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# *Interactive comment on* "Temporal inventory of glaciers in the Suru sub-basin, western Himalaya: Impacts of the regional climate variability" *by* Aparna Shukla et al.

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Authors sincerely thank the editorial team for timely processing of the article and the referee for his/her valuable comments and suggestions on our manuscript. Please find the detailed specific responses to the referee's comments below. Revisions to the manuscript are mentioned in track change mode in the revised manuscript and also appended at the end of this document. Regards. Aparna Shukla.

Referee # 1:

Comment 1: Long-term climate data presentation and analysis needs attention. Page



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8, Line 183; Mean precipitation of the SSB for the period 1901-2017 has been 393 ±76 mm. However, if we see plots in figure 3(d), 3(e) and 3(f), monthly mean precipitation for the same period are quite high indicating high precipitation during the same period. Response 1: Thanks for pointing out. The annual average precipitation for the Suru sub-basin amounts to 393 ±76 mm during the period 1901-2017. However, the monthly mean precipitation values during the same period had been overestimated due to computational error. This error was introduced due to the variance in formats available for the CRU-TS derived precipitation data and hence was mistaken with the other format (mm/day). The error has now been rectified in the revised manuscript (Page 8; Figure 3d, 3e & 3f). The revised figures (3d, 3e, 3f) show monthly mean precipitation (Jan-Dec) variations of 33 ±14 mm/month in the entire Suru sub-basin, while 37 ±15 mm/month and 30 ±12 mm/month in the GHR and LR, respectively during the period 1901-2017.

Figure 3 (revised manuscript): 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 Suru sub-basin (SSB), Greater Himalayan range (GHR) and Ladakh range (LR) (sub-regions), respectively during the period 1901-2017. The light and dark grey colored lines depict the respective trend lines for precipitation 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.

Comment 2: Figure 3(a), 3(b) and 3(c) shows continuous increase in the temperature during the period 1995-96 onwards till 2005-06. It shows sudden change in the temperature pattern. The reason for the sudden shift in temperature pattern should be discussed. It will be interesting to see the temperature pattern of the IMD recorded data at Leh or any other in-situ recorded data in the study region during the same period. Response 2: Agreed. The mean annual temperature depicted in figure 3(a), 3(b) and

3(c) shows an overall increase of 0.71°C, 0.72°C, 0.71°C in the Suru sub-basin, GHR and LR, respectively, during 1995/96 till 2005/06 period as mentioned by the referee. The globally averaged combined land and ocean surface temperature data of 1983-2012 period is considered as the warmest 30-year period in the last 1400 years (IPCC, 2013). This unprecedented rate of warming has been 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 increment in temperature pattern is possibly due to the greenhouse effect from enhanced emission of black carbon in this region (by 61%) from 1991-2001 (Sahu et al., 2008). Evidences of incessant increase in temperature during 1990s have 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 ENSO, which is possibly one of the reasons for the considerable rise in temperature throughout the Himalaya (Shekhar et al., 2017). The same has now been discussed in the revised manuscript as suggested (Page 17, lines 470-480). Due to the unavailability of in-situ climate dataset for the Suru sub-basin, station data is obtained from nearest stations of Kargil and Leh and compared with the CRU-TS derived data for the entire Suru sub-basin during 1901-2002 period.

Figure R1: Mean annual temperature and precipitation patterns of CRU-TS derived gridded data and IMD recorded station at different locations.

The mean annual temperature pattern of Suru sub-basin shows a near decreasing trend till 1936, with an increase thereafter. Similar trends have been observed for Kargil and Leh, despite their distant location from the Suru sub-basin (areal distance of Kargil and Leh is ~63 and 126 km, respectively from the centre of Suru sub-basin). 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). Indeed, these results are interesting and we observe an almost similar trend in all the cases (Figure

R1), 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 Suru sub-basin, Kargil and Leh, respectively (Figure R1). While the change (increase) in mean annual temperature observed during the same period, i.e., 1901-2002 is found to be 0.34, 0.13 and 0.44 °C in Suru sub-basin, Kargil and Leh, respectively. 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.

Comment 3: A comparison of the CRU data with in-situ (temperature and precipitation) in the study region will provide information about the biases in the CRU data. Response 3: Agreed. Due to the unavailability of meteorological observatories in the Suru sub-basin, station data is obtained from nearest available IMD sites, i.e., Kargil and Leh and compared with their respective CRU-TS data (mean annual temperature and precipitation).

Figure R2: Mean annual temperature and precipitation patterns of IMD recorded station data at Kargil and Leh and their respective CRU-TS derived gridded data.

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 (Figure R2). The annual mean temperature/ precipitation have 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 (Figure R2).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 Suru sub-basin as well, since we learn that the reported temperature and precipitation changes are probably on the lower side of the actual variations. In case the reviewer thinks it's appropriate, this analysis may be incorporated at some suitable place in the manuscript or supplementary data.

Comment 4: Page 13, Line 339; How authors will explain the mean slope variation of 16.2° ±71° to 41° ±66°? Response 4: Thanks for pointing it. In this study, range of slope was reported initially depicting minimum and maximum variations in the overall data, i.e., in 16.2° ±71°, 16.2° was the average minimum slope and 71° was the deviation in this minimum slope considering the entire basin. Similarly, in 41° ±66°, 41° was the average maximum slope while 66° was the deviation in this maximum slope considering the entire basin. However, we now realize this form of data representation misleading. Therefore, we have now mentioned the mean slope of 24 ±6° and 25 ±6° in GHR and LR glaciers, respectively. The same has now been incorporated in the revised manuscript (Page: 13, Line: 347). Comment 5: Figure 4(a) Frequency distribution histogram depicting maximum frequency in the percent area change between 0.52-0.97. How it concludes that majority of the glaciers have undergone an area loss of 3.3%.

Response 5: The statement mentioning that the majority of the glaciers have undergone area change of 3.3% was based on mid-point of a legend category (0.8-6%) as shown in the chloropleth map. This was misleading as the categories of percent area change depicted in histogram differed from those shown in the chloropleth map. However, now we have simplified the histogram and the chloropleth map by keeping same divisions (range of percent area change) for both. In the revised Figure 4a, it may be observed that majority of the glaciers have undergone area change of the range 6-12% and same is depicted in the chloropleth.

Figure 4: (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.

Comment 6: Figure 5; Majority of the glaciers have undergone length change of 5% is not seen in the frequency distribution histogram. Response 6: The statement mentioning that the majority of the glaciers have undergone length change of 5% was based on mid-point of a legend category (0.9-8%) as shown in the chloropleth map. This was misleading as the categories of percent length change depicted in histogram differed from those shown in the chloropleth map. However, now we have simplified the histogram and the chloropleth map by keeping same divisions (range of percent length change) for both. In the revised Figure 5, it may be observed that majority of the glaciers have undergone length change of the range 6-14% and same is depicted in the chloropleth.

Figure 5: 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 in the range 6-14%.

Comment 7: What could be the possible reasons of decrease in SLA in LR glaciers despite of increase in temperature and retreat in glacier length in the region? Response 7: Yes, if we simply try to equate the absolute temperature change in LR with the overall SLA and/or length changes observed in this region then the results might seem counter-intuitive. However, such is not the case. While SLA (often used as a reliable proxy for glacier mass balance changes (Guo et al., (2014)) responds directly to the changes in meteorological variables mostly temperature, length changes or retreat are much delayed response of the glaciers towards climate change (Bolch et al., 2012; Paul et al., 2017). Besides, glacier retreat is often strongly influenced by the local snout characteristics and conditions such as presence of proglacial lakes, supraglacial debris coverage and differential shadowing (Sakai, 2012; Shukla and Qadir, 2016; Garg et al., 2017). For these reasons SLA and retreat trends may not always be in-sync. Coming to the reported increase in temperature in the LR, this increase has been estimated using following formulation which takes into account longterm mean and trends of entire temperature data series in the form of Sen's slope. Change in Temperature and Precipitation=($\beta$*L)/M where $\beta$ is Sen's slope estimator, L is length of period and M is the long term mean. Contrary to this, the reported SLA changes are simple difference between the average SLAs of 1977 and 2017. Thus, the SLA changes seem counter-intuitive to the temperature variations and do not correlate well with it. However, if we break this long time frame of 40 years (1977–2017) into shorter time periods then we find that the SLA in LR had been responding excellently to the ongoing temperature changes (Table R1). Also, the SLA and temperature changes have, as expected, high negative correlation with each other (i.e., -0.82). Table RT1: Period wise variations in SLA of the LR glaciers and changes in temperature conditions during the corresponding time interval.

Comment 8: Page 16; Line 405; there is a large difference in the number of glaciers reported in the sub basin by earlier researchers and reported in the present paper. It needs discussion and possible reasons. Is there any difference in defining a glacier? Response 8: Statistics of the year 2000 reveal a total of 240 glaciers in the Suru sub-basin (Page 16; Line: 404 of the original manuscript). This is, though comparable with that reported by Sangewar and Shukla, (2009) i.e. 284, varies drastically from SAC report, (2016) and RGI (2 different analysts) [110 and (514 & 304), respectively].One possible reason could be the difference in methodology adopted for glacier delineation leading to systematic errors (Page: 16; Lines: 410-411 of the original manuscript). Secondly, the involvement of multiple analysts may introduce random errors, as in case of RGI (Page: 16; Lines: 411-412 of the original manuscript). Yes, as already pointed out there is a difference in defining a glacier in these studies, which is yet another plausible reason for introducing the bias in the glacier count. RGI have provided separate glacier id to each polygon in the Sub-basin, which might be the reason for overestimation of glaciers. While no such information regarding the definition of glacier has been provided in the SAC report, 2016. However, in this study, the glacierets / tributary glaciers contributing to the main trunk are considered as a single glacier entity, which is a standard procedure for assigning the glacier id. The statement was somehow missing from the original manuscript which would have created the confusion, therefore, now it has been incorporated in the revised manuscript (Page 10, lines 239-240).

Comment 9: Page 18, Line 462; statement ’However a sudden decrease in the precipitation anomaly is observed in the year 2016 with an increase thereafter’, it is not clear to me that Figure 3(a), (b) and (c) are showing ’precipitation’ or ’precipitation anomaly’? Year 2016 is missing in the Figure. Response 9: Figure 3(a) (b) and (c) are showing ’5 year moving average of average annual precipitation’. The statement mentioned in the original manuscript regarding ‘precipitation anomaly’ was previously included in the graphs. However, these graphs were changed (with different mode of representation) later owing to more information shown by present graphs included in the manuscript (Figure 3). These lines should have been removed from the text as well. We regret their inclusion. The vertical bars show 5 year moving average of mean annual precipitation during the period 1901-2017.

Comment 10: Page 18, Line 462-463; statement regarding mean annual precipitation is not clear if I look at Figure. Response 10: Similar to Response 9

Comment 11: Page 18, Line 463-464; ’temperature and precipitation anomaly’ not understood. Response 11: Thanks for pointing out. The statement mentioned in the original manuscript regarding ‘temperature and precipitation anomaly’ was previously included in the graphs. However, these graphs were changed (with different mode of representation) later owing to more information shown by present graphs included in the manuscript (Figure 3). These lines should have been removed from the text as well. We regret their inclusion. The statement has now been edited to "Besides these general trends in mean annual temperature and precipitation, an overall absolute increase in the mean annual temperature (Tmax & Tmin) and precipitation data have





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been noted as 0.77 °C (0.25 °C & 1.3 °C) and 158 mm, respectively during the period 1901-2017" (Revised manuscript; Page 17; lines 482-484).

Comment 12: It is advised to draw a trend line for temperature and precipitation variation in Figure 3. Response 12: Thanks for the suggestion. A trend line for temperature and precipitation variations have now been added in Figure 3 of the revised manuscript.

Comment 13: Page 18, Line 466; 'Percentage increase in the average, maximum and minimum temperature observed to be 99, 12 and 17%', generally temperature variation is not shown in percentage. I will give an example, if mean temperature varies from 0.1°C to 0.2°C for one year and next year it drops to 0.1°C again, should one conclude that temperature variation was 100% increasing for the first year and 100% decreasing for next year. Statement will be misleading, since the temperature variation was minimal. If the unit of temperature changes from °C to K, then still the statement will hold good? It is advised not to represent temperature variation in % throughout the manuscript. Response 13: Agreed. As suggested, we have now reported the temperature and precipitation changes in absolute form rather than in percentage.

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AUTHOR'S CHANGES IN THE MANUSCRIPT On Page 8; Figure 3 has been updated as suggested by reviewer in Comments 1 and 12.Line stating "The glacierets/ tributary glaciers contributing to the main trunk are considered as single glacier entity" has been added on Page 10; lines: 239-240 according to comment 8.

On page 13, lines: 346-347 have been edited to "Mean slope of the glaciers is 24.8 $\pm$5.8° and varies from 24 $\pm$6° to 25 $\pm$6° in the GHR and LR, respectively" based on reviewer's comment 4.

Page 13 and 14, lines: 354-355 and figure 4 have been edited as suggest in comment 5.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.4a).

Page 14, lines: 373-374 and figure 5 have been edited as suggest in comment 6. 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.5).

Page 17, lines: 470-480 stating: 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 is considered as the warmest 30-year period in the last 1400 years (IPCC, 2013). This unprecedented rate of warming has been 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 increment 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 have 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 ENSO, which is possibly one of the reasons for the considerable rise in temperature throughout the Himalaya (Shekhar et al., 2017) have been added as suggested by the Reviewer in comment 2.

Page 17; lines 480-482 stating 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) have been edited as suggested by the Reviewer in comments 9,10 and 11.

Please also note the supplement to this comment:
https://www.earth-syst-sci-data-discuss.net/essd-2019-122/essd-2019-122-AC1-supplement.pdf

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Interactive comment on Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2019-122, 2019.

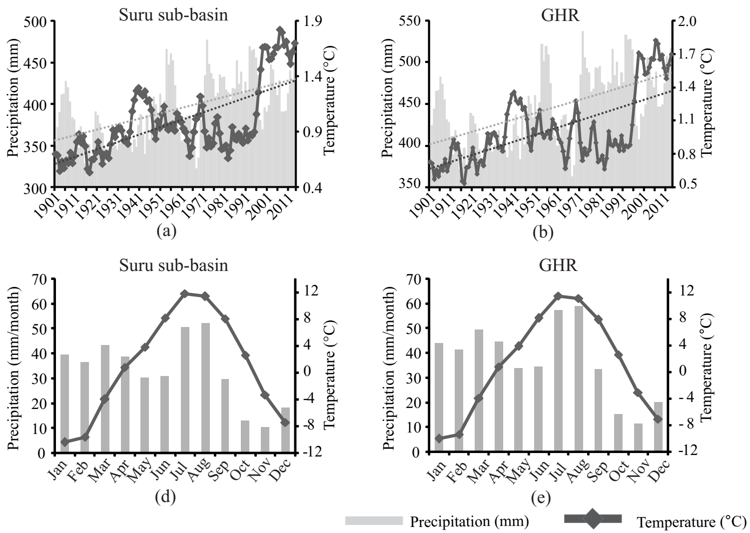


**Fig. 1.** Annual and seasonal variability in the climate data for the period 1901-2017.



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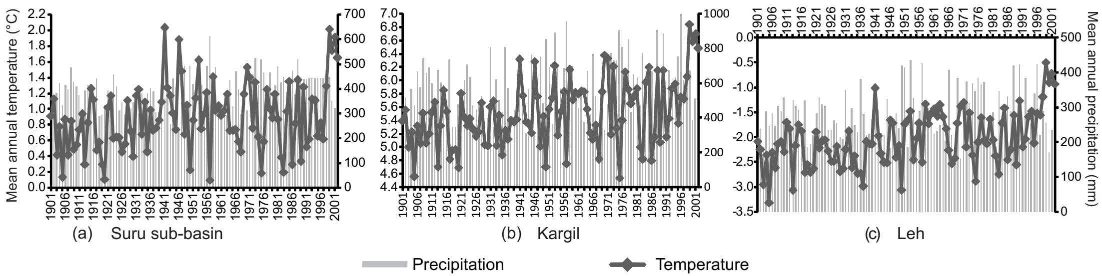


**Fig. 2.** Mean annual temperature and precipitation patterns of CRU-TS derived gridded data and IMD recorded station at different locations.



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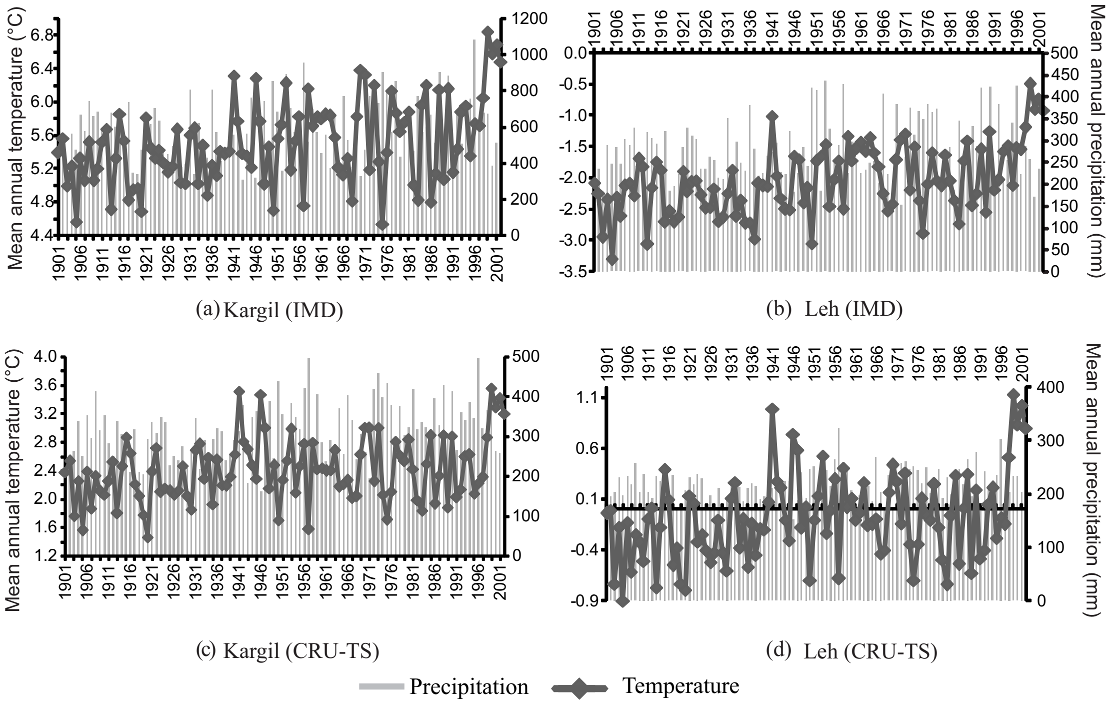


**Fig. 3.** Mean annual temperature and precipitation patterns of IMD recorded station data at Kargil and Leh and their respective CRU-TS derived gridded data.



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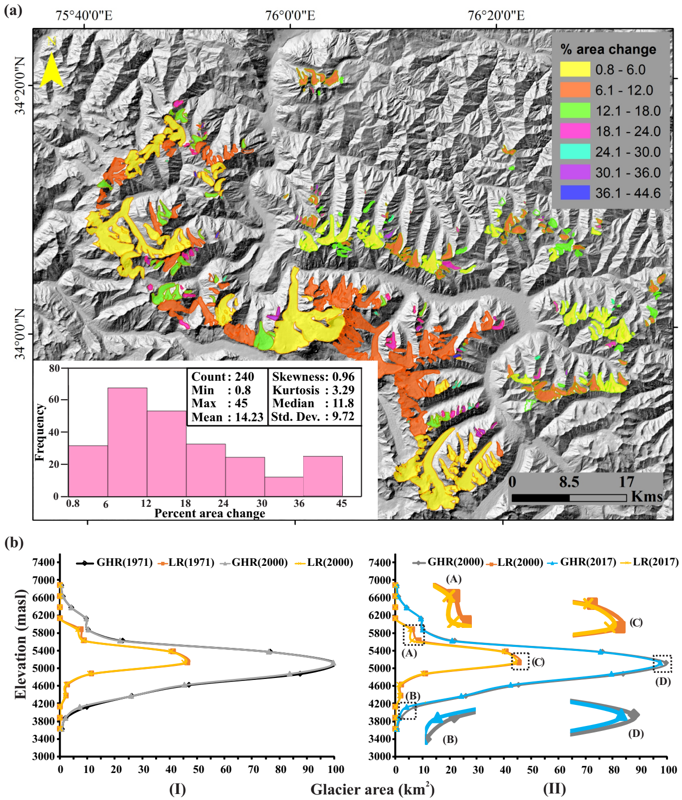


**Fig. 4.** Percent area loss of the glaciers in the SSB during the period 1971-2017.

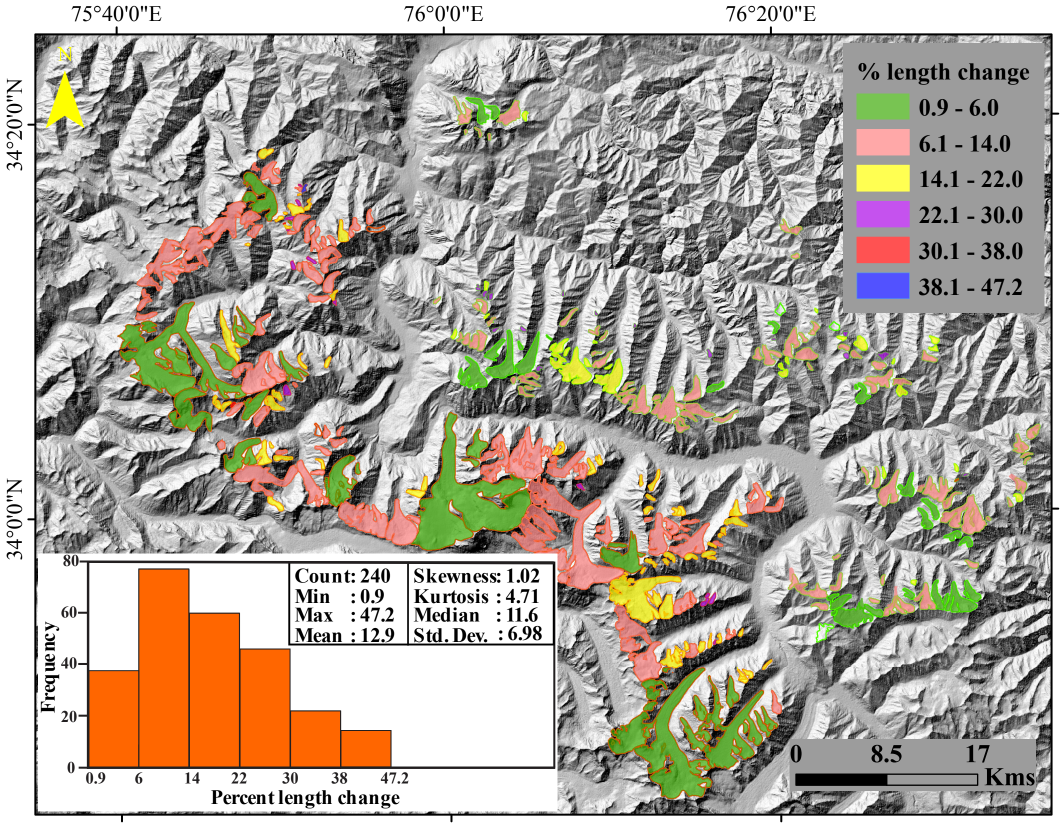


**Fig. 5.** Percent length change of the glaciers in the SSB during the period 1971-2017.