remote Sensing*, 2003, 81–90.
36. Kulkarni, A. V., Rathore, B. P., Mahajan, S. and Mathur, P., Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh. *Curr. Sci.*, 2005, **88**, 1844–1850.
37. Kulkarni, A. V., Dhar, S., Rathore, B. P., K., B. G. R. and Kalia, R., Recession of Samudra Tapu glacier, Chandra River Basin, Himachal Pradesh. *J. Indian Soc. Remote Sensing*, 2006, **34**(1), 39–46.
38. 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.
39. Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K. and Dhar, S., Glacial retreat in Himalaya using Indian Remote Sensing Satellite data. *Curr. Sci.*, 2007, **92**, 69–74.
40. 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.
41. SAC, Final Technical Report on snow and glacier studies (a joint project of the Ministry of Environment and Forests and Department of Space, Government of India. Space Applications Centre, ISRO, Ahmedabad, Technical Report No. SAC/RESA/MESG/SGP/TR/59/2010, 2010, p. 268.
42. Bahuguna, I. M. *et al.*, Are the Himalayan glaciers retreating? *Curr. Sci.*, 2014, **106**(7), 1008–1013.
43. Bhambri, R., Bolch, T. and Chaujar, R. K., Automated mapping of debris-covered glaciers in the Garhwal Himalayas using ASTER DEMs and multi-spectral data. *Int. J. Remote Sensing*, 2011, **32**(23), 8095–8119; doi:10.1080/01431161.2010.532821.
44. Paul, F., Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 TM and Austrian Glacier Inventory data. *Int. J. Remote Sensing*, 2002, **23**, 787–799.
45. Paul, F., Combined technologies allow rapid analysis of glacier changes. *Eos, Trans. Am. Geophys. Union*, 2002, **83**(23), 253.
46. Rastner, P., Bolch, T., Notarnicola, C. and Paul, F., A comparison of pixel- and object-based glacier classification with optical satellite images. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sensing*, 2014, **7**(3), 853–862.
47. Robson, B. A., Nuth, C., Dahl, S. O., Hölbling, D., Strozzi, T. and Nielsen, P. R., Automated classification of debris-covered glaciers combining optical, SAR and topographic data in an object-based environment. *Remote Sensing Environ.*, 2015, **170**, 372–387.
48. Shukla, A. and Ali, I., A hierarchical knowledge-based classification for glacier terrain mapping: a case study from Kolahoi Glacier, Kashmir Himalaya. *Ann. Glaciol.*, 2016, **57**(71), 1–10.
49. Kulkarni, A. V. and. Bahuguna, I. M., Role of satellite images in snow and glacial investigations. *Geol. Soc. India Spec. Publ.*, 2001, **53**, 233–240.
50. Pattnaik, S., Singh, S. K. and Bahuguna, I. M., Change detection of debris free glaciers from IRS LISS III images. *Int. J. Rec. Sci. Res.*, 2018, **9**(1J), 23617–23621.
51. Cuffey, K. M. and Paterson, W. S. B., *The Physics of Glaciers*, Academic Press, Amsterdam, 2010, 4th edn, p. 704, ISBN-13: 978-0-1233-69461-4.
52. Scherler, D., Bookhagen, B. and Strecker, M. R., Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.*, 2011, **4**, 156–159.
53. Mattson, L. E., Gardener J. S. and Young, G. J., *Ablation on Debris Covered Glaciers: An Example from Rakhiot Glacier, Punjab Himalaya*, IAHS Publication, 1993, pp. 289–296.
54. Kayastha, R. B., Takeyuchi, Y., Nakawo, M. and Ageta, Y., Practical prediction of ice melting under various thickness of debris cover of Khumbu glacier, Nepal using a positive degree day factor. In *Debris Covered Glacier* (eds Nakawo, M., Raymond, C. F. and Fountain, A.), IAHS Publication, 2000, vol. 264, pp. 71–81.
55. Brahmbhatt, R. *et al.*, A comparative study of deglaciation in two neighbouring basins (Warwan and Bhut) of Western Himalaya. *Curr. Sci.*, 2012, **103**(3), 298–304.

56. Dobhal, D. P., Mehta, M. and Srivastava, D., Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India. *J. Glaciol.*, 2013, **59**(217), 961–971.
57. Banerjee, A., Brief communication: thinning of debris-covered and debris-free glaciers in a warming climate. *Cryosphere*, 2017, **11**, 133–138.
58. Herreid, S. *et al.*, Satellite observations show no net change in the percentage of supraglacial debris-covered area in northern Pakistan from 1977 to 2014. *J. Glaciol.*, 2015, **61**(227), 524–536.
59. Brahmbhatt, R. M. *et al.*, Significance of glacio-morphological factors in the glacier retreat: a case study of part of Chenab basin, Himalaya. *J. Mt. Sci.*, 2017, **14**, 128–141.
60. Negi, H. S., Kanda, N., Shekhar, M. S. and Ganju, A., Recent wintertime climatic variability over the North West Himalayan cryosphere. *Curr. Sci.*, 2018, **114**(4), 760–770.
61. Pelto, M., Winter Season Ablation in 2018 Mount Everest Region, American Geophysical Union blog 'Blogosphere'; https://blogs.agu.org/fromaglaciersperspective/2018/05/17/winter-season-ablation-in-2018-mount-everest-region-himalaya/ (accessed on 6 June 2021).
62. Reid, T. D. and Brock, B. W., An energy-balance model for debris-covered glaciers including heat conduction through the debris layer. *J. Glaciol.*, 2010, 903–916.
63. Benn, D. I. and Evans David, D. J. A., *Glaciers and Glaciation*, Arnold, London, UK, 2010, p. 734.
64. Valdiya, K. S., *The Making of India: Geodynamic Evolution*, MacMillan Publishers, India Ltd, New Delhi, 2010, p. 796.
65. Ye, Q. H. *et al.*, Monitoring glacier variations on Geladandong Mountain, Central Tibetan Plateau, from 1969 to 2002 using remote-sensing and GIS technologies. *J. Glaciol.*, 2006, **52**(179), 537–545.
66. Kaushik, S., Dharpure, J. K., Joshi, P. K., Ramanathan, A. L. and Singh, T., Climate change drives glacier retreat in Bhaga basin located in Himachal Pradesh, India. *Geocarto Int.*, 2019, **35**, 1179–1198; doi:10.1080/10106049.2018.1557260Kaushik2018.
67. Schmidt, S. and Nüsser, M., Changes of high altitude glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, Northwest India. *Arct., Antarct., Alp. Res.*, 2012, **44**(1), 107–121.
68. Schmidt, S. and Nüsser, M., Changes of high altitude glaciers in the trans-Himalaya of Ladakh over the past five decades (1969–2016). *Geosci. J.*, 2017, **7**, 27; doi:10.3390/geosciences7020-027.
69. 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**, 543–556; doi:https://doi.org/10.3189/002214311796905604.

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