Temporal inventory of glaciers in the Suru sub-basin, western Himalaya: Impacts of the regional climate variability

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Abstract

Updated knowledge about the glacier extent and characteristics in the Himalaya cannot be overemphasised. Availability of precise glacier inventories in the latitudinally diverse western Himalayan region is particularly crucial. In this study we have created an inventory of the Suru sub-basin, western Himalaya for year 2017 using Landsat OLI data. Changes in glacier parameters have also been monitored from 1971 to 2017 using temporal satellite remote sensing data and limited field observations. Inventory data show that the sub-basin has 252 glaciers covering 11% of the basin, having an average slope of 25 ±*6*° and dominantly north orientation. The average snow line altitude (SLA) of the basin is 5011 ±*54* masl with smaller (47%) and cleaner (43%) glaciers occupying the bulk area. Longterm climate data (1901-2017) show an increase in the mean annual temperature (T_{max} & T_{min}) by 0.77 ºC (0.25 & 1.3 ºC) in the sub-basin, driving the overall glacier variability in the region. Temporal analysis reveals a glacier shrinkage of ~6 ±0.02%, an average retreat rate of 4.3 ±1.02 ma^{-1}, debris increase of 62% and 22 ±*60* m SLA rise in past 46 years. This confirms their transitional response between the Karakoram and the Greater Himalayan Range (GHR) glaciers. Besides, glaciers in the sub-basin occupy two major ranges, i.e., GHR and Ladakh range (LR) and experience local climate variability, with the GHR glaciers exhibiting a warmer and wetter climate as compared to the LR glaciers. This variability manifestes itself in the varied response of GHR and LR glaciers. While the GHR glaciers exhibit an overall rise in SLA (GHR: 49 ±*69* m; LR: decrease by 18 ±*50* m), the LR glaciers have deglaciated more (LR: 7%; GHR: 6%) with an enhanced accumulation of debris cover (LR: 73%; GHR: 59%). Inferences from this study reveal prevalence of glacier disintegration and overall degeneration, transition of clean ice to partially debris covered glaciers, local climate variability and non-climatic (topographic and morphometric) factor induced heterogeinty in glacier response as the major processes operatives in this region. The dataset Shukla et al., (2019) is accessible at https://doi.pangaea.de/10.1594/PANGAEA.904131

Key words: Suru sub-basin, western Himalaya, glacier inventory, climate change

1 Introduction

State of the Himalayan cryosphere has a bearing on multiple aspects of hydrology, climatology, environment and sustenance of living organisms at large (Immerzeel et al., 2010; Miller et al., 2012). Being sensitive to the ongoing climate fluctutations, glaciers keep adjusting themselves and these adaptations record the changing patterns in the global climate (Bolch et al., 2012). Any alteration in the glacier parameters would ultimately affect the hydrology of the region, thereby influencing the downstream communities (Kaser et al., 2010; Pritchard, 2017). Owing to these reasons, quantifying the mass loss over different Himalayan regions in the past years, ascertaining present status of the cryosphere and how these changes are likely to affect the freshwater accessibility in the region are at the forefront of contemporary cryospheric research (Brun et al. 2017; Sakai and Fujita, 2017). This aptly triggered several regional (Kaab et al., 2012; Gardelle et al., 2013; Brun et al. 2017; Zhou et al., 2018; Azam et al., 2018; Maurer et al., 2019), local (Bhushan et al., 2018; Vijay and Braun, 2018) and glacier specific studies (Dobhal et al., 2013; Bhattacharya et al., 2016; Azam et al., 2016) in the region. These studies at varying scales contribute towards solving the jigsaw puzzle of the Himalayan cryosphere. The regional scale studies operate on small scale for bringing out more comprehensive, holistic and synoptic spatio-temporal patterns of glacier response, the local scale studies monitor glaciers at basin level or groups and offer more details on heterogenous behaviour and plausible reasons thereof. However, the glacier specific studies whether based on field or satellite or integrative information are magnified versions of the local scale studies and hold the potential to provide valuable insights into various morphological, topographic and local-climate induced controls on glacier evolution. Despite these efforts, data on the glacier variability and response remain incomplete, knowledge of the governing processes still preliminary and the future viability pathways of the Himalayan cryospheric components are uncertain.

Though the literature suggests a generalised mass loss scenario (except for the Karakoram region) over the Himalayan glaciers, disparities in rates and pace of shrinkage remain. Maurer et al. (2019) report the average mass wastage of -0.32 m w.e.a^{-1} for the Himalayan glaciers during 1975-2016. They suggest that the glaciers in the eastern Himalaya (-0.46 m w.e.a^{-1}) have experienced slightly higher mass loss as compared to the western (-0.45 m w.e.a^{-1}), followed by the central (-0.38 m w.e.a^{-1}). However, considerable variability in the glacier behaviour exists within the western Himalayas (Scherler et al., 2011; Kaab et al., 2012; Vijay and Braun, 2017; Bhushan et al., 2018; Mölg et al., 2018). Studies suggest that largely the glaciers in the Karakoram Himalayas have either remained stable or gained mass in the last few decades (Kääb et al., 2015; Cogley, 2016), while a contrasting behaviour is observed for the GHR glaciers experiencing large scale degeneration, with more than 65% glaciers retreating during 2000-2008 (Scherler et al., 2011). However, there are two views pertaining to the glaciers in the Trans Himalayan range, with one suggesting their intermediate response between the Karakoram Himalaya and GHR (Chudley et al., 2017) and the other emphasizing upon their affinity either towards the GHR or the Karakoram Himalayan glaciers (Schmidt and Nuesser, 2017). Therefore, in order to add more data and build a complete understanding of the glacier response, particularly in the western Himalaya, more local scale studies are necessary.

Complete and precise glacier inventories form the basic prerequisites not only for comprehensive glacier assessment but also for various hydrological and climate modelling related applications (Vaughan et al., 2013). Information on spatial coverage of glaciers in any region is a much valued dataset and holds paramount importance in the future assessment of glaciers. Errors in the glacier outlines may propagate and introduce higher uncertainties in the modelled outputs (Paul et al., 2017). Besides, results from modelling studies conducted over same region but using different sources of glacier boundaries are rendered uncomparable, constraining the evaluation of models and thus their future development. On the other hand, quality, accuracy and precision associated with glacier mapping and outline delineation requires dedicated efforts. Several past studies discuss the methods for, challenges in achieving an accurate glacier inventory and resolutions for the same (Paul et al., 2013; 2015; 2017). Thorough knowledge of glaciology and committed manual endeavour are two vital requirements in this regard. Realisation of above facts did result in several devoted attempts to prepare detailed glacier inventories at global scale, such as Randolph glacier inventory (RGI), Global land ice measurements from space (GLIMS) and recently Chinese glacier inventory (CGI) and Glacier area mapping for discharge from the Asian mountains (GAMDAM) (Raup et al., 2007; Pfeffer et al., 2014; Shiyin et al., 2014; Nuimura et al., 2015). However, several issues related to gap areas, differences in mapping methods and skills of the analysts involved act as limitations and need further attention.

Considering the above, present work studies the glaciers in the Suru sub-basin (SSB), western Himalaya, Jammu and Kashmir. Primary objectives of this study include: 1) presenting the inventory of recent glacier data [area, length, debris cover, SLA, elevation (min & max), slope and aspect] in the SSB; 2) assessing the temporal changes for four epochs in past 46 years; and 3) analysing the observed glacier response in relation to the regional climate trends, local climate variability and other factors (regional hypsometry, topographic characteristics, debris cover and geomorphic features). Several remote sensing and field based studies of regional (Vijay and Braun, 2018) , local (Bhushan et al., 2018, Kamp et al., 2011; Pandey et al., 2011; Shukla and Qadir, 2016, Rashid et al 2017, Murtaza and Romshoo, 2015) and glacier-specific nature (Garg et al., 2018; 2019; Shukla et al., 2018) have been conducted for monitoring the response of the glaciers to the climate change. Glaciological studies carried out in or adjacent to the SSB suggest increased shrinkage, slowdown and downwasting of the studied glaciers at variable rates (Kamp et al., 2011; Pandey et al., 2011; Shukla and Qadir, 2016; Bhushan et al., 2018). These studies also hint towards the possible role of topographic & morphometric factors as well as debris cover in glacier evolution, though confined to their own specific regions. Previous studies have also estimated the glacier statistics of SSB and reported the total number of glaciers and the glacierized area to be 284 and 718.86 km^2 (Sangewar and Shukla, 2009) and 110 and 156.61 km^2 (SAC report, 2016), respectively. While the RGI reports varying results by two groups of analysts (number of glaciers: 514 & 304 covering an area of 550 & 606 km^2, respectively) for 2000 itself.

Previous findings suggesting progressive degeneration of glaciers, apparent variation and discrepancies in inventory estimates and also the fact that the currently available glacier details for the sub-basin are nearly 20 years old, mandate the recent and accurate assessment of the glaciers in the SSB and drive the present study.

2 Study area

The present study focuses on the glaciers of the SSB situated in the state of Jammu and Kashmir, western Himalaya (Fig. 1). The geographic extent of the study area lies within latitude and longitude of 33° 50' to 34° 40' N to 75° 40' to 76° 30' E, respectively.

Geographically, the sub-basin covers part of two major ranges, i.e., GHR and LR and shows the presence of the highest peaks of Nun (7135 masl) and Kun (7077 masl) in the GHR (Vittoz, 1954). The glaciers in these ranges have distinct morphology, with the larger ones located in the GHR and comparatively smaller towards the LR (Fig. 1).

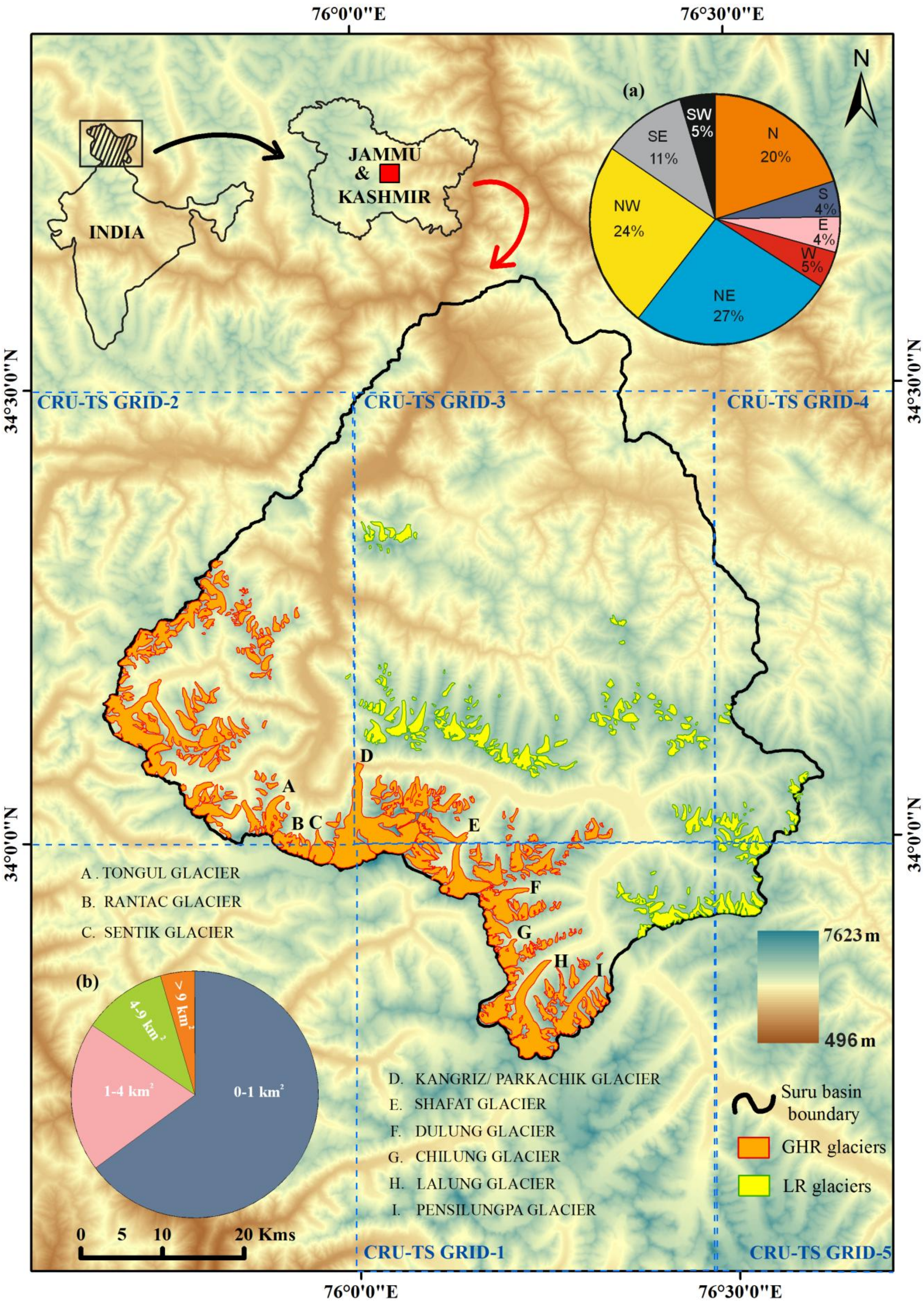

Figure 1. Location map of the study area. The glaciers in the Suru sub-basin (SSB: black outline) are studied for their response towards the climatic conditions during the period 1971-2017. Blue rectangles with dashed outlines (GRID-1, 2, 3, 4 and 5) are the Climate Research Unit (CRU)-Time Series (TS) 4.02 grids of dimension 0.5° x 0.5°.(a) Pie-chart inset showing orientation-wise percentage distribution of glaciers in the sub-basin. North (N), north-east (NE), north-west (NW), south (S), south-east (SE), south-west (SW), east (E) and

west (W) represents the direction of the glaciers. (b) Pie chart inset showing size-distribution of glaciers in the SSB. The glacier boundaries [GHR (orange) and LR (yellow)] are overlain on the Advanced Land Observing Satellite (ALOS) Digital Surface Model (DSM).

The meltwater from these glaciers feeds the Suru River (tributary of Indus River), which emerges from the Pensilungpa glacier (Fig. 2a) at an altitude of ~4675 m asl. The river further flows north for a distance of ~24 kms and takes a westward turn from Rangdum (~4200 m asl). While flowing through this path, the Suru River is fed by some of the major glaciers of the GHR namely Lalung, Dulung (Fig. 1), Chilung (Fig. 2b), Shafat (Fig. 2c; d), Kangriz/ Parkachik (Fig. 2e), Sentik, Rantac (Fig. 2f), Tongul (Fig. 2g) and Glacier no.47 (Fig. 2h). Amongst these major glaciers, Kangriz forms the largest glacier in the SSB, covering an area of ~53 km^2 and descends down from the peaks of Nun and Kun (Garg et al., 2018). The Suru River continues to flow for a distance of nearly 54 kms and after crossing a mountain spur and the townships of Tongul, Panikhar and Sankoo, the river further flows north until it finally merges with River Indus at Nurla (~3028 m asl).

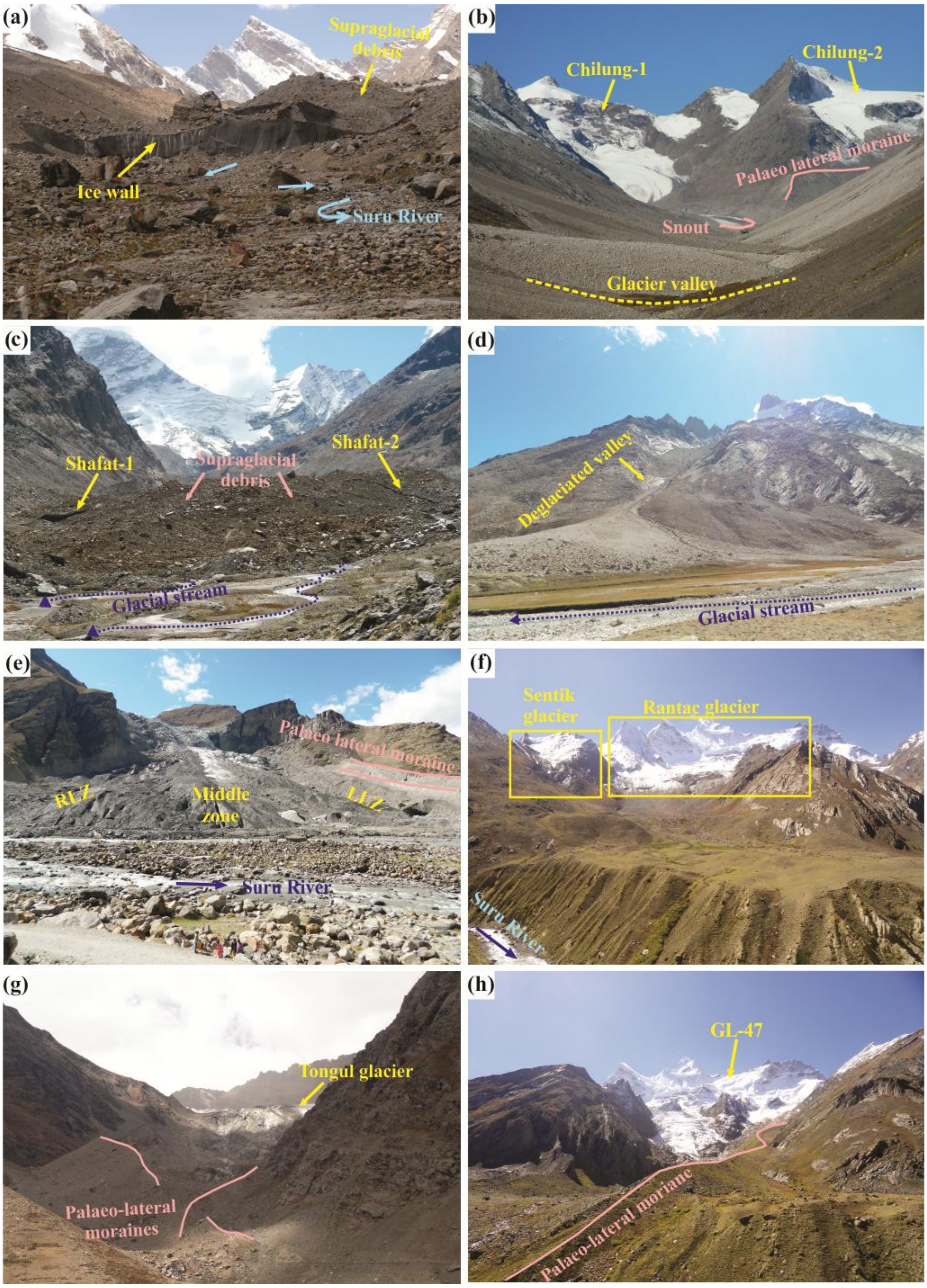

Figure 2. Field photographs of some of the investigated glaciers in the study area captured during the field visits in September, 2016 and 2017. (a), (b), (c), (e), (f), (g), (h) Snouts of Pensilungpa, Chilung, Shafat, Kangriz, Sentik & Rantac, Tongul glaciers and Glacier no.47, respectively. (d) Deglaciated valley near the Shafat glacier.

The westerlies are an important source of moisture in this region (Dimri, 2013) with wide range of fluctuations in snowfall during winters. In the Padum valley, annual mean precipitation (Snowfall) and temperature amounts to nearly 2050 to 6840 mm and 4.3 °C, respectively (Raina and Kaul, 2011; http://en.climate-data.org). The longterm average annual temperature and precipitation have varied from 5.5 °C/ 588.77 mm (Kargil) to -2.04

°C/ 278.65 mm in Leh during the period 1901-2002 (IMD, 2015). However, in order to understand the long term variability of climatic conditions in the SSB, we have utilized the Climate Research Unit (CRU)-Time Series (TS) 4.02 data during the period 1901-2017 (Fig. 3; Harris and Jones, 2018). Derived from this data, the annual mean temperature and precipitation of the SSB for the period 1901-2017 has been 0.99 ±*0.45* °C and 393 ±*76* mm, respectively. (Standard deviations associated with the mean temperature and precipitation have been italicized throughout the text).

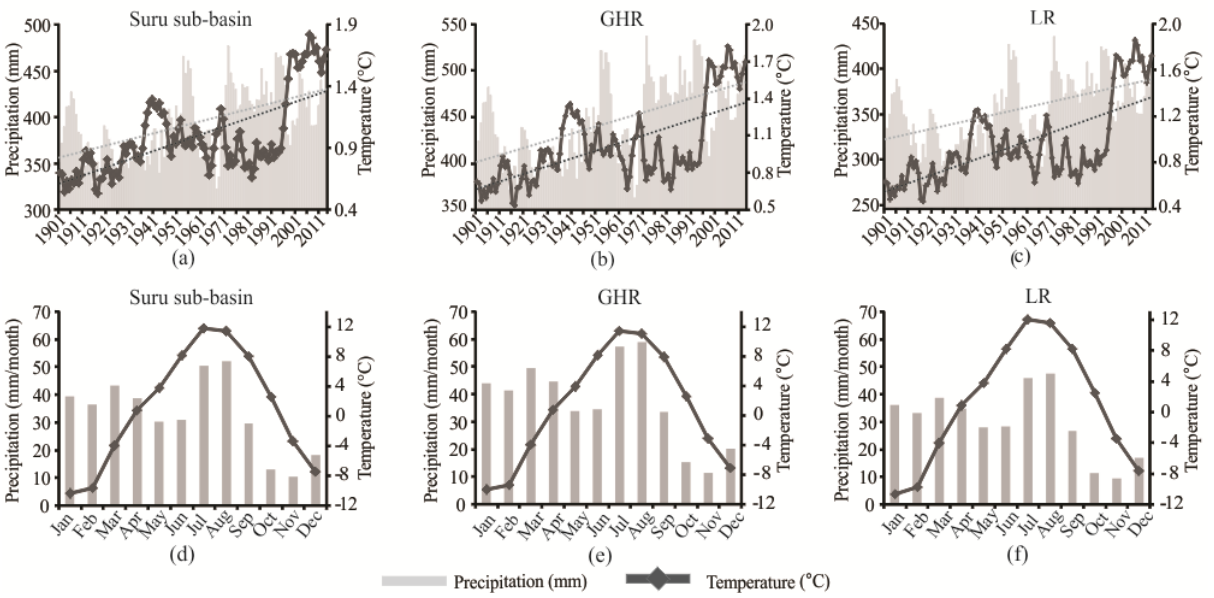

Figure 3. Annual and seasonal variability in the climate data for the period 1901-2017. (a), (b) and (c) 5 year moving average of the mean annual precipitation (mm) and temperature (°C) recorded for 5 grids covering the glaciers in the entire SSB, GHR and LR (sub-regions), respectively during the period 1901-2017. The light and dark grey colored dashed lines depict the respective trend lines for precipiatation and temperature conditions during the period 1901-2017. (d), (e) and (f) Monthly mean precipitation and temperature data for the entire SSB, GHR and LR (sub-regions), respectively for the time period 1901-2017.

3 Datasets and Methods

3.1 Datasets used

The study uses multi-sensor and multi-temporal satellite remote sensing data for extracting the glacier parameters for four time periods, i.e., 1971/1977, 1994, 2000 and 2017, details of which are mentioned in Table 1. It involves 6 Landsat level 1 terrain corrected (L1T), 3 strips of declassified Corona KH-4B and 1 Sentinel multispectral scenes, downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/). Besides, a global digital surface model (DSM) dataset utilizing the data acquired by the Panchromatic remote-sensing Instrument for Stereo Mapping (PRISM) onboard the Advanced Land Observing Satellite (ALOS) have also been incorporated (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/). ALOS World 3D comprises of a fine resolution DSM (approx 5m vertical accuracy). It is primarily used for delineating the basin boundary, extraction of SLA, elevation range, regional hypsometry and slope.

Table 1. Detailed specifications of the satellite data utilised in the present study. GB= glacier boundaries, DC=debris cover

S. no	Satellite sensors (Date of acquisition)	Remarks on quality	Scene Id	RMSE error	Registration accuracy (m)	Purpose
1.	Corona KH-4B (28 Sep 1971)	Cloud free	DS1115-2282DA056/ DS1115-2282DA055/ DS1115-2282DA054	0.1	0.3	Delineation of GB
2.	LandsatMSS (19 Aug 1977/ 1 Aug 1977)	Cloud free/ peak ablation (17 Aug)	LM02_L1TP_159036_19770819_20180422_01_T2/ LM02_L1TP_159036_19770801_20180422_01_T2	0.12	10	Delineation of GB, SLA&DC
3.	LandsatTM (27 Aug 1994)	Partially cloud covered/ peak ablation	LT05_L1TP_148036_19940827_20170113_01_T1/ LT05_L1GS_148037_19940827_20170113_01_T2	0.22	6	Delineation of GB, SLA&DC
4.	LandsatTM (26 July 1994)	Seasonal snow cover	LT05_L1TP_148036_19940726_20170113_01_T1	0.2	6	Delineation of GB
5.	LandsatETM$^+$ (4 Sep 2000)	Cloud free/ peak ablation	LE71480362000248SGS00	Base image		Delineation of GB, SLA& DC
6.	LandsatOLI (25July 2017)	Partially cloud covered/ peak ablation	LC08_L1TP_148036_20170810_01_T1	0.15	4.5	Delineation of GB & DC, estimation of SLA
7.	Sentinel MSI (20 Sep 2017)	Cloud free	S2A_MSIL1C_20170920T053641_N0205_R005_T43SET_20170920T053854	0.12	1.2	Delineation of GB & DC
8.	LISS IV (27Aug2017)	Cloud free	183599611	0.2	1.16	Accuracy assessment

The aforementioned satellite images were acquired keeping into consideration certain necessary pre-requisites, such as, peak ablation months (July/ August/ September), regional coverage, minimal snow and cloud cover for the accurate identification and demarcation of the glaciers. Only three Corona KH-4B strips were available for period 1971, which covered the SSB partially, i.e., 40% of the GHR and 57% of the LR glaciers. Therefore, rest of the glaciers were delineated using the Landsat MSS image of the year 1977 (Table 1). Similarly, some of the glaciers could not be mapped using the Landsat TM image of 27 Aug 1994 as the image was partially covered with clouds. Therefore, 26 July 1994 image of the same sensor was used in order to delineate the boundaries of the cloud covered glaciers.

Besides, long term climate data have been obtained from CRU-TS 4.02, which is a high resolution gridded climate dataset obtained from the monthly meteorological observations collected at different weather stations of the World. In order to generate this long term data, station anomalies from 1961-1990 are interpolated into 0.5° latitude and longitude grid cells (Harris and Jones, 2018). This dataset includes six independent climate variables (mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapour pressure and cloud cover). However, in this study monthly mean, minimum and maximum temperature and precipitation data are taken into consideration.

3.2 Methodology adopted

The following section mentions the methods adopted for data extraction, analysis and uncertainty estimation.

3.2.1 Glacier mapping and estimation of glacier parameters

Initially, the satellite images were co-registered by projective transformation at sub-pixel accuracy with the Root Mean Square Error (RMSE) of less than 1m (Table 1), taking the Landsat ETM^+ image and ALOS DSM as reference. However, the Corona image was co-registered following a two step approach: (1) projective transformation was performed using nearly 160-250 GCPs (2) spline adjustment of the image strips (Bhambri et al., 2012). The glaciers were mapped using a hybrid approach, i.e., normalized difference snow index (NDSI) for delineating snow-ice boundaries and manual digitization of the debris cover. Considering that not many changes would have occurred in the accumulation region, major modifications have been done in the boundaries below the equilibrium line altitude (ELA) (Paul et al., 2017). The glacierets/ tributary glaciers contributing to the main trunk are considered as single glacier entity. NDSI was applied on a reference image of Landsat ETM^+ using an area threshold range of 0.55-0.6. A median filter of kernel size 3*3 was used to remove the noise and very small pixels. In this manner, glaciers covering a minimum area of 0.01 km^2 have been mapped. However, some pixels of frozen water, shadowed regions were manually corrected. Thereafter, the debris covered part of the glaciers was mapped manually by taking help from slope and thermal characteristics of the glaciers. Besides, high resolution imageries from the Google Earth™ were also referred for the accurate demarcation of the glaciers. Identification of the glacier terminus was done based on the presence of certain characteristic features at the snout such as ice wall, proglacial lakes and emergence of streams. Length of the glacier was measured along the central flow line (CFL) drawn from the bergschrund to the snout. Fluctuations in the snout position (i.e., retreat) of an individual glacier was estimated using the parallel line method, in which parallel strips of 50 m spacing are taken on both sides of the CFL. Thereafter, the average values of these strips intersecting the glacier boundaries were used to determine the frontal retreat of the glaciers (Shukla and Qadir, 2016; Garg et al., 2017a;b). Mean SLA estimated at the end of the ablation season can be effectively used as a reliable proxy for mass balance estimation for a hydrological year (Guo et al., 2014). The maximum spectral contrast between snow and ice in the SWIR and NIR bands helps in delineation of the snow line separating the two facies. The same principle was used in this study to yield the snow line. Further, a 15 m sized buffer was created on both sides of the snow line to obtain the mean SLA. Other factors such as elevation (max & min), regional hypsometry and slope were extracted utilising the ALOS DSM.

3.2.2 Analysis of climate variables

To ascertain the long term climate trends in the sub-basin, mean annual temperature (min & max) and precipitation are derived by averaging the mean monthly data of the respective years. Besides, seasonal trends are also analysed for winter (November-March) and summer (April-October) months. Moreover, the climate variables are assessed separately for the ~46 year period (1971-2017), which is the study period of present research. Further, the climate dataset was statistically analysed for five grids using Mann-Kendall test to obtain the magnitude and significance of the trends (Table S2). The magnitude of trends in time series data was determined using Sen's slope estimator (Sen, 1968). Quantitatively, the temperature and precipitation trends have been assessed here in absolute terms (determined from Sen's slope). The change in climate parameters (temperature and precipitation) was determined using following formula:

$$\text{Change} = (\beta * L) / M \qquad (1)$$

where β is Sen's slope estimator, *L* is length of period and *M* is the long term mean.

These tests were performed at confidence level, S= 0.1(90%), 0.05(95%) and 0.01(99%), which differed for both the variables (Table S2). Spatial interpolation of climate data was achieved using the Inverse Distance Weighted (IDW) algorithm. For this purpose, a total number of 15 CRU-TS grids (in vicinity of our study area) were taken so as to have an ample number of data points in order to achieve the accurate results.

Further, in order to check data consistency, we have taken instrument data from nearest stations of Kargil and Leh (due to the unavailability of meteorological stations in the SSB) and compared with the CRU-TS derived data for the entire SSB during 1901-2002 period (Fig. 4).

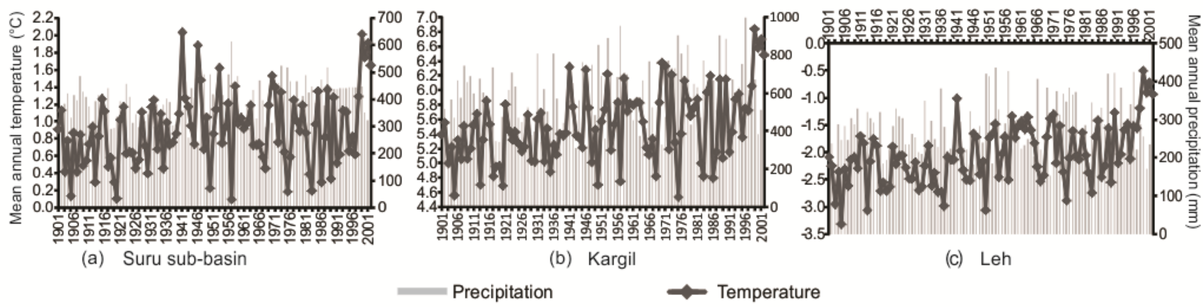

Figure 4. Mean annual temperature and precipitation patterns of climate research unit (CRU)-time series (TS) derived gridded data in (a) Suru sub-basin and Indian Meteorological Department (IMD) recorded station at (b) Kargil and (c) Leh.

The mean annual temperature pattern of SSB shows a near negative trend till 1937, with an increase thereafter. Similar trends have been observed for Kargil and Leh, despite their distant location from the SSB (areal distance of Kargil and Leh is ~63 and 126 km, respectively from the centre of SSB). However, it is noteworthy to mention that all the locations had attained maximum mean annual temperature in 1999 (Suru: 2.02°C; Kargil: 6.84°C; Leh: -0.5°C). We observe an almost similar trend in all the cases (Fig. 4), with an accelerated warming post 1995/96. However, the magnitude varies, with longterm mean annual temperature of 0.9, 5.5 and -2.04°C observed in SSB, Kargil and Leh, respectively (Fig. 4). The possible reason for this difference in their magnitudes could possibly be attributed to their distinct geographical locations and difference in their nature, with former being point, while latter being the interpolated gridded data.

Also, we have used the station data, obtained from nearest available Indian Meteorological Department (IMD) sites, i.e., Kargil and Leh and compared with their respective CRU-TS data (mean annual temperature and precipitation).

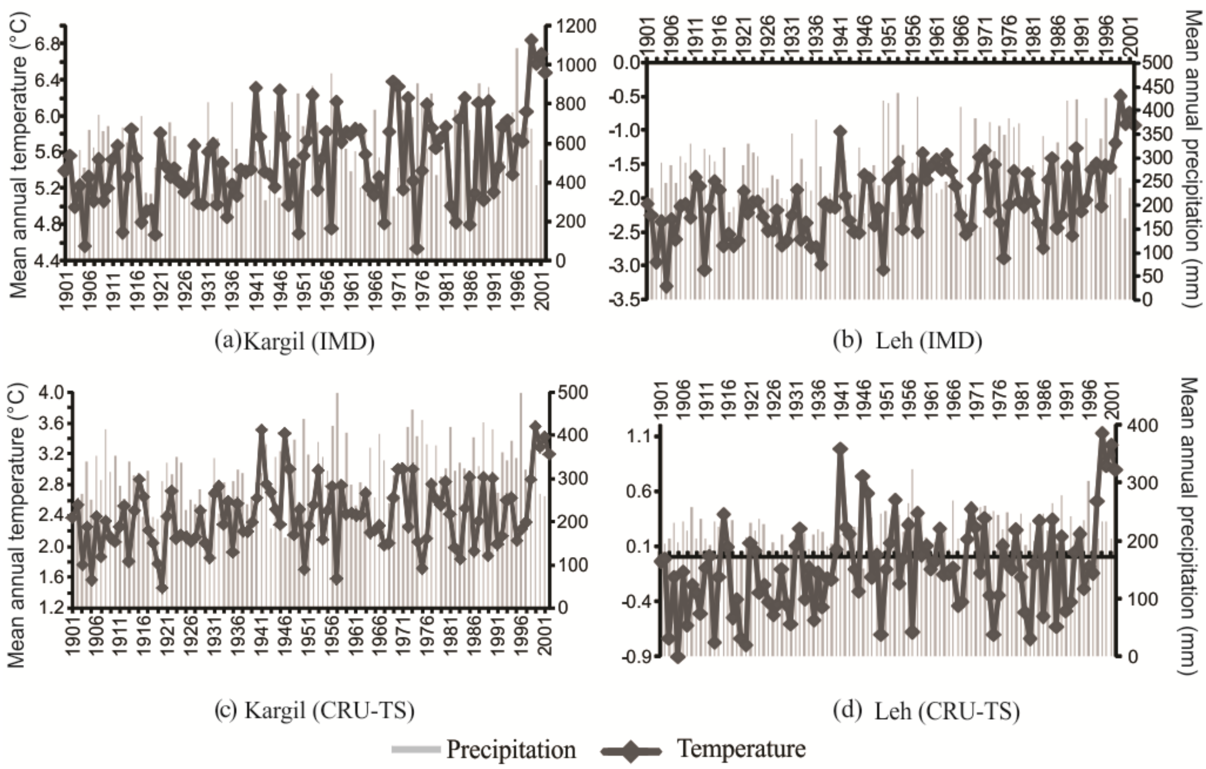

Figure 5. Analysis of meteorological (mean annual temperature and precipitation) datasets derived from Indian Meteorological Department (IMD) stations at (a) Kargil & (b) Leh and the respective [(c) Kargil and (d) Leh] gridded data obtained from climate research unit (CRU)-time series (TS).

Though varying in magnitude, the climate data obtained from IMD as well as CRU-TS suggest almost similar trends of temperature and precipitation during the period 1901-2002 for both Kargil and Leh (Fig. 5). The annual mean temperature/ precipitation amounted to 5.5°C/589 mm (IMD) and 2.4°C/315 mm (CRU-TS) in Kargil, while -2.04/279 mm (IMD) and -0.09/ 216 mm (CRU-TS) in Leh during the period 1901-2002 (Fig. 5).We observed that climatic variables show lower magnitude in case of CRU-TS as compared to the station data from IMD (except CRU-TS derived temperature data recorded for Leh). The possible reason for this difference between CRU-TS and station data can primarily be attributed to the difference in their nature, with former being point, while latter being a gridded data (0.5° latitude and longitude grid cells). This analysis aptly brings out the bias in the CRU-TS gridded data. Majorly the comparison shows that though the gridded data correctly bring out the temporal trends in meteorological data, but differ with station data in magnitude (being on lower side than the station estimates). This helps us better appreciate the climate variations in the SSB as well, since we learn that the reported temperature and precipitation changes are probably on the lower side of the actual variations.

3.2.3 Uncertainty assessment

This study involves extraction of various glacial parameters utilizing satellite data with variable characteristics, hence, susceptible to uncertainties, which may arise from various sources. These sources may be locational (LE), interpretational (IE), classification (CE) or processing (PE) errors (Racoviteanu et al., 2009; Shukla and Qadir, 2016). In our study, the LE and PE may have resulted on account of miss-registration of the satellite images and inaccurate mapping, respectively. While IE and CE would have introduced due to the miss-interpretation of glacier features during mapping. The former can be rectified by co-registration of the images and estimation of sub-pixel co-registration RMSE (Table 1) and using standard statistical measures. However, the latter can be visually identified and corrected but difficult for exact quantification owing to lack of reliable reference data (field data) in most cases. As a standard procedure for uncertainty estimation, glacier outlines are compared directly with the ground truth data as acquired using a Differential Global Positioning System (DGPS) (Racoviteanuet al., 2008a). In this study, DGPS survey was conducted on the Pensilungpa and Kangriz glaciers at an error of less than 1cm. Therefore, by comparing the snout position of Pensilungpa (2017) and Kangriz (2018) glaciers derived from DGPS and OLI image, an accuracy of ±23 and ±1.4 m, respectively was obtained. Also, the frontal retreat estimated for the Kangriz glacier using DGPS and OLI image is found to be 38.63 ±47.8 and 39.98 ±56.6 m, respectively during the period 2017-18. In this study, high resolution Linear imaging self-scanning system (LISS)-IV imagery (spatial resolution of 5.8 m) is also used for validating the glacier mapping results for the year 2017 (Table 1). Glaciers of varying dimensions and distribution of debris cover were selected for this purpose. The area and length mapping accuracy for these selected glacier boundaries (G-1, G-2, G-3, G-13, G-41, G-209, G-215, G-216, G-220, G-233) was found to be 3% and 0.5%, respectively.

The multi-temporal datasets were assessed for glacier length and area change uncertainty as per the methods given by Hall et al. (2003) and Granshaw and Fountain (2006). Following formulations (Hall et al., 2003) were used for estimation of the said parameters:

$$\text{Terminus uncertainty } (U_T) = \sqrt{a^2 + b^2} + \sigma \qquad (2)$$

where, 'a' and 'b' are the pixel resolution of image 1 and 2, respectively and 'σ' is the registration error. The terminus and areal uncertainty estimated are given in Table 2.

$$\text{Area change uncertainty } (U_A) = 2 * UT * x \qquad (3)$$

where, 'x' is the spatial resolution of the sensor.

Table 2. Terminus and Area change uncertainty associated with satellite dataset as defined by Hall et al. (2003). U_T = terminus uncertainty, U_A= area change uncertainty, x= spatial resolution, σ = registration accuracy.

Serial no.	Satellite sensor	Terminus uncertainty $U_T = \sqrt{a^2 + b^2} + \sigma$	Area change uncertainty $U_A = 2\ U_T * x$
1.	Corona KH-4B	3.12 m	0.00007 km^2

2.	Landsat MSS	123.13 m	0.03km^2
3.	Landsat TM	41.42 m	0.003 km^2
4.	Landsat ETM$^+$	48.42 m	0.003km^2
5.	Landsat OLI	46.92 m	0.003km^2

Area mapping uncertainty was estimated using the buffer method, in which, a buffer size equal the registration error of the satellite image was taken into consideration (Bolch et al., 2012; Garg et al., 2017a,b). Error estimated using this method is found to be 0.48, 27.2, 9.6 and 3.41 km^2 for the 1971 (Corona), 1977 (MSS), 1994 (TM) and 2017 (OLI) image, respectively. Since the debris extents were delineated within the respective glacier boundaries, the proportionate errors are likely to have propagated in debris cover estimations which were estimated accordingly (Garg et al., 2017b).

Uncertainty in SLA estimation needs to be reported in the X, Y and Z directions. In this context, error in X and Y directions should be equal to the distance taken for creating the buffer on either side of the snow line demarcating the snow and ice facies. Since, the buffer size taken in this study was 15 m, therefore, error in X and Y direction was considered as ±15 m. However, uncertainty in Z direction would be similar to the ALOS DSM, i.e., ±5 m.

4 Results

The present study involved creation of glacier inventory for the year 2017 and estimation of glacier (area, length, debris cover and SLA) parameters for four different time periods. For detailed insight, the variability of the glacier parameters have also been evaluated on decadal scale, in which the total time period has been sub-divided into three time frames, i.e., 1971-1994 (23 years), 1994-2000 (6 years) and 2000-2017 (17 years).

4.1 Basin statistics

The SSB covers an area of ~4429 km^2. In 1971, the sub-basin had around 240 glaciers, with 126 glaciers located in the GHR and 114 in the LR, which remained the same till 2000. However, a major disintegration of glaciers took place during the period 2000-2017, which resulted into the breakdown of about 12 glaciers into smaller glacierets. The recent (2017) distribution of the glaciers in the GHR and LR is 130 and 122, respectively (Table S1). The overall glacierized area is ~11%, with the size and length of the glaciers varying from 0.01 to 53.1 km^2 and 0.15 to 16.34 km, respectively.

Within the sub-basin, the size range of glaciers in the GHR and LR vary from 0.01 (G-115) to 53.1 km^2 (G-50) and 0.03 (G-155/165) to 6.73 km^2 (G-209), respectively. Considering this, glaciers have been categorized into small (0-7 km^2/ 0-2 km), medium (7-15 km^2/ 2-7 km) and large (>15 km^2/ >7 km). Based on size distribution, small (comprising all the LR and some GHR glaciers), medium and large glaciers occupy 47%, 15% and 38% of the glacierized sub-basin. Depending upon the percentage area occupied by the supraglacial debris out of the total glacier area, the glaciers have been categorized into clean (CG: 0-25%), partially debris-covered (PDG: 25-50%) and heavily debris-covered (HDG: >50%). Categorization of the glaciers based on this criteria shows their proportion in the glacierized basin as: CG (43%), PDG (40%) and HDG (17%). Majority of the glaciers in the sub-basin are north facing (N/ NW/NE: 71%), followed by south (S/ SW/ SE: 20%), with very few oriented in other (E/ W: 9%) directions (Fig. 1a). The mean elevation of the glaciers in the SSB is 5134.8 ±*225* masl, with an average elevation of 5020 ±*146* and 5260 ±*117* masl in the GHR and LR, respectively. Mean slope of the glaciers is 24.8° ±*5.8*° and varies from 24° ±*6*° to 25° ±*6*° in the GHR and LR, respectively. While, percentage distribution of glaciers shows that nearly 80% of the LR glaciers have steeper slope (20-40°) as compared to the GHR glaciers (57%).

4.2 Area changes

The glaciated area reduced from 513 ±14 km^2 (1971) to 481 ±3.4 km^2 (2017), exhibiting an overall deglaciation of 32 ±9 km^2 (6 ±0.02%) during the period 1971-2017. Percentage area loss of the individual glaciers ranges between 0.8 (G-50; Parkachik glacier) - 45 (G-81) %, with majority of the glaciers undergoing an area loss in the range 6-12% during the period 1971-2017 (Fig. 6a).

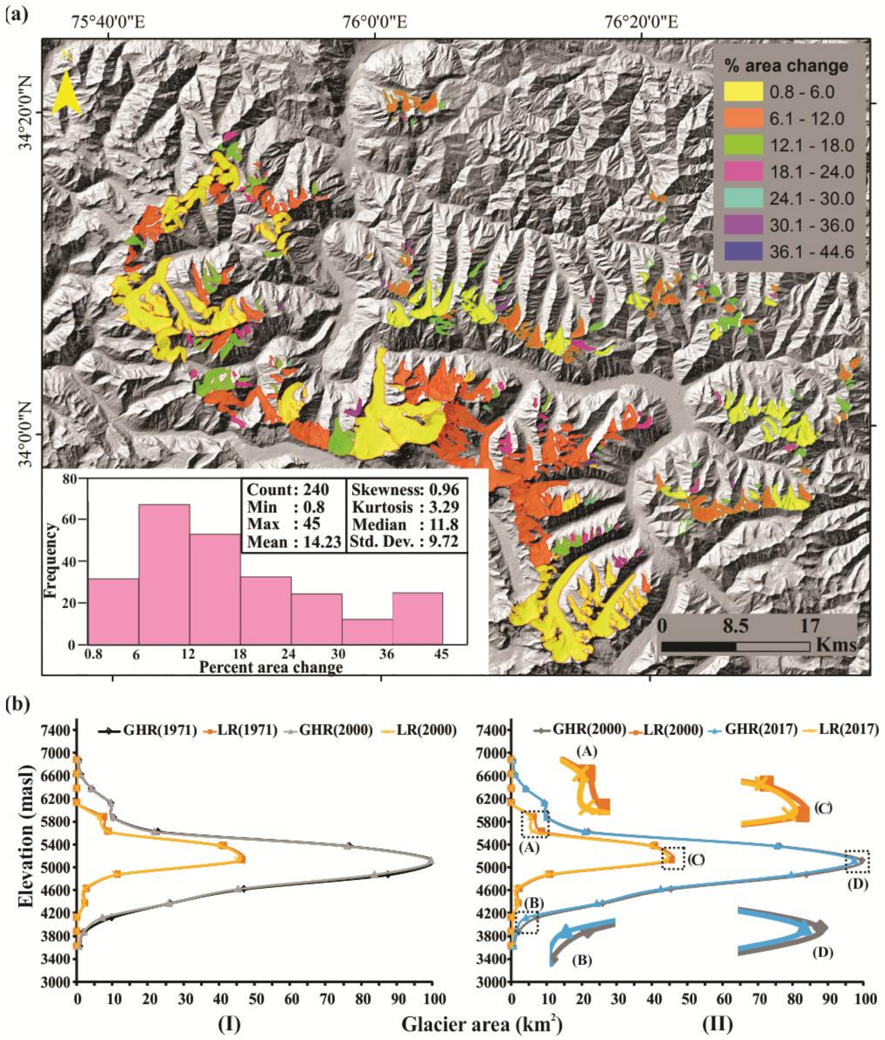

Figure 6. (a) Percent area loss of the glaciers in the SSB during the period 1971-2017. Frequency distribution histogram depicting that majority of the glaciers have undergone an area loss in the range 6-12%. (b) Hypsometric distribution of glacier area in the GHR and LR regions during the period (I) 1971-2000 and (II) 2000-2017. (A), (B), (C) and (D) insets in (II) shows the significant change in area at different elevation range of the GHR and LR glaciers.

Results show that the highest pace of deglaciation is observed during 1994-2000 (0.95 ±0.005 km^2a^{-1}) and 2000-2017 (0.86 ±0.0002 km^2a^{-1}) followed by 1971-1994 (0.5 ±0.001 km^2a^{-1}) (Fig. S1a).Within the SSB, glaciers in the LR exhibit higher deglaciation (7 ±7.2%) as compared to GHR (6 ±2%) during the period 1971-2017. Apart from deglaciation, G-50 also showed increment in glacier area during the period 1994-2000, however, insignificantly.

4.3 Length changes

Fluctuations in the glacier snout have been estimated during the period 1971-2017 and it is observed that nearly all the glaciers have retreated during the said period, however the retreat rates vary considerably. The overall average retreat rate of the glaciers is observed to be 4.3 ±1.02 ma^{-1} during the period 1971-2017. Percentage length change of the glaciers ranges between 0.9 to 47%, with majority of the glaciers retreating in the range 6-14% during the period 1971-2017 (Fig. 7).

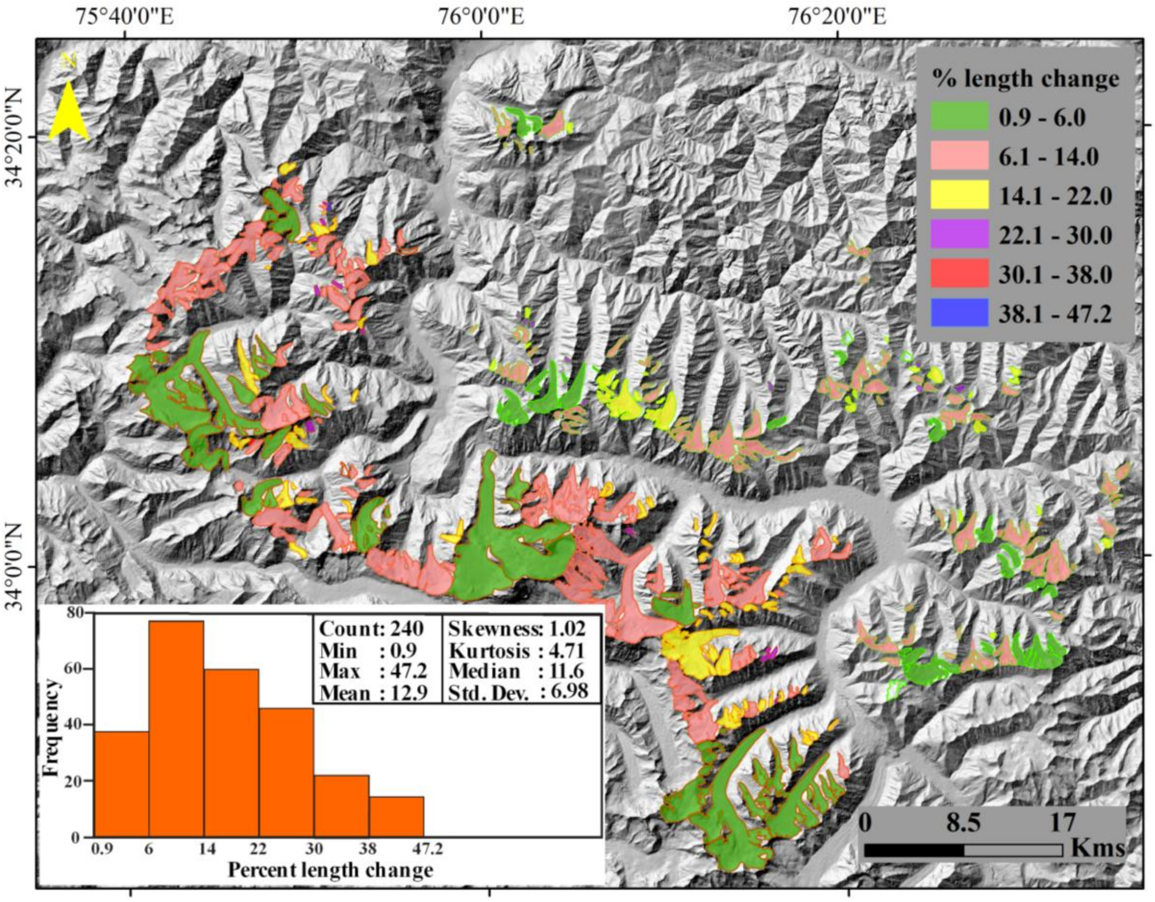

Figure 7. Percent length change of the glaciers in the SSB during the period 1971-2017. Frequency distribution histogram showing that majority of the glaciers have undergone length change of in the range 6-14%.

Decadal observations reveal the highest rate of retreat during 1994-2000 (7.37 ±8.6 ma^{-1}) followed by 2000-2017 (4.66 ±1.04 ma^{-1}) and lowest during 1971-1994 (3.22 ±2.3 ma^{-1}) (Fig. S1b). Also, the average retreat rate in the GHR and LR glaciers was observed to be 5.4 ±1.04 ma^{-1} and 3.3 ±1.04 ma^{-1}, respectively, during the period 1971-2017. The retreat rate of individual glaciers varied from 0.72 ±1.02 ma^{-1} (G-114) to 28.92 ±1.02

ma^{-1} (G-7, i.e., Dulung glacier) during the period 1971-2017. Besides, the Kangriz glacier (G-50) also showed advancement during the period 1994-2000 by 5.23 ±8.6 ma^{-1}.

4.4 Debris-cover changes

Results show an overall increase in debris-cover extent by 62% (~37 ±0.002 km^2) in the SSB glaciers during the period 1971-2017. Decadal variations exhibit the maximum increase in the debris-cover by approximately 19 ±0.00004 km^2 (24%) during 2000-2017 followed by an increase of 13 ±0.0001 km^2 (20%) and 5 ±0.0001 km^2 (9%) during 1994-2000 and 1971-1994, respectively (Fig. S1c). However, GHR and LR glaciers show an overall increase of debris cover extent by 59% and 73%, respectively during the entire study period, i.e., 1971-2017.

4.5 SLA variations

The mean SLA shows an average increase of 22 ±*60* m during the period 1977-2017. On the decadal scale, SLA variations showed the highest increase (161 ±*59* m) during 1994-2000 with a considerably lower increase (8 ±*59* m) during 1977-1994 and decrease (150 ±*60* m) during 2000-2017. Amongst the four time periods (1977, 1994, 2000 & 2017) used for mean SLA estimation, the highest SLA is noted during 2000 (5158 ±*65* masl) and minimum during 1977 (4988 ±*65* masl) (Fig. S1d).

During the period 1977-2017, the average SLA of the LR glaciers is observed to be relatively higher (5155 ±*7* masl) as compared to the GHR glaciers (4962 ±*9* masl). In contrast, an overall rise in mean SLA was noted in GHR (49 ±*69* m), while a decrease in LR glaciers (18 ±*45* m) during the time frame of 1977-2017.

5 Discussion

The present study reports detailed temporal inventory data of the glaciers in the SSB considering multiple glacier parameters, evaluates the ensuing changes for ascertaining the status of glaciers and relates them to climate variability and other inherent terrain characteristics. The results suggest an overall degeneration of the glaciers with pronounced spatial and temporal heterogeneity in response.

5.1 Glacier variability in Suru sub-basin: A comparative evaluation

Basin statistics reveal that in the year 2000, the SSB comprised of 240 glaciers covering an area of approximately 496 km^2. However, these figures differ considerably from the previously reported studies in this particular sub-basin, with the total number of glaciers and the glacierized area varying from 284/ 718.86 km^2 (Sangewar and Shukla, 2009) to 110/ 156.61 km^2 (SAC report, 2016), respectively. In contrast, the glacierized area is found to be less, however comparable with the RGI boundaries (550.88 km^2). Besides, debris cover distribution of the glaciers during 2000 is observed to be ~16% in the present study,which is almost half of that reported in RGI (30%). Variability in these figures is possibly due to the differences in the mapping techniques, thereby increasing the risk of systematic error. Moreover, due to the involvement of different analysts in the latter, the results may more likely suffer with random errors.

Results from this study reveal an overall deglaciation of the glaciers in the SSB at an annual rate of ~0.1 ±0.0004% during the period 1971-2017. This quantum of area loss is comparatively less to the average annual rate of 0.4% reported in the western Himalaya (Table S3). However, our results are comparable with Birajdar et al. (2014), Chand and Sharma (2015) and Patel et al. (2018) and differ considerably with other studies in the western Himalayas (Table S3). Period wise deglaciation varied from 0.1 ±0.0007 to 0.2 ±0.005% a^{-1} during 1971-2000 and 2000-2017, respectively. This result is in line with the recent findings by Maurer et al. (2019), who suggest a higher average mass loss post 2000 (-0.43 m w.e.a^{-1}), which is almost double the rate reported during 1975-2000 (-0.22 m w.e.a^{-1}) for the entire Himalaya.

Comparing the deglaciation rates of the glaciers within the western Himalayan region reveals considerable heterogeneity therein (Table S3). It is observed that the Karakoram Himalayan glaciers, in particular had been losing area till 2000 at an average rate of 0.09% a^{-1}, with an increase in area thereafter by ~0.05%a^{-1} (Liu et al., 2006; Minora et al., 2013; Bhambri et al., 2013). However, glaciers in the GHR and Trans Himalayan range have been deglaciating with higher average annual rate of 0.4 and 0.6%a^{-1}, respectively during the period 1962-2016 (Kulkarni et al., 2007; Kulkarni et al., 2011; Rai et al., 2013; Chand and Sharma, 2015; Mir et al., 2017; Schmidt and Nuesser, 2017; Chudley et al., 2017; Patel et al., 2018; Das and Sharma, 2018). In contrast to these studies, deglaciation rates in SSB, which comprises of glaciers in GHR as well as LR have varied from 0.1%a^{-1} (GHR) to 0.2%a^{-1} (LR) (present study). These results evidently depict that the response of the SSB glaciers is transitional between the Karakoram Himalayan and GHR glaciers. Period wise area loss of the glaciers in the Himalayan region suggest maximum average deglaciation of eastern (0.49%/yr), followed by central (0.36%/yr) and western (0.35%/yr) Himalayan glaciers before 2000. Contrarily, after 2000, the central Himalayan glaciers deglaciated at the maximum rate (0.52%/yr) followed by western (0.46%/yr) and eastern (0.44%/yr) Himalayan glaciers (Fig. 8). Though these rates reflect the possible trend of deglaciation in the Himalayan terrain, however, any conclusion drawn would be biased due to insufficient data, particularly in eastern and central Himalaya.

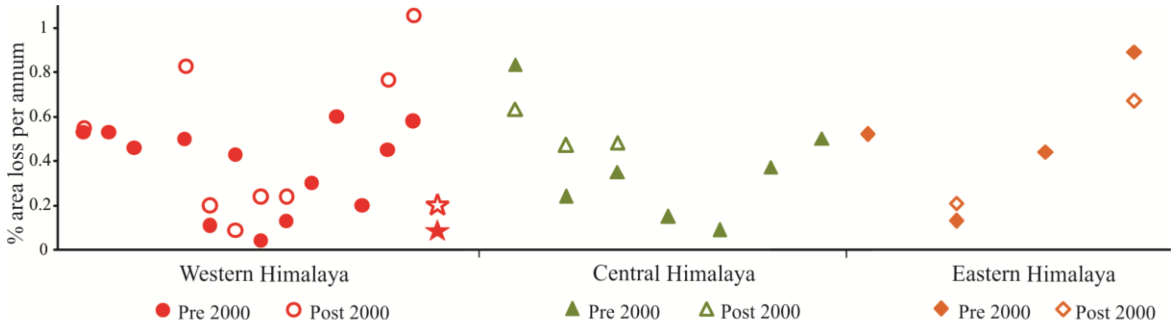

Figure 8. Annual rate of percentage area loss of glaciers in three major sections of Himalaya before and after 2000. Details of the same have been mentioned in Table S3. Results from the present study have been star marked in the western Himalaya.

In this study, we found an overall average retreat rate of 4.3 ±1.02 ma^{-1} during the period 1971-2017. However, the average retreat rates of seven glaciers in the SSB, reported by Kamp et al., (2011) is found to be nearly twice (24 ma^{-1}) of that found in this study (10 ma^{-1}). The comparatively higher retreat rates in the former might be due to the consideration of different time frames. The average retreat rates in other basins of the western Himalaya is also found to be higher (7.8 ma^{-1}) in the Doda valley (Shukla and Qadir, 2016), 8.4 ma^{-1} in Liddar valley (Murtaza and Romshoo, 2015), 15.5 ma^{-1} in the Chandra-Bhaga basin (Pandey and Venkataraman, 2013) and 19 ma^{-1} in the Baspa basin (Mir et al., 2017). These results show lower average retreat rate of the glaciers in the SSB as compared to the other studies in the western Himalaya.

The observed average retreat rates during 2000-2017 (4.6 ±1.02 ma^{-1}) is found to be nearly twice of that, noted during 1971-2000 (2 ±1.7 ma^{-1}). Similar higher retreat rates post 2000 have been reported in the Tista basin (Raina, 2009), Doda valley (Shukla and Qadir, 2016), Chandra Bhaga basin (Pandey and Venkataraman, 2013) and Zanskar basin (Pandey et al., 2011). However, these studies may not sufficiently draw a generalized picture of glacier recession in the Himalayan region.

5.2 Spatio-temporal variability in the climate data

Climatic fluctuations play a crucial role in understanding glacier variability. In this regard, CRU-TS 4.02 dataset helped in delineating the long term fluctuations in the temperature and precipitation records.

5.2.1 Basin-wide climate variability

During an entire duration of 116 years, i.e. from 1901-2017, maximum mean annual temperature is observed in 2016 (3.23 °C) and minimum during 1957 (-0.51 °C). Mean annual temperature shows an almost uniform trend till 1996, with a pronounced rise thereafter till 2005/06 period (Fig. 3a;b;c). The globally averaged combined land and ocean surface temperature data of 1983-2012 period are considered as the warmest 30-year period in the last 1400 years (IPCC, 2013). This unprecedented rate of warming primarily attributed to the rapid scale of industrialization, increase in regional population and anthropogenic activities prevalent during this time period (Bajracharya et al., 2008; IPCC, 2013). Thus, one of the probable reason for this sudden increase in temperature pattern is possibly due to the greenhouse effect from enhanced emission of black carbon in this region (by 61%) from 1991-2001. Evidences of incessant increase in temperature during 1990s has also been observed (through chronology of Himalayan Pine) from the contemporaneous surge in tree growth rate (Singh and Yadav 2000). In fact, 50% of the years since 1970 have experienced considerably high solar irradiance and warm phases of El-Nino southern oscillation, which is possibly one of the reasons for the considerable rise in temperature throughout the Himalaya (Shekhar et al., 2017). Maximum mean annual precipitation is noted during 2015 (615 mm) and minimum during 1946 (244 mm). However, the mean annual precipitation followed a similar trend till 1946 with an increasing thereafter (Fig. 3a;b;c). Besides these general trends in temperature and precipitation,an overall absolute increase in the mean annual temperature (T_{max} & T_{min}) and precipitation data have been noted as 0.77 °C (0.25 °C & 1.3 °C) and 158 mm, respectively during the period 1901-2017. These observations suggest an enhanced increase in T_{min} by nearly 5 times as compared to the T_{max} alongwith a simultaneous increase in the precipitation during the period 1901-2017.

Seasonal variations reveal monthly mean temperature and precipitation of 6.7 °C and 1071 mm during summer (Apr-Oct) and -6.9 °C and 890 mm during winter (Nov-Mar) recorded during 1901-2017 period. Maximum monthly mean temperature and precipitation have been observed in July (11.8 °C/ 50.4 mm) and August (11.4 °C/ 52 mm) during the period 1901-2017, suggesting them to be the warmest and wettest months. While, January is noted to be the coldest (-10.4 °C) and November (10.3 mm) to be the driest months in the duration of 116 years (Fig. 3d;e;f). Summer/ winter mean annual temperature and precipitation have increased significantly by an average 0.74/ 1.28 °C and 85/ 72 mm, respectively during the period 1901-2017. These values reveal a relatively higher rise in winter average temperature in contrast to the summer. However, enhanced increase in T_{min} (1.8°C) during winter and T_{max} (0.78°C) during summer have also been observed during the 1901-2017 time period. The relatively higher rise in the winter temperature (particularly T_{min}) and precipitation possibly suggest that the form of precipitation might have changed from solid to liquid during this particular time span. Similar increase in the winter temperature have also been reported from the NW Himalaya during the 20th century (Bhutiyani et al., 2007).

In contrast to the long-term climate trends, we have also analyzed the climate data for the study period, i.e., 1971-2017. An overall increase in the average temperature (0.3°C), T_{max} (0.45°C) T_{min} (1.02°C) and precipitation by 213 mm is observed. Meanwhile, an enhanced increase in winter T_{min} (1.7°C) and summer T_{max} (0.45°C) are observed. These findings aptly indicate the important role of winter T_{min} and summer T_{max} in the SSB.

5.2.2 Local climate variability

Apart from these generalized climatic variations, grid-wise analysis of the meteorological parameters reveal existence of local climate variability within the sub-basin (Fig. 3; 9).

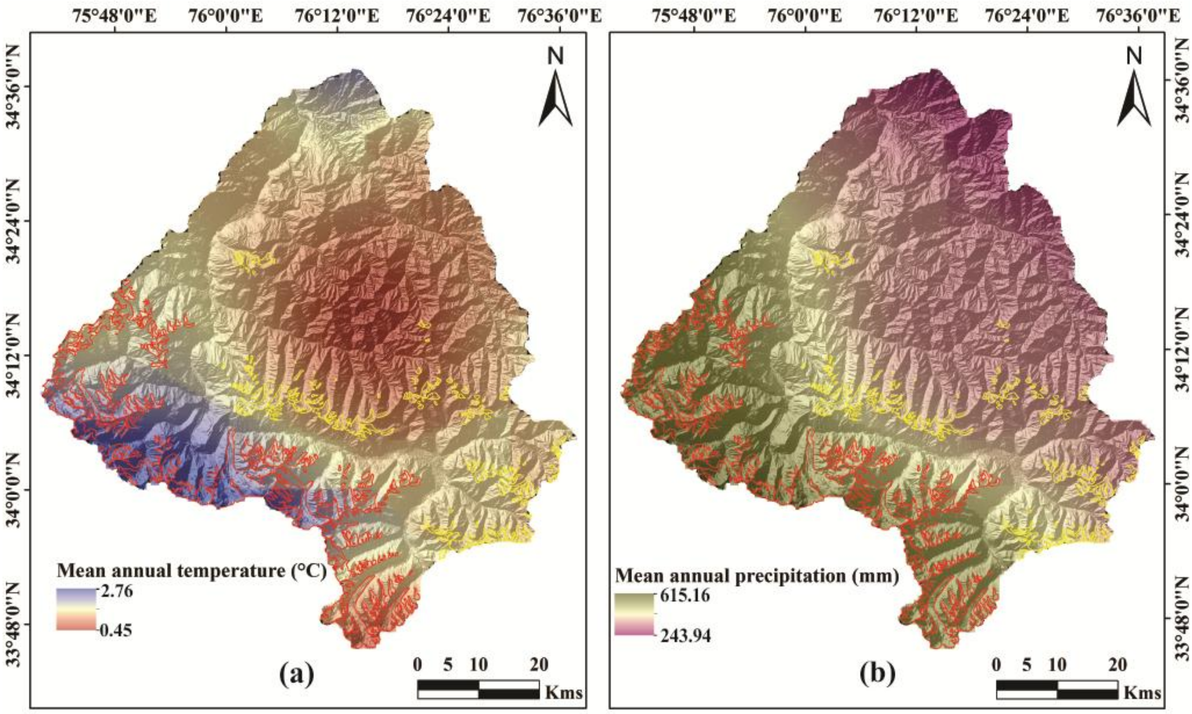

Figure 9. Spatial variation in meteorological data recorded for 15 grids in the SSB during the period 1901-2017. Map showing the long term mean annual (a) temperature (°C) and (b) precipitation (mm) data within the sub-basin suggesting the existence of significant local climate variability in the region. Glacier boundaries are shown as: GHR (red) and LR (yellow).

Observations indicate that the glaciers covered in grid 4 have been experiencing a warmer climatic regimes with the maximum annual mean temperature of 1.69 °C as compared to the other glaciers in the region (grid 2 = 1.4 °C, grid 5 = 0.74 °C, grid 1 = 0.65 °C and grid 3 = 0.45 °C). Spatial variability in annual mean precipitation data reveal that grid 2 (448 mm) & grid 1 (442 mm) experienced wetter climate as compared to grid 4 (383 mm), grid 3 (373 mm) and minimum in grid 5 (318 mm). These observations suggest that GHR glaciers have been experiencing a warmer and wetter climate (1.03 °C/ 445 mm) as compared to the LR glaciers (0.96 °C/ 358 mm) (Fig. 3e;f). These observations clearly show that local climate variability does exist in the basin for the entire duration of 116 years (Fig. 9).

5.3 Glacier changes: Impact of climatic and other plausible factors

The alterations in the climatic conditions, discussed in Sect. 5.2, would in turn, influence the glacier parameters, however varying with time. This section correlates the climatic and other factors (elevation range, regional hypsometry, slope, aspect and proglacial lakes) with the variations in the glacier parameters.

5.3.1 Impact of climatic factors

An overall degenerating pattern of the glaciers in the SSB is observed during the period 1971-2017, with deglaciation of 32 ±9 km^2 (6 ±0.02%). In the same duration, the glaciers have also retreated by an average 199 ±46.9 m (retreat rate: 4.3 ±1.02 ma^{-1}) alongwith an increase in the debris cover by ~62%. The observed overall degeneration of the glaciers have possibly resulted due to the warming of climatic conditions during this particular time frame. The conspicuous degeneration of these glaciers might have led to an increased melting of the glacier surface, which in turn would have unveiled the englacial debris cover and increased its coverage in the ablation zone (Shukla et al., 2009; Scherler et al., 2011). An enhanced degeneration of the glaciers have been noted during 2000-2017 (0.85 ±0.005 km^2a^{-1}) than 1971-2000 (0.59 ±0.005 km^2a^{-1}). Also, nearly 12 glaciers have shown disintegration into glacierets after 2000. These observations may be attributed to the relatively higher annual mean temperature (1.68 °C) during the former as compared to the period 1971-2000 (0.89 °C). Concomitant to the maximum glacier degeneration during the period 2000-2017, debris cover extent has also increased more (24%) as compared to 1971-2000 (16%). The enhanced degeneration of the glaciers during 2000-2017 might have facilitated an increase in the distribution of supraglacial debris cover. A transition from CGs to PDGs has also been noticed which resulted due to increase in the debris cover percentage over nearly 99 glaciers. The conversion from PDGs to HDGs (39) and from CGs to HDGs (2) has also occurred. Also, most of these transitions have occured during 2000-2017, which confirms the maximum degeneration of the glaciers during this particular period.

It is observed in our study that smaller glaciers have deglaciated more (4.13%) than the medium (1.08%) and larger (1.03%) sized glaciers during the period 1971-2017 (Fig. S2). This result depicts an enhanced sensitivity of the smaller glaciers towards the climate change (Bhambri et al., 2011; Basnett et al., 2013; Ali et al., 2017). A similar pattern of glacier degeneration is noted during 1971-2000, with smaller glaciers deglaciating more (5%) as compared to the medium sized (3%) and larger (1%) ones. However during 2000-2017, medium glaciers showed slightly greater degeneration (3.9%) as compared to the smaller (3.7%) followed by larger ones (1.5%). We have also observed maximum length change for smaller glaciers (8%) in comparison to medium (5%) and large glaciers (3%). These results indicate that the snout retreats are commonly associated with small and medium sized glaciers (Mayewski et al., 1980).

Temporal and spatial variations in SLAs are an indicator of ELAs, which in turn provide direct evidences related to the change in climatic conditions (Hanshaw and Bookhagen, 2014). SLAs are amongst the dynamic glacier parameters that alters seasonally and annually, indicating their direct dependency towards the climatic factors such as temperature and precipitation. In the present study, the mean SLA has gone up by an average 22 ±*60* m during the period 1977-2017. This rise in SLA is synchronous with the increase in mean annual temperature by 0.43°C. Moreover, the maximum rise in SLA during 1994-2000 is contemporaneous with the rise of temperature by 0.64 °C during this time period.

Further, in order to understand the regional heterogeneity in glacier response within the sub-basin, parameters of the GHR and LR glaciers are analyzed separately at four different time periods and correlated with the climatic variables. It is found that the LR glaciers have deglaciated more (7.2%) as compared to the GHR glaciers (5.9%). Similarly, more debris cover is found to have accumulated over the LR (73%) glaciers as compared to the GHR (59%) glaciers during 1971-2017. This result shows that the relatively cleaner (LR) glaciers tend to deglaciate more alongwith accumulation of more debris as compared to the debris and partially debris covered glaciers (GHR glaciers) (Bolch et al., 2008; Scherler et al., 2011). Moreover, increase in mean annual temperature in the LR (0.3°C) is slightly greater than in GHR (0.25°C) during the period 1971-2017, thus exhibiting a positive correlation with deglaciation and debris cover distribution in these regions. We also observed that the glacier area, length and debris cover extent of the LR glaciers show a good correlation with winter T_{min} and average precipitation as compared to the GHR glaciers (Table 3). This shows that both temperature as well as precipitation influence the degeneration of the glaciers and in turn affects the supraglacial debris cover. It is believed that winter precipitation has a prime control on accumulation of snow on the glaciers, hence acts as an essential determinant of glacier health (Mir et al., 2017). Also, the negative correlation of glacier area with precipitation in this study possibly indicate the major role of increased winter temperature and precipitation, which might have decreased the accumulation of snow, thereby decreasing the overall glacier area. The average SLA for LR glaciers is observed to be higher as compared to the GHR glaciers. However, a relatively higher rise in SLA is observed for GHR in contrast to the LR glaciers. Also, the mean SLA of the GHR glaciers shows a good positive correlation with summer T_{max} as compared to the LR glaciers, while a negative correlation with precipitation in the respective year (Table 3). Considering these observations, it appears that a general rise in SLA can be attributed to regional climatic warming while that of individual SLA variation in glaciers may be related to their unique topography (Shukla and Qadir, 2016).

From this analysis, it is quite evident that climatic factors directly influence the glacier response. Also, summer T_{max} have a stronger control over SLA, while glacier area,length and debris cover are predominantly controlled by the winter T_{min} in the sub-basin.

Table 3. Coefficients of determination (r) between respective meteorological (temperature and precipitation) data and observed glacier parameters in the Greater Himalayan Range (GHR) and Ladakh Range (LR) at 90% confidence.T_{avg}, T_{min} and T_{max} are monthly mean, monthly mean minimum, monthly mean maximum temperatures and Ppt is monthly mean precipitation during different point in time (1971,1994, 2000 and 2017).

Major Mountain Ranges	Glacier Parameters	Climate Variables			
		Tavg	Tmin	Tmax	Ppt
Greater Himalayan Range (GHR)	Area	-0.826	**-0.897**	-0.347	-0.670
	Length	-0.908	**-0.926**	-0.345	-0.719
	Debris cover	0.842	**0.847**	0.434	0.593
	SLA	0.725	0.209	**0.725**	-0.315
Ladakh Range (LR)	Area	-0.900	**-0.942**	-0.568	-0.779
	Length	-0.909	**-0.939**	-0.569	-0.778
	Debris cover	0.929	**0.907**	0.595	0.719
	SLA	0.658	0.395	**0.658**	-0.505

5.3.2 Impact of other factors

In addition to the climate variables, other factors such as hypsometry, maximum elevation, altitude range, slope, aspect and proglacial lakes also influence the response of an individual glacier.

Glacier hypsometry is a measure of mass distribution over varying altitudes. It is affected by the mean SLA of the glaciers to a greater extent, as it is considered that if a large portion of the glacier has elevation equivalent to SLA, then even a slight alteration in SLA might significantly change the ablation and accumulation zones (Rivera et al., 2011; Garg et al., 2017b).

In this study, we observed that GHR and LR glaciers have nearly 45% and 10% of their area at an elevation similar to SLA. This suggests that GHR glaciers are more susceptible to retreat as compared to the LR glaciers, as a larger portion of the former belongs to the SLA. Moreover, the hypsometric distribution of glacier area in the GHR and LR of the SSB reveals maximum area change post 2000 (Fig. 6b). In this regard, while GHR glaciers have undergone relatively higher area loss (21%) at lower elevation (3800-4200 masl), the LR glaciers lost maximum area (30%) at much higher elevation (5600-5900 masl) ranges (Fig. 6b). Besides, a significant area loss has also been observed for both GHR (6%) and LR (7%) glaciers at their mean elevations post 2000 (Fig. 6b).

Elevation plays an important role in understanding the accumulation pattern at higher and ablation in the lower altitudes. The general perception is that the glaciers situated at relatively higher elevation are subjected to greater amount of precipitation and hence are susceptible to less deglaciation or even mass gain (Pandey and Venkataraman, 2013). Similarly, we have also noticed that the glaciers extending to comparatively higher maximum elevation experience minimum retreat (10%) and exhibit higher percentage deglaciation (33%) as compared to the glaciers having lower maximum elevation (retreat: 15% & deglaciation: 20%) (Fig. 10a).

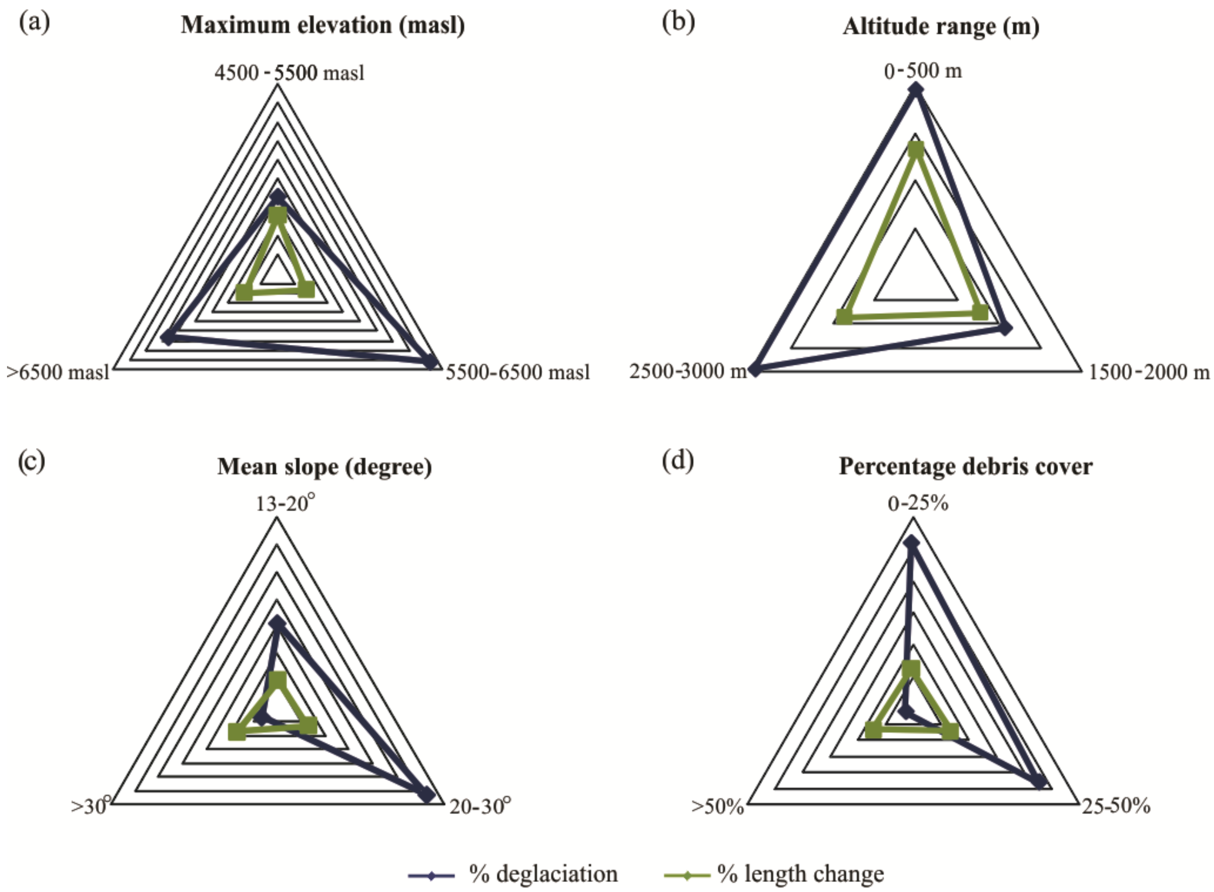

Figure 10. Differential degeneration of the glaciers during the period 1971-2017 with variability in non-climatic factors. (a) Percentage deglaciation and length change of the glaciers at different ranges of maximum elevation, (b) altitude range, (c) mean slope and (d) percentage debris cover.

Moreover, our study shows that the glaciers having lower altitude range have retreated and deglaciated more (13% & 20%, respectively) as compared to the counterparts (Fig. 10b). These observations indicate that glaciers which possess higher maximum elevation and altitudinal range are subjected to less retreat and undergo greater deglaciation.

Slope is another important factor which has a major role in the sustenance of the glacier as accumulation of ice is facilitated by a gentler bedrock topography (DeBeer and Sharp, 2009; Patel et al., 2018). It is observed that glaciers having steep slopes (30-40°) have retreated more (17%), however with minimum deglaciation (7%) during the period 1971-2017 (Fig. 10c). Similar results with steeper glaciers exhibiting minimum deglaciation have been reported in the Parbati, Chandra and Miyar basins (Venkatesh et al., 2012; Patel et al., 2018). However, it differs with Pandey and Venkataraman (2013) and Garg et al., (2017b), likely due to the differing average size: 25 ±33.78 and 17 ±33.2 km^2 (present study: 2 ±5.7 km^2) and slope: 5-20° and 12-26° (present study: 13-41°), respectively, of glaciers used in these studies.

Presence of supraglacial debris cover influences the glacier processes. Depending on thickness, debris cover may either enhance or retard the ablation process (Scherler et al., 2011). In this study, we observed that clean glaciers have undergone maximum deglaciation (52%) as compared to the partially (46%) and heavily debris covered glaciers (2%). However, they all have retreated almost similarly (12 to 14%), with slightly higher retreat of partially debris covered glaciers (Fig. 10d). Aspect/ orientation of glaciers provide information regarding the duration for which they are exposed to the incoming solar radiation. Since, the south facing glaciers are subjected to longer duration of exposure to the solar radiations as compared to the north facing glaciers, therefore, are prone to greater deglaciation and retreat (Deota et al., 2011). Here, it is observed that the glaciers having northerly aspect (north, north-east, north-west) have undergone maximum deglaciation as compared to the counterparts. However, majority (71%) of the glaciers have northerly aspect, so any inferences drawn in this respect would be biased. It is worthwhile to state that most of the south facing slopes in the basin are devoid of glaciers but show presence of relict glacier valleys which would have been glaciated in the past. At present only 48 south facing glaciers (south, south-east, south-west) with an average size of 1 ±*1.9* km^2 exist in the SSB.

Similarly, the glacier changes are also influenced by the presence of certain features such as glacial (proglacial or supraglacial) lakes or differential distribution of supraglacial debris cover. The presence of a proglacial or supraglacial lakes significantly enhances the rate of glacier degeneration by increasing the melting processes (Sakai, 2012; Basnett et al., 2013). As per our results, highest average retreat rate (~31ma^{-1}) is observed for glaciers G-4 (Dulung glacier). Although, it is a debris free glacier, shows the highest retreat rates. Also, a moraine-dammed lake is observed at the snout of this glacier and has continuously increased its size from 0.15 km^2 in 1977 to 0.56 km^2 in 2017. This significant increase in the size of moraine-dammed lake has possibly influenced the enhanced retreat rate of the glacier.

6 Dataset availability

Temporal inventory data for glaciers of Suru sub-basin, western Himalaya is available at https://doi.pangaea.de/10.1594/PANGAEA.904131 (Shukla et al., 2019).

7 Conclusions

The major inferences drawn from the study include:

1. The sub-basin comprised of 252 glaciers, covering an area of 481.32 ±3.41 km^2 (11% of the glacierized area) in 2017. Major disintegration of the glaciers occurred after 2000, with breakdown of 12 glaciers into glacierets. Small (47%) and clean (43%) glaciers cover maximum glacierized area of the sub-basin. Topographic parameters reveal that majority of the glaciers are north facing and the mean elevation and slope of the glaciers are 5134.8 ±*225* masl and 24.8° ±*5.8*°, respectively.

2. Variability in glacier parameters reveal an overall degeneration of the glaciers during the period 1971-2017, with deglaciation of approximately 0.13 ±0.0004%a^{-1} alongwith an increase in the debris cover by 37 ±0.002 km^2 (~62%). Meanwhile, the glaciers have shown an average retreat rate of nearly 4.3 ±1.02 ma^{-1} with SLA exhibiting an overall rise by an average 22 ±*60* m.

3. Long-term meteorological records during the period 1901-2017 exhibit an overall increase in the temperature (T_{min}: 1.3°C, T_{max}: 0.25°C, T_{avg}: 0.77°C) and precipitation (158 mm) trends. Both temperature and precipitation gradients influence the changes in glacier parameters, however, winter T_{min} strongly influencing the glacier area, length and debris cover while summer T_{max} controlling the SLA. Spatial patterns in change of climate

parameters reveal existence of local climate variability in the sub-basin, with progressively warmer (1.03°C) and wetter (445 mm) climatic regime for glaciers hosted in the GHR as compared to the LR (0.96°C/ 358 mm).

4. The inherent local climate variability in the sub-basin has influenced the behavior of the glaciers in the GHR and LR. It has been observed that LR glaciers have been shrinking faster (area loss: 7%) and accumulating more debris cover (debris increase: 73%) as compared to the GHR glaciers (6% and 59%) during the period 1971-2017. The GHR glaciers have, however, experienced greater rise in SLA (220 ±*121* m) in comparison to the LR ones (*91* ±*56* m) during the period 1977-2000, with a decrease thereafter.

Results presented here show the transitional response of the glaciers in the SSB between the Karakoram Himalayan and GHR glaciers. The study also confirm the possible influence of factors other than climate such as glacier size, regional hypsometry, elevation range, slope, aspect and presence of proglacial lakes in the observed heterogenous response of the glaciers. Therefore, these factors need to be accounted for in more details in future for complete understanding of the observed glacier changes and response.

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Author contribution

A.S. and S.G. conceived the idea and led the writing of manuscript. A.S. structured the study. S.G. performed the temporal analysis of the data. M.M. and V.K. helped in the field investigation of the glaciers. All the authors helped in interpretation of results and contributed towards the final form of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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