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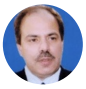

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# Recent Glacier Changes in the Kashmir Alpine Himalayas, India

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## Abstract

Using Landsat data at decadal interval (1980-2013), the glacier fluctuations (glacier area, equilibrium line altitude and specific mass balance) of nine benchmark glaciers in Kashmir Himalaya was estimated. The observed changes were related with topographic and climatic variables in order to understand their influence. From the data analysis, it was observed that the glaciers have shrunk by 17%, *ELA* has shifted upwards (80-300 m), and *SMB* shows variation in glacier mass loss from -0.77 to -0.16 m.w.e. Annual air temperature showed a significant increasing trend and a slight but insignificant decrease in precipitation was observed during the period. It is evident that, in the same climatic regime, varying topography plays a key role in determining the glacier changes. It is believed that the observed changes in the glacier geometry and dynamics, if continued, shall have adverse effect on the streamflows, water supplies and other dependent sectors in the region.

**Keywords:** Glaciers, Mass balance, Equilibrium Line Altitude, Accumulation area ratio, Climate Change

## Introduction

Glaciers are one of the important natural resources with immense importance as a perennial source of fresh water, hydropower generation and regional climatology. However, the climate change has impacted the cryosphere with the consequent impacts on streamflow, food production and even tourism (Slingo et al. 2005; Scott et al. 2012; Dar et al. 2014; Romshoo et al. 2015). The world's average surface temperature has increased between 0.3°C and 0.6°C over the past hundred years (IPCC 1992; Bajracharya et al. 2008) and the increase in global temperature is predicted to rise continuously during the current century (Bhutiyani et al. 2009, Rashid et al., 2015). Studies by the Intergovernmental Panel on Climate Change (IPCC) concluded that the Earth's average temperature has increased by 0.6±0.2°C during the 20th century. The rise in the temperature has resulted in the shrinkage of most glaciers and ice caps all around the world (Sorg et al. 2012). Analysis of the glacier response to the climate change leads to an understanding of the mechanism of glacier fluctuations (Dyurgerov & Meier 2000; Anderson et al. 2008).

Outside the Polar Regions, Himalayan glaciers form one of the largest concentrations of ice. Himalayan glaciers constitute an important proportion of fresh water of the major river systems of the Asia such as Indus, Brahmaputra, and Ganges. The climate of the Himalayas is highly variable because of its wide range of geographical factors that contribute to variations in temperature and precipitation (Young & Hewitt 1990). Average temperatures are predicted to rise between 3.5°C and 5.5°C by 2100 in the Indian sub-continent (Lal 2002) and by 6.43°C (±1.72) in the Kashmir Himalayas (Rashid et al. 2015). The most immediate impact of this rise in temperature will adversely affect the glacier recession rate in the Himalayas, because of the sensitivity of cryosphere to temperature changes (Hasnain 2008; Bhambri et al. 2011). Various studies implied that the Himalayan glaciers have been retreating since the end of Little Ice Age (LIA) (Vohra 1981; Dobhal et al. 2004). However, more recent studies also suggest that the rate of retreat has increased during the past few decades (Bolch et al. 2008).

Various approaches have been employed to study the glacier recession rate of selected glaciers in Himalayas based on field investigations (Dobhal et al. 1999), satellite images and topographical maps (Kulkarni 1992; Pankaj et al. 2012). However, the direct measurements of glacier changes are very abstruse due to their remote location, uninhabited neighbourhood, spotty distribution and cold climatic conditions. These factors have motivated researchers to use new technologies such as remote sensing for investigating the glacier changes in different mountain regions of the world, including the Himalaya (Bolch et al. 2010; Ajai et al. 2011). Remote sensing provides multi-sensor and multi-temporal satellite images which are useful for mapping, monitoring and systematic assessment of glacial extent and change with the advantage of synoptic view over a large area (Hubbard & Glasser 2005). Satellite imagery is especially useful in rugged Himalayan terrain along with field-based glaciological measurements (Gao & Liu 2001; Andreassen et al. 2008; Heid & Kääb 2012).

Several studies have been conducted on Himalayan glaciers by using satellite data to assess the glacier extents, recession rates using snout monitoring, accumulation and ablation zones, etc. (Bahuguna et al., 2014; Racoviteanu et al. 2008). Most of these studies have attributed climatic and topographic variations for varying glacier retreat in the Himalayas (Bhutiyani 1999; Hasnain 2008). Anthropogenic activities and black carbon have also been reported as one of the major factors for depleting Himalayan glaciers (Hansen & Nazarenko 2004; IPCC 2007; Yasunari et al. 2010). Various methods have been used to delineate the glacier area such as on-screen delineation, image rationing, supervised and unsupervised classification, indices and sub-pixel classification based techniques (Albert 2002; Vikhamar & Solberg 2003; Shukla et al. 2009). Mass balance of valley glaciers has been determined using the glaciological, geodetic and hydrological methods (Ostrem & Stanley 1969). However, field-based glacier mass-balance data collected through glaciological method is available for a very few glaciers in the Himalayas because of the remoteness and logistic constraints faced in regular monitoring and collection of data through field methods. Dyurgerov & Meier (2005) compiled mass balance data of eight Indian Himalayan glaciers with the globally available mass balance series. Overall, the global mass balance records of the Himalayan glaciers are incomplete. Therefore, several studies have advocated using approximate estimates to assess mass balance for glaciers in this region (Kulkarni, 1992; Pelto 2010; Brahmbhatt et al. 2012). These studies have demonstrated that if the relationship between AAR or ELA and specific mass balance is established, specific mass balance can be estimated from the ELA or AAR using remote sensing data. Kulkarni et al. (2004) has discussed the applicability and robustness of Accumulation Area Ratio (AAR) and Equilibrium Line Altitude (ELA) methods for the estimation of mass balance of Himalayan glaciers. Satellite data has also been used widely to calculate changes in glacier volume (Storvold et al. 2005, Surazakov & Aizen 2006). Loss in glacier volume is normally directed by the glacier retreat (Dobhal et al. 2004).

The objective of this research was to assess the glacier recessions and the changes in the glacier geometry and dynamics for nine benchmark glaciers in the Lidder valley of Kashmir, India using a time series of Landsat satellite images (1980, 1992, 2001, 2010 and 2013). The observed changes in various glacier parameters are explained in terms of the topographic variations and climatic changes observed in the area.

## Study Area

The Lidder valley is located in the south-eastern corner of Kashmir valley giving passage to a river of same name and is situated between geographical co-ordinates of $33^0$ $43^'$-$34^0$ $15^'$ N latitude and $75^0$ $05^'$-$75^0$ $32^'$ E longitude. Lidder is known for its pristine and varied water resources in the form of snow, glaciers, springs, streams and alpine water bodies. The Glaciers are presently confined along the northern ridge of the east and west Lidder valley. Kolahoi glacier is the largest glacier in the west Lidder valley and Shishram glacier is the largest glacier in the east Lidder. Lidder River is one of important tributaries of river Jhelum, formed by the union of two major streams, the East Lidder and the West Lidder streams at Pahalgham. The east Lidder drains the Great Himalayan mountain torrents from Shishnag carving a deep gorge round Pisu hills and flows past Chandanwari up to Pahalgam. The west Lidder torrent rising from the south of Kolahoi glacier, receiving a tributary from the Sanasar Lake near Kolahoi Ganj valley and joins the eastern Lidder torrent at Pahalgam. The location of the glaciers with glacier number is shown in Figure 1.

## Material and Methods

In this study, a time series of snow and cloud-free Landsat satellite data were chosen for mapping and monitoring the changes in glacier geometry and dynamics. Image selection for glacier mapping is guided by acquisition at the end of the ablation period, cloud-free conditions and lack of snow packs adjacent to glaciers (Paul et al. 2002; Kääb et al. 2002). Landsat imageries from different sensors of the years; 1980 (MSS), 1992 (TM), 2001 (ETM+), 2010 (TM) and 2013 (OLI) were available for the area which fulfilled the above mentioned suitability criteria. ASTER GDEM was also used to generate the altitude, slope and aspect of the glaciers. Table 1 shows the data sets used in this study.

Meteorological Data

Time series of meteorological data of Lidder valley at Pahalgam station, obtained from Indian Meteorological Department (IMD) and comprising of air temperature ($T_{Max}$ and $T_{Min}$) and precipitation data of last three decades was used to assess the changes in the climatic variables. The Mann-Kendall statistical non parametric test was used for determining the significance of the trends of the meteorological parameters (Mann1945; Kendall 1975). The mathematical equation for calculating Mann-Kendall statistics S, V(S) and standardized test statistics Z are as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sig}\left(X_j - X_i\right),$$

$$sgn\left(X_j - X_i\right) = \begin{cases} +1 \; if \left(X_j - X_i\right) > 0 \\ 0 \;\; if \left(X_j - X_i\right) = 0 \\ -1 \; if \left(X_j - X_i\right) < 0, \end{cases}$$

$$V\,(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\,\left(t_p - 1\right)\left(2t_p + 5\right)\right],$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR\ (S)}}\ if\ S > 0 \\ 0 \quad if\ S = 0 \\ \frac{S+1}{\sqrt{VAR\ (S)}}\ if\ S < 0. \end{cases} \qquad \text{………………..} (1)$$

Where, $X_i$ and $X_j$ are the time series observations in chronological order, $n$ is the length of time series, $t_p$ is the number of ties for $p$th value, and $q$ is the number of tied values. Positive $Z$ values indicate an upward trend in the hydrologic time series; negative $Z$ values indicate a negative trend. If $|Z| > Z_{1-\alpha/2}$, ($H_0$) is rejected and a statistically significant trend exists in the hydrologic time series. The critical value of $Z_{1-\alpha/2}$ for a $p$ value of 0.05 from the standard normal table is 1.96.

## Glacier Mapping

Glaciers in the Lidder valley were mapped using multi-temporal optical remote sensing data from the Landsat series. An integrated approach of different techniques was used for mapping and monitoring of glaciers (Figure 2). Visual image interpretation along with various digital algorithms such as band ratios (TM4/TM5), band contrasting and spectral indices (NDGI) were used to map various glacial features (Paul et al. 2002; Bolch & Kamp 2006; Racoviteanu et al. 2009). Position of glacier snout was delineated by identifying features such as the origin of the stream from the terminus, crevasses, disposition of end moraines. Position of few glacier snouts was also mapped and verified during field surveys using Global Positioning System (GPS). The glacier boundaries on the satellite images were mapped on 30,000 scale using on-screen digitization with the aide of various above mentioned image processing techniques.

The snow line altitude (SLA) divides the ice facies of the ablation zone from the snow facies of the accumulation zone. If measured at the end of the melt season, the SLA is coincident with equilibrium line altitude (ELA). If measured before the end of the melt season, the SLA may be lower than the ELA (Khalsa et al. 2004). The equilibrium-line coincides with the snowline in temperate glaciers, because of the insignificant extent of superimposed-ice zone (Paterson 1998). Therefore, the snow line at the end of ablation season is treated as equivalent of the equilibrium line. On glaciers, the ELA is the average elevation at which accumulation precisely balances ablation, taken over a period of one year (Hoinkes 1970). ELA is a key parameter for establishing accumulation area ratio (Kulkarni et al. 2004; Pandey et al. 2013). The ELA was calculated from the ASTER GDEM.

Keshri et al. (2009) have proposed a spectral indices known as Normalized Difference Glacier Index (NDGI) for detailed mapping of supra glacial terrain. NDGI works on the premise that the reflectance of snow remains equally high in both green and red regions of electromagnetic spectrum compared to the reflectance of ice which is relatively lower. This difference and spectral contrast is picked by NDGI to differentiate snow from ice facilitating the delineation of the accumulation and ablation zones on the glacier. The equation of the *NDGI* is given below;

$$NDGI = \frac{\mathrm{GREEN_{band}} - \mathrm{RED_{band}}}{\mathrm{GREEN_{band}} + \mathrm{RED_{band}}} \qquad \text{…………..(2)}$$

*NDGI* frequency distribution also possesses a bimodal distribution, and can be used for the discrimination of snow/ice versus ice mixed debris (Keshri et al. 2009). The threshold value of 0.29 has been found suitable for mapping and differentiating between accumulation and ablation zones.

The accumulation area ratio (AAR) is a ratio between accumulation area and total area of a glacier (Georges 2004). AAR is important for the estimation of mass balance of glaciers. Mass balance is defined as the total change (loss or gain) in the glacier mass at the end of the hydrological year (Heilskanen et al. 2002) and depending upon the specific environmental setting, each glacier has its own annual net mass balance. Mass balance measurements are done per unit area basis, known as specific mass balance and expressed as mm of water equivalent. Mass balance is estimated by quantifying the amount of seasonal snow accumulation and snow/ice ablation. Mass balance of the glaciers was estimated using the following equation (Kulkarni 1992);

$$b = 243.01 * X - 120.187 \qquad \text{…………. (3)}$$

Where b is the specific mass balance in water equivalent (cm) and X is the accumulation area ratio. Glacier volume of different years of observation period was calculated using the following equation (Kulkarni 1992, Kulkarni et al. 2004);

$$H = 11.32 + 53.21F^{0.3} \qquad \text{..………… (4)}$$

Where ‘H’ is the mean glacier thickness (m) and ‘F’ is the glacier area (km$^2$). The equation had been primarily used for calculation of thickness and volume of Himalayan glaciers.

## Uncertainty estimation

Glacier boundaries derived from various remote sensing data of different times with varying snow cover, cloud and shadow conditions have different levels of accuracy. The sources of error in area and length estimation are due to co-registration and glacier area delineation. Therefore, estimation of the error is important to know the accuracy and significance of the results. First, the terminus change uncertainty U was estimated by using the following equation (Silverio & Jaquet 2005; Wang et al. 2009; Bhambri et al. 2012);

$$U = \sqrt{a^2 + b^2} + \qquad \text{……………….. (5)}$$

Where ‘a’ and ‘b’ are the spatial resolutions of images ‘a’ and ‘b’, respectively and **σ** is the error in the image registration.

The registration error while registering 1980 MSS image was approximately 13 m, for 1992 Landsat TM, it was 8 m, for 2001 Landsat ETM+, it was 7 m and for 2010 Landsat TM, it was 7 m. The registration error was added to the uncertainty value to compute the overall measured error between any two images. Changes in the snout position of glaciers were measured digitally with an accuracy of ±80 m when registering 1980 MSS image to the base image (Landsat OLI 2013), ±50 m when registering the Landsat TM image of 1992, ±49 m when registering the Landsat ETM+ image of 2001 and ±49 m when registering the Landsat TM image of 2010 to the base image. The error in manual digitization of glacier boundaries was estimated to be one pixel (Congalton 1991; Zhang & Goodchild 2002; Hall et al. 2003).

The uncertainties of the glacier area estimates were determined by the buffer method suggested by Granshaw and Fountain (2006) for each glacier. The area of the buffer around each glacier was set to twice the digitization error (Racoviteanu et al. 2008; Wang et al. 2009; Bolch et al. 2010). Then, the measurement of uncertainty of glacier area ($U_{area}$) for each glacier was obtained by using the following equation (Hall et al. 2003; Ye et al. 2006);

$$U_{area} = 2UV \qquad \text{……………… (6)}$$

Where *U* is the terminus uncertainty and *V* is the image pixel resolution.

Thus, the final uncertainty (a combination of mapping uncertainty and the uncertainty of the misregistration) in the area extent of the glaciers was estimated to be ±0.0096 $km^2$ using 1980 MSS image, ±0.0030 $km^2$ using 1992 TM image, 0.0029 $km^2$ using 2001 ETM+ image and 0.0029 $km^2$ using 2010 TM image.

## Results and Discussions:

### Glacier area change

Nine glaciers was mapped from 1980 (MSS), 1992 (TM), 2001 (ETM+), 2010 (TM) and 2013 (OLI) Landsat images. The analysis of the data showed that the areal extent of glaciers has receded significantly from 1980-2013. The total glaciated area of the nine benchmark glaciers in 1980 was 29.01 $km^2$ which reduced to 27.77 $km^2$ in 1992, 26.26 $km^2$ in 2001, 24.89 $km^2$ in 2010 and 23.81 $km^2$ in the year 2013. Therefore, the area has witnessed a deglaciation of about 5.20 $km^2$ or 17.92% during 33 years. However, the rate of retreat is varying among these nine glaciers and this variation might be because of the size, altitude, slope, aspect and geomorphic set up of the glaciers. Figure 3 shows the retreat of glaciers during the study period. Kolahoi glacier (G1) is the biggest glacier in the study area which shows area change of 2.33 km$^2$ from 1980 to 2013, having reduced from 13.57 km$^2$ in 1980 to 11.24 km$^2$ in 2013. Kolahoi glacier has two snouts and both the snouts are showing upward shifting trend. The smallest glacier G3 has reduced from 0.34 km$^2$ in 1980 to 0.23 km$^2$ in 2013. Table 2 shows the detailed statistics of the area and snout changes of the benchmark glaciers. Further, in order to see the variation in glacier recession as a function of glacier size, the glaciers were categorized into three classes; glaciers with area <1 km$^2$, between 1-5 km$^2$ and with area between 5-15 km$^2$. The analysis showed that the smaller glaciers (<1 km area) have lost 25% of their area during the observation period, followed by the glaciers in 1–5 km$^2$ class (by 23%), and about 13% by the glaciers in the 5–15 km$^2$ class. Various studies have reported that response time of glaciers is directly proportional to their thickness (Johannesson et al. 1989) which in turn depends upon the size of a glacier (Chaohai & Sharma 1988). Therefore, smaller glaciers are under bigger threat due to changing climate as compared to the larger glaciers. Armstrong et al. (2009) and Kulkarni et al. (2007) have also reported that due to changes in climate, small glaciers are likely to face more melting than larger ones. Table 3 shows the comparison of changes in glacier cover for different glacier categories during the observation period.

The influence of topographical parameters such as glacier aspect and snout elevation on glacier area change was studied using the ASTER GDEM. The advance and retreat of glaciers also depends on the aspect (Wang et al. 2009; Bhambri et al. 2011). To assess the effect of aspect, the study area was divided into nine classes i.e. Flat, North, North East, East, South East, South, South West, West, and North West. It was observed that north-facing glaciers are shrinking less than the south-facing glaciers. Overall, the south-facing glaciers were found to have lost 31% of the glacier area, followed by the north-west-facing glaciers which lost about 20% area and the lowest recession was found in glaciers facing north-east which lost about 17% area during the observation period (Table 4). To understand the influence of altitude on glacier retreat, glaciers were classified on the basis of snout altitude and were categorised into two classes of 3500-4000 m and 4000-4500 m. It was observed that the glaciers, with snout at lower altitudes, have lost about 21% of their area, while as the glaciers with snouts at higher altitudes have lost 23% of their area (Table 5). However these results are showing an opposing trend than that reported in various other studies. The possible reason for the higher recession rate of high altitude glaciers may be related to their size i.e. small glaciers are showing high recession rates as compared to larger glaciers in the study area because of their more sensitive to climate change. Statistical analysis revealed that all the glaciers whose snout altitude are falling in the higher altitudes (4000-4500 m) are smaller glaciers with less than 1 km$^2$ in size.

## Glacier Dynamic Parameters

Different glacier dynamic parameters such as accumulation area, accumulation area ratio (AAR) and equilibrium line altitude (ELA) were mapped for all the nine benchmark glaciers. Figure 4 shows the NDGI image which was used to differentiate the accumulation area and ablation area. Accumulation area of all the glaciers is continuously showing a decreasing trend from 1980 to 2013. Accumulation area for each glacier varied from year to year depending upon the snow-line altitude at the end of the ablation season. Mean accumulation area of the glaciers ranged from 0.10 km$^2$ (G3) to 7.10 km$^2$ (G1). Accumulation area of all glaciers is showing a continuous decrease and the fluctuations are shown in table 6.

Accumulation Area Ratio (AAR) has significant effect on the retreat or advance of any glacier. AAR of the nine glaciers was extracted based on the snow line at the end of ablation season using satellite images of ablation season for the year 1980, 1992, 2001, 2010 and 2013. The changes in AAR of the glaciers ranged from 0.07 (G2) to 0.32 (G6) with an average of 0.19 during the observation period. The mean AAR of all the glaciers was showing decreasing trend from 0.58 in 1980 to 0.39 in 2013. Another important glacier dynamic parameter, Equilibrium Line Altitude (ELA) is a very crucial parameter for knowing the glacier health (Benn & Lehmkuhl 2000; Bryan & Geoffrey 2005; Sharma & Owen 1996). The shifting of ELA relative to its current position is an important indicator of the mass balance and health of the glacier. The average elevation of ELA of the glaciers ranged from 4,212 m to 4,367 m. The ELA showed a clear upward rise from 1980 to 2013. G9 glacier shows the highest upward movement of ELA and has shifted by 300 m during the period while as, the G5 glacier shows the lowest upward movement of ELA (60 m) during the same period. Mean ELA of the glaciers shifted upwards from 4212 m in 1980 to 4269 m in 1992, 4309 m in 2001, 4346 m in 2010 and 4367 m in 2013. Figure 5 shows the demarcated of ELA of Kolahoi glacier. The variations in snow line fluctuations are attributed to the varying topography (slope, aspect), and variations in the micro climate which includes wind slope, glacier wind (Oerlemans 2010) and the altitude of the accumulation zone of each glacier. Table 7 shows the fluctuations in the AAR and ELA during the observation period (1980-2013). In order to have reliable estimates of the AAR and ELA and to reduce errors, it was made sure to use the snow free satellite data at the end of the ablation season. There are several data constraints for determing the glacier parameters from the satellite data and these could be addressed by the judicious selection of appropriate data and methods (Romshoo & Rashid, 2011; Murtaza & Romshoo 2014).

## Glacier Mass Balance

The specific mass balance (cm) of the glaciers was calculated for the years 1980, 1992, 2001, 2010 and 2013 which varied significantly from the maximum of 72.20 cm water equivalent (G6) to minimum of -56.79 cm water equivalent (G3) during the study period. Table 8 shows the detailed mass balance changes of all the nine benchmark glaciers. Specific mass balance of glaciers for the year 1980 ranged from 72.20 cm to -22.98 cm with an average value of 21.54 cm; for 1992, it ranged from 57.21 cm to -24.26 cm with an average value 12.74 cm; for the year 2001, it varied from 54.17 cm to -33.64 cm with an average value 5.29 cm; for the year 2010, it ranged from 52.13 cm to -44.88 cm with an average value 1.47 cm and for the year 2013, it varied from -5.02 cm to -54.23 cm with an average of -24.78 cm. Variation of mass balance among the glaciers is generally governed by combination of various processes which include accumulation of snow and the melting of ice. However, in the same climatic regime, the variation of the geomorphological and topographic characteristics plays a vital role in determining the variations in the mass blance estiamtes. Overall, the mass balance of glaciers kept a fluctuating trend throughout the observation period with an overall decreasing trend (Table 8). An attempt was made to understand the mass balance fluctuations with respect to the glacier size (area wise). For this purpose, all the glaciers were grouped into three classes and the statistical analysis showed that smaller glaciers have lost higher glacier mass followed by the medium and large-sized glaciers as is shown in Table 3. Orientation of the glacier also seems to have profound influence on mass balance of glaciers; It was seen that the north facing glaciers have lost less glacier mass (-40.06 cm) than that of the south facing glaciers (-64.03 cm) as shown in table 4. Correlation between different glacier dynamic parameters (Figure 6) was calculated and it was observed that there is an inverse relationship between SMB/ELA and ELA/AAR and direct relationship between SMB/AAR. This just demonstrates that the consistent variations of ELA, AAR and SMB over a period of time could serve as an indicator of the health of a glacier and this correlation is similar to that reported in various other studies (Kulkarni et al. 2004; Pratap et al.2015). It must be kept in mind that the mass balance of the benchmark glaciers was estimated using the equation developed on the basis of the relationship observed between AAR and mass balance of two glaciers in Himachal Himalayas, western Himalayas with correlation coefficient equal to 0.96. It is assumed that since the accumulation patterns of glaciers in Western Himalayas don't vary significantly (Kulkarni et al. 2004), the relationship might be valid for mass balance estimation of other glaciers in the western Himalayas. However, it has been observed that the oberved relationship between AAR and mass balance using a larger set of six glaciers spread over a wider geographic range even in the Western Himalayas yielded a weaker relationship (correlation coefficient of 0.75). However, the relationship was constraned by the availability of mass balance data for a shorter period (Kulkarni, 1992). It is therefore likely that the mass balance estimates of the benchmark glaciers determined in this study might have errors which could not be quantified due to lack of field based mass balance measurements in the area.

## Glacier Volume Changes

Glacier data was also used to estimate the changes in the volume of the benchmark glaciers which ranged from 0.349 km$^3$ in 1980, 0.312 km$^3$ in 1992, 0.288 km$^3$ in 2001, 0.277 km$^3$ in 2010 to 0.265 km$^3$ in 2013 with an average loss of -0.08 km$^3$ during 33 years of the observation period. The ice loss showed a progressive increasing trend during the obsevation period (Table 8).

## Meteorological data analysis

Trend analysis was carried out for the mean annual temperature ($T_{Max}$ and $T_{Min}$) and the total annual precipitation (1980–2010) available from the Pahalgham station, which is closest to the glaciers, using the Mann-Kendall test. Both the average minimum temperature and average maximum temperature (figure 7) have gradually increased with interannual fluctuations over the observation period. The most significant evidence for regional and global climate change is the increase in minimum temperature. The lowest average minimum temperature for Pahalgam was 1.78°C in 1986 while as the highest was 4.35°C in 2006. The mean annual $T_{Min}$ showed an increasing trend. Similarly, the lowest average maximum temperature for Pahalgam was 14.3°C in 1986 while as the highest was 18.14 °C in 2001. The trends for temperature ($T_{Max}$ and $T_{Min}$) were found statistically significant at the confidence level of 0.01 (Table 9). Lidder valley receives precipitation both in the form of snow and rainfall. The highest precipitation of 1,624 mm was recorded during the year 1994 and the lowest of 705 mm during the year 1985. Precipitation (figure 8) showed decreasing but statistically insignificant trend during the observation period (Table 9). The analysis of the climate data reveals that the glacier fluctuations have correlation with the observed changes in the air temperature and precipitation. The results therefore indicate that the significant increase in the temperature ($T_{min}$ and $T_{max}$) and small decrease in the precipitation over the area may have attributed to increased ablation and less accumulation resulting in the observed glacier changes. The Indian Himalayan region, inlcuding Kashmir, is facing a change in the form of precipitation from solid to liquid phase which has been described as one of the significant factors responsible for less accumulation of snow on glaciers (Thayyen et al. 2005; Dimri & Mohanty 2007; Romshoo et al. 2015). In the Himalayas, the rise in the average temperature during winter months has brought a change in the precipitation pattern with December and January months now receiving scanty snowfall while February and March are witnessing relatively more snowfall (Dar et al. 2014; Mir et al. 2014). An increase in the temperature is usually accompanied by a decreasing trend in precipitation, and a reduction in the total seasonal snowfall (Dimri & Kumar 2008; Shekhar et al. 2010; Dar et al. 2014) which might have made a profound negative impact on the glacier health in the region. Temperature and precipitation are the two major climatic variables affecting the ablation and accumulation characteristics of glaciers. An important link between the changing climate and glacier retreat has been reported in various studies carried out during the last century (Hasnain 2002; Haeberli et al. 2005; Kaser et al. 2006; Romshoo et al. 2015).

## Conclusions

Mapping the changes in the glacier extents and dynamics of the nine benchmark glaciers in the Lidder valley revealed that the glaciers have significantly receded in areal extent during the last 33 years (1980 to 2013). The total loss of area for the benchmark glaciers during the period is 5.20 $km^2$ or 17.92 % of the total glacier area. Analysis of the data showed that the smaller glaciers (<1 km) have lost 25% of their area, medium size glacier (1–5 $km^2$ area) have lost 23% and about 13% loss was shown by the glacier in the range of 5–15 $km^2$. Most of the glacier snouts of the benchmark glaciers are mainly located at the altitude of 3500-4500 m and there is general recession of snouts of all the nine glaciers by varying lengths. Glaciers with lower snout altitude have lost less glacier area than that of glaciers with higher snout altitudes primarily because of being smaller in size. Aspect of glaciers seems to have an impact on glacier recession rates. From the analysis of data, it was observed that the north-facing glaciers were showing less recession rate than that of the south-facing glaciers. An upward rise of ELA of the studied glaciers was observed in the present study. The mass balance of the glaciers exhibited a fluctuating trend throughout the observation period and indicated that the glaciers in the basin are losing mass. Mean specific mass balance of the glaciers declined from 21.54 cm in 1980 to 12.74 cm in 1990, 5.29 cm in 2001, 1.47 cm in 2010 and -24.78 cm in 2013. This loss in the mass of glaciers has profoundly influenced the extent and health of the glaciers. In the present study, the influence of annual temperature and precipitation trends on glaciers was investigated. Trend analyses showed that the mean annual temperature ($T_{Max}$ and $T_{Min}$) has increased and there is insignificant decrease in the total annual precipitation in the area. From the analysis of the data, it is inferred that the rising temperature and declining precipitation might have contributed to the glacier recession in the area. Based on varying response of the benchmark glaciers studied in this study, it is concluded that the glacier system is very complex and is responding differently to the changing climate depending upon its topographic set up in terms of altitude, slope and aspect. However, it is very evident from this study that the glacier cover is depleting steadily and if this trend of recession continues into the next few decades, it may pose serious threat to the water availability for irrigation, hydropower generation, horticulture and recreational use in the region.

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## Figure Captions

**Figure 1:** Distribution of glaciers with glacier ids.

**Figure 2:** Image processing techniques: (a) NDGI image (b) Contrasting image and (c) Ratio image.

**Figure 3:** Retreat of glaciers during the study period of 1979–2013.

**Figure 4**: NDGI image which was used to differentiate the accumulation area of glaciers.

**Figure 5:** Demarcated ELA of Kolahoi glacier: (a) 1980(MSS) (b) 1992(TM) (c) 2001 (ETM+) (d) 2010(TM) (e) 2013 (OLI) and (f) Superimposed ELA's of all dates on Landsat ETM+ (2001) image.

**Figure 6:** Showing correlation between ELA (m) and SMB (cm), AAR and SMB (cm) and AAR and ELA.

**Figure 7:** Mean maximum and minimum temperature (°C) from 1980 to 2010.

**Figure 8:** Total annual precipitation (mm) from 1980 to 2010.

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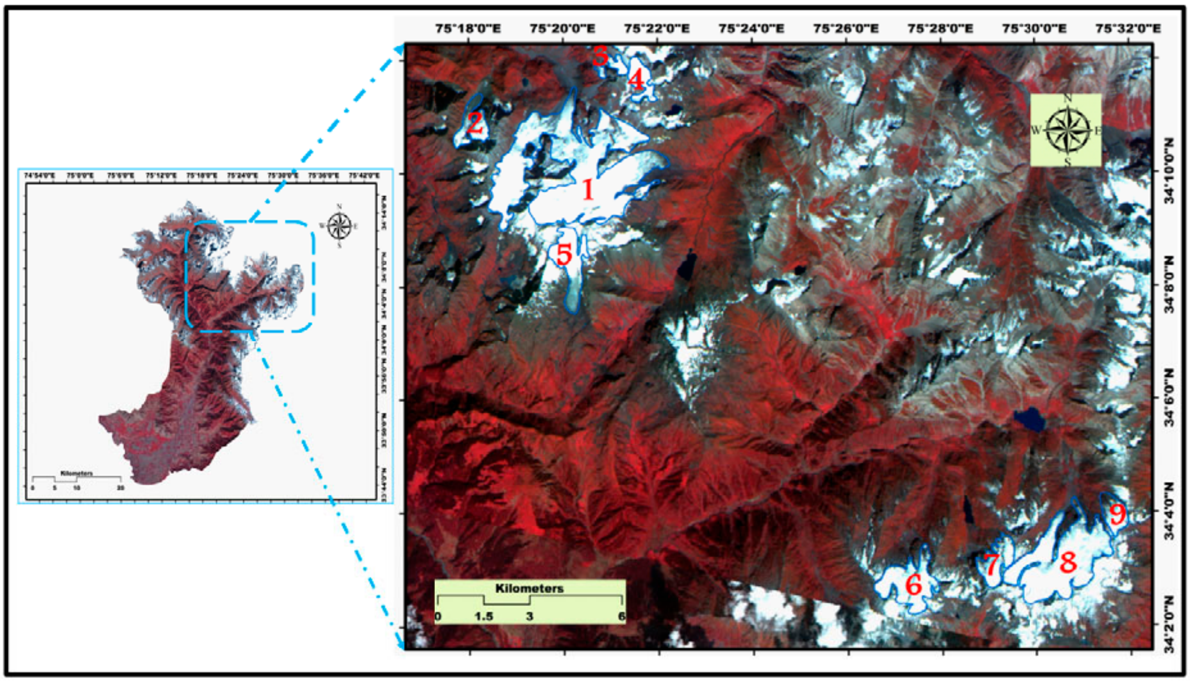

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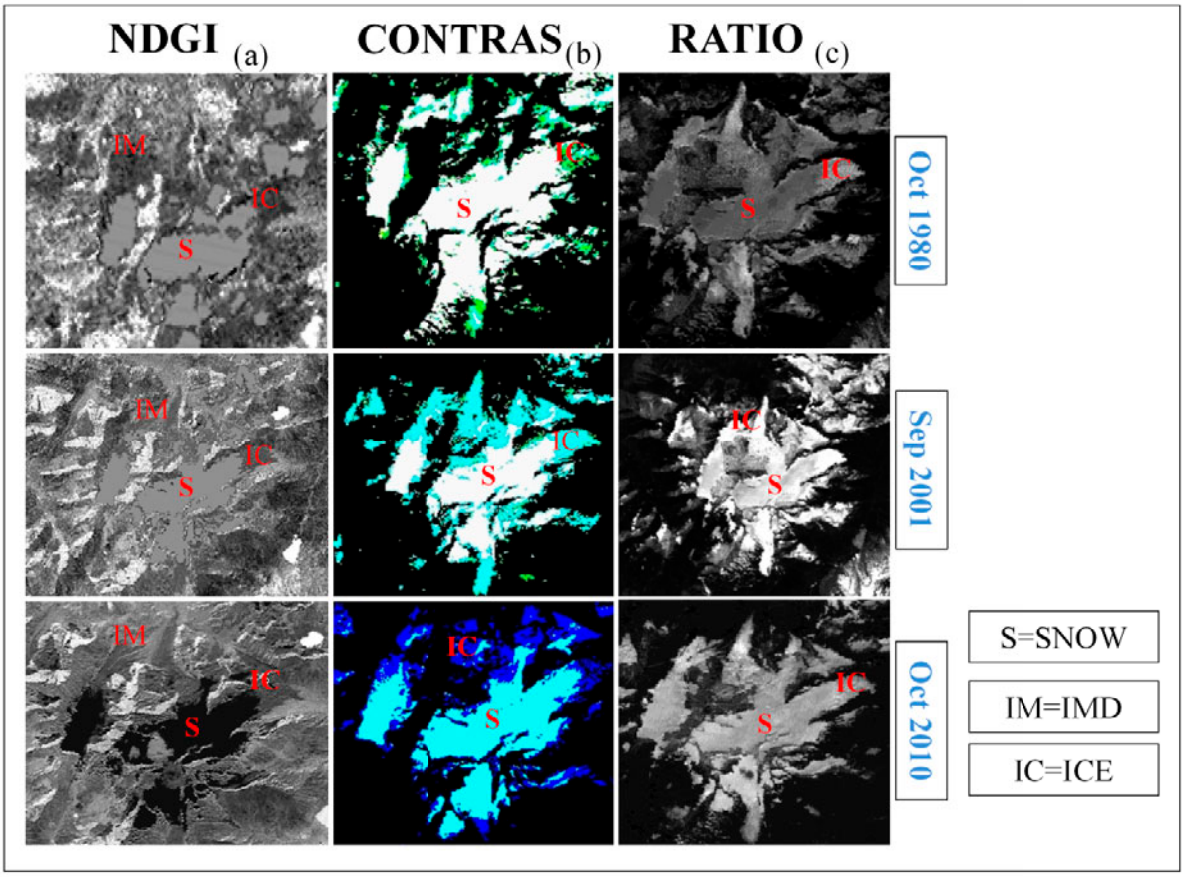
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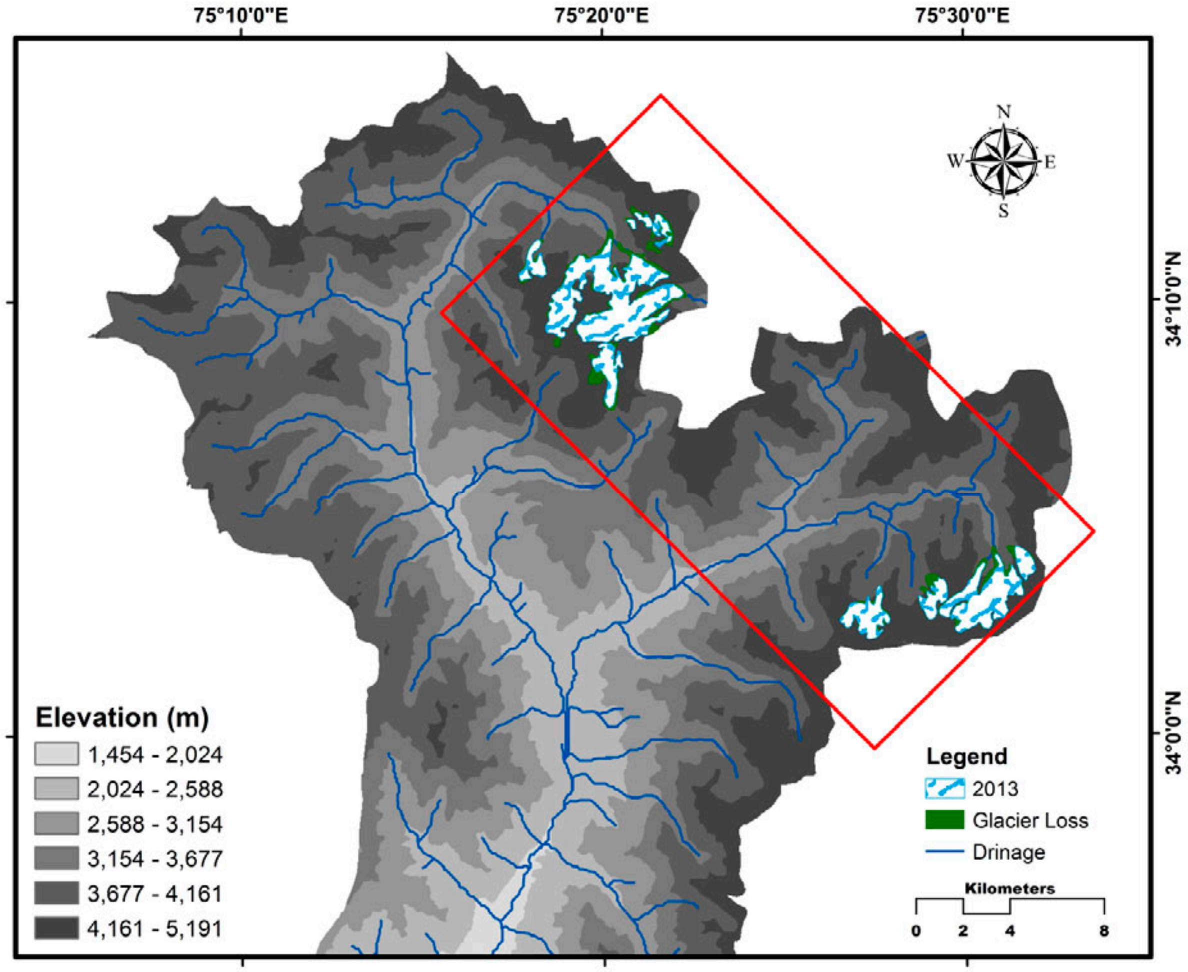
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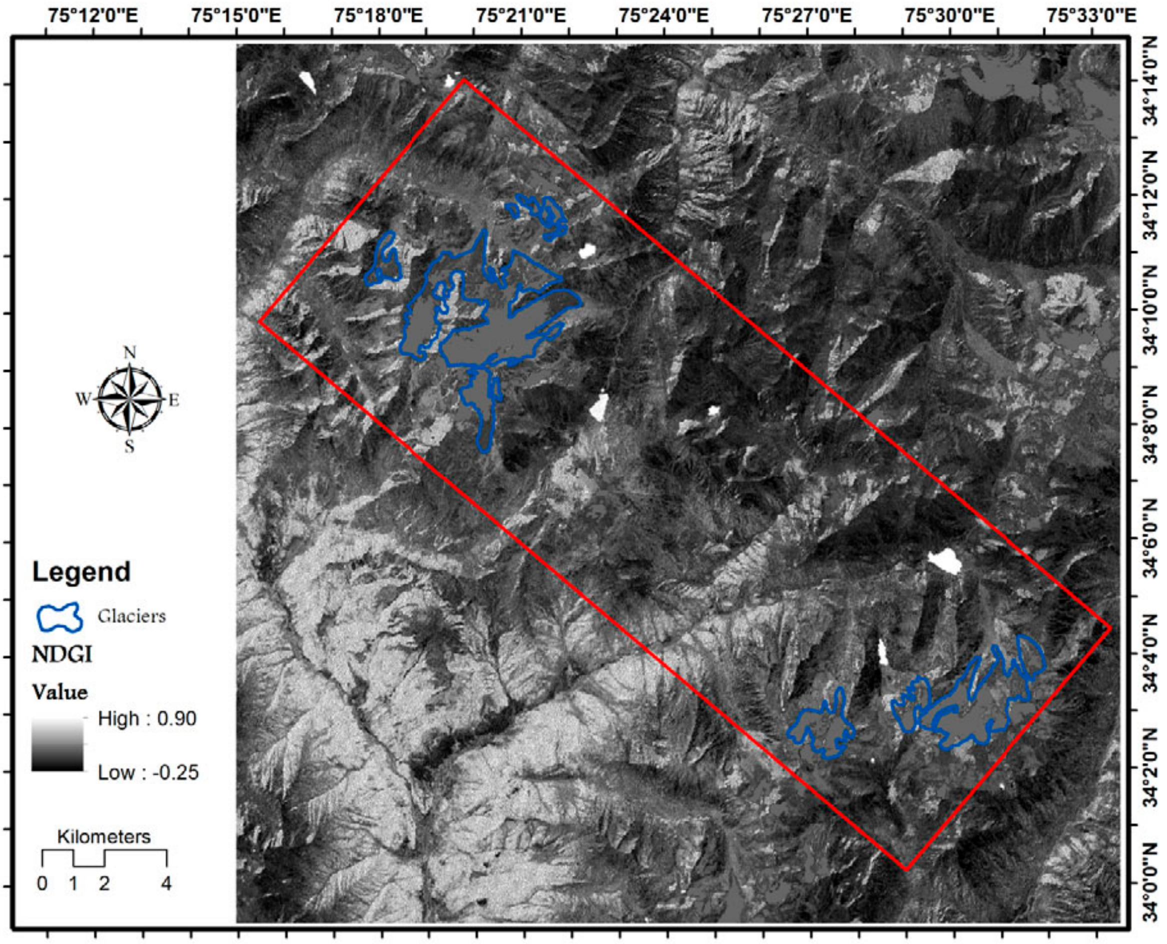
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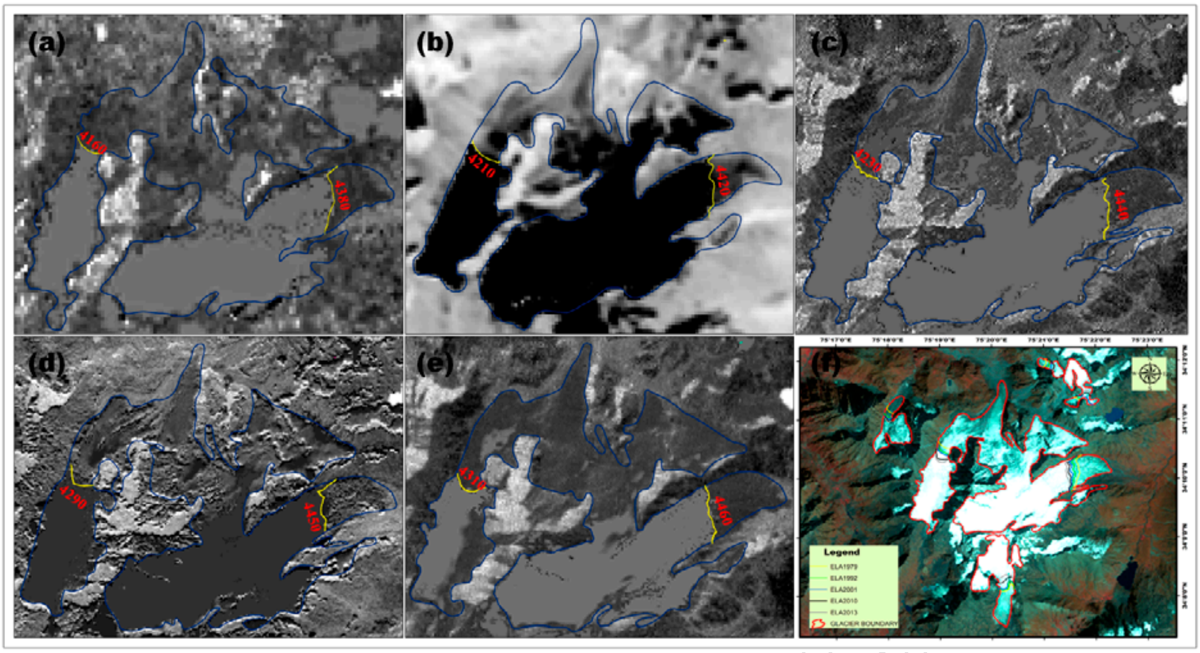
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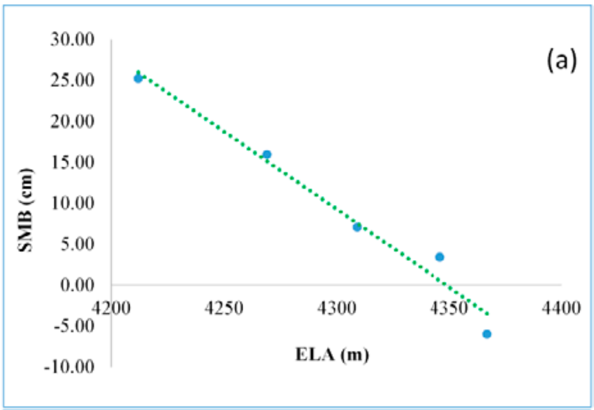
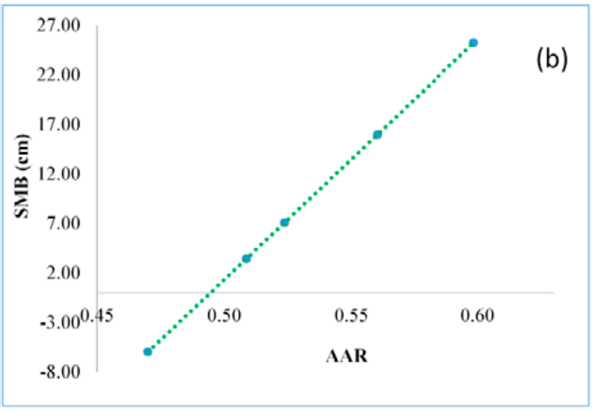
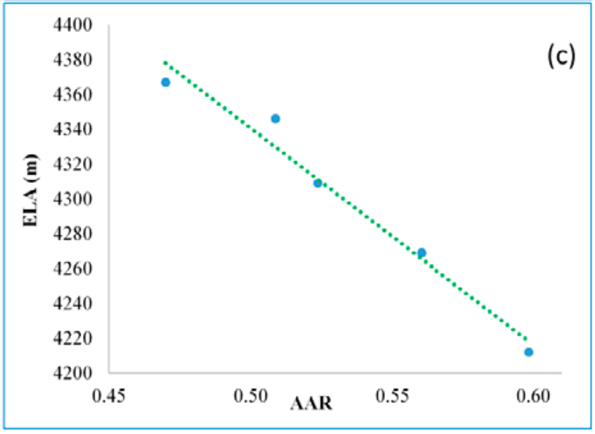


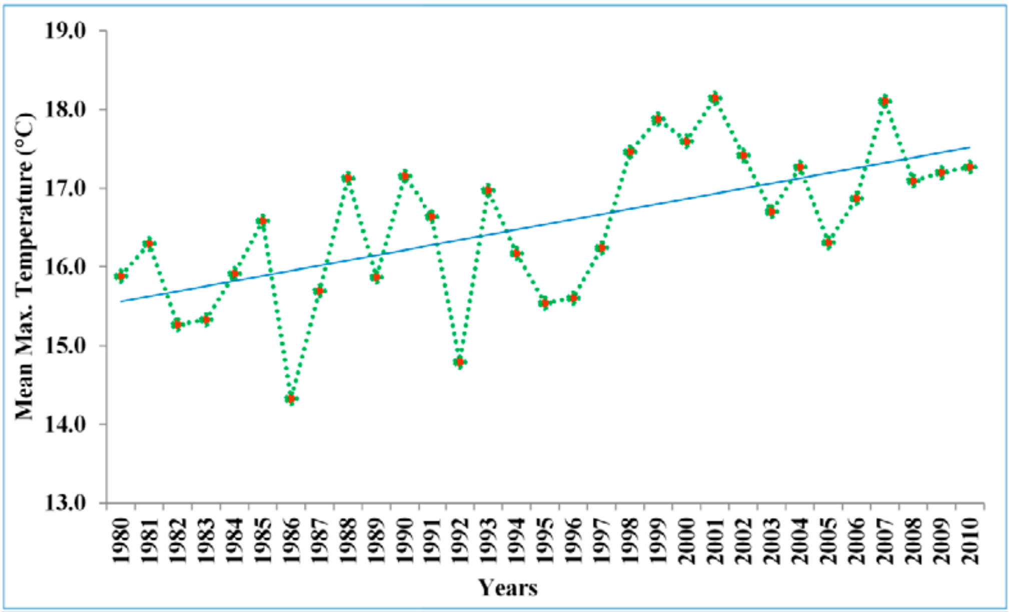




**(a) = Correlation between ELA and SMB**

**(b) = Correlation between AAR and SMB**

**(c) = Correlation between AAR and ELA**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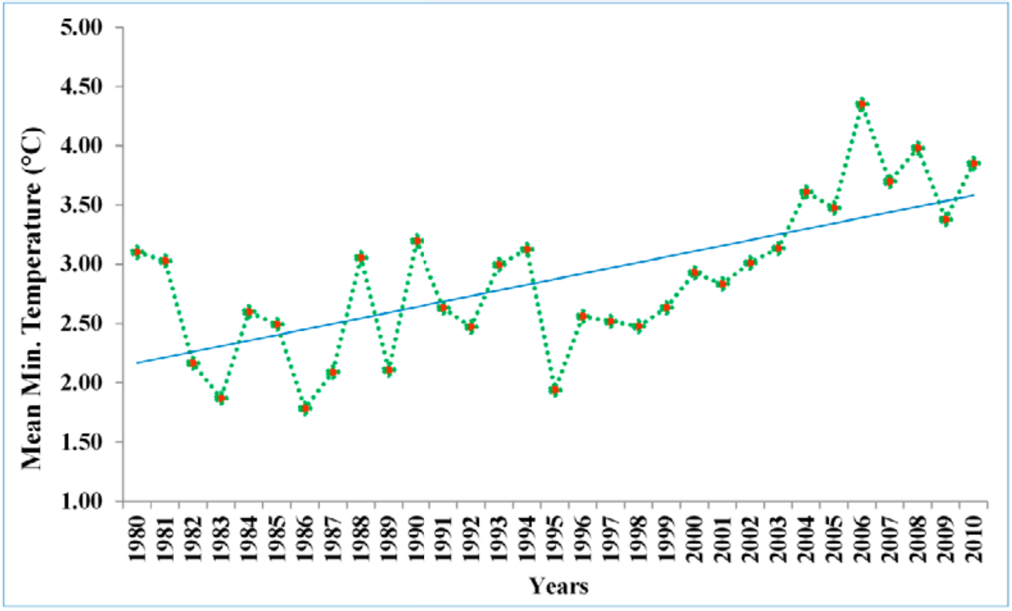
15.0
14.0
13.0
Mean Max. Temperature (°C)
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years


5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
Mean Min. Temperature (°C)
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years

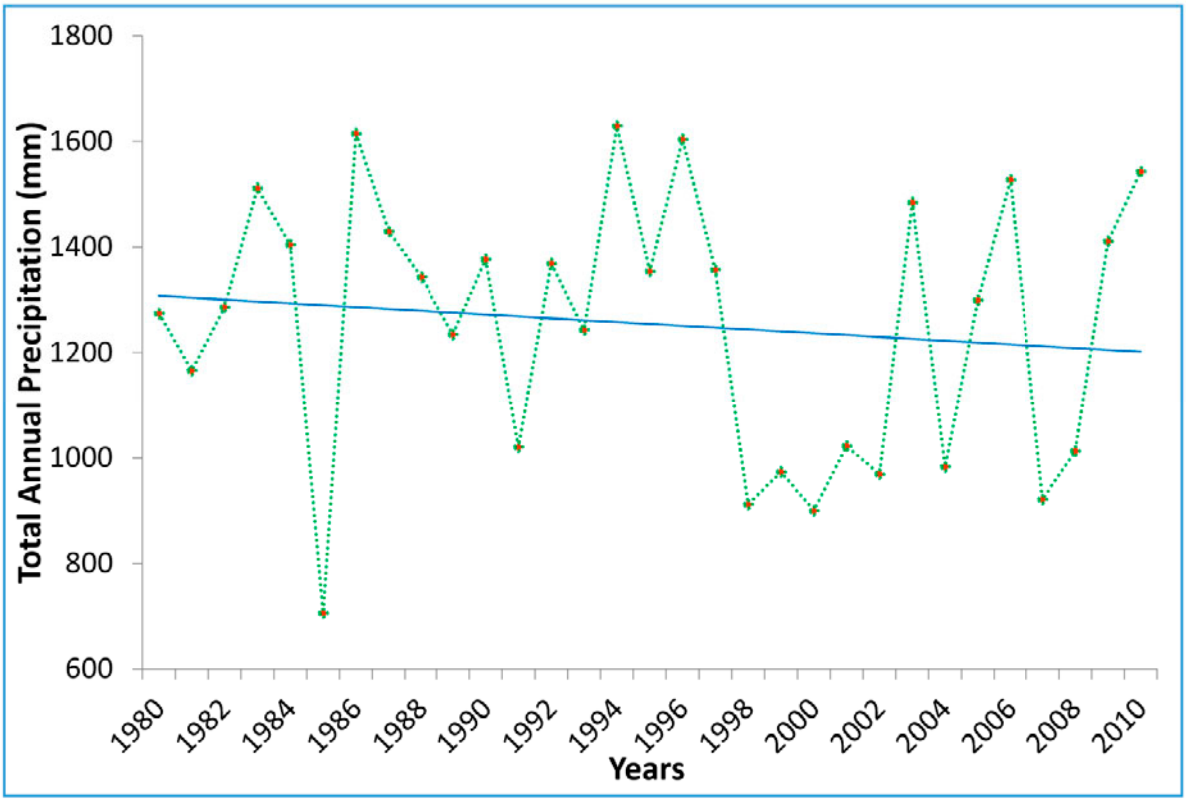

Total Annual Precipitation (mm)
1800
1600
1400
1200
1000
800
600
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Years

**Table 1:** Data sources used for the study.

| Image/sensor type | Resolution | Acquisition date | Source |
|---|---|---|---|
| Landsat MSS | 57 | 06 October 1980 | http://earthexplorer.usgs.gov/ |
| Landsat TM | 30 | 15 October 1992 | http://earthexplorer.usgs.gov/ |
| Landsat ETM+ | 30 | 30 September 2001 | http://earthexplorer.usgs.gov/ |
| Landsat TM | 30 | 17 October 2010 | http://earthexplorer.usgs.gov/ |
| Landsat OLI | 30 | 27 October 2013 | http://earthexplorer.usgs.gov/ |
| ASTER GDEM | 30 | | |

**Table 2:** Statistics of area change and snout change of glaciers.

| | **Year** | **G1** | **G2** | **G3** | **G4** | **G5** | **G6** | **G7** | **G8** | **G9** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Area (km$^2$)** | ***1980*** | 13.57 | 1.38 | 0.34 | 0.95 | 2.7 | 2.4 | 1 | 5.87 | 0.8 |
| | ***1992*** | 13.03 | 1.36 | 0.31 | 0.84 | 2.44 | 2.33 | 0.9 | 5.8 | 0.76 |
| | ***2001*** | 12.42 | 1.20 | 0.27 | 0.76 | 2.20 | 2.23 | 0.74 | 5.70 | 0.73 |
| | ***2010*** | 12.00 | 1.10 | 0.24 | 0.69 | 1.90 | 2.20 | 0.71 | 5.32 | 0.71 |
| | ***2013*** | 11.24 | 1.03 | 0.23 | 0.67 | 1.82 | 2.11 | 0.70 | 5.29 | 0.70 |
| **Area change** | ***1980-2013*** | -2.33 | -0.35 | -0.11 | -0.28 | -0.88 | -0.29 | -0.30 | -0.58 | -0.10 |
| ***% change*** | ***1980-2013*** | 17.17 | 25.36 | 32.35 | 29.47 | 32.59 | 12.08 | 30.00 | 9.88 | 12.50 |
| **Snout Change (m)** | ***1980-2013*** | 340 | 162 | 95 | 250 | 359 | 203 | 210 | 450 | 329 |

**Table 3:** Influence of size (area) on glacier cover changes and specific mass balance.

| **Area (km$^2$)** | **No. of Glaciers** | **% Change** | **Mean SMB (cm)** |
|---|---|---|---|
| **<1** | *4* | 24.61 | -47.90 |
| **1-5** | *3* | 23.35 | -46.47 |
| **5-15** | *2* | 13.53 | -42.95 |

**Table 4:** Influence of dominant aspect on glacier recession and specific mass balance.

| **Dominant-Aspect** | **No. of Glaciers** | **%change** | **Mean SMB (cm)** |
|---|---|---|---|
| **NE** | *1* | 17.17 | -38.37 |
| **NW** | *6* | 20.36 | -41.74 |
| **SW** | *2* | 31.03 | -64.03 |

**Table 5:** Influence of snout altitude on glacial retreat.

| **Snout-Altitude (m)** | **No. of Glaciers** | **%change** |
|---|---|---|
| **3500-4000** | *6* | 21.18 |
| **4000-4500** | *3*<br>*(All less than <1)* | 22.81 |

**Table 6:** Accumulation area fluctuations.

| | **Year** | **G1** | **G2** | **G3** | **G4** | **G5** | **G6** | **G7** | **G8** | **G9** |
|---|---|---|---|---|---|---|---|---|---|---|
| **ACC Area (km$^2$)** | ***1980*** | 8.30 | 0.60 | 0.18 | 0.73 | 1.70 | 1.90 | 0.59 | 3.70 | 0.32 |
| | ***1992*** | 7.8 | 0.55 | 0.12 | 0.6 | 1.50 | 1.70 | 0.52 | 3.60 | 0.30 |
| | ***2001*** | 7.3 | 0.46 | 0.08 | 0.5 | 1.30 | 1.60 | 0.40 | 3.32 | 0.26 |
| | ***2010*** | 07 | 0.41 | 0.07 | 0.45 | 1.10 | 1.56 | 0.36 | 3.05 | 0.22 |
| | ***2013*** | 5.1 | 0.38 | 0.06 | 0.25 | 0.8 | 1 | 0.32 | 2.3 | 0.19 |
| **Change (km$^2$)** | ***1980-2013*** | -3.2 | -0.22 | -0.12 | -0.35 | -0.9 | -0.9 | -0.27 | -1.4 | -0.13 |

**Table 7:** Fluctuations in AAR and ELA of glaciers from 1980-2013.

| | **Year** | **G1** | **G1/ S2** | **G2** | **G3** | **G4** | **G5** | **G6** | **G7** | **G8** | **G9** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **AAR** | ***1980*** | 0.61 | | 0.43 | 0.53 | 0.63 | 0.63 | 0.79 | 0.59 | 0.63 | 0.40 |
| | ***1992*** | 0.60 | | 0.40 | 0.39 | 0.60 | 0.61 | 0.73 | 0.58 | 0.62 | 0.39 |
| | ***2001*** | 0.59 | | 0.38 | 0.30 | 0.59 | 0.59 | 0.72 | 0.54 | 0.58 | 0.36 |
| | ***2010*** | 0.58 | | 0.37 | 0.29 | 0.58 | 0.58 | 0.71 | 0.51 | 0.57 | 0.31 |
| | ***2013*** | 0.45 | | 0.37 | 0.26 | 0.37 | 0.44 | 0.47 | 0.46 | 0.43 | 0.27 |
| **Change** | ***1980-2013*** | -0.16 | | -0.07 | -0.27 | -0.26 | -0.19 | -0.32 | -0.13 | -0.20 | -0.13 |
| **ELA (m)** | ***1980*** | 4160 | 4380 | 3940 | 4380 | 4460 | 4360 | 4000 | 4320 | 4100 | 4100 |
| | ***1992*** | 4210 | 4420 | 3950 | 4430 | 4480 | 4370 | 4100 | 4380 | 4180 | 4210 |
| | ***2001*** | 4230 | 4440 | 4010 | 4490 | 4490 | 4380 | 4190 | 4440 | 4220 | 4290 |
| | ***2010*** | 4290 | 4450 | 4040 | 4520 | 4500 | 4440 | 4200 | 4500 | 4250 | 4380 |
| | ***2013*** | 4310 | 4460 | 4050 | 4510 | 4520 | 4480 | 4280 | 4510 | 4260 | 4400 |
| **Change (m)** | ***1980-2013*** | 150 | 80 | 110 | 130 | 60 | 120 | 280 | 190 | 160 | 300 |

**Table 8**: Statistics of mass balance and volume changes of glaciers from 1980-2013.

| | **Year** | **G1** | **G2** | **G3** | **G4** | **G5** | **G6** | **G7** | **G8** | **G9** |
|---|---|---|---|---|---|---|---|---|---|---|
| **SMB (cm)** | ***1980*** | 28.45 | -14.53 | 8.47 | 33.29 | 32.82 | 72.20 | 23.19 | 32.99 | -22.98 |
| | ***1992*** | 25.28 | -21.91 | -26.12 | 24.46 | 29.20 | 57.12 | 20.22 | 30.65 | -24.26 |
| | ***2001*** | 22.64 | -27.03 | -48.18 | 23.70 | 23.41 | 54.17 | 11.17 | 21.36 | -33.64 |
| | ***2010*** | 21.57 | -29.61 | -49.31 | 20.69 | 20.50 | 52.13 | 3.03 | 19.13 | -44.89 |
| | ***2013*** | -9.92 | -30.53 | -56.79 | -29.51 | -13.37 | -5.02 | -9.10 | -14.53 | -54.23 |
| **SMB change (cm)** | ***1980-2013*** | -38.37 | -16.00 | -65.26 | -62.80 | -46.19 | -77.21 | -32.29 | -47.52 | -31.24 |
| **Volume (km$^3$)** | ***1980*** | 1.894 | 0.064 | 0.014 | 0.064 | 0.176 | 0.215 | 0.087 | 0.585 | 0.044 |
| | ***1992*** | 1.712 | 0.049 | 0.010 | 0.050 | 0.150 | 0.185 | 0.074 | 0.537 | 0.040 |
| | ***2001*** | 1.591 | 0.046 | 0.008 | 0.030 | 0.136 | 0.166 | 0.061 | 0.513 | 0.039 |
| | ***2010*** | 1.559 | 0.048 | 0.007 | 0.030 | 0.110 | 0.147 | 0.060 | 0.496 | 0.037 |
| | ***2013*** | 1.500 | 0.042 | 0.006 | 0.021 | 0.097 | 0.142 | 0.054 | 0.488 | 0.034 |
| **Change in Vol. (km$^3$)** | ***1980-2013*** | -0.394 | -0.022 | -0.008 | -0.043 | -0.079 | -0.074 | -0.033 | -0.097 | -0.01 |

**Table 9:** Statistical analysis of average minimum temperature, maximum temperature and total annual precipitation at Pahalgam meteorological station.

| **Name of the Test** | **Test Static** | **Result** | **Parameter** |
|---|---|---|---|
| Man-Kendall | 3.43 | S (0.01) | Temperature Maximum |
| | 3.77 | S (0.01) | Temperature Minimum |
| | -0.44 | NS | Total Precipitation |