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Research paper

Regional representation of glaciers in Chandra Basin region, western Himalaya, India

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ABSTRACT

Hamtah and Chhota Shigri are two nearby, well monitored glaciers of western Himalaya, lying in the same climatic zone and driven by the same climatic conditions. In this study, topographical characteristics of both the glacier have been explored to understand the role of topography in controlling the glacier response. Further, their topographical characteristics and possible response towards climatic variations have been compared with each other and also with that of the other glaciers in the basin to find out the suitability of these two glaciers to be considered as representative of the region. Multi sensor and multi temporal remote sensing data have been used to carry out to fulfill the objectives. It is found that being in the same climatic zone, the mean accumulation area ratio of Chhota Shigri is 54% and Hamtah is 11% between 1980 and 2014. In comparison to Hamtah, Chhota Shigri glacier has a small upslope area, low compactness ratio indicating the ability of the glacier to receive direct precipitation and solar radiation. The analysis revealed that the Chhota Shigri glacier has a closer resemblance with the other glaciers in the region than Hamtah glacier. Also, the topographical settings of Chhota Shigri glacier are suitable for recording and reflecting year-to-year climatic variations.

1. Introduction

Glaciers respond directly to climate and therefore serve as the best early indicator of climate change. The study of glaciers can provide reconstructions of the past climate, the understanding of present climate and an assumption of future climate. Himalaya, the youngest and highest mountain chain in the world is home to a large number of glaciers, some of which are largest in the world outside the polar regions. There are around 10,000 glaciers in the Indian Himalaya (Sangewar and Shukla, 2009), located at high and inaccessible regions. Monitoring and measurement of these glaciers are important in climatological, hydrological and societal aspects. However, pertaining to the complexities of terrain, harsh environment and logistic difficulties, it is not humanly possible to visit and directly monitor all the glaciers of Himalaya. In spite of the constraints there are a few glaciers in Indian Himalaya which have been taken up for direct field measurements by various Indian research institutes, universities and government organizations (DST, 2012). The field measurement of Chhota Shigri (By Jawaharlal Nehru University, India), Hamtah (by Geological Survey of India), Dokriani and Chorabari (both by Wadia Institute of Himalayan Geology, India) are continuously being carried out since past few years. The Chhota Shigri and Hamtah are two nearby glaciers (within ~15 km of each other) which fall under the same climatic zone. The melt water of both glaciers feed to the Chandra River, Chandra Basin, western Himalaya. The study of mass balance of Chhota Shigri glacier has reported that the glacier has been experiencing mass loss with a rate of -0.30 ± 0.36 mwe y^{-1} over a period of 1969–2012 (Azam et al., 2014b), with a slight gain in the mass during 1988 and 1999 (Vincent et al., 2013). Whereas, Hamtah glacier has a strong negative mass balance and is losing mass since 2001 with a rate of -1.45 mwe y^{-1} (Geological Survey of India, 2011; GSI henceforth). These results indicate variance in the

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response of Chhota Shigri and Hamtah glaciers towards the same climatic fluctuations. Further, there are about 201 glaciers in the Chandra Basin (Sangewar and Shukla, 2009) and it is beyond the capacity of any institute or organization to monitor each glacier individually in the field. The objective of the present study is to find out which glacier between Hamtah and Chhota Shigri is more likely to record climatic signals and can effectively reflect year-to-year climatic variations and can better represent the region. Therefore, the long term records available from the representative glaciers can be utilized as input to various climatological and hydrological models to predict the future response of glaciers. However, with the disparity in the responses of the two glaciers, the question arises as to which glacier reflects the climate fluctuations and can be taken as the representative of the whole region for modeling studies. In view of this, the present study aims at addressing two fundamental aspects:

(1) What are the key factors responsible for the variations in the responses of Chhota Shigri and Hamtah glaciers and which glacier between the two can be taken as representative for the region; and
(2) Which glacier between these two is able to record climatic signals and can reflect year-to-year climatic fluctuations for inferring climatic variability.

If climate is the driving force behind the glacier change, the glacier topographical parameters are the controlling factors which modulate the changes. Glacial topography has a strong influence on glacier dynamics and also explains the variability in the recessional rates of glaciers of the same basin (Davies et al., 2011). In addition, the hypsometry of a glacier that determines the ratio of solid and liquid precipitation within a basin is an important factor (Lutz et al., 2014). Hypsometry (area-altitude relationship) of a glacier plays a critical role in the response of the terminus to change in equilibrium line altitude (ELA; Furbish and Andrews, 1984). Moreover, it has been demonstrated that the termini of glaciers with different hypsometry behave differently under similar climatic forcing, highlighting the fundamental importance of geometry as a control on the behavior of glaciers (Jiskoot et al., 2009), an aspect that deserves consideration in assessment of glacier variation in the context of current climate change (De Angelis, 2014). A similar study on the concept of benchmark glaciers and their representativeness is reported by Fountain et al. (2009). This study attempts to find out the climatic response of the two glaciers by studying their accumulation area ratio (AAR) and to understand the variability in the response by analyzing their topographic, morphometric and hypsometric settings. Glacier mass balance is the un-delayed and unfiltered response of the glacier to climate change and AAR can be taken as the proxy for mass balance (Paterson, 1994). Therefore, by estimating the variation in the value of AAR we can infer the variability in the climatic parameters such as temperature and precipitation. The topographical parameters, indices and AAR in this study have been derived from multi-spectral, multi-temporal remote sensing data.

2. Study area

Chhota Shigri and Hamtah glaciers are the two "nearby" Indian Himalayan glaciers which have been continuously monitored for mass balance, glacier melt runoff, glacier meteorological and debris cover studies and are acknowledged by World Glacier Monitoring Service (2012) (WGMS, 2012) for contribution of data. These glaciers are located in the Chandra Basin on the northern slopes of Pir-Panjal range of Himalaya, in the Lahaul-Spiti valley of Himachal Pradesh (GSI, 2007; Ramanathan, 2011) and drain into the Chandra River. The Chhota Shigri glacier is ~15 km east of Hamtah glacier and both are roughly oriented from south to north (Fig. 1).

Chhota Shigri glacier (32.2°N, 77.5°E) is a compound valley type glacier covering an area of ~15 km^2 and has a length of ~9 km extending between 4050 to 6363 masl (Vincent et al., 2013). The mean width of the glacier is ~1.1 km (Sangewar and Shukla, 2009) and the maximum width is ~1.8 km near equilibrium line altitude (Kumar and Dobhal, 1997). The snout of the glacier is steep, at an angle of 35° (Kumar and Dobhal, 1997) and heavily covered with debris. The thickness of the debris cover decreases from snout upstream to the glacier (Vincent et al., 2013). Towards the east of the glacier, a well defined lateral moraine with an average height of ~35 m is present. This lateral moraine descends from an elevation of 4460 masl and extends downstream to the Chandra River. The peri-glacier features in the west side of the glacier are deformed and show no clear morphological features; however, the moraines on the right flank of the glacier valley (east side) are well preserved and are laterally continuous till the Chandra River. The Chhota Shigri glacier is a well-documented glacier and more information can be obtained from Dobhal et al. (1995), Kumar and Dobhal (1997), Wagnon et al. (2007), Ramanathan (2011), Vincent et al. (2013), Azam et al. (2014a).

Hamtah glacier (32.24°N, 77.37°E) is a relatively simple valley type glacier having a single lobe, extending from south to north between 5000 and 4020 masl covering an area of about ~3 km^2 and is ~6 km long (GSI, 2007). According to the inventory report by Sangewar and Shukla (2009) the mean width of the glacier is

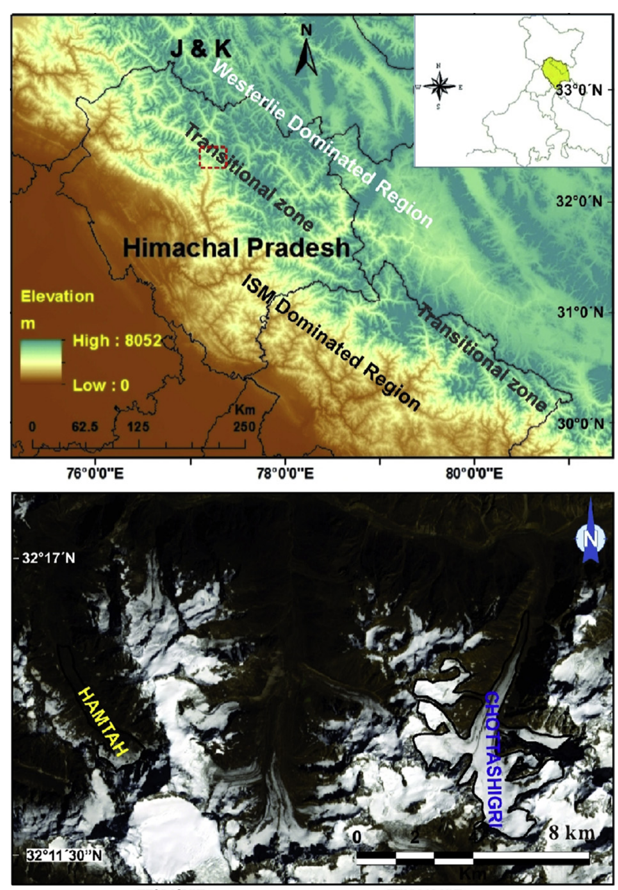

Figure 1. Location map of Chhota Shigri and Hamtah glaciers. The upper image illustrates the dominated climatological zones of Western Himalaya, shown on SRTM DEM. The lower image shows Chhota Shigri and Hamtah glaciers on Landsat 8 image of October 2014.

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0.5 km. The glacier has a single accumulation zone with prominent lateral moraines on both sides of the glacier and is bound by steep ridges. The glacier is heavily covered with debris from snout up to the upper zone of the glacier.

3. Climatic settings of the region

The Himalayan region is influenced by two major weather systems viz. the Indian Summer Monsoon (ISM) and the mid-latitude westerlies (Finkel et al., 2003; Yang et al., 2008) and hence experience contrasting precipitation regimes (Bolch et al., 2012). The influence of these two weather systems varies both temporally and spatially. The ISM predominantly influences most of the southern and eastern part of Himalaya and causes pronounced summer precipitation. The summer precipitation gradient is orographically controlled, hence the north and northwestern regions of the Himalaya receives scanty monsoon precipitation compared to its southern counterpart. Similarly, the influence of mid-latitude westerlies has its dominant role in the northwestern parts of the Himalaya and Karakoram, and decreases from northwest to southeastern parts of Himalayan arc (Benn and Owen, 1998). This complex climate diversity results in a contrasting pattern of glacier change throughout the range. The site selected in the present study is important as it falls in the monsoon–arid transition zone and is alternatively influenced by Indian Summer Monsoon during summer and mid latitude westerlies during winter (Bookhagen and Burbank, 2010). Unfortunately, climate data of this region are very sparse and there is no meteorological observatory near the study area due to the difficulty involved in maintaining and monitoring the station. Study by Shekhar et al. (2010) employing observed data from several stations of west and northwestern Himalaya between 1988 and 2007 showed that the winter temperature of the Pir-Panjal range has increased whereas the snowfall has decreased. Beside, an automatic weather station (AWS) installed on the Chhota Shigri glacier and a precipitation gauge at the base camp of the glacier, maintained by the glaciological team of Jawaharlal Nehru University, India, are the only source which can provide some factual insights on the glacier climatic paradigm for the surrounding region. The temperature, wind and incoming and outgoing solar radiation are some of the meteorological parameters obtained by AWS on the glacier. The details of the meteorological data from AWS on the Chhota Shigri glacier can be obtained from Azam et al. (2014b). The nearest Indian Meteorological Department (IMD) observatory is in Bhuntar which is at a distance of 50 km from Chhota Shigri glacier and also has different climatology than Chandra-Bhaga basin as it falls in the windward side of the ISM, whereas the Chandra Basin lies in the leeward side of it. However, Azam et al. (2014b) have attempted to extrapolate the climatic parameters from Bhuntar to Chhota Shigri to understand the climatological settings of the glacier. The study carried out by Azam et al. (2014) is the only study available with some limitations, which provides an idea about the climatic settings of Chhota Shigri glacier. Azam et al. (2014b) have reported a high humid, warm and calm summer monsoon from June to September and cold and windy winter from December to March. Further, they have found that the glacier (Chhota Shigri) to be a winter accumulation type receiving ~80% of its annual precipitation from mid latitude westerlies during winter and ~20% from ISM during summer. Apart from few sparse data, there is a scarcity of climatological data in the Indian Himalaya.

4. Datasets and methods

The objectives of the study have been accomplished by utilizing remote sensing data from various sources and sensors. The mean area and mean AAR of glaciers of the basin have been taken from the inventory report by Sangewar and Shukla (2009). To show the yearly variation in AAR of Hamtah and Chhota Shigri glaciers, satellite data from Landsat Multi-spectral Scanner (MSS), Landsat Thematic Mapper (TM), Landsat Operational Land Imager (OLI), Panchromatic and Thermal Infrared Sensor (TIRS), Line Imaging Self-Scanner Sensor (LISS-III) and Advanced Wide Field Sensor (AWiFS) sensors of Indian Remote Sensing Satellite (IRS) have been used between 1980 and 2014 (Table 1). Cloud free images at the end of ablation season have been employed for this purpose. The years for which cloud free and recent snowfall data were not available, have not been included in the study. Preprocessing of the raw satellite data has been done before analysis. Preprocessing of images involve geometric correction and digital numbers (DN) to reflectance calculations. First, DN images have been converted to radiance images and then radiance images to reflectance images. Various parameters like mean solar exoatmospheric spectral irradiances in sensor bands, maximum and minimum radiance in the sensor bands obtained from the satellite header information, solar declination and the digital elevation information have been used as the input. All the multispectral images and DEM have been co-registered with each other.

Glacier topographical parameters (slope, aspect and elevation), morphometry and radiation have been derived from freely available ASTER GDEM version 2. Glacier hypsometry has been obtained from LISS III image of 2000 and SRTM DEM of the same year. To derive the percentage of debris cover on glacier surface, high resolution panchromatic band (15 m resolution) of Landsat 8 has been merged with the reflectance images. The resolution merging has been done in ERDAS Imagine using Brovery Transform method. On the merged images, the debris-covered part of the glacier has been demarcated and percentage of debris cover has been calculated.

4.1. Accumulation area ratio (AAR)

AAR is the ratio between accumulation area and total glacier area, calculated at the end of ablation season. Accumulation and ablation zone and the total glacier area can be differentiated on reflectance images based on the difference in their spectral signatures. Total glacier area has been obtained by manual digitization. The accumulation area has been derived by delineating the accumulation zone on reflectance image based on visual interpretation. The DN images have been converted to reflectance image prior to the computation of accumulation area and total glacier area. The uncertainties associated with the calculation of area are due to the employment of images from different sensors, with different spatial resolutions, the co-registration error and the error of manual digitization. The uncertainties in the area estimation has been computed following Congalton (1991), Zhang and Goodchild

Table 1
Details of data used in the study.

Sensor	Acquisition date	Resolution (m)	Scene ID
Landsat MSS	16 September 1980	60	M3158037/38_03719800916
Landsat TM	9 October 1989	30	p147r37_5t19891009
LISS III	27 September 1999	23.5	097136000101
LISS III	11 September 2000	23.5	1009548L000
LISS III	13September 2001	23.5	109548L0001
LISS III	16 September 2005	23.5	097130400101
LISS III	18September 2006	23.5	097130400201
LISS III	30 September 2007	23.5	097130400301
AWiFS	14 September 2008	56	36AWFBST00B2345F
AWiFS	30 August 2010	56	22AWFBST00B2345F
Landsat OLI/TIRS	28 September 2014	30	LC8147037/382014271LGN00

DEMs: ASTER GDEM and SRTM.

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(2002), Hall et al. (2003), Silverio and Jaquet (2005), Granshaw and Fountain (2006), Racoviteanu et al. (2008), Wang et al. (2009), Bolch et al. (2010), Bhambri et al. (2012). The uncertainty in snout location, *e*, was estimated using Eq. (1):

$$e = \sqrt{a^2 + b^2} + E \quad (1)$$

where *a* and *b* represent the spatial resolution of the two images used, and *E* is the error of image registration. The uncertainties of glacier area estimation were determined by the buffer method suggested by Granshaw and Fountain (2006) for each glacier. The area of buffer size around each glacier was set to twice the digitization error (Granshaw and Fountain, 2006; Racoviteanu et al., 2008). The overall uncertainties associated with the area estimation found to be up to 4%.

4.2. Hypsometry, morphometry and topographic settings of the glaciers

Glacier hypsometry, morphometry, topographic parameters and indices for both the glaciers have been computed by following the methods suggested by DeBeer and Sharp (2007), Jiskoot et al. (2009) and Way et al. (2014). Hypsometry (area-altitude relationship) is the distribution of terrain area over its elevation range. Both Chhota Shigri and Hamtah glaciers have been divided into 100 m elevation bins and hypsometry has been calculated. To derive hypsometric curve of the glaciers, the area has been calculated from LISS III images of September 2000 and the elevations have been extracted from SRTM DEM since the SRTM DEM is acquired in the same year (i.e., 2000). The SRTM has been used for hypsometric calculations to maintain the homogeneity and accuracy of the study. The total area and elevation of the glaciers have been normalized and normalized hypsometric curve has been plotted for the comparison. A normalized hypsometric curve is the plot of normalized area vs. normalized elevation and describes the distribution of topographic character of terrain with variable elevation ranges. The normalized hypsometric curve has been derived following Jiskoot et al. (2009) and from hypsometric index the glacier hypsometric type has been identified. The average slope, average aspect, minimum, maximum and median elevations of the glaciers have been extracted from the ASTER GDEM in ArcGIS. The compactness ratio, the relative upslope area and the slope of the upslope area, which are the indices providing the contribution of the avalanching from the surrounding to the mass balance of the glacier have been calculated by methods discussed in DeBeer and Sharp (2007) and Way et al. (2014). The compactness ratio is the measure of glacier morphometry and has been derived from the formula (4 × pi × area)/(perimeter)^2 following DeBeer and Sharp (2007) and Way et al. (2014). The compactness ratio indicates potential mass inputs from surrounding avalanching zones. The compactness ratio has been derived by using total glacier area and the perimeter of the glacier. Further, the contributions of avalanching sites have been included by upslope area and the slope of the upslope area. The upslope area is the contributing area above each glacier and represents the contribution of the surrounding upslope area in the glacier mass balance. The relative upslope area is defined as the ratio between the upslope areas to the glacier surface area. The relative upslope area has been derived by following the method provided by DeBeer and Sharp (2007). The area from the upslope edge of the glacier to the lateral extreme of the glacier has been considered as the upslope area. This has been divided by the glacier surface area to obtain the relative upslope area of the glacier. The mean slope of the upslope portion of the glacier has been deduced from the ArcGIS. To represent the potential intensity of solar radiation in the clear sky condition during ablation season, reaching to glacier surface, mean solar radiation has been derived using method suggested by DeBeer and Sharp (2007). The mean solar radiation has been calculated at solar noon, during the peak of ablation season i.e. 31st August using ArcGIS. The potential intensity of solar radiation reaching on the glacier surface during the ablation season has been derived to understand the portions and locations of glacier surface liable to receive solar inputs, which subsequently affect energy balance and hence mass balance.

5. Results

5.1. Accumulation area ratio

The accumulation area ratios of Chhota Shigri and Hamtah glaciers as estimated from satellite images from 1980 to 2014 were found to be far different from each other. The mean AAR of Chhota Shigri glacier from 1980 to 2014 was 54% (±19%), whereas the mean AAR of Hamtah glacier was only 11% (±8%). The AAR of Chhota Shigri glacier varied between 29% and 80% during the studied period while for Hamtah glacier the AAR ranged between 1.5% and 30%. Fig. 2 depicts the year wise variation of AAR of Chhota Shigri and Hamtah glaciers.

5.2. Glacier hypsometry

The hypsometric analysis of glaciers indicated distinct pattern of area-elevation distribution for Chhota Shigri and Hamtah glaciers (Fig. 3). Chhota Shigri glacier was found to be an equi-dimensional to slightly bottom heavy glacier, for which there was approximately equal distribution of area above and below the median elevation of the glacier. However, Hamtah glacier revealed to be a top-heavy glacier with more than half of the area above the median elevation of the glacier. An elevated portion near the median point of Hamtah glacier was noticed which is peculiar. Previous research on the hypsometric pattern of glaciers have suggested that the glaciers for which maximum area lie above the median elevation are more affected by changes in snowline than the bottom heavy or equi-dimensional glaciers (Jiskoot et al., 2009). A slight rise of ELA will alter significantly the proportion of accumulation and ablation area of the top heavy glacier, while the bottom heavy or the equi-dimensional glacier will be less affected (Brocklehurst and Whipple, 2004; Jiskoot et al., 2009). Based on these studies, the same has been suggested to be applicable for Chhota Shigri and Hamtah glaciers. From the hypsometric aspect it can be inferred that Hamtah glacier was more sensitive to ELA change than Chhota Shigri glacier. The hypsometry of glacier also influences the distribution and amount of snow/rain ratio on the glacier surface. More area above median elevation indicates that more portion of the glacier is apt to receive precipitation in the form of snowfall. However, a glacier with more area distributed below the median

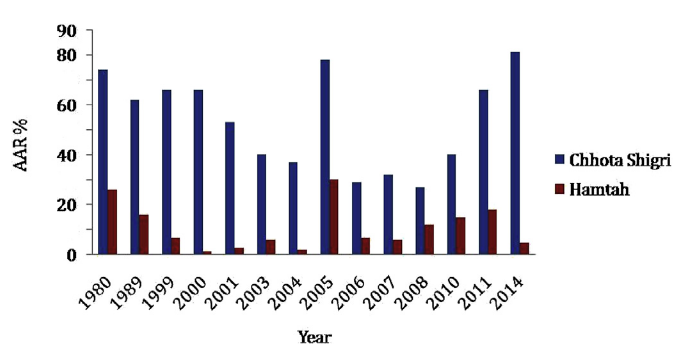

Figure 2. The variation in the AAR of Chhota Shigri and Hamtah glaciers.

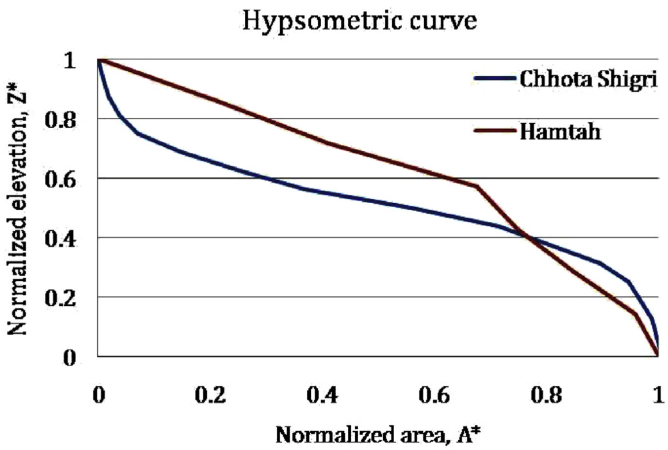

Figure 3. Hypsometric curves of Chhota Shigri and Hamtah glaciers. The plots are between normalized area (A*) and normalized elevation (Z*) of Chhota Shigri and Hamtah glaciers.

elevation will receive more precipitation in the form of rain than snow. However, in case of Hamtah glacier, the altitudinal range is much lesser than Chhota Shigri glacier which indicates that most part of the glacier receives precipitation in the form of rainfall.

5.3. Morphometric and topographic analysis

The area of Chhota Shigri glacier is extended between elevations of 4060 to 6000 masl. The mean elevation of ablation zone of the glacier is ∼4700 masl while that of accumulation zone is ∼5250 masl. The altitudinal range of Hamtah glacier is 4020–5000 m, which is smaller than that of Chhota Shigri glacier. The mean elevation of accumulation zone of Hamtah glacier is ∼4750 masl indicating that the elevation of accumulation zone of Hamtah is at similar altitude to that of ablation zone of Chhota Shigri. The area-elevation distributions of glaciers strongly influence the pattern of precipitation (snow/rain) and therefore size of accumulation and ablation zone of the glacier.

The compactness ratio, relative upslope area, slope of upslope area, mean-maximum-minimum elevations, slope and aspect of the glaciers are given in Table 2. The compactness analysis has shown that the Chhota Shigri is an open glacier with low compactness ratio, while Hamtah has very high compactness ratio indicating that the glacier to be very confined. The derivation of area and slope of upslope of Hamtah and Chhota Shigri glaciers have shown that Hamtah glacier has a very high and steep upslope than Chhota Shigri glacier. The total upslope area of Hamtah is ∼3.7 km^2 which is more than the total area of the glacier itself, while that of Chhota Shigri is about ∼7 km^2. The Hamtah glacier originates from the underneath of a steep and high back wall which has a height of about 1.25 km and mean slope of 45°. The presence of back wall, steep and higher relative upslope area, morphometry and higher value of compactness ratio made Hamtah glacier an avalanche-fed glacier. This was again confirmed from the visualization of a series of satellite image, which proved that the glacier has very small accumulation area near the underneath of the head wall of the glacier. No such significantly large upslope area was found to be present for Chhota Shigri glacier. However, the eastern tributary of glacier is surrounded by steep upslope. The main glacier has no steep back wall and the glacier is mainly open with gradual slopes. The accumulation zone of Chhota Shigri glacier is therefore found to be not affected from any shadow or sheltering effect. Lesser upslope area and small compactness of Chhota Shigri glacier made the glacier open for receiving direct precipitation (snowfall). The glacier has accumulation contributed mainly by three cirques, one from main glacier trunk and one each from eastern and western part of the glacier (tributaries).

Both Hamtah and Chhota Shigri glaciers have moderate average slopes (Fig. 4a). The mean slope of the Hamtah is found to be about 9°, with ablation part of the glacier having gentle slope of about 7°, while the upper reaches of the glacier are steeper with slopes varying from 30° to 70°. The mean slope of Chhota Shigri glacier was 14°, snout of Chhota Shigri being slightly steeper than the rest of the ablation area. The accumulation zone at the central tongue of the Chhota Shigri glacier is less steep (slope varying between 25° to 50°) than the tributaries. The mean slope of the accumulation zone of the Chhota Shigri glacier is about 23°.

Aspect of glacier modulates the incoming solar radiation falling on the surface of the glacier and therefore plays a significant role in controlling the energy balance of glaciers. The orientation of the Hamtah glacier is roughly of north-northwest ward. The mean orientation of Chhota Shigri glacier, calculated from the central flow line of the glacier has been found to be northward in the ablation zone, while the accumulation parts of the glacier have a variety of aspects (Fig. 4b). Apart from a central accumulation zone, Chhota Shigri has tributaries to both sides of the glacier. The eastern parts of the tributaries are oriented towards west, while the western parts of the glacier have west to east orientation, whereas the main tongue of the glacier has a rough northward orientation.

The incoming solar radiation is greatly affected by surface slope and aspect of glacier surface (Arnold et al., 2006). Total incoming solar radiation on a typical solar noon time during the peak of melting season is shown in Fig. 4c for Chhota Shigri and Hamtah glaciers. The shadow from the steep back wall sheltered the accumulation part of Hamtah glacier from receiving direct solar radiation. However, the ablation part of the Hamtah glacier received high amount of solar radiation (Fig. 4c). The distribution of solar radiation is opposite for Chhota Shigri glacier with more radiation falling near the accumulation zone and lesser near the ablation zone. The slope of surface of glacier determines the intensity of solar radiation through angle of incidence of the direct solar radiation (Arnold et al., 2006). At gentle surface of a glacier, the solar radiation has greater potential to heat up the glacier surface and melt the ice. A hypothesis can be proposed that at the shallower slope and gentle surface, the direct solar radiation has greater potential for heating the surface and subsequently melting the ice than a surface with steeper slope. Ablation area of the Hamtah glacier has a very shallow slope, allowing solar radiation to fall directly on it and therefore have intensified effects on the glacier. The accumulation area of the Chhota Shigri glacier is located at higher elevation and

Table 2
Topographic and morphometric parameters of Chhota Shigri and Hamtah glaciers.

	Chhota Shigri	Hamtah
Area (km^2)	∼15	∼3
Length (km)	∼9	∼5
Mean AAR (%)	54	13
Average slope (°)	∼19	∼9
Ablation zone slope (°)	∼14	∼7
Slope of upslope (°)	∼35	∼45
Relative upslope	0.47	1.2
Compactness ratio	0.06	0.24
Average solar radiation (Whm^{-2})	2230	2268
Av. Solar radiation, ablation zone	2272	2294
Mean backwall height (km)	0.23	1.25
Debris cover (%)	3.4	73
Minimum elevation (masl)	4050	4020
Maximum Elevation (masl)	5700	4750
Median Elevation (masl)	5020	4452

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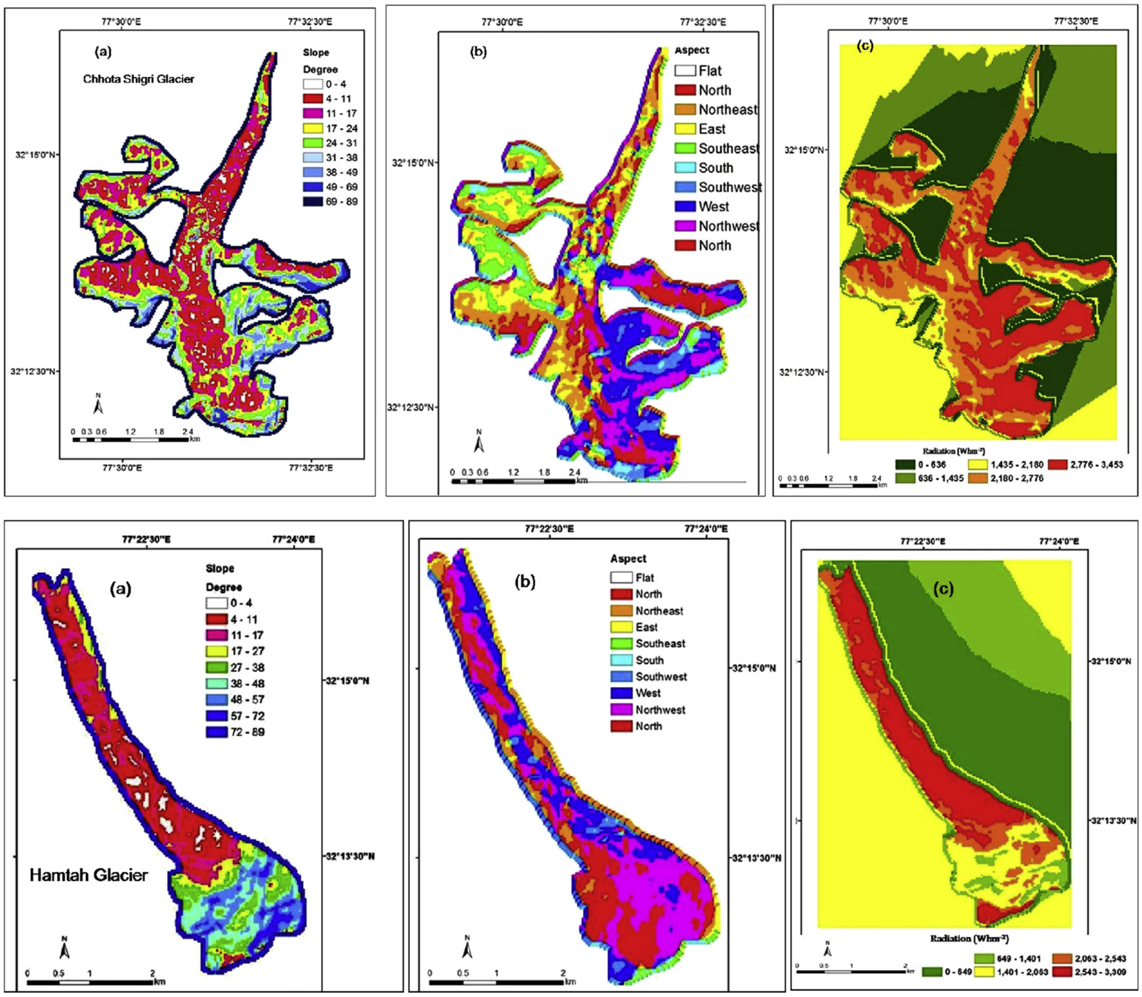

Figure 4. The topographical parameters of the Chhota Shigri and Hamtah glaciers respectively. (a) Slope map of the Chhota Shigri and Hamtah glaciers; (b) aspect maps of the glaciers and; (c) solar radiation of the glaciers.

favorable to receive considerable amount of direct solar radiation. However, the higher mean slope of accumulation area of Chhota Shigri might lessen the potential intensity of the direct solar radiation.

6. Representativeness of glaciers

There are certain criteria to select a glacier for carrying out various glaciological studies and also for representing the region at the same time. The Himalayan mountainous weather is extremely harsh and the terrains are inaccessible and different. Therefore, the most important criteria to carry out glaciological studies on a particular glacier are location and accessibility of the glacier. However, there is always a trade-off between ideal and accessible glacier.

In view of the difficulties associated in field monitoring of a large number of glaciers, selecting a representative glacier for the region and carrying out detail field monitoring on the same glacier is need of the hour. However, selecting a representative glacier may not be easy as each glacier has unique topographical settings. Therefore, in this study we have attempted to find topographical similarity of glaciers of Chandra Basin with the Hamtah and Chhota Shigri glaciers to find out which between the two glaciers can be taken as representative for the region, and the result of which glacier can be better generalized.

The glacier selected for field measurements should be easily approachable with simpler geometry. Besides location, the other very crucial criteria is the sensitivity of the glacier towards climatic fluctuations and also if the response of the glacier towards these fluctuations is in similar manner to most of the glaciers in the region (Kaser et al., 2003). For being able to record even small climatic fluctuations, the glacier should not have local effect of shading and avalanching (Hoffman et al., 2007). The glacier should be either clean (debris free) or should have very less amount of debris cover. Further, a very essential criterion is the topographical settings of the glacier such as glacier area, length, slope, aspect, elevation, area-elevation distribution and altitude range. Therefore, the representative glacier should be sensible to climatic variations, able to record year-to-year climate signals and represent the region topographically. Both Hamtah and Chhota Shigri are regularly being monitored for field based glaciological studies. The field data of Hamtah and Chhota Shigri glaciers have important use in validation/input for space based studies and glacier modeling for the region. However, it is needed to find out which glacier is appropriate and suitable to be taken as representative. To find the answer, detail study has been carried out and discussed subsequently.

To find a representative glacier for the study area, we examined the AAR, percentage of debris cover, topographical characteristics and morphometric parameters of the glaciers of Chandra Basin. The topographical parameters and the debris cover have been derived from satellite remote sensing data as discussed previously. The mean AAR and the area of the glaciers of Chandra Basin have been taken from the glacier inventory of Sangewar and Shukla (2009). The yearly variation of AAR of Hamtah and Chhota Shigri glaciers has been computed by analyzing remote sensing data. The Chandra Basin is trending N–S, NW–SE to E–W and occupies an area of ~2381 km^2 and supports 201 glaciers covering an area of ~703.64 km^2, constituting 29.54% of the total basin area. To evaluate the representativeness of Chhota Shigri and Hamtah glaciers for the Chandra Basin, comparisons have been made between the topographical characteristics of glaciers in the Chandra Basin and those of Chhota Shigri and Hamtah glaciers.

The extraction of percentage of debris on the glaciers revealed that debris cover in the glaciers of Chandra Basin varied from 0 to 86%. The 86% of glacier area of Hamtah is covered with debris whereas only 3% area of the Chhota Shigri glacier is covered with debris. Most of the glaciers in the Chandra Basin were either clean glacier and free from any debris cover or with a debris cover less than 20% of their total area. The scatter plot revealed that in terms of debris cover on the glacier surface, Chhota Shigri glacier is more representative to the region than the Hamtah glacier (Fig. 5a). Out of 56 glaciers studied in this region, only 4 glaciers have debris cover more than 20% of their total area. Most of the glaciers in this region have debris cover less than 6% of their total area.

The mean elevation of the Chandra Basin is ~4980 masl which is more than 191 masl from the mean elevation of Chhota Shigri glacier and more than ~636 masl from Hamtah glacier. Most of the glaciers in the Chandra Basin are located at higher elevation and their altitude range is more comparable to Chhota Shigri glacier than Hamtah glacier (Fig. 5c). Hamtah glacier is a low elevation glacier with less altitudinal range. The glacier elevation and the area-altitude distribution modulate the rain/snow ratio of the precipitation in the basin. As evident from Fig. 5c also, the mean elevation of the glaciers in the Chandra Basin has more resemblance with the Chhota Shigri than Hamtah glacier. Therefore, it can be inferred that the mean precipitation in the Chandra Basin will be more identical to that of Chhota Shigri glacier than Hamtah glacier. Further, the average slope of the glaciers of Chandra Basin is found to be 12° which is more akin to the average slope of Chhota Shigri glacier (14°) than the average slope of Hamtah glacier (7°). The scatter plots suggest that in terms of slopes of the basin, Chhota Shigri glacier is more comparable to the other glaciers of the basin than Hamtah glacier (Fig. 5d).

To evaluate whether year to year climatic variations of the region are captured and reflected by Chhota Shigri and/or Hamtah glacier, the AAR of the rest of the glaciers of Chandra Basin have been compared with the AAR of Chhota Shigri and Hamtah glaciers (Fig. 5b). The mean AAR of the Chandra Basin is ~44% which is similar to the AAR of Chhota Shigri glacier at ~50%. The mean AAR of Hamtah is only ~6% and in the scatter plot the glacier lies as an outlier. It can be interpreted that behavior and response of most of the glaciers of the Chandra Basin can be well represented by the response of Chhota Shigri glacier.

Chhota Shigri glacier is a roughly northward glacier extending from south to north, however, in the accumulation zone the glacier has all the possible aspects. The main trunk is joined by tributaries from the east and west side of the glacier. These tributaries have dominant aspects of east and west. Therefore, the net mass balance of the Chhota Shigri glacier has contribution from all possible aspects making it more general and representative since most the glaciers are not simple glaciers and have branches and tributaries with all possible aspects.

A quantitative analysis employing the Euclidean distance formula has also been performed between Chhota Shigri and Hamtah glaciers and each data point of the glaciers (%debris cover, %AAR, Slope and Elevation) to evaluate the representation capability of these two glaciers for the basin. The Euclidean distance represents relationship between points. From the estimation of Euclidean distance it is clearly visible that for each parameter the distance is closer to Chhota Shigri than Hamtah glacier as evident from the Fig. 6 also. The Euclidean distance plots clearly manifest that the most of the glaciers have characteristics similar to Chhota Shigri. The Euclidean analysis and plots quantitatively approve the qualitative analysis to find the representativeness of Hamtah and Chhota Shigri glaciers. Fig. 6 confirms that the Chhota Shigri glacier is more representative of the Chandra Basin than Hamtah glacier.

7. Discussion

The results presented in the study highlighted the morphometric, hypsometric and the topographical settings of Chhota

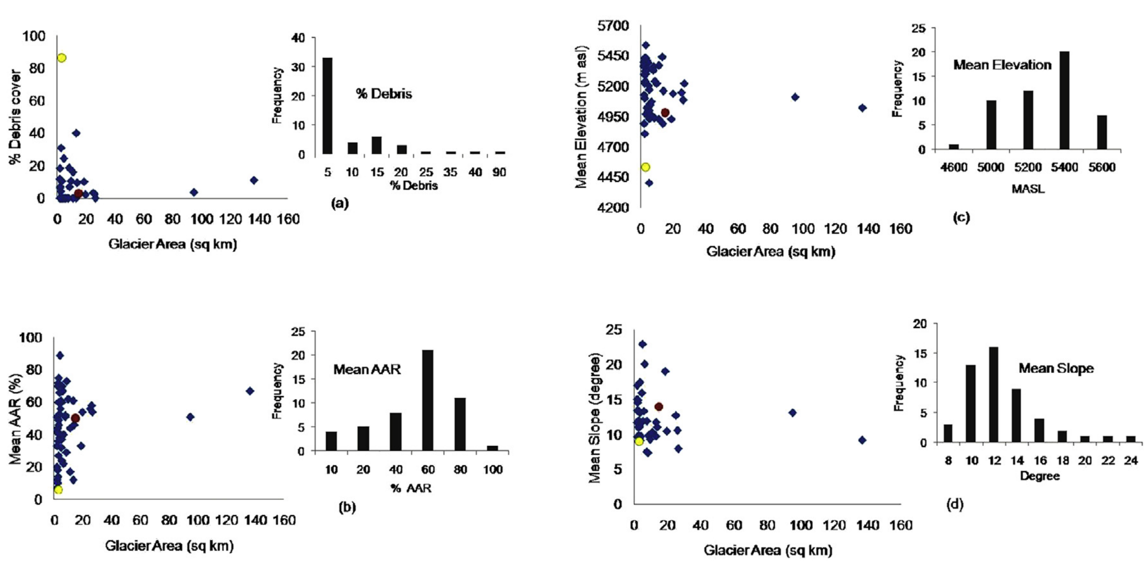

Figure 5. Scatter plots and histograms of (a) percentage of debris cover; (b) mean AAR; (c) mean elevation; (d) mean slope of the glaciers in the Chandra Basin vs. their area. The Red circle marks Chhota Shigri glacier and yellow circle indicated Hamtah glacier.

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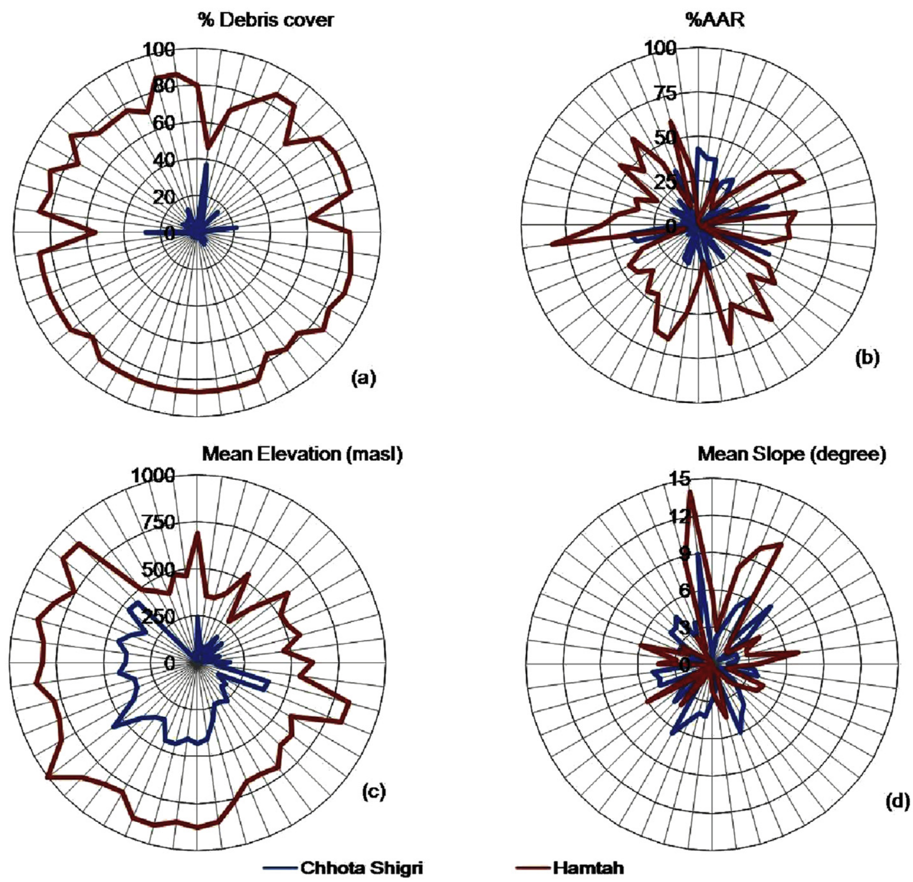

Figure 6. Euclidean distance plot of (a) debris cover (%); (b) AAR; (c) mean elevation and (d) mean slope of the glaciers of Chandra Basin from that of Chhota Shigri and Hamtah glaciers.

Shigri and Hamtah glaciers in order to understand the response of both the glaciers towards climatic variations as both of them are located in the same climatic zone. AAR has been presented as a proxy for mass balance of the glaciers between 1980 and 2014 to understand the glacier response towards climate change. The AAR of Hamtah glacier is much lesser than the Chhota Shigri glacier at each year of investigations. Hamtah glacier is found to be significantly affected by the avalanches from the upslope zones. The compactness ratio and the relative upslope area and slope analysis of the glaciers confirmed that Hamtah is a confined glacier with bulk of relative upslope area contributing to the snow and rock avalanches, which feed the glacier. The snow accumulation of Hamtah glacier is dependent on the avalanche depositions near the foot of the headwall. Chhota Shigri glacier has a low compactness ratio with lower relative upslope area, making the glacier open and suitable to receive direct precipitation/snowfall. The glaciers fall into a monsoon-arid transition zone and are influenced by both summer monsoon (ISM) as well as the winter westerlies almost equally. Azam et al. (2014b) have hypothesized that the Indian summer monsoon (ISM) is the main driver in controlling the mass balance of the Chhota Shigri glacier than the winter precipitation. The ISM hits the region during summer from the south east direction. The starting of the Hamtah glacier is from the underneath of a back wall with a height of 1.25 km and height of the peak being around 6100 masl. There is a large possibility that this back wall acted as a barrier for monsoon wind to enter the valley of Hamtah glacier and preventing the precipitation on the glacier. Year to year analysis of satellite images has confirmed the presence of a large cirque glacier at the south of the back wall of Hamtah glacier. The moist summer wind hit the back wall and brought precipitation to the southern end of the glacier, depositing snow in the cirque. The Hamtah valley is located in the leeward side of the peak and therefore had lesser chance of receiving good precipitation from Indian summer monsoon. The topographical settings of Chhota Shigri glacier are favorable for receiving precipitation from both mid latitude westerlies as well as Indian summer monsoon.

Despite being under the influence of two climatic systems, Hamtah is probably less liable to be affected significantly by summer monsoon and hence might possibly be invariant to any fluctuations pertaining to Indian summer monsoon. Chhota Shigri glacier has favorable topography to record the variations in both westerlies and summer monsoon.

The final criteria in consideration for selection of a representative glacier are the elevations and altitudinal ranges of glaciers. The uppermost boundary of Hamtah glacier is found to be at an altitude of ∼4900 masl which is the average altitude of ELA for Chhota Shigri glacier. Pandey et al. (2012) have shown that the mean snow line altitude of the region at the end of ablation season, which can be considered as ELA, is ∼5200 masl. The accumulation zone of the Hamtah glacier is at much lower altitude than the mean ELA of the region. The elevations of the glaciers also affect the rain to snow precipitation ratio on the glacier. The area-altitude distribution of Hamtah glacier indicated that maximum precipitation on the Hamtah glacier must be in the form of rain instead of snow. Precipitation in the form of rain on the surface of glacier enhances the melting. Further, because of its low elevation, the surface of Hamtah glacier is not able to retain the snow cover. The hypsometry of

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Hamtah glacier is such that a small change in ELA would affect a large proportion of the glacier, eventually causing change in glacier area. However, Chhota Shigri glacier has a hypsometry such that any small change in ELA would not significantly influence the mass balance of the glacier and hence glacier size. This is reflected in the responses of Chhota Shigri and Hamtah glaciers as the rate of retreat of Hamtah glacier is significantly higher (16 m/year) than the rate of retreat of Chhota Shigri (7 m/year). Further, the variation in incoming solar radiation due to the slope of the glacier is one of the major controls for variation in energy balance and hence mass balance. On a particular surface of glacier with very low slope, the amount of solar radiation will be available more to the surface than a surface of with higher slopes. The large solar radiation receipt on the ablation surface of Hamtah glacier will enhance the melting and affect the energy balance of the glacier. The bulk of ablation part of Chhota Shigri glacier receives lesser solar radiation.

Debris on the surface of glacier influences the melting processes of the glacier and hence amount of ablation. The response of a heavily debris-covered glacier to a change in climate will be slower than that of a clean glacier. The debris cover modifies the mass balance of glacier by modulating ablation.

8. Conclusions

The present study provides new insight into the role of hypsometry, morphometry and topographical settings on the ablation pattern and inconsistencies in the responses of Chhota Shigri and Hamtah glaciers. The study also assesses the representativeness of Chhota Shigri and Hamtah glaciers for the Chandra Basin region. The main conclusions drawn from the analyses are:

(1) The hypsometrical pattern of Hamtah glacier is such that a small rise in ELA would expose significant area of the glacier for melting and hence mass balance, while for Chhota Shigri glacier small changes in ELA would not have very crucial effect on the mass balance of the glacier.
(2) In comparison to Chhota Shigri, Hamtah has a large and steep upslope area with a 1.25 km, high head wall that prevents precipitation in summer. Small values of AAR at the end of ablation season indicate that winter snow is not much retained and does not contribute to the mass of the glacier.
(3) The topographical settings of Chhota Shigri glacier, AAR and debris cover are comparable to the most of the glaciers in the Chandra Basin and receive direct snowfall, free from any shadow effect, minimum avalanches and almost debris free making it fit for long term monitoring and a representative of the region.
(4) The available long term data from the Chhota Shigri glacier can be the best used of extrapolation for the whole basin as done by Huss (2014) for the European Alps.
(5) The AAR-specific mass balance relationship developed from the field data of Chhota Shigri can be used to construct the mass balance of rest of the glaciers in the basin.
(6) The representativeness of Chhota Shigri glacier brings confidence in using various field data of the glacier in regional hydrological and climatological modeling as well as in validation purposes.

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