

Estimation of the Frontal Retreat Rate of the Pindari Glacier, Central Himalaya Using Remote Sensing Technique

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ABSTRACT

In the present scenario of climate change, climatologists are concerned with the soaring rates of deglaciation in high mountain areas. Being the most sensitive climate change indicators, there has been a phenomenal increase in the interpretation of changing glaciers using remote sensing images. However, the data generated needs to be validated and the inferences drawn must be supported by logical explanations to facilitate the understanding of the relevant processes. The present study investigates the frontal (snout) changes of Pindari glacier through a comprehensive analysis of remote sensing data and field validations. Regional case studies of glacier front changes demonstrate that the Himalayan glaciers are retreating; however, the rate of retreat is variable over time. The Pindari glacier has witnessed highest rate of retreat (73.27m) during 2009-2010. The in-situ measurements have recorded a high recession during 1845 to 1958, that significantly decreased during 1958-1966. Subsequently, a gradual increase in the rate of recession till 2010 has been reported and is evident in remote sensing data also. However, since 2010, the rate of retreat has again slowed down. The present observations may be interpreted as direct consequence of the rapidly changing climate wherein the glaciers are witnessing a negative mass balance and hence the retreat. Our data is in accordance with other local and regional studies and imply mass wasting of glaciers as a response to global climate warming.

Keywords: Remote sensing; Rate of retreat; Pindari glacier; Central Himalaya

INTRODUCTION

The increasing interest of the scientific community and policy makers in the Himalayan cryosphere is because of the alarming rate of deglaciation (glacier melting) during the past few decades; making the situation complex for the planners and dependents. Fragile 'edge of the range' environments (Bellwood, 2013) like the Himalayas are the most vulnerable candidates of ongoing climate change and global warming (Safari, 2012). This warming has been attributed to a progressive increase in the atmospheric concentration of greenhouse gases (IPCC, 2014). The rapid climate change in the Himalayas is expected to have a significant impact on the freshwater resources, biodiversity, ecosystems and human well-being (Myers *et al.*, 2000; Chaudhary and Bawa, 2011; Chand *et al.*, 2019).

Please cite this article as: Ali, Sheikh Nawaz, Singh, Rupendra and Pandey Pratima (2019) Estimation of the frontal retreat rate of the Pindari glacier, Central Himalaya using remote sensing technique. e-Journal Earth Science India, v. 12 (III), pp. 146-157 <https://doi.org/10.31870/ESI.12.3.2019.11>

Explicit reports of significant warming trends in the Himalayan region (Hamid *et al.*, 2014) leading to glacier mass loss (Bajracharya *et al.*, 2015; Bolch *et al.*, 2012; Lama *et al.*, 2015;), increase in glacier lakes (number as well as area; Singh *et al.*, 2018; Bajracharya and Mool, 2009; Scherler *et al.*, 2011; Riaz *et al.*, 2014; Khanal *et al.*, 2015; Nie *et al.*, 2013), effects on the hydrological cycle (Immerzeel *et al.*, 2010; Yang *et al.*, 2011) of important river systems and the consequences on downstream populations (Sharma *et al.*, 2009; Chaudhary *et al.*, 2011; Vedwan *et al.*, 2001) has been a concern of the scientific fraternity. The Himalayan glaciers have considerable influence on the climate, water resources and socio-economy of the region with large human concentration. This makes the monitoring of these glaciers imperative and help in assessing the overall reservoir health (Kulkarni *et al.*, 2007). Being a significant source of stored fresh water (Immerzeel *et al.* 2010; Kaser *et al.*, 2010) and one of the most important indicators of climate change (Kaser *et al.*, 2006; Bolch *et al.*, 2012), studies related to glacier health and its influence on the Himalayan rivers must be precisely addressed. Accuracy and authenticity in data must be well established and thoroughly cross-checked because the search for truth based on empirical data and its unbiased reporting are ultimate goals of conducting scientific research (Marco and Larkin, 2000).

The Himalayas, forming the largest mountain chain over the earth are the custodian of the third largest ice reserves after the Polar Regions. However, the lack of data over this complex terrain (rugged topography, harsh climate and remote location of glaciers) is a major hurdle for establishing and predicting future glacier trends accurately. Satellite based remote sensing has proved to be an important tool for mapping and monitoring the changes in the area, length, surface elevation, surface flow fields, accumulation/ablation rates etc. (Konig *et al.*, 2001). But, with the varying and conflicting dataset related to the estimation of glacier changes, the authenticity, accuracy, and sensitivity of the results derived from remote sensing data have become questionable, and influence all other inferences based on such dataset. Therefore, it is necessary to validate the remote sensing observations with ground data. The validation becomes important, otherwise the consequences of errors is (are) alarming. For example the Section on 'The Himalayan glaciers' (IPCC Fourth Assessment Report; IPCC, 2007), reporting that the Glaciers in the Himalaya would disappear by the year 2035 and perhaps sooner if the Earth keeps warming at the current rate. It is well established now that the Himalayan glacier have substantially receded during the last century, however the rate of retreat is variable (Kulkarni *et al.*, 2007; Immerzeel *et al.*, 2009; Kargel *et al.*, 2010). Keeping the above facts in view, the present study aims at estimating the retreat of Pindari glacier and validating our results with the previous observations (Strachy, 1847; Tewari and Jangpangi, 1958, 1966; Tewari, 1973; Bali *et al.*, 2013; Raczowska and Joshi, 2016; Pandey *et al.*, 2018). Field validation of remote sensing data is mandatory to quantify the reliability of products/results (Justice *et al.*, 2000; Zhang *et al.*, 2010; Wang *et al.*, 2016).

STUDY AREA

Pindari glacier (30°16'5"-30°19'10"N and 79°59'00"-80°01'55"E) is a ~9 km long south facing glacier located in the Indian summer monsoon-dominated (ISM) Central Himalaya, India (Fig. 1). This glacier is one of the few glaciers in the Indian Himalaya, which has long trail of historical observations dating back to 1845 (Strachy, 1847) and Cotter and Brown (1907).

The In-situ monitoring of snout positions of this glacier has been done by the Geological Survey of India in 1958, 1962 and 1966 and further updated by Bali *et al.* (2013). Besides snout monitoring, the Pindar valley has preserved the moraines of different glacial stages and associated glacial geomorphological features (Bali *et al.*, 2013; Fig. 2).

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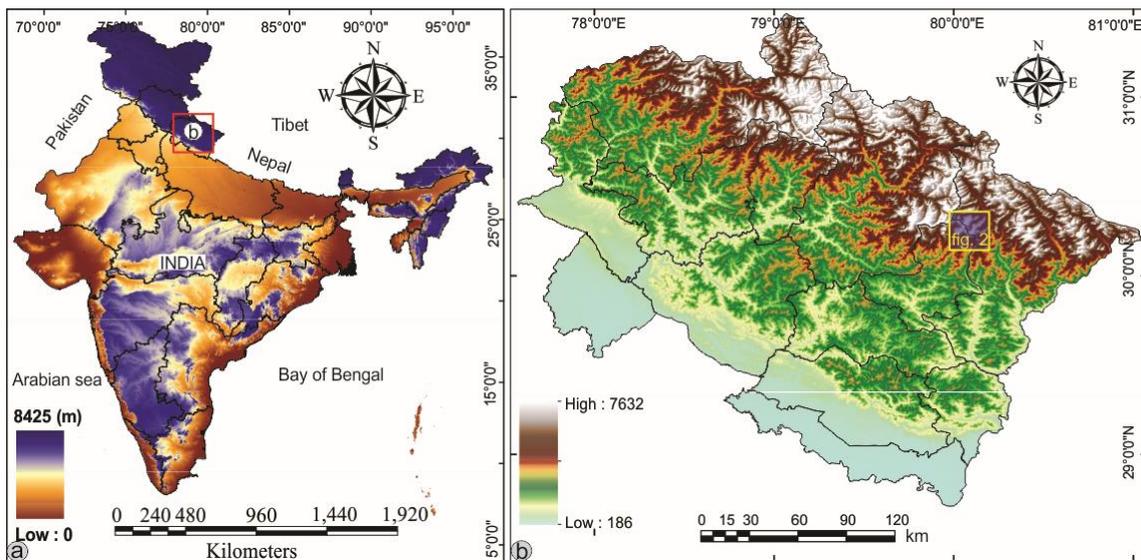
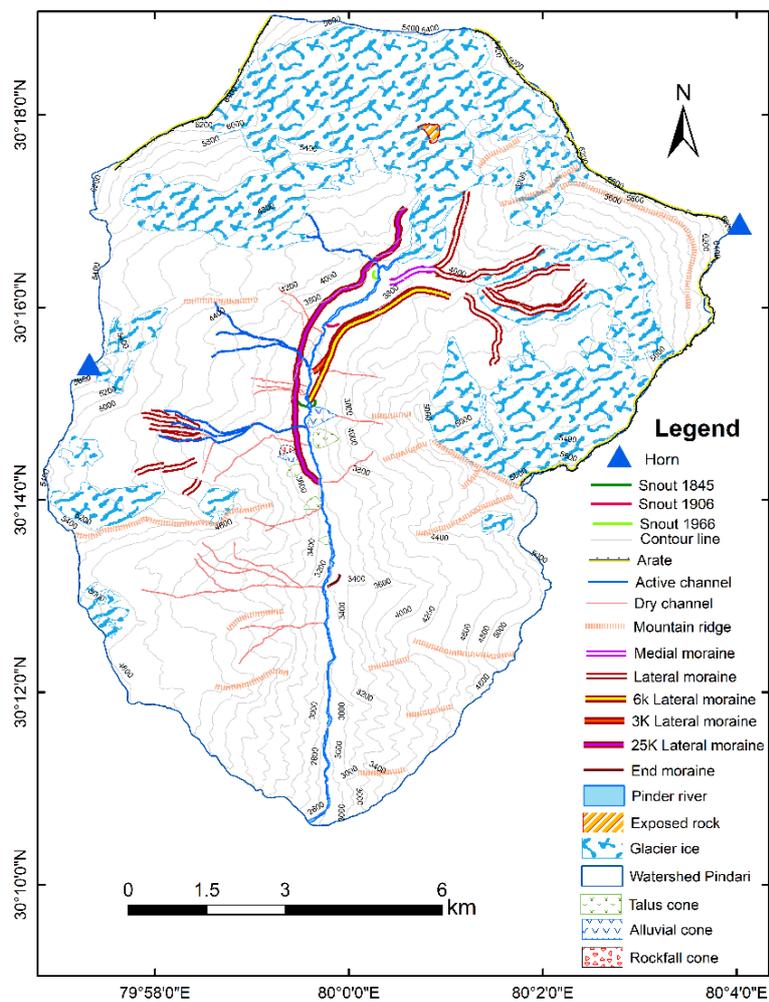


Fig. 1: Map showing (a) the location of the study area *i.e.* the Central Himalaya in India, (b) shuttle radar topographic mission (SRTM) digital elevation model (DEM) of Uttarakhand showing the study area in a yellow rectangle.



(a)



Fig. 2: (a) Detailed geomorphological map of the Upper reaches of Pindar valley (b) Google Earth Pro Imagery of 2005 showing the Pindari glacier, adjoining Chhanguch valley, the medial moraine between them and the water fall.

DATA-SETS AND METHOD

The data used in our study include Landsat MSS/TM/ETM+/OLI, Sentinel-2A, Survey of India (SOI) topographical map and Google Earth pro imagery. All the remote sensing data (Table-1) were obtained from the United States Geological Survey website (USGS; <http://earthexplorer.usgs.gov>). To reduce potential uncertainty in glacier area delineation, satellite scenes with minimum cloud cover (<10%) during the ablation season from 1976 to 2017 were selected. The bands, 1 to 5 are MSS (Multispectral bands) with a spatial resolution of 30 m (for Landsat 2 to 8), while the panchromatic band 8 (Landsat 7 and 8) has a spatial resolution of 15 m. To achieve a better MSS resolution we merged band 8 with MSS band using PAN-sharpening in Leica-Erdas Software. The resultant image with a 15 m spatial resolution gave better results (Bhambri *et al.*, 2018). Besides this, High resolution (10m) Sentinel-2A satellite images acquired on 14 October 2017 were also used for better results. We have used the Sentinel-2A satellite data because it has a Multi-Spectral Instrument (MSI), that scans the Earth's objects at different spatial resolutions with a revisit time of 10 days. It operates on thirteen different bands of which four bands have a spatial resolution of 10m, six bands have a resolution of 20m, and rest three bands have a resolution of 60m. For the present study, 10 m spatial resolution band 8b- NIR, band 4-Red, band 3-Green, and band 2-Blue were used (Singh *et al.*, 2018). The Sentinel-2A images have been processed using Sentinel Application Platform (SNAP), a free open-source platform jointly developed by Brockmann Consult, Array Systems Computing and C-S (SNAP; <http://step.esa.int/main/toolboxes/snap/>).

All the satellite images were co-registered and the error of co-registration is within ~1 RMSE. Glacier mapping was carried out in ArcGIS 10.2. The glacier boundaries were qualitatively validated using Google Earth Pro (3D) to fix any potential problems. Delineation of glacier boundaries is based on the strong spectral differences in the reflectance of snow, ice, and debris in the visible and near-infrared bands (VNIR) in comparison to the shortwave

infrared band (SWIR) (Dozier 1989). Snow and ice have a very high reflectance in the VNIR whereas a very high absorption in SWIR. The band combination of 5, 4, 3 and 4, 3, 2 for Landsat ETM+ and OLI have been found to give better results of glacier delineation. This is because of the contrasting spectral characteristics of the snow, ice, and debris in VNIR and SWIR.

Since, the meteorological data from the higher Himalayan region is not available, therefore, we used the the Climatic Research Unit Timeseries gridded temperature and precipitation datasets of nearest grid points (30.25 N, 80.25 E Pindari glacier) through Climatic Research Unit (CRU TS. 4.02, 0.5 latitude x 0.5 longitude, 1901-2017 CE; Harris *et al.*, 2014). The analysis of CRU TS data suggests that the Mean annual temperature (MAT) are (is) around $\sim 3.41^{\circ}\text{C}$ while the mean annual precipitation (MAP) are(is) ~ 774 mm respectively (Fig. 3). It is clear from the data that temperature (all annual, summer and winter) show an increasing trend while the precipitation is decreasing during the study period (Fig. 3).

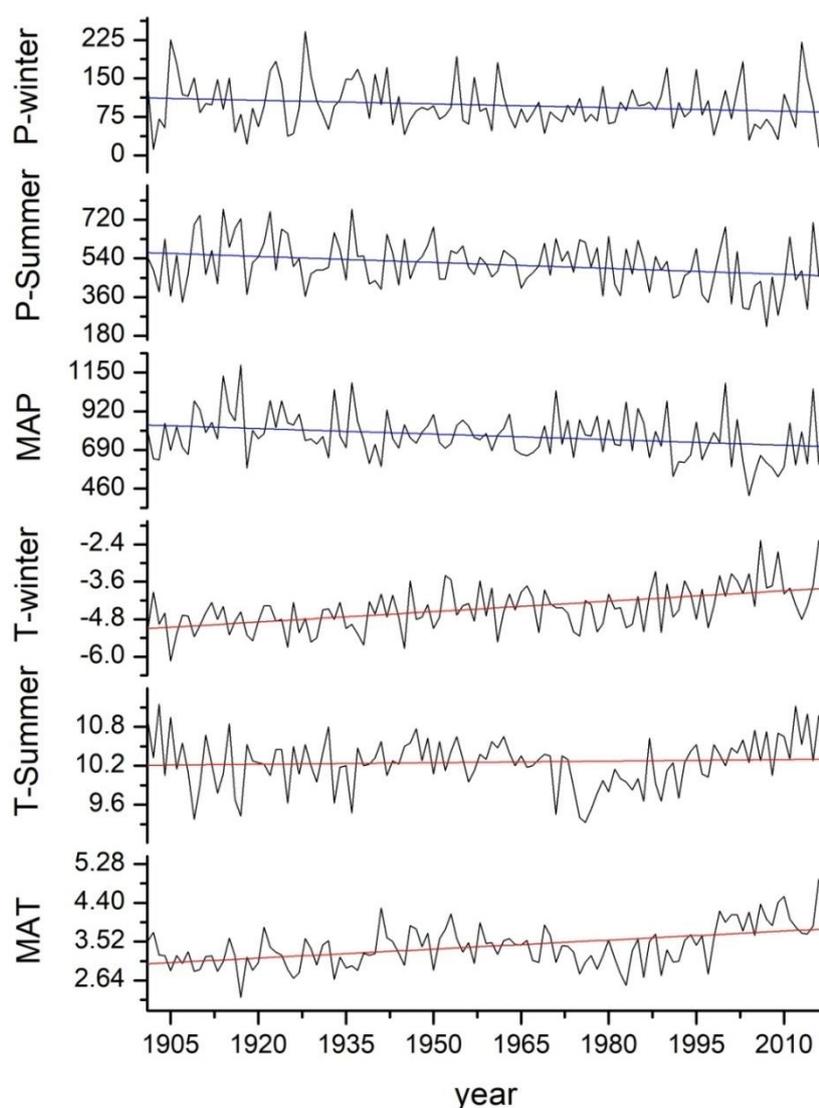


Fig. 3: Line plot of CRU TS-4.02 data showing the Mean annual temperature (MAT), Temperatuer of the summer (T-summer; JJAS), Temperatuer of the winter (T- winter; DJF), Mean annual precipitation (MAP), precipitation of the summer (P-summer; JJAS), precipitation of the winter (P- winter; DJF) and their linear trends.

Table-1: Details of the remote sensing data used for the present study with date of acquisition, Path/Row, spatial resolution and Sensor. Rate of recession estimated for Pindari glacier in the present study, recessional rates recorded by different workers and comparison of the present recessional rate with that on Pandey *et al.*, 2018.

Sr. No.	Data source	Acquisition Date	Path / Row	spatial resolution (m)	Sensor
1.	Landsat2	19 Nov. 1976	156-39	57	MSS
2.	Landsat 4	09 Oct. 1989	145-39	30	TM, MSS
3.	Landsat5	28 Sept. 1996	145-39	30	TM
4.	Landsat7	15 Oct. 1999	145-39	15	ETM+
5.	Landsat7	23 Oct. 2002	145-39	15	ETM+
6.	Landsat5	02 Oct. 2009	145-39	30	TM
7.	Landsat5	21 Oct. 2010	145-39	30	TM
8.	Landsat8	29 Oct. 2013	145-39	15	OLI
9.	Sentinel-2A	14 Oct. 2017	T44RLU	10	MSI
Recessional rates recorded by different workers					
S. No.	years	Recession (m)	No. of Years	Avg. recession per annum (m)	Reference
1	1845–1906	1600	61	26.23	Cotter, 1906
2	1906-1958	1040	52	20	Tiwari <i>et al.</i> , 1958
3	1958-1966	61	8	6.62	Tiwari <i>et al.</i> , 1966
4	1966-2007	262	41	6.39	Bali <i>et al.</i> , 2013
5	2007-2008	15	1	15	Bali <i>et al.</i> , 2013
6	2008-2009	32	1	32	Bali <i>et al.</i> , 2013
7	2009-2010	70	1	70	Bali <i>et al.</i> , 2013
8	1966-1976	257.11	12	21.42	Present study
9	1976-1989	50.36	13	3.87	Present study
10	1989-1996	40.86	7	5.83	Present study
11	1996-1999	28.19	3	9.4	Present study
12	1999-2002	21.08	3	7.02	Present study
13	2002-2009	87.18	7	12.45	Present study
14	2009-2010	73.27	1	73.27	Present study
15	2010-2013	40.01	3	13.34	Present study
16	2013-2017	39.29	4	9.82	Present study
Retreat rate comparison					
1	1976-1999	1178.31	23	51.23	Pandey <i>et al.</i> , 2018
2	1999-2014	390.70	15	26.05	Pandey <i>et al.</i> , 2018
3	1976-1999	119.41	23	5.19	Present study
4	1999-2017	260.83	18	14.5	Present study

RESULTS, DISCUSSION AND COMPARISON

The Pindari glacier is one of the well-studied glaciers in Indian Himalayas for which historical records of frontal changes (snout monitoring) are available since 1845 (Strachy, 1847). Strachy (1847) was the pioneer worker to document the snout position of the Pindari glacier and latter on Cotter and Brown (1907) studied it again and have reported a recession

of around 1600 m during 1985 and 1906. After 1906, significant information on the retreat of Pindari glacier was provided by Tiwari and Jangpangi who have estimated a retreat rate of around 20 m/yr between 1906 and 1958 and around 6.62 m/yr during 1958 to 1966. Later on, field-based mapping of the Pindari glacier and snout monitoring revealed that the rate of retreat during 1966 and 2007 was around 6.39 m/yr (Bali *et al.*, 2013). Continuous field-based measurements between 2007 and 2010 suggested a variable retreat rate (Bali *et al.*, 2013). It has been estimated that the Pindari glacier retreated by around 15 m/yr during 2007-08; around 32 m/yr during 2008-09 and around 70 m/yr during 2009-10.

We have used high/medium resolution remote sensing data to document the frontal changes of this glacier. The results obtained from the analysis of remote sensing data in the present study are in-sync with the field observation (as evident from the rate of retreat of the glacier between 2009 and 2010; see Fig. 4 (a) - (h) and Table-1). Both field investigation and remote sensing analysis demonstrated a significant recession of Pindari glacier during 2009-2010 (70 m/yr and 73 m/yr respectively; Bali *et al.*, 2013). The present analysis of remote sensing data (1976 and 2017) revealed that the Pindari glacier has receded with an average rate of around 9 m/yr. This is in agreement with the in-situ measurements of Bali *et al.* (2013). The assessment and correlation of the results suggest that the Pindari glacier has retreated at a rate of around 5 m/yr between 1976 and 1999, and is contrary to a rate of retreat of around 51.23 m/yr shown by Pandey *et al.* (2018) during the same time period. We attribute this to the misinterpretation of snout position inferred from satellite data by Pandey *et al.* (2018). The remote sensing based estimation of the rate of retreat of the Pindari glacier during 1999 and 2017 by Pandey *et al.* (2018) is ten folds higher than the actual rate of retreat. Further, between 1999 and 2017 the glacier receded at a rate of around 14 m/yr, but Pandey *et al.* (2018) have reported a rate of around 26 m/yr between 1999 and 2014. Review of the previous works, field-observations, and present investigation (in-situ and remote sensing data) suggest that retreat of the Pindari glacier between 1976 and 2017 was around 9 m/yr and is contrary to the estimates of around 41 m/yr during the same period by Pandey *et al.* (2018).

It is clear from the snout position of 1980 that Pandey *et al.* (2018) have not reviewed the earlier published data and the snout position seems to be inaccurately marked (please see Bali *et al.*, 2013). Their results, show the position of Pindari glacier snout far (downstream) from the medial moraine (Figs. 1 and 2) during 1958, however, a clear examination of the data (Tewari and Jangpangi, 1966; Bali *et al.*, 2013; Raczowska and Joshi, 2016) reveals that during 1958 the Pindari and the adjoining Chhanguch glaciers coalesced downhill and formed a single snout. While during 1966, the two glaciers (Pindari and Chhanguch) have receded in their respective valleys and the snout of Pindari glacier was well above the frontal base of the medial moraine (Fig. 2). Further, Pandey *et al.* (2018) have marked the snout position of 1976 near the snout marked for 1906 on the basis of field evidence/palae table survey (Tewari and Jangpangi, 1966). It has to be mentioned that the delineation of glacier boundaries in remote sensing data is based on the strong spectral differences in the reflectance of snow, ice, and debris in the visible and near-infrared bands (VNIR) in comparison to the shortwave infrared band (SWIR) (Dozier, 1989). Snow and ice have a very high reflectance in the VNIR, whereas a very high absorption in SWIR. The mapping of glacier area from the satellite images require conventional band combinations. The band combination of 5, 4, 3 and 4, 3, 2 for Landsat ETM+ and OLI have been found to give better results for glacier delineation. This is because of the contrasting spectral characteristics of the snow, ice, and debris in VNIR and SWIR. The example of the effect of proper band combination in the glacier delineation is shown in Fig. 5.

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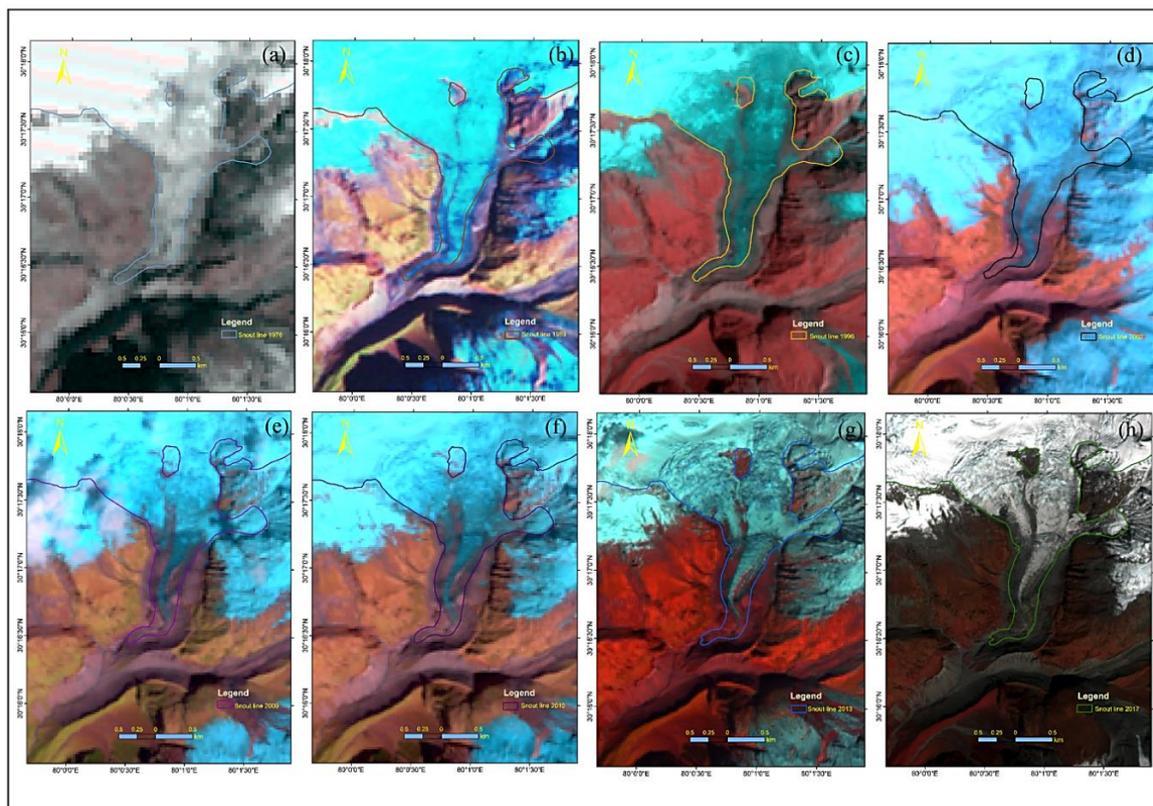


Fig. 4: Figure compilation showing the demarcated snout position viz. a) The Snout position of Pindari glacier in 1976, (b) The Snout position of Pindari glacier in 1989, (c) The Snout position of Pindari glacier in 1996, (d) The Snout position of Pindari glacier in 2002, (e) The Snout position of Pindari glacier in 2009, (f) The Snout position of Pindari glacier in 2010, (g) The Snout position of Pindari glacier in 2013 and (h) The Snout position of Pindari glacier in 2017.

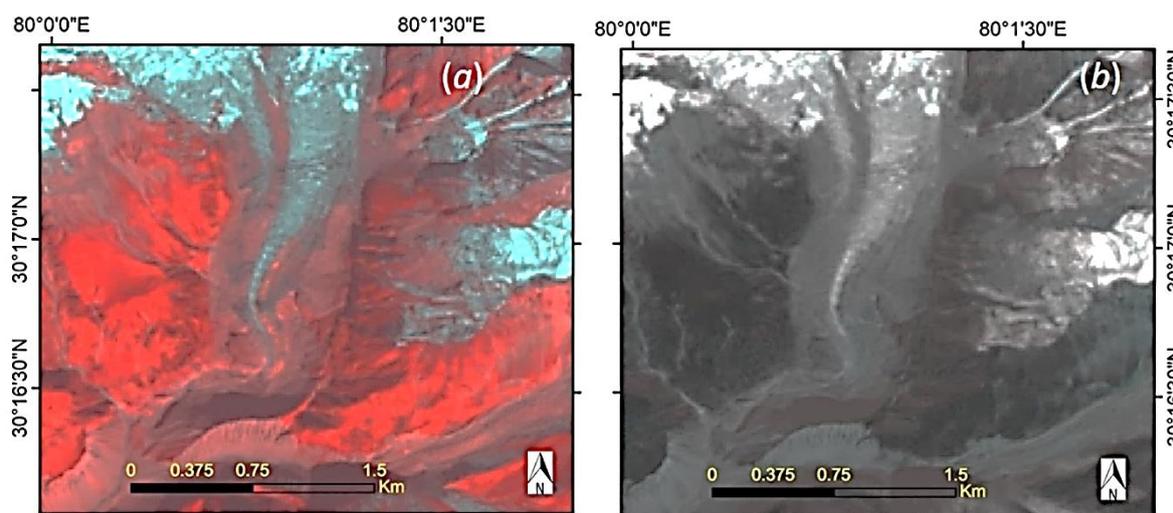


Fig. 5: Image showing a suitable band combination that significantly enhances the identification of features on imagery and hence accurate delineation; a) Proper combination of viz. band combinations 5 4 3 for Landsat OLI; b) band combinations 1 2 3 for the same image and area (inappropriate).

It is observed that majority of Himalayan glaciers are shrinking (retreating) and is consistent with atmospheric warming and decreasing precipitation (Kulkarni *et al.*, 2007; Bolch *et al.*, 2012; Azam *et al.*, 2018). This progressively increasing temperature trend has been implicated for the accelerated melting of glaciers elsewhere (King *et al.*, 2018; Wang *et al.*, 2017; Xiang *et al.*, 2018). The contemporary observations of the Pindari glacier, Central Himalaya also demonstrate glacier sensitivity to the ongoing climate warming (Fig. 6).

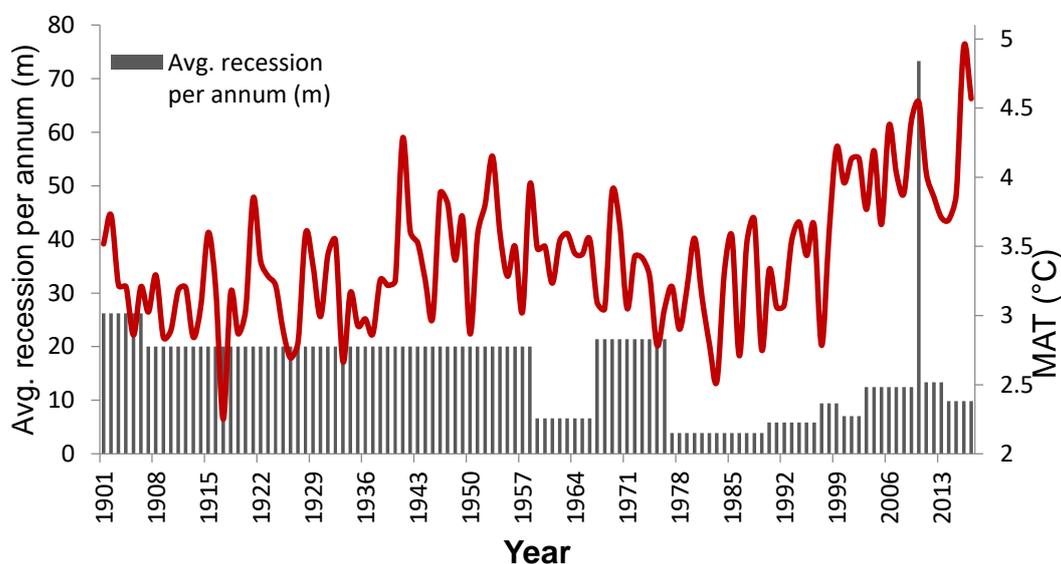


Fig. 6. A cross plot of average annual glacier retreat (grey bars) vis-a-vis mean annual temperature (red line).

From both in-situ and remote sensing data, it is obvious that the Pindari glacier is retreating; however, the rate of retreat has been variable. Nevertheless, the glacier shows a continuous melting and the increase in temperature and decrease in snowfall seen under global climate change is implicated. As per the Intergovernmental Panel on Climate Change (IPCC, 2014), the “warming of the climate system is unequivocal, and since 1950, many of the observed changes are unprecedented over decades to millennia”. This has resulted into the warming of oceans and significantly diminished the snow and ice (glaciers). The situation is furthering worrisome, because the rate of mean annual maximum temperature in the Himalayas has shown a two-fold increase than the outer Himalayan belt and is more than the global averages (Shrestha *et al.*, 1999). The winter temperatures are further disturbing as there is a general agreement on increased winter warming.

CONCLUSION

It is evident from the field as well as remote sensing data observations that the rate of recession/melting during the last five decades has increased. However, the rate is not as high as mentioned in the earlier remote sensing based study by Pandey *et al.* (2018). We suggest that the glacier melting data has manifold impacts on scientific as well social levels and has a high relevance to climate change, glacial hazards, and other socio-economic aspects. Therefore, researchers must be careful during their studies to have cross checks on the data many times so that one can provide a clear and accurate information to the society, the scientific community and the policy-makers.

Acknowledgments: SNA and PP are thankful to the Directors of Birbal Sahni Institute of Palaeosciences, Lucknow, and Indian Institute of Remote Sensing, Dehradun, India respectively, for their support and providing infrastructural facilities.

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(Submitted: 02.11.2018; Accepted: 09.05.2019)