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Spatio-temporal changes in the Machoi glacier Zanskar Himalaya India using geospatial technology

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ABSTRACT

We present the temporal changes of Machoi glacier, Zanskar region of the north-western Himalaya, India using multi-temporal Landsat satellite data from 1973 to 2018. The results suggest that the Machoi glacier has retreated consistently from last 45 years with an uneven retreat rate. The temporal fluctuations since 1973 AD reveal that the glacier snout has retreated ~563 m at an average of ~12.51 m yr^{-1}. However, the snout has retreated at variable rates during different time intervals e.g., 80 m (average of ~11.43 m yr^{-1}) from 1973 to 1980 AD, 120 m (average of ~12.0 m yr^{-1}) from 1980 to 1990 AD, 123 m (average of ~12.3 m yr^{-1}) from 1990 to 2000 AD, 128 m (average of ~12.8 m yr^{-1}) from 2000 to 2010 AD and 112 m (average of ~14 m yr^{-1}) from 2010 to 2018AD. The highest rate of snout (~14 m yr^{-1}) retreat during 2010–2018 AD is linked to the changing climate in the region as observed from the meteorological data. The analysis of meteorological data suggests that during this period temperature as well as the liquid precipitation have increased due to global warming whereas the extent of solid precipitation has decreased which might be the possible causes of higher retreat of Machoi glacier.

1. Introduction

Glaciers in the Himalayas are spread from east to west in mountainous part of Indus, Ganga and Brahmaputra (IGB) basins. However, the concentration of glacier varies from northeast to northwest of Himalayas because of variability in latitude and altitude. The Himalayas comprises around 9500 glaciers which cover 37000 km^2 of area (Raina and Srivastava, 2008) and are considered as third pole of the earth, forming a permanent storage house of water and act as reservoirs of the natural fresh water (Brahmbhatt et al., 2015; Abdullah et al., 2020; Bisht et al., 2021; Singh et al., 2021a,b; Sood et al., 2021a). The mass balance estimations carried recently using Spot-5 and Shuttle Radar Topography Mission (SRTM) derived Digital Elevation Model (DEM) for Himalayas, demonstrates that mass loss is less in the central and eastern Himalaya compared to the western Himalaya (Gardelle et al., 2013). Furthermore, the estimated ice loss for the end of 21st century is maximum for glaciers of Jammu-Kashmir region (Kaab et al., 2012).

In general, the Himalayan glaciers are retreating faster than other glaciers on the earth, with an average area loss of ~0.4% per year in response to the climate changes (Bolch et al., 2012; Kulkarni et al., 2011). The glaciers of Karakoram region are stable or advancing, commonly called as “Karakoram anomaly”, as compared to retreating

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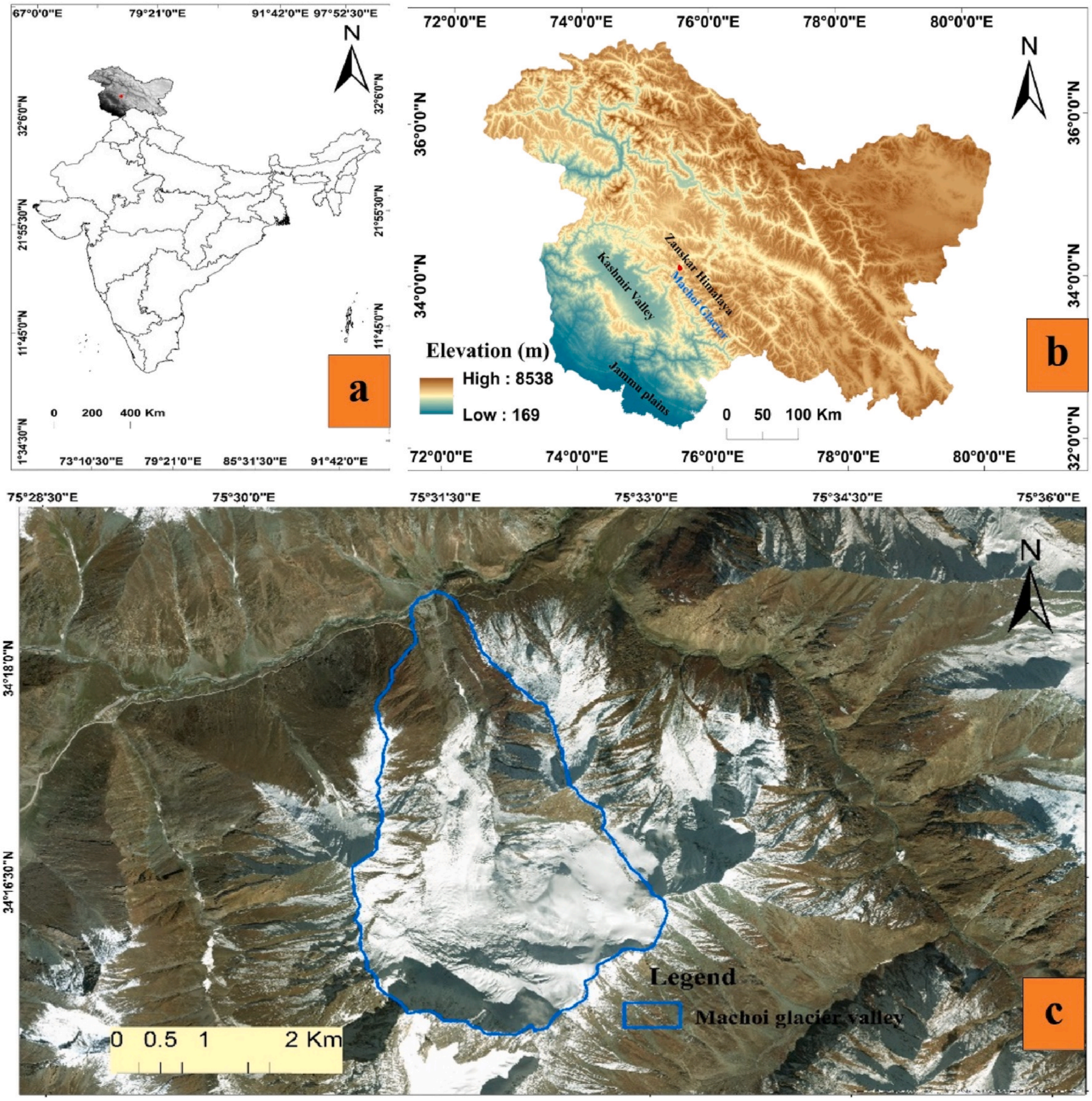

Fig. 1. Location map of study area 1a. Location of India, 1b. ALOS PLASAR Dem elevation combined map of the Union Territory(UT) of Jammu and Kashmir and UT of Ladakh,(erstwhile state of Jammu and Kashmir) and 1c. Google image showing the Machoi glacier valley.

trend of glaciers in other glaciated mountain regions (Hewitt, 2011). Therefore, save from Karakoram range, all the Himalayan glaciers are retreating, with a rate varying from few meters to- 60 m/year (Bolch et al., 2012; Kulkarni and Karyakarte, 2014). The varying retreat rate is mainly determined by the geomorphological characteristics of the glacier (Bolch et al., 2008; Immerzeel et al., 2010). Besides, the rise in temperature due to human emission of carbon dioxide in the atmosphere (Thomas et al., 2009) might be a reason behind the anomalous behavior of Himalayan glaciers. The global temperature is predicted to rise continuously during the current time period (Bhutiyani et al., 2007; Kamp et al., 201; Randhawa et al., 2021). Compared to the global trend, western part of Himalayan regions is also witnessing a rising trend of temperature and decreasing snowfall (Shekhar et al., 2010). Likewise, Kripalani et al. (2003) have also revealed that across the western part of Himalayan region snow covered area is declining.

Since, glaciers respond directly to the change in the climatic conditions and therefore, act as a good indicators of climate change. Most of the glaciers have retreated rapidly between 1865 and 1880, followed by a short advance period before 1900 (Cuffey and Paterson, 2010). Therefore, the study of the recession and advance of Himalayan glaciers, which are retreating at variable rates (Dobhal et al., 2004), is necessary for observing the response of these glaciers to climate change (Kulkarni et al., 2007; Chaujar, 2009; Prasad et al., 2009; Ghosh et al., 2014; Sood et al., 2020; Singh et al., 2021a,b). However, due to high altitude, uneven topography and unfavourable weather conditions, the Himalayan region is complex to study through conventional field-based methods. Satellite data because of its synoptic view, high temporal frequency, different spectral property of snow and glaciers, aided by advanced satellite image processing and an analysis technique gives precise and consistent observations. Therefore, Remote Sensing (RS) based method coupled with Geographical Information System (GIS) techniques have become extremely important tools to estimate precisely the retreating rate of the glaciers in remote terrain of the Himalayas (Ghosh et al., 2014; Taloor et al., 2019; Sood et al., 2021b). Machoi being a benchmark glacier of the Zanaskar Himalaya has been investigated from the last 135 years. Lawrence (1875) in the Valley of Kashmir showed the extended Machoi glacier with its rock cliff in contact with base of lateral moraine. Oldham (1904) described that Machoi glacier is about half mile from the road head, has evidently extended almost down to where road now runs and is shown by heaps of moraines material and later confirmed by Raina (1971) in the snout study of Machoi glacier. Therefore, in the present we tried to estimate the temporal changes in

Table 1
Data sets used for the analysis in the present study.

Year	Glaciated area (Km^2)	Data source Satellite and Sensor	Spatial resolution (m)	Acquisition date
1973	5.37 ± 1.5	Landsat 1 Multispectral Scanner System (MSS)	90	29-9-73
1980	5.21 ± 1.3	Landsat-5 MSS	90	24-10-1980
1990	5.06 ± 1.23	Landsat-5 Thematic Mapper (TM)	30	15–6.1990
2000	4.98 ± 1.18	Landsat-5 Enhanced Thematic Mapper (ETM)	30	22-10-2000
2010	4.80 ± 1.15	Landsat-7 Enhanced Thematic Mapper Plus (ETM+)	30	18-10-2010
2018	4.21 ± 1.09	Landsat-8 Optical Land Imager (OLI)	30	11-9-2018

glacier snout by areal monitoring, and the effect of the temperature and precipitation on the Machoi glacier by using long term meteorological data.

2. Study area

The Drass valley experiences complex environmental conditions with cold climate prevailing most of the year. 80% of precipitation from the western disturbances which come from November to May and sometimes prolongs up to June. In the higher parts the precipitation occurs in solid during both winter and summer (Fig. 1). The Machoi glacier, in the Drass region of Ladakh, has a distinct climate due to high altitude, and it is covered all sides by mountain ranges. Machoi is transverse valley type glacier placed 11 km southeast from the world famous Zoji La, a passage which join the valley of Kashmir to Ladakh. The basin of Machoi glacier lies 34° 15′ to 34° 17′ 40′′ N latitude and 15° 31 ′ to 15° 33′ longitude, Zanskar Himalaya, district Kargil of erstwhile state of Jammu and Kashmir (Fig. 1). The Machoi glacier has broad head cylindrical body tapping down to a narrow tongue like terminus at an altitude of 3650 m and it is very close to the National Highway that joins Leh and Srinagar. Based on topographic map of the Survey of India (SoI), the Machoi glacier is 1.75 km wide with 6 km^2 area. The Machoi is the highest peak which lies at an elevation of 5448 m at the eastern part of the glacier. The Machoi glacier is a source of Sind river and Drass river which flows westward and eastward direction respectively.

3. Material and methods

3.1. Satellite data

Monitoring the changes in snout position gives useful information for understanding the impact of several factors on retreat of the glacier (Kaser et al., 2003). To monitor temporal changes in snout position of Machoi glacier of Zanskar region from 1973 to 2018, multi-temporal Landsat series satellite data were used. The palaeoglacial fluctuations of Machoi glacier has been estimated using SoI topographic map, Landsat series of satellites data Landsat-1 MSS (1973), Landsat −3 MSS (1980), Landsat −5 TM (1990, 2000), Landsat-7 ETM+ (2010) and Landsat-8 OLI (2018). The SoI maps (1:50,000 scale) were used for co-registering the satellite data and for ground control point (GCP) collections (Table 1). Image enhancement techniques such as the linear and nonlinear improvement and tuning of contrast, brightness and transparency were used to determine difference between non-glacial and glacial areas for better interpretation. For calculating the glacier length several stripes were drawn parallel to the flowing direction of glacier. The changes in the length were calculated as the mean length from the intersection of glacier outlines with the parallel stripes (Koblet et al., 2010).

Table 2
Interpretation of different glacio-geomorphological features in the study area.

Glacial Feature	Identification (morphology, colour/texture/structure, location)
Striation marks and polished marks (Erosional)	Striations are the long, deep and parallel grooves that are generated when rocks embedded in the glacier ice scratch the bedrock during glacier movement. Striations are micro relief features formed by abrading rock fragments carried in the sole of glacier ice. Striations and polished rock surfaces are preserved along the valley head and valley walls as well as along the hanging valleys. These are preserved on granite, limestone and slates. The striations can be prominently seen on volcanic boulders.
Debris cone	Sub-horizontal fans on valley sides. Typically fed by a melt-water channel or stream formed by several processes such as avalanches, mass wasting and hill slope evolution. Mostly concentrated to the eastern slope of the valley
Cirques	Universal in occurrence in the glaciated mountain regions, formed through glacial erosion formed at the head of a valley glacier where some snow accumulates. In Machoi glacier a long chain of cirques found in the left side of valley head primarily carved in granite and are well developed.
Horn	Horn is a steep pyramid-shaped rock summit created when glaciers erode three or more cirques into different sides of a peak. Found in the southern part of the Machoi glacier
Erratic boulder	A foreign boulder or other rock fragment in a deglaciated valley. Located at the base of Machoi glacier.
Whaleback (erosional)	Glacially moulded, hard rock surfaces where length is greater than height produced as a result of glacier abrasion. Whalebacks in the study region are rounded and elongated hillocks. Mostly in the northern side of the basin near road head primarily composed of hard limestone
Roche mountain (Erosional)	Comparatively gentle abraded stoss slope and steep and rugged lee slope. The shape of the roche moutonnées attributes their origin to combined processes of abrasion and plucking. The forms are longer than their width and attain height from less than a meter to tens of meters. The orientation of the long axis of roche moutonnéesis roughly parallel to the direction of ice motion. They reveal the thickness of ice and indicate the sides, either stoss or lee as evidence by striation that was taken by ice. Located at different altitudes and are observed near the fringe of glacial retreat. Carved from granite tops are generally well preserved.
Kettle lake	The moraine is dotted with kettles caused by buried glacial ice that calved off the terminus of a receding glacier and got entirely or partly buried in glacial sediment and subsequently melted. This process left depressions ranging from small ponds to large lakes and enclosed valleys. Two kettle lakes have been observed in the vicinity of 3580 and 3750 m confined between two hummocky ridges separated by low relief in central axis. The hummocky ridges of medium high lateral moraine have height of 58 m–67 m.
Moraines Terminal/end moraine	Prominent cross-valley single or multiple ridges with positive relief. Linear, curved, sinuous or saw-toothed in plan. Shadowing due to change in relief and change in colour where moraines are vegetating. End moraines of Machoi valley are observed at different altitudes of valley in the vicinity of present day snout as well at the bank of Gumeri River. Their morphology reflects their mode of deposition to dumping and pushing. The push end moraines are formed by the ice pushing debris into a prominent ridge by compressive flow of a glacier. The dumped end moraines in the Machoi glacier valley are marked by heaps of rounded and sub-rounded

(*continued on next page*)

Table 2 (*continued*)

Glacial Feature	Identification (morphology, colour/texture/ structure, location)
	boulders embedded in sand-silt matrix in the vicinity of road head as well on river bank.
Lateral moraines	Lateral moraines are the most common feature primarily in the form of thrust ridges. Primarily comprise granite and limestone besides rock fragments of shale, slates, and calcareous sandstones also form part of moraine deposits ranging in size from clay to boulder. The highest moraines have larger concentration granite and limestone rocks along with crystalline, thereby indicating local source of material in the vicinity of 5000 m asl. Lateral are lobately in the valley bottom section and have formed a sequence of three lateral moraine ridges coalescing with one another on the either side Machoi river.

3.2. Climate and meteorological data analysis

Due to harsh climatic conditions and poor accessibility field measurements regarding the climate and meteorological data are difficult to preserve in high mountain areas. In this region, the Kargil station is the only India Meteorological Department (IMD) station operating since 1990. A good network of meteorological stations is necessary to infer good climatic data. But in the whole northwestern Himalaya a poor meteorological network is present for determining hydro-meteorological parameters. Therefore, to obtain meteorological data, we have used the Climate Research Unit (CRU) Time Series (TS) Version 4.01 (CRUTS-4.01) dataset of 0.5°*0.5° grids which covers the period 1901–2016 (Harris et al., 2014). This data is one of the most trusted meteorological datasets for the long term variations over the rugged Himalayan terrain to understand general temperature and precipitation conditions over the region.

3.3. Mapping

The boundary of the glacier has been manually delineated through digitization technique in Arc GIS. The digitization by manual technique is best to take out the most information from satellite imageries (Taloor et al., 2020). The digitization of each and every feature of interest was carried out on various times to diminish the percentage of error. The glaciers outlined were manually digitized both from the satellite data and SoI maps in GIS.

3.4. Uncertainty estimation

The uncertainty U in image co-registration was measured by following methodology outlined in (Mir et al., 2017)

$$U = \sqrt{a^2 + b^2} + \sigma$$

Where ‘a’ and ‘b’ are spatial resolution of satellite images respectively and σ is the co-registration error. The registration error was 63 m, 41 m, 32 m and 18 m for MSS, TM, ETM+ and OLI respectively. The final calculated uncertainty was ±0.002 km^2 for TM/ETM, ±0.007 km^2 for MSS and ±0.0005 km^2 for OLI. For SoI map, ±0.02 km^2 (2%) uncertainty was calculated by using the area and width digitizing errors (RMSR = 10 m, Mir et al., 2017).

3.5. Glacio-geomorphological mapping

The geomorphic mapping of glacier landforms of Machoi valley was carried out using Landsat 8 OLI (Operational Land Imager) draped onto the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) DEM. The glacier features

Table 3
Retreating rate of the snout at different interval from 1973 to 2018.

Time period	Total average snout retreat (m)	Snout Rate of retreat m yr^{-1}
1973–1980	80 ± 12.3	11.43 ± 3.07
1980–1990	120 ± 14.3	12.0 ± 3.09
1990–2000	123 ± 17.2	12.30 ± 3.34
2000–2010	128 ± 19.3	12.80 ± 3.42
2010–2018	112 ± 13.5	14.0 ± 3.53
Total	563	Average = 12.51

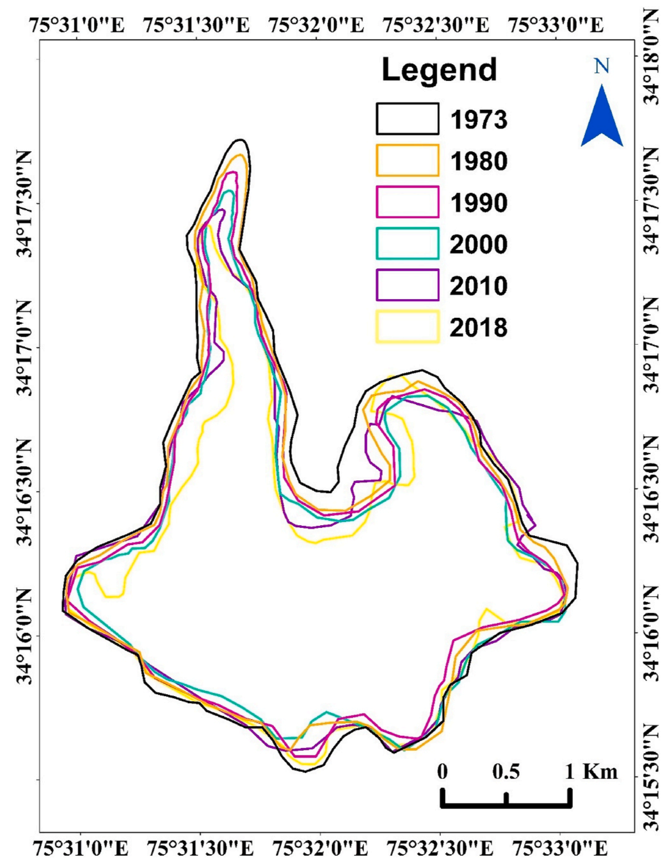

Fig. 2. Temporal changes in the areal extent of Machoi basin from 1973 to 2018.

which are not well interpreted or visible on the Landsat data were digitized from the Google Earth images. Further, different glacial geomorphological features identified during the limited fieldwork aided with GPS were used to validate the output results. The criteria used to map the various glacial geomorphological features is given in Table 2.

4. Results

Machoi glacier has a large ablation area lying between the snout and equilibrium line (3652–4620 m). According to degree day melting, the ablation zone of Machoi glacier is sub-divided into lower zone with low melting (3652–3760 m), middle lower zone with moderate melting (3800–4080 m), middle higher zone with high melting (4080–4400 m) and upper zone with low melting (4400–4580 m).

4.1. Changes in position of snout and areal extent of Machoi glacier

The results derived from these long term satellite imageries shows that the snout position (Fig. 3) of the glacier is uneven and its outline is in the form of pointed tongue with 3680 m–3652 m elevation. Snout of

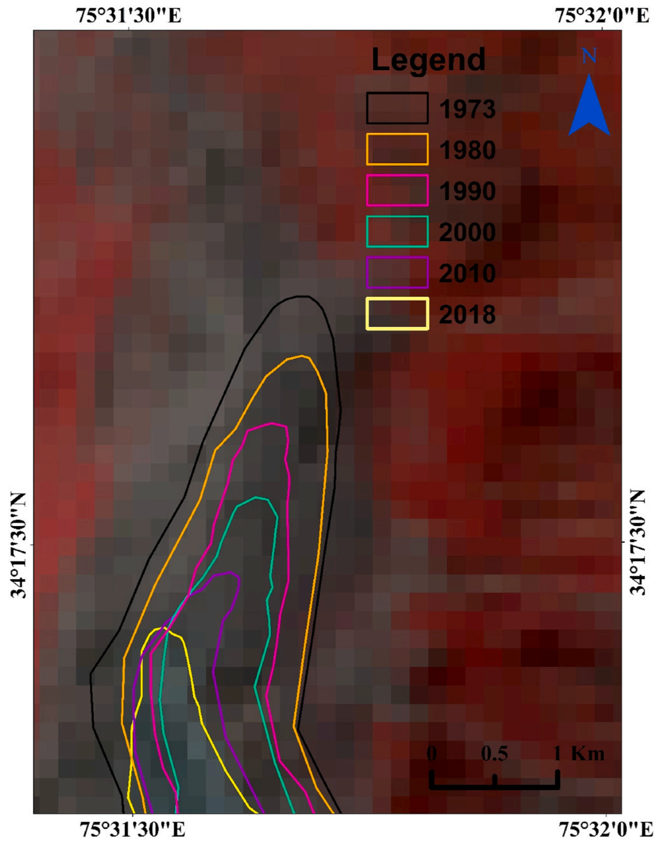

Fig. 3. Spatio-temporal retreat of the snout of Machoi glacier from 1973 to 2018.

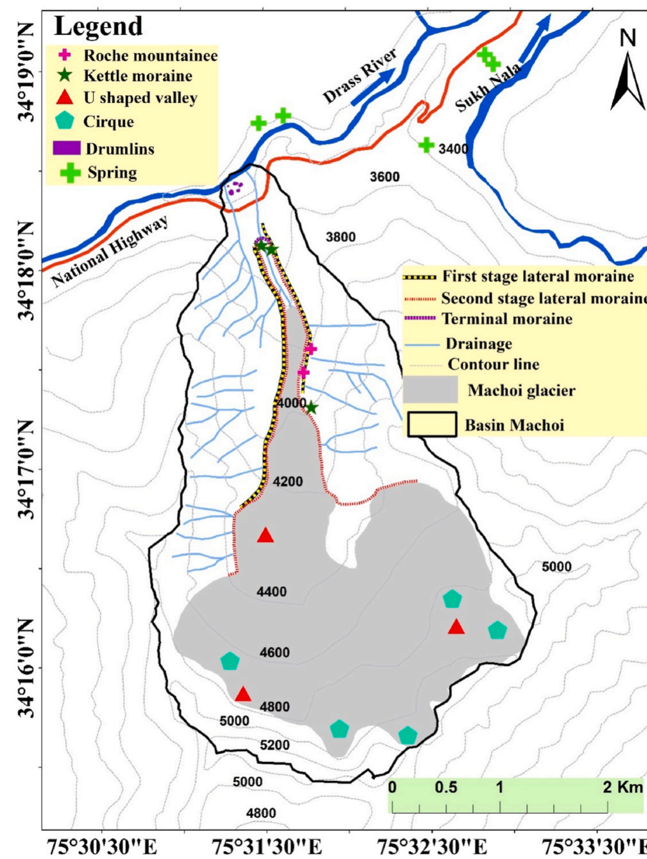

Fig. 4. Geomorphological map of Machoi glacier valley showing the various field and satellite data based geomorphological features.

Table 4
Variations in the area of Machoi glacier since past 45 years from 1973 to 2018.

Year	Area (Km^2)	Period	Area change (Km^2)
1973	5.37 ± 1.5	1962–1973	0.63 ± 0.008
1980	5.21 ± 1.3	1973–1980	0.16 ± 0.008
1990	5.06 ± 1.23	1980–1990	0.15 ± 0.0034
2000	4.98 ± 1.18	1990–2000	0.08 ± 0.0034
2010	4.80 ± 1.15	2000–2010	0.18 ± 0.0034
2018	4.21 ± 1.09	2010–2018	0.59 ± .0005

the glacier retreated largely over the 45 years a total of 563 m (12.51 m yr^{-1}). The snout has retreated at variable rate during different time intervals e.g. 80 m (average of ~11.43 myr^{-1}) from 1973 to 1980 AD, 120 m (average of ~12.0 myr^{-1}) from 1980 to 1990 AD, 123 m (average of ~12.3 myr^{-1}) from 1990 to 2000 AD, 128 m (average of ~12.8 myr^{-1}) from 2000 to 2010 AD and 112 m (average of ~14 myr^{-1}) from 2010 to 2018AD (Table 3). The glacier area (Fig. 2) has been reduced by 0.16 ± 0.008 km^2 from 1973 to 1980; 0.15 ± 0.0034 km^2 from 1980 to 1990; 0.08 ± 0.0034 km^2 from 1990 to 2000; 0.18 ± 0.0034 km^2 from 2000 to 2010 and 0.59 ±0 .0005 km^2 from 2010 to 2018 (Table 4). The ablation zone contains the transverse crevasses. The lower part is covered with thin debris particularly along its margins and high melting were present here during summer. The present-day snout position of the Machoi is highly irregular in outline and is in a tongue like form and is sharply pointed with elevation ranging between 3652 m (west) to 3664 m (east) and in central depression at an altitude of 3650 m.

4.2. Geomorphological observations and glacial landform

Glacial landforms provide vital evidences for the glaciological history of an area which in turn provide evidences for climate change. Besides, the mapping of glacier features along with landform chronology provides important information for reconstruction and modeling past glacier dynamics. Field evidences reveal the presence of periglacial, glacial and glacio-fluvial landforms, in the Machoi glacier valley. Major part of glaciated landscape is covered by moraines that are arranged in the form ridges running parallel to each other and also to the side of the valley. Majority of the first and second order lateral moraines consist of sub rounded to rounded rock fragments brought from valley heads and valley walls. The moraines are also deposited at terminus of the glacier as terminal moraines (Fig. 4). Moreover, the saddle shaped Machoi glacier (Fig. 5a) is situated the complex environmental conditions sub-arid in ablation part and cold arid permafrost in accumulation part. The accumulation zone is primarily confined in cyclopean cirque zone, where valley walls are very steep and the rocks are highly jointed due to intense freeze and thaw actions. Besides, the rocks are subjected to intense pressure conditions at the ice rock contact leading to mechanical weathering and production of rock debris (Fig. 5b). The occurrence of striations and rochee moutonnée provides evidences for the intensity of erosion in the valley and ultimately to the thickness of the past glaciers. Besides this, various other geomorphological features like cirque, drumlins, kettle, u-shaped valley, erratic boulderare also identified and picturized in the field (Fig. 6a–d). The various other glacio-geomorphological features which were identified during the field are interpreted in Table 2.

4.3. Change in climatic conditions observed by meteorological parameters and its impact on glaciers

There are several studies which shows a rapid recession of glacier in Himalayas (Bhambri et al., 2012; Mir et al., 2017) in response to

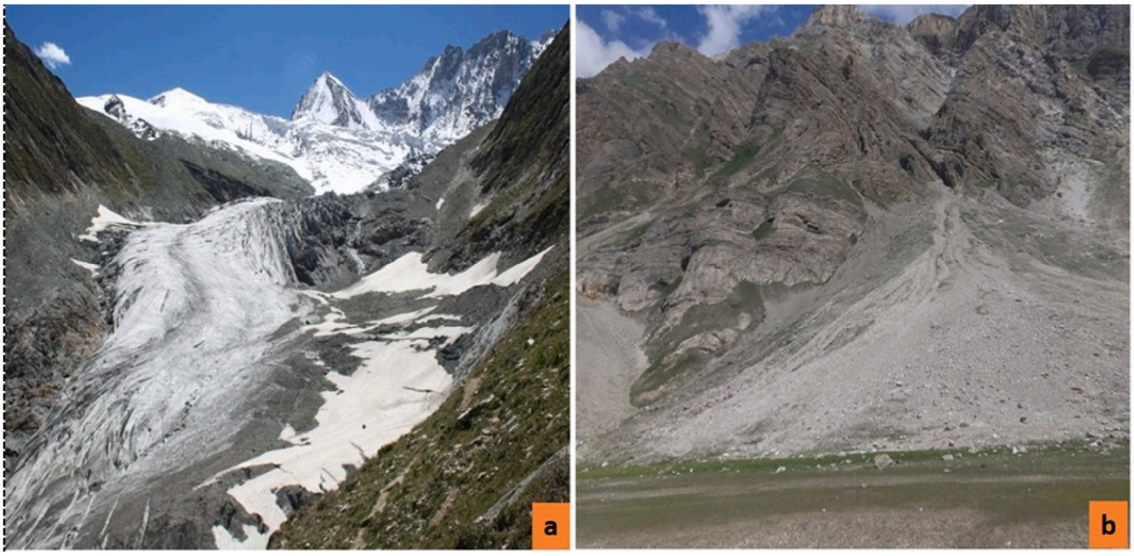

Fig. 5. (a) Showing the saddle of the Machoi glacier geomorphological features, (b) Debris fan formed near the snout of the Machoi glacier through the sediment derived from the moraines.

Fig. 6. Field photographs(a-c) showing erratic boulders with striation marks near the snout of Machoi glacier its indicates the past movement of the glacier and (d) Stabilised lateral moraines present in a deglaciated valley of Machoi glacier.

precipitation and temperature changes (Racoviteanu et al., 2008; Mir, 2018). Likewise, some studies have also reported a warming of climate in the western part of Himalayan region. For example, Bhutiyani et al. (2007) have reported a detailed long-term trend of the minimum, maximum and average temperatures over the northwestern part of Himalayan. They suggested that during the 20th century air temperature has increased with warming of winter season occurring at a faster rate. The stability or even decrease of retreating rate of some glaciers in the

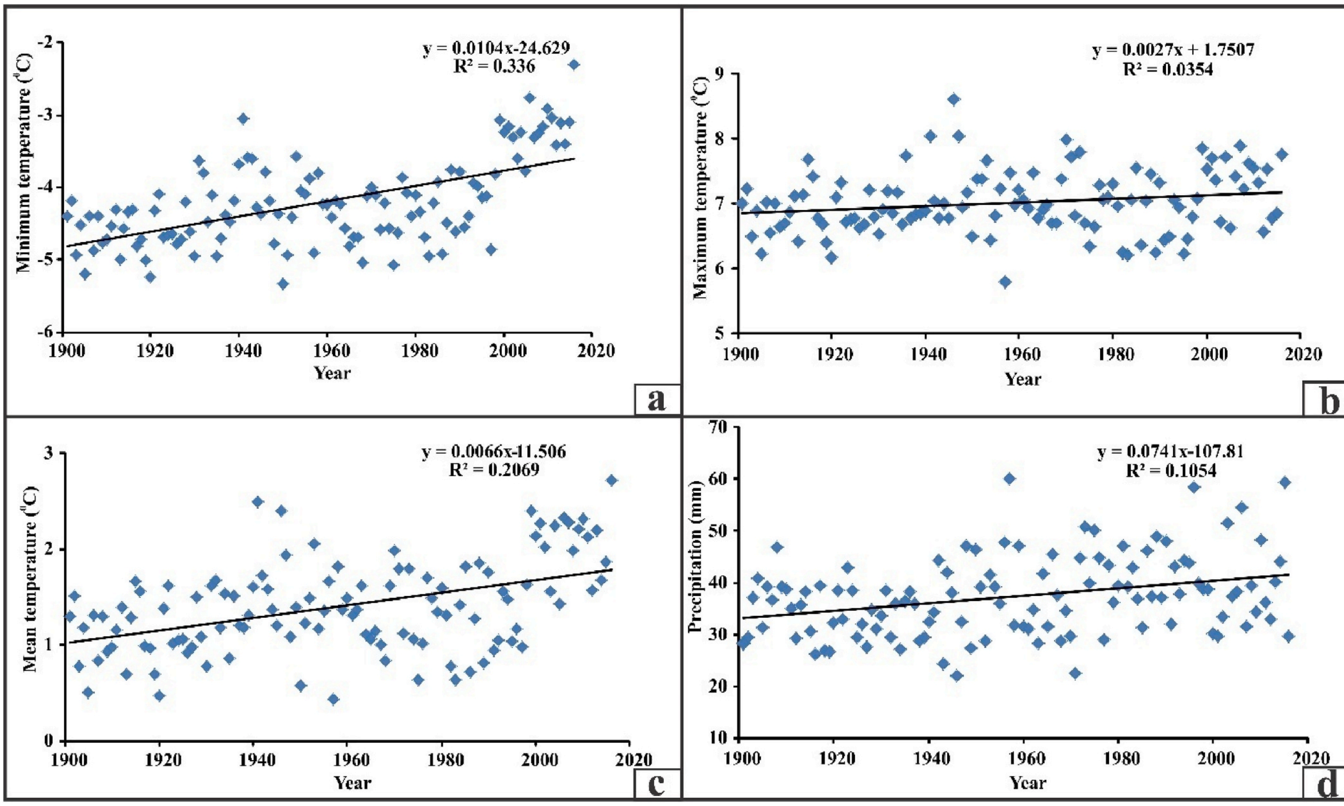

Fig. 7. Average annual minimum temperature (a), maximum temperature (b) mean temperature (c) and precipitation (d) from 1901 to 2016 (data derived from CRUTS 4.1).

Himalayan region are also reported (Schmidt and Nüsser, 2009; Hewitt, 2005, 2011; Bisht et al., 2020) which might be due to glacier characteristics and decrease summer temperature and increased winter precipitation. Previous studied related to Zanskar Himalayas have shown that there is an increase in the temperature which led to the retreat of glaciers and are expected to experience continued mass loss throughout the twenty-first century (Stocker et al., 2013; Taloor et al., 2019). Although some of the studies related to the Karakoram Himalaya have shown that the advancing of the glaciers due to various factor such as altitude and latitude position (Kaab et al., 2012). The peculiar characteristic of the Zanaskar Himalayas where due to increase in temperature the amount of liquid precipitation also showing an increase trends linked to the western disturbances (Yadav et al., 2017; Taloor et al., 2019) whereas it is reversed in the study of the Kumaun Himalayan region where due to increase in temperature the liquid precipitation showing the decreasing trend (Taloor et al., 2021a) as region is affected by Indian Summer Monsoon (ISM). The variability in the retreating trend of different glaciers located in the different region is also might be due to glacier characteristics (Singh et al., 2017; Bisht et al., 2019, 2020; Singh et al., 2020) . The Machoi glacier has experienced an increase in the minimum and maximum temperature and liquid precipitation and decrease in the solid precipitation due to global increase of temperature.

Based on the meteorological data it found that temperature has increased from last century (Fig. 7a, b,c). However, interestingly, the precipitation data from (CRUTS-4.1) show a raise of 0.1 mm/y liquid precipitation due to rise in temperature (see Fig. 7d). Moreover, the increased tourism activities and other anthropogenic activities increase around the Machoi basin has possibly led to the retreat of the glacier cover.

5. Discussion

Mayewski and Jeschke (1979) indicated that the glaciers of Himalayan region have been receding since 1850. The advance or retreat of glaciers mainly depends on the dynamic and static factors. The dynamic factors are annual ablation and accumulation of snow and ice. The static factors are slope, width and size of the valley and altitude distribution of the glaciers. These static and dynamic factors further depend on daily and yearly variations in Solid/liquid precipitation, temperature, heat flow from crust of the earth, debris cover on glacier surface and cloud cover. The fluctuations in the glacier snout are considered to be very reliable indicators of the changing climatic trends. Bahuguna et al. (2014) have monitored a total of 2018 glacier snouts through the help of satellite data, according to his study 1752 glaciers (86.8%) of them are in stable condition (no considerable change in the snout position), 248 glaciers (12.3%) are in retreating phase and 18 glaciers (0.9%) are experiencing the advancement. The results derived from their study suggested that mean retreat of snout is maximum in the Sikkim followed by Karakoram, Himachal, Uttarakhand and Zanskar region. Some studies also suggested that the glaciers of the Zanskar region do not showing a major retreat in the last 50 years (Koul et al., 2016). Recent studies on Himalayan glaciers indicate that many Himalayan glaciers are exhibiting an increased receding trend in the last decades (Kulkarni et al., 2007; Bolch et al., 2008; Taloor et al., 2021a,b, c). It is believed that Earth's climate change might be amplified by greenhouse, caused due to anthropogenic changes. In last few decades, several studies have been carried out on the Himalayan glaciers to assess their recession rates and extent by using mainly the satellite data (Bhambri et al., 2012; Racoviteanu et al., 2015; Mir, 2018; Kumar et al., 2021) and field surveys (Kamp et al., 2011; Dobhal et al., 2013; Bisht et al., 2020). Various scientific studies revealed that glaciers of Himalaya have retreated over a period of time (Yamada et al., 1992; Naithani et al., 2001) although, the retreat is continuous with non-uniform rate (Kumar et al., 2007, 2017; Prasad et al., 2009; Kulkarni et al., 2011; Scherler et al., 2011; Benn et al., 2012; Bhambri et al., 2012; Racoviteanu et al., 2015; Bhattacharya et al., 2016; Shukla et al., 2016; Singh et al., 2017; Bisht et al., 2019, 2020; Rawat et al., 2021; Sood et al., 2021b; Randhawa et al., 2021). Climate change is major reason behind it, which affecting the worldwide retreating process of the glaciers during past hundred years. The Western Disturbances (WDs) carry intense snow fall on high altitude areas in western part of Himalaya, mainly over Zanskar Himalaya. The WDs are dynamic in the months of winter (November–February). The WDs (between 30° −60° latitude) initiate mainly from Mediterranean Sea and move towards the direction eastward India across Afghanistan/Pakistan (Pisharoty and Desai, 1956; GSI, 2001; Dimri and Niyogi, 2013; Dimri et al., 2013; Kotlia et al., 2015; Yadav et al., 2017). Recent studies have shown that the Himalayan glaciers retreating rate has accelerated due black carbon deposition and change in debris cover pattern (Scherler et al., 2011).

6. Conclusion

The fluctuation in the recession pattern of Himalayan glaciers have wider implications over the Indian sub-continent as it provides water for agricultural activities of the fertile lands in Indus Ganga Brahmaputra (IGB) plains and hydro-electric power projects. In current research the GIS and remote sensing techniques have been applied to study the recessional history of the Machoi glacier in Zanskar Himalaya. The results derived from Landsat series satellite data suggested that glacier has receded consistently from 1973 to 2018 AD. The glacier area has reduced by 0.16 ± 0.008 km^2 from 1973 to 1980; 0.15 ± 0.0034 km^2 from 1980 to 1990; 0.08 ± 0.0034 km^2 from 1990 to 2000; 0.18 ± 0.0034 km^2 from 2000 to 2010 and 0.59 ±0 .0005 km^2 from 2010 to 2018. Reconstruction of the past position of snout and cumulative trend of retreat clearly shows that the snout of the glacier retreated largely over the 45 years a total of 563 m (12.51 m yr^{-1}). The snout has retreated at variable rate during different time intervals e.g. 80 m (average of ~11.43 m yr^{-1})from 1973 to 1980 AD, 120 m (average of ~12.0 m yr^{-1}) from 1980 to 1990 AD, 123 m (average of ~12.3 m yr^{-1}) from 1990 to 2000 AD, 128 m (average of ~12.8 m yr^{-1}) from 2000 to 2010 AD and 112 m (average of ~14 m yr^{-1})from 2010 to 2018AD. The analysis of climatic factors showed a significant rise in the temperature from last century (i.e. 1901–2016) with consistent decrease of solid precipitation due to warming of the region. The variability in the meteorological parameters is probably the main cause of glacier retreat in the Machoi basin.

Contribution

AKT collected the data, made the analysis and also prepare the manuscript draft; GCK, DSM, HB,PM,MS, SM contributed in the manuscript preparation; SR, AK, SA work in data downloading and processing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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