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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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Dear Referee, Authors thank the anonymous reviewer for his/her valuable comments and suggestions on our manuscript and the editorial team of the Earth System Science Data for timely processing of the article. Responses to the referee's comments are as follows: Regards. Aparna Shukla.

General comments:

Comment GC1: The study by Shukla et al. entitled, "Temporal inventory of glaciers in the Suru sub-basin, western Himalaya ....." provides very useful data sets of glaciers in

the Suru Sub-Basin in Western Himalaya that are very useful for better understanding the status and fate of the glaciers in the Western Himalaya. The data and manuscript quality is good, except that it would require a major revision to make it in the framework of data paper. Currently, larger focus is on the scientific implications of the data, which is not focus of the journal. While authors have also followed standard methods to process and analyse the data, the methods are not unique.

Response GC1: We agree with your opinion regarding focus of the journal, which aims at publishing articles with original research dataset having the potential to contribute significantly towards the field of Earth Science. In line with the intent of the journal: 1. We have prepared a multi-temporal inventory for four different time periods, which in itself is unique and scarce in the Himalayan region. Apart from addressing the discrepancies, this research also aims to update the data presented in existing inventories (of Suru sub-basin) in order to have a recent and more accurate estimate of glaciers. 2. Inherent data characteristics (glacier area, length, debris cover and snow line altitude changes) have also been assessed to understand the spatial and temporal variability of the glaciers in response to the climate change. 3. Besides, the response of glaciers in Suru sub-basin has also been assessed with respect to other basins of the Himalaya to develop a regional picture. 4. The influence of factors other than climate such as glacier size, regional hypsometry, elevation range, slope, aspect and presence of proglacial lakes have also been evaluated to understand the heterogenous response of the glaciers. To accomplish our objectives, a hybrid methodology is adopted, in which the snow-ice boundaries are mapped using a semi-automatic technique of NDSI and debris coverage through manual digitization. Similar methods of glacier mapping have been employed in other glaciological studies (Bolch et al, 2010; Bhambri et al., 2011; Frey et al., 2012; Chand and Sharma, 2015; Mir et al., 2017; Murtaza and Romshoo, 2015; Molg et al., 2018). In addition, methods have also been employed for estimation of uncertainties which might have introduced from various sources (Hall et al., 2003; Granshaw and Fountain, 2006; Paul et al., 2013;17).

Comment GC2: Overall, large amount of digitization work has been done for this study. However, the Suru basin is a small sub-basin of the Indus river basin, with only 11% of its area is covered with glaciers. So the authors need to substantially revise the manuscript to be useful as a regional representative of Western Himalayan glaciers. Considering the unique scope of the journal, it would therefore, require that the authors to incorporate similar dataset from other distinct basins of Upper Indus Basin to make it more regionally relevant.

Response GC2: Thanks for the suggestion. Suru is actually a sub-basin of Jhelum river basin, which comprises an overall basin area of 50,844 km2 and glacierization of mere 1.4% (733 glaciers) (Bajracharya et al., 2019). In this respect, the Suru sub-basin covers ∼9% basin area and 34% glacier count of the entire Jhelum river basin. The prime reason for selection of this very sub-basin for our study purpose was its significant amount of glacier coverage with respect to the entire basin size of the Jhelum. Despite, low percentage coverage (11%), glaciers in the Suru sub-basin show large scale variability locally as well as regionally. Also, the study is unique in itself, as it presents a long time series data of glacier changes and climate patterns, which helps in developing a comprehensive understanding of glacier response on the basin scale (i.e. Suru sub basin). Moreover, existing inventories of the Suru sub-basin as mentioned in the manuscript (Page: 4; lines:132-136) have disparate estimates which need updation. Besides, the Suru sub-basin covers part of two major ranges, i.e., the Greater Himalayan (GHR) and the Ladakh (LR) range, which helps in understanding the existing intra-regional heterogeneity in glacier response and compare it with other basins as well.

The datasets in the manuscript have been processed using a hybrid methodology: Normalized Differential Snow Index (NDSI) for delineation of ice and snow covered boundaries and manual editing for debris cover (Page 10; lines: 231-232 of the original manuscript). The debris cover boundary is manually delineated as no apt technique has been developed till date, which could extract it automatically using optical satellite

images. Moreover, we have also taken assistance of thermal and slope maps for manual digitization of the debris cover boundaries. Similar mapping methodology has been followed by several researchers (Bolch et al., 2010; Chand and Sharma, 2015; Mir et al., 2017; Molg et al., 2018).

Specific comments:

Comment 1:Unlike the Karakoram, the Ladakh Range is not a well known nomenclature. Chudley et al., (2017) have used the Karakoram and Ladakh range, not differentiated about Karakoram and GHR. Mir et al. (2018) have represented it as a part of the GHR. It is therefore, important to define/clarify the same.

Response 1:We agree that the Ladakh range was not a well known nomenclature in the field of glaciology , however, is well recognized in studies pertinent to Himalayan geology (Raz and Honeggar, 1989; Weinberg and Dunlap, 2000; Kirstein et al., 2006; St-Onge et al., 2010; Borneman et al., 2015). Nevertheless, such studies have now become prevalent in glaciology as well, with increase in the number of studies in this region (Schmidt and Nusser, 2012; 2017; Chudley et al., 2017). Chudley et al., (2017) have considered the central and eastern Ladakh range as their research area and have shown that the response of glaciers in these regions is consistent with that in the western Himalaya (to the south), however in contrast to the Karakoram (to the north) Himalaya (Figure R1). In this scenario, our study area covers part of southern Ladakh range (33°54′ to 34°21′ N and 76°00′ to 76°36′ E) and part of Greater Himalayan range (33°43′ to 34°19′ N and 76°37′ to 76°18′ E), lying at the northernmost end of Zanskar range.

Figure R1: Studies conducted in different parts of the western Himalaya (modified after Schmidt and Nusser, 2017)

Mir and Mazeed, (2016), on the other hand, have conducted their study on the Parkachik glacierlocated in the Suru sub-basin. Similar to our study, they have also included the Parkachik/ Kangriz glacier in the GHR (Figure 1 of the original manuscript).

Comment 2: The accuracy of CRU-TS data is not analysed independently. It is critical as the Fig. 3 data looks bit unrealistic. The temperature data indicate dramatic changes after 1990, which needs to be confirmed. Since India Met Department has long term station data in this region as well as gridded data (http://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html), it is critical to check the data consistency and conduct error statistics.

Response 2: Thanks for pointing out. In Fig.3 of the original manuscript, the monthly mean precipitation values during the period 1901-2017 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: 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 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.

As rightly indicated by the reviewer, a drastic increase in the mean annual temperature is noticed post 1990, especially from 1995/96 till 2005/06. The mean annual temperature as depicted in figure 3(a), 3(b) and 3(c) shows an overall increase of 0.69°C, 0.66°C, 0.71°C in the Suru sub-basin, GHR and LR, respectively, during period 1990-2017. Infact, 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). In order to check data consistency, we have taken up instrument data from nearest stations of Kargil and Leh (due to the unavailability of meteorological stations in the Suru sub-basin) and compared with the CRU-TS derived data for the entire Suru sub-basin during 1901-2002 period (Figure R2).

Figure R2: Mean annual temperature and precipitation patterns of CRU-TS derived gridded data in (a) Suru sub-basin and IMD recorded station at (b) Kargil and (c) Leh. The mean annual temperature pattern of Suru sub-basin 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 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). The results are interesting and we observe an almost similar trend in all the cases (Figure R2),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 R2). 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.

This analysis aptly brings out the bias in the CRU TS gridded data. Majorly the comparison shows that though the gridded data correctly brings out the temporal trends in meteorological data but differ with station data in magnitude (being on lower than the station estimates). This helps us better appreciate the climate variations in Suru subbasin as well since we learn that the reported temperature and precipitation changes are probably on the lower side of the actual variations. Also, we have used the station data, 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 R3: 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 R3). 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 R3).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.

Comment 3: Considering the large uncertainty involved in Landsat MSS data, it is important to mention the inherent uncertainties while interpreting the temporal variability.

Table 1: include the Scene ID for clarity.

Response 3: We agree with the reviewer. Despite large uncertainties involved in Landsat MSS dataset, we have utilized it to compensate for the data gap in the Corona imageries (covering 40% of the GHR and 58% of the LR glaciers). Previous studies have frequently utilized the Landsat MSS imagery for glacier mapping and analysis for the 1970s period (Pandey and Venkatraman, 2013; Rai et al., 2013; Shangguan et al., 2014; Thakuri et al., 2014; Brahmbhatt et al., 2015; Shukla and Qadir, 2016; Mir et al., 2017). Moreover, we have also accounted for uncertainties using prevalent methods (area and length change uncertainty by Hall et al., 2003 and mapping uncertainty using buffer method by Granshaw and Fountain, 2006)) associated with glacier changes (area and length) using Landsat MSS data and also incorporated the same in the original manuscript (Table 2).

In addition to this, we have now taken 2 glaciers, GL-157 (small, 5.5 km2) and Kangriz glacier (largest, 53 km2) and digitized their boundaries using both the Corona and Landsat MSS imageries. On comparing the glacier boundaries using the two datasets, we noticed that higher uncertainty is associated with the GL-157 (22%) as compared to the Kangriz glacier (0.1%).Considering this, we could say that, though larger in magnitude the uncertainty estimates using Landsat would not affect GHR glaciers much (comparatively larger in size) as compared to the LR (smaller in size) glaciers.

As suggested, the Scene IDs have now been incorporated with theTable1.

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

Comment 4: Lines 236-240: The procedures used for determining the glacier boundaries are apparently manual digitization. While this is reasonable to undertake manual processing in such complicated areas, it also necessitates a study of uncertainty estimations in such manual work. Authors may also undertake repeatability tests with different analysts to determine repeatability.

Response 4:We have followed a 'hybrid approach', involving normalized difference snow index (NDSI) for delineation of snow-ice boundaries and manual digitization for mapping the debris cover (Page: 10; lines: 231-232 of the original manuscript). Similar mapping methodology has been followed by several researchers (Chand and Sharma, 2015; Mir et al., 2017; Molg et al., 2018). As aptly pointed out by the reviewer, we also agree that manual processing of the database necessitates uncertainty estimation. However, the essence of this work lies in the mapping of the glaciers for multiple (four) time periods by a single analyst, which minimizes the errors to a great extent. While, the repeatability tests are more relevant for studies concerning global scale inventory such as Randolph glacier inventory (RGI), Global land ice measurements from space (GLIMS) and recently Chinese glacier inventory (CGI), where multiple analysts are involved. Nevertheless, we have performed the repeatability tests on the Pensilungpa glacier by delineating its boundary for the year 2017 by 4 different analysts. The test result shows variation in glacier size by all four analysts (17.003 km2, 16.22 km2, 16.59 km2 and 14.67 km2). These values have varied significantly and slightly overestimated from the size estimated using the semi-automatic approach (15.57 km2). The fluctuations in glacier size have varied within the range of 5-10%, i.e., by 9, 4, 6.5 and 6%, respectively), which is acceptable for glacier mapping (Paul et al., 2013).

Comment 5:Lines 272 – 300: The uncertainty assessment is biased with the very limited field validation on only one glacier for a very limited time frame. One issue that needs to be addressed is the reliability of ground truth data when different types of data were used through the nearly 50 years' time period.

Response 5: We agree that very limited field validation has been incorporated for a limited time frame, however, ground based monitoring of the glaciers is difficult and often constrained by extreme conditions prevailing in the Himalayan glaciated terrain. This is very well discerned from the limited field studies (11 in western, 4 in central, 1 in eastern) being conducted in the Himalayan region till date (Pratap et al., 2015; Raina and Srivastava, 2008). In this study, the aim of comparing our results with field

data (initially for 2017) was basically validating the mapping method as data related errors are being already accounted for in the other methods of uncertainty estimation. However, to enhance the reliability of ground data, we have now incorporated field data of the Kangriz glacier as well for year 2018 (obtained from DGPS). On comparing the snout position of the Kangriz glacier derived from DGPS and OLI image, an accuracy of ±1.4 m is obtained. Also, the frontal retreat estimated 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. While the mapping uncertainty of the Kangriz glacier is found to be 0.96%, which shows that our remotely derived estimates matches well with that of field and hence, supports our mapping method. This result has now been incorporated in the revised manuscript (Page: 11; lines: 288-290).

Comment 6: Please discuss why the projective transformation was required for the satellite data sets other than Corona?

Response 6: We have used projective transformation for co-registration of all the images, i.e., Landsat as well as Corona (Page: 10; lines: 227-231 of the original manuscript) in order to maintain uniformity in data processing method. Projective transformation is a novel technique of image registration which projects the 2-dimensional image on the radius and angular coordinates, respectively. Moreover, this method has been used because in contrast to the other methods of image registration, i.e., polynomial and rubber sheeting, projective transformation involves the input reference of DEM which allows the analyst to capture the dynamics of the image and enhances the quality of the two-dimensional data.

Comment 7: Line 328- 330: Categorization of glaciers - is there a scientific standard for categorizing the glaciers in the different categories or was more based on the author's selectivity? Check DeBeer and Sharp (2009, Journal of Glaciology). Since the data descriptions needs to be internationally consistent, may revise.

Response 7: It is a welcome suggestion. However, glacier size is a variable parameter which fluctuates from basin to basin and hence, cannot be standardized globally or for a particular region. Moreover, to the best of our knowledge, there is no scientific standard for categorizing the glaciers and for this study, it is entirely based on investigators selectivity. DeBeer and Sharp, (2009) have categorized small glaciers in the British Columbia as per the size distribution of the glacier in the region, i.e., <0.4 km2 as very small and 0.4-5 km2 as large glaciers. However, in the Himalayan region different studies have used different size class for the glaciers (Table RT1). Owing to this heterogeneity in glacier size classification, we have not followed any particular study, but, have given a separate categorization (Page:12,lines:328-330 of the original manuscript).

Table RT1: Size distribution of glaciers in different basins of the Himalaya.

Comment 8: Statistical significance could be included to explain the effect of spatial characteristics (size, aspect, debris cover) or any difference spatial control over LR and GHR.

Response 8: Thanks for the suggestion. We understand the reviewer's point that GHR and LR comprises of different glaciers having distinct morphology. However, in our analysis, we have taken into account the change in glacier parameters in terms of percentage, which is normalized. Hence, the data is not susceptible to any biases. Moreover, we have followed a sequential method of data analysis: in which all the glaciers are first investigated for parametric changes and we observe regional heterogeneity in glacier response. Thereafter, we went for understanding the possible controls on the reported changes, in which we noted that the glacier response is primarily influenced by climate variability (statistical significance taken into account). The study also confirms the possible controls of non-climatic factors (in terms of percentage) on heterogeneous glacier response. However, we have now incorporated the statistical significance to explain the effect of spatial characteristics (size, slope, debris cover and elevation) over LR and GHR (Supplementary material of the revised manuscript). For this, the non-climatic factors were subsequently correlated with the change in glacier dimensional

parameters, i.e., area change and retreat using some statistical tests (Figure R4a,b; Table RT2). In the statistical analysis, the variables were initially tested for normality and visual inspection of the histogram. The test showed normal distribution for nearly all the variables and the correlations were found to be significant at α < 0.05 (except for mean elevation). These correlations also showed the presence of few outliers (not removed in this study), which indicate the possible role of any other factor due to which these glaciers have deviated from the general trend of area loss and retreat (Figure R4a;b).

Table RT2:Correlation (r) and Pearson's correlation (p) coefficient computed between non-climatic factors (size, slope, debris cover and elevation) and glacier changes (% deglaciation & retreat rate). These relationships were found to be significant at α < 0.05 (Except for mean elevation: Italicized).

Figure R4a. Scatter plots displaying the relation between topographic factors with percent deglaciation during the period 1971-2017. All the relationships were found to be significant at confidence level, i.e., α<0.05 (Except mean elevation).

Figure R4b. Scatter plots displaying the relation between topographic factors with retreat rate during the period 1971-2017. All the relationships were found to be significant at confidence level, i.e., α<0.05 (Except mean elevation).

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Please also note the supplement to this comment:

https://www.earth-syst-sci-data-discuss.net/essd-2019-122/essd-2019-122-AC2-supplement.pdf

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

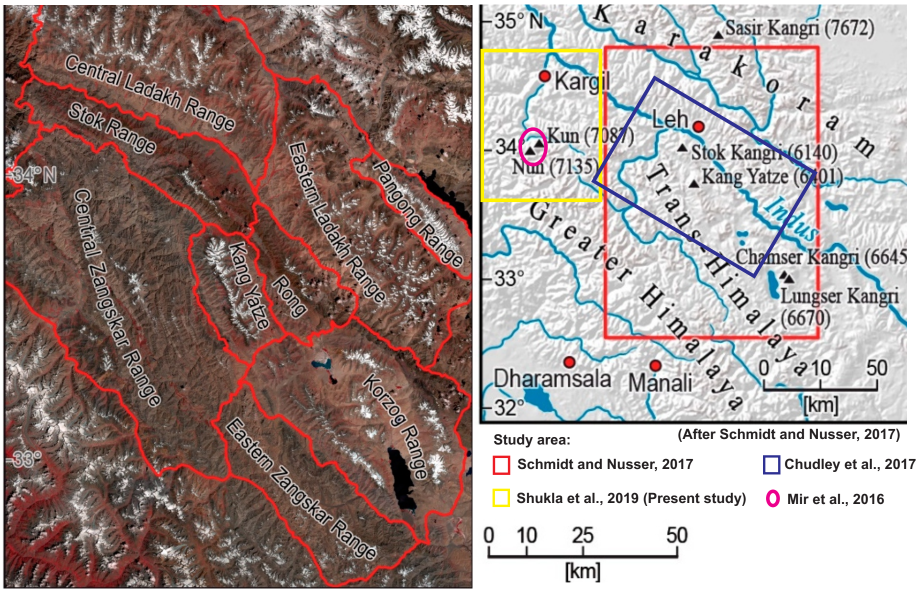


Fig. 1. Figure R1: Studies conducted in different parts of the western Himalaya (modified after Schmidt and Nusser, 2017)

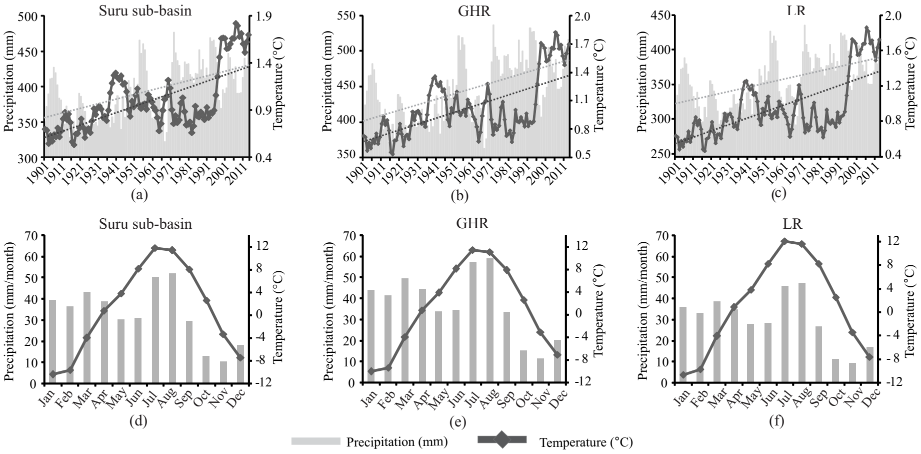


Fig. 2. Figure 3: Annual and seasonal variability in the climate data for the period 1901-2017.

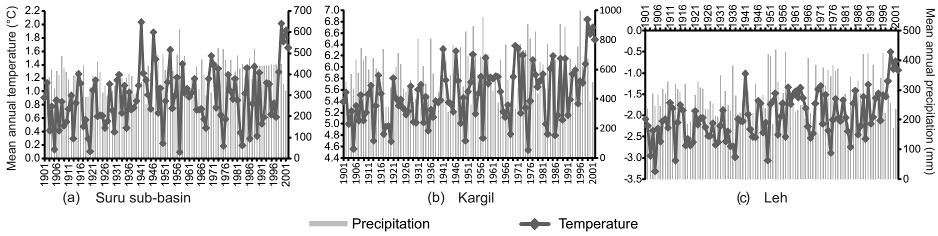
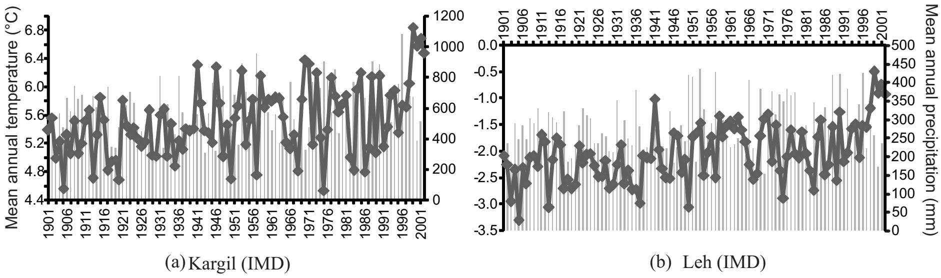


Fig. 3. Mean annual temperature and precipitation patterns of CRU-TS derived gridded data in (a) Suru sub-basin and IMD recorded station at (b) Kargil and (c) Leh.



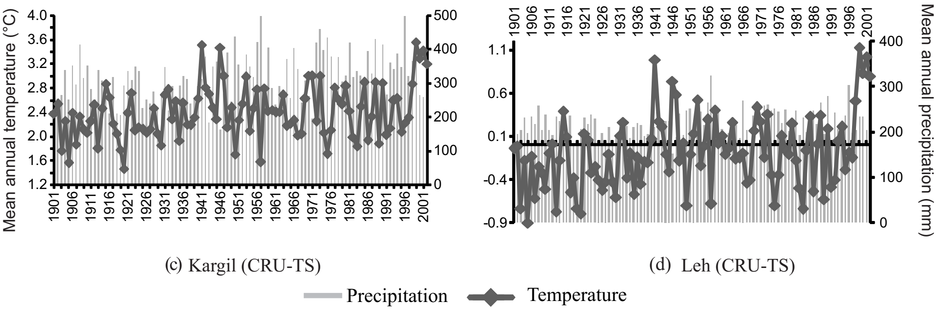


Fig. 4. Mean annual temperature and precipitation patterns of IMD recorded station data at Kargil and Leh and their respective CRU-TS derived gridded data.

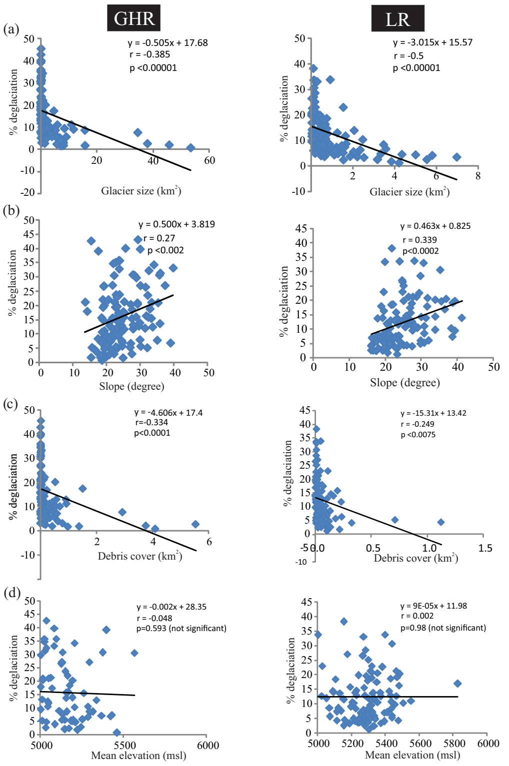


Fig. 5. Scatter plots displaying the relation between topographic factors with percent deglaciation during the period 1971-2017.

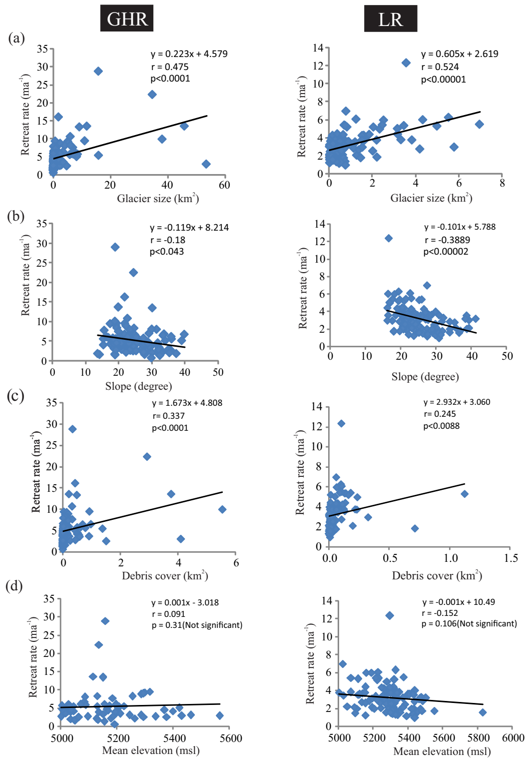


Fig. 6. . Scatter plots displaying the relation between topographic factors with retreat rate during the period 1971-2017.