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Assessing the status of glaciers in part of the Chandra basin, Himachal Himalaya: A multiparametric approach

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Abstract

This study investigates the change in multiple glacier parameters of three valley-type glaciers (Sakchum (SC), Chhota Shigri (CS), and Bara Shigri (BS)) located in Chandra basin, Himachal Himalaya, sharing the same climatic regime, and assesses the control of nonclimatic factors on wholesome glacier response. Multitemporal satellite remote sensing data from Landsat-TM/ETM/OLI (1993-2014), and Terra- ASTER (2002-2014) along with an SRTM digital elevation model were used for extraction of the glacier parameters. Results show that while SC and BS retreated (SC: 10.65 ± 2.52 m/y; BS: 15.51 ± 2.52 m/y) and lost area (SC: 0.49 ± 0.0032 km², BS: 1.18 ± 0.0032 km²), the CS remained relatively stable (retreat rate: 4.06 ± 2.52 m/y, area loss: 0.19 ± 0.0032 km²) during 1993-2014. However, results of surface ice velocities (SIV) change (SC: 24.41%, CS: 21.60%, and BS: 28.49%) and surface elevation change (SC: -1.22 m/y, CS: -0.91 m/y and BS: -1.21 m/y) suggest a comparable slowing down and surface lowering from 2002 to 2014. Debris cover also varied substantially (SC: 30.25%, CS: 11.96%, BS: 19.61%) on these glaciers. Results reveal that higher retreat/deglaciation of glaciers was associated with higher altitudinal range, slow SIV in lower ablation zones (LAZ), and glacier hypsometry. Debris cover on glaciers was found to be controlled by slope, higher deglaciation rates, higher SIV in the upper ablation zone (UAZ) coupled with lower SIV in LAZ and surface lowering. Glacier SIV was primarily governed by slope gradient, differential surface lowering, and size of accumulation zone (ACZ). The SIV results confirm the presence of stagnant zones in the lower ablations of SC (<1 km upstream) and BS (<6 km upstream) and a major SIV dropdown in the UAZ (SC: 34.48%, BS: 37.35%), indicating the expansion of stagnant zones farther up. Glacier surface lowering seemed to be influenced by ice-flux, changing spatial distribution of debris cover, presence of supraglacial lakes, and ice cliffs bordering them. Melting around supraglacial lakes and backwasting of ice cliffs may be the prime reasons behind intense mass loss observed in the stagnant zone of the Bara Shigri glacier, where surface lowering was ~32% higher than glacier-wide thinning. Differential surface lowering in glaciers reduced the surface gradient and hence the SIV. Also, rapid surface gradient changes and SIV dropdown in the Sakchum glacier indicate possible development of supraglacial lakes on it in the future. Interestingly, despite close proximity, SC, CS, and BS demonstrate three distinct ablation patterns, reemphasizing the role of nonclimatic factors. Overall, the study states that mutual

variation of glacier parameters together with nonclimatic factors exercise a great control on glacier response.

Keywords: glacier response; multiparametric approach; nonclimatic factors; western Himalaya

1. Introduction

Mountain glacier's inherent ability of responding rapidly (on decadal scale) to any variation in regional environment enables it to serve as a reliable indicator of climate change (IPCC, 2007; Scherler et al., 2011). Himalaya stores the largest number of mountain glaciers with varying geometry that serve as the prime source of fresh water for habitations downstream (Dyurgerov and Meier, 1998; Kaul et al., 1999; Sangewar and Shukla, 2009). Moreover, as Himalayan glaciers are particularly susceptible to climate change (Nakawo et al., 1997; Naito et al., 2000), systematic and accurate assessment of their temporal response is of utmost importance in order to understand climate signals. Glaciers tend to amend their geometries in accordance with prevailing climatic conditions in order to attain equilibrium. Consequently, they have been receding worldwide at varying rates providing substantial evidence of a warming earth (IPCC, 2007; Paul et al., 2007).

Glacier response can be defined as the collective variations in different glacier parameters over a period of time. Previous studies have reported that an individual glacier's response to climate change is distinct and multidimensional (Aizen et al., 2007; Fujita and Nuimura, 2011; Kulkarni et al., 2011; Scherler et al., 2011). Remotely detectable glacier responses may include temporal and spatial variation in glacier parameters such as (i) geometry, i.e., length and area; (ii) debris cover extent; (iii) surface ice velocity (SIV); (iv) surface elevation changes; (v) equilibrium line altitude (ELA) variation; and (vi) development and enlargement of peri/supraglacial lakes, etc. A multiparametric monitoring approach would thus give a more comprehensive picture about the status of glaciers. Changes in these parameters are primarily affected by climatic and nonclimatic factors; however, they are also found to be interlinked. Temporal variation in any glacier parameter is thus, a resultant of a complex interplay of many factors (Paul et al., 2013b). For instance, one parameter (e.g., debris cover) influences other parameters (e.g., surface thinning), especially once a critical thickness is exceeded (Fujita and Nuimura, 2011; Zhang et al., 2011). Besides climate factors, several nonclimatic forcing factors

1 have been recognized that have considerable control on the glacier response; these include (i)
2 glacier size, (ii) topography, (iii) orientation, (iv) extent of debris cover, (v) accumulation and
3 ablation area, and (vi) altitudinal and latitudinal position, etc. (Kulkarni and Alex, 2003; Scherler
4 et al., 2011; Pandey and Venkataraman, 2013). In some cases, the regional and local geomorphic
5 features have equal influence on glacier response as the climatic parameters (Raina, 2009).

6 In this study the multiparametric response of three glaciers located in the Chandra River
7 basin, western Himalaya (WH), with ongoing climate variations has been monitored. The
8 glaciers located in WH exercise a profound impact on availability of water resources, which
9 makes their repetitive multidimensional monitoring and assessment quite important. Regardless
10 of this, field-based monitoring of glaciers in this region is sparse (Cogley, 2011; Bolch et al.,
11 2012) and only a few glaciers (~6) have a mass balance record for more than ~8-10 years
12 (Vincent et al., 2013). Moreover, in WH, only Chhota Shigri glacier has extensively and
13 continuously been monitored for its various aspects, such as mass balance, thickness change,
14 SIV, and debris cover's influence on melt rates (Wagnon et al., 2007; Azam et al., 2012; Vincent
15 et al., 2013; Mandal et al., 2014). In mountainous regions where field based observations are
16 challenging (Dobhal et al., 2008; Bhambri et al., 2011), remote sensing offers the most suitable
17 platform to monitor multidimensional glacier parameters over time (Berthier et al., 2004;
18 Racoviteanu et al., 2008b). Various studies have employed well-established image processing
19 techniques for retrieval of glacier parameters to monitor the response of glaciers of WH, such as
20 length/area (Kulkarni and Alex, 2003; Kulkarni et al., 2007; Ghosh and Pandey, 2013), debris
21 cover variation (Shukla et al., 2009), surface elevation change (Berthier et al., 2007; Vincent et
22 al., 2013), SIV (Berthier et al., 2007; Tiwari et al., 2014, 2016), and ELA (Kulkarni et al., 2011;
23 Hanshaw and Bookhagen, 2014). Most of these studies report deteriorating glacier health in WH
24 and relate this mass wasting directly or indirectly to temperature rise, which is a major
25 consequence of global warming. However, some studies report the heterogeneous behavior of
26 glaciers even within the same climatic settings and attribute this to various nonclimatic factors
27 that modify the glacier response. For instance, Kulkarni and Alex (2003) and Iturrizaga (2011)
28 found that altitudinal distribution affects the individual glacier dynamics, whereas influence of
29 topographic gradient on glacier recession was emphasized by Scherler et al. (2011), Negi et al.
30 (2013), and Pandey and Venkataraman (2013). Several studies have highlighted the role of
31 debris cover on different glacier parameters such as retreat/deglaciation (Shukla et al., 2009;

Scherler et al., 2011; Negi et al., 2013), surface elevation changes (Berthier et al., 2007; Vincent et al., 2013), and mass balance (Wagnon et al., 2007; Berthier et al., 2007; Vincent et al., 2013; Mandal et al., 2014). Moreover, significant control of glacier dimension (e.g., glacier size) on its response has also been reported in the context of WH (Kulkarni et al., 2007; Deota et al., 2011; Brahmabhatt et al., 2012).

Nearly all these studies conducted over WH suggest that glaciers of this region are shrinking and their response is controlled by climatic as well as nonclimatic factors. However, most of the measurements, whether derived from field or remote sensing methods, have focused on assessing two-dimensional (2D; area, length) glacier response only (Dyurgerov and Meier, 2005; Cogley, 2011; Kargel et al., 2011; Bhambri et al., 2012; Bolch et al., 2012; Bahuguna et al., 2014). Two-dimensional measurements, though easy to estimate and directly (in some cases reliable) observed terrestrial indicators of climate change (IPCC, 2007), are poor reflectors of the overall state of glaciers (Johanneson et al., 1989; Luckman et al., 2007). Thus, literature is scarce on studies that assimilate multidimensional glacier parameters to ascertain wholesome glacier response. Moreover, only a few studies report the mutual impact of few of these parameters and the influence of nonclimatic factors on their changes (Kulkarni and Alex, 2003; Scherler et al., 2011; Negi et al., 2013). Motivated from the above-mentioned gaps and limitations, an attempt has been made in the present study to address these issues; and thus, the major objectives of this paper are:

- Multiparametric (length/area, debris cover, surface elevation changes, SIV, and ELA) monitoring of glacier response.
- Examining mutual impact of the monitored glacier parameters on each other.
- Assessing the role of nonclimatic factors on glacier response.

2. Study area

The study area is comprised of three valley glaciers, namely Bara Shigri (length 27.7 km; area 126.45 km²), Chhota Shigri (length 9 km; area 15.03 km²), and Sakchum (length 6.2 km; area 15.12 km²) located in the Chandra River basin, Lahaul-Spiti Valley, WH (Fig. 1; length and area mentioned here are for the year 2014). The area is bounded by the latitude 32.08 N to 32.30 N and longitude 77.39 E to 77.82 E. The relief varies from 3440 m above sea level (asl) to 6632

m asl. All three glaciers have nearly similar orientation, i.e., they flow south to north while debris cover extent amongst them varies drastically. The snout elevation of Sakchum, Chhota Shigri, and Bara Shigri are ~4380, ~4107, and ~4005 m asl, respectively. Meltwater originating from these glaciers significantly contributes to Chandra River. Bara Shigri is the longest glacier of the Himachal Pradesh. Chhota Shigri is one of the most extensively studied glaciers of this region with continuous mass balance records since 2002 (Vincent et al., 2013).

The Lahaul-Spiti valley is heavily glaciated and lies in monsoon–arid transition zone, which experiences Indian monsoons in summer and mid-latitude westerlies in the winter (Bajpai, 1995; Bookhagen and Burbank, 2010). This region, because of its high altitude, experiences a very cold, alpine and glacial climate (Bajpai, 1995) and remains cut off from the rest of the world during the winters. Meteorological observations for summer months (July–September) during 1987–1989 on Chhota Shigri indicated temperatures ranging from -5.2°C to $+10.5^{\circ}\text{C}$ at 4600 m asl (Dobhal et al., 1995). Recently, Azam et al. (2014) reported, based on automatic weather station data (4863 m asl; 1 October 2009 to 30 September 2013) at Chhota Shigri glacier, that the coldest month is January (-15.8°C) and the warmest month is August (4.3°C). Physiographically the area can be divided into high ridges, steep valley walls, and deep cut valleys. Geologically, the region is mainly determined by metamorphic rocks mostly of meso- to keta-zonal metamorphites, migmatites, and gneisses (Kumar and Dobhal, 1997).

3. Materials and methods

3.1. Data sources

The data set used in this study is comprised primarily of Landsat- TM/ETM/OLI, Terra- ASTER, Worldview images, and Shuttle Radar Topographic Mission (SRTM) Global Digital Elevation Model version-3 (GDEM-v3). Temporary snow and cloud cover influence the suitability of satellite imagery for glacier mapping to a great extent (Burns and Nolin, 2014), therefore, we selected cloud free (as far as possible) peak ablation period (September–November) images for the study.

All scenes of Landsat and SRTM GDEM-v3 were downloaded from the U.S. Geological Survey (USGS) website <http://earthexplorer.gov.in>. SRTM GDEM-v3 was used as reference

elevation data primarily for the retrieval of altitudinal ranges of glaciers and to ortho-rectify ASTER images. This DEM was released by the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) for Indian region in January 2015 which provides elevation data in 1 arc-second or about 30 m spatial resolution (<http://www2.jpl.nasa.gov/srtm/>). ASTER images used here were downloaded at no cost from NASA's Earth Observing System Data and Information System (website: <http://reverb.echo.nasa.gov>) under the auspices of GLIMS project. Worldview image was provided by DigitalGlobe (<http://www.digitalglobe.com>) under 'Worldview-2 8-Band Challenge' and mainly used for validation of glacier boundaries digitized from Landsat. Table 1 lists the complete details and purpose of satellite data used.

Apart from satellite data, we utilized Survey of India (SOI) toposheet (scale 1:50,000) no. 52H/7, 52H/8, 52H/11, and 52H/12 for collection of ground control points (GCPs) for ASTER DEM generation.

3.2. Methods applied

As a first step, data from multiple sources were coregistered, taking Landsat 2000 ETM image as base with an adequate accuracy of RMSE <1 pixel. Coregistration accuracy with reference to 2000 ETM were calculated to be 0.3 (~9 m) and 0.35 (~10.5 m) pixel for 1993 TM and 2014 OLI respectively. Since this study is focused on deriving multiple glacier parameters namely area/length, debris cover, SIV, surface elevation change and ELA, therefore, various methods were followed to systematically extract them from satellite images.

We used manual digitization to delineate the glacier outlines from remotely sensed data because, though laborious, it is one of the most accurate methods (Albert, 2002). Boundaries of all three glaciers were digitized on Landsat image of 1993, 2000, and 2014 using different false color composites (FCC) such as SWIR-NIR-Green, NIR-SWIR-Red, and NIR-Red-Green etc. To delineate uppermost glacier boundary and to differentiate confusing water divides, the watershed boundaries extracted from SRTM GDEM-v3 were used. Snouts were identified with the help of ice wall shadows near snout, proglacial morphological features, and the presence of streams originating from it. For interpreting the glacier boundary in areas such as bergschrund or to distinguish flat glacier surfaces with abruptly rising side walls, three dimensional visualization

1 technique was used. For this, satellite images were draped over SRTM DEM-v3 in a GIS
2 environment. Moreover, relatively higher reflectance of snow/ice, rough texture of the debris-
3 covered part, flow patterns of ice movement, and shape of the glacier-occupied valley facilitated
4 the precise mapping of glacier boundaries. Also, we included only those tributaries as part of the
5 glacier that connected with the main trunk glacier through ice and rest were excluded. Glacier
6 length was measured along the central flow line from the uppermost crevasse, i.e., bergschrund
7 to the lowermost point of glacier, i.e., snout. We estimated snout fluctuation during 1993, 2000,
8 and 2014 using respective glacier boundaries. Frontal parts of a glacier are often asymmetric,
9 making snout fluctuation measurement rather difficult. For this, we followed the method
10 proposed by Bhambri et al. (2012) in which strips with an offset of 50 m are drawn parallel to the
11 central flow line and retreat is calculated as an average of the intersection of strips with the
12 glacier boundaries.

13 Literature suggests various methods for mapping of supraglacial debris cover from
14 remote sensing data including supervised and unsupervised classification techniques (Aniya et
15 al., 1996; Shukla et al., 2010b; Shukla and Yousuf, 2016), techniques combining thermal and
16 topographical properties (Shukla et al., 2010a; Bhambri et al., 2011), etc. In this study, to extract
17 debris cover extent, we used the artificial neural network (ANN) technique. Given the well-
18 defined and well-distributed training sets, a three layer ANN model was iteratively optimized to
19 find the most suitable network parameters and to arrive at the solution with least error (Shukla
20 and Yousuf, 2016). The ANN classifies the debris-covered areas and snow/ice areas efficiently
21 but sometimes fails in deep shadow regions, which were corrected manually during post-
22 processing.

23 The SIV can be estimated from the field by monitoring the spatial position of stakes or
24 from remotely sensed data using SAR interferometry, SAR image data intensity tracking, or
25 feature tracking from optical data (Paul et al., 2013b). We monitored SIV for 2003/04 and
26 2013/14 using the feature tracking approach (Leprince et al., 2007; Scherler et al., 2008; Scherler
27 and Strecker, 2012). This approach measures the displacement of ice pinnacles, crevasses,
28 boulders, or any other pattern of debris/ice over repeat images. To obtain horizontal velocities,
29 sequential steps were followed and executed on time series ASTER band-3N. These steps
30 include tie point collection; GCPs generation and optimization, coregistration, and

1 orthorectification; correlation of time series data set; estimation of east-west/north-south
2 horizontal displacement; flow vector generation; and finally velocity retrieval in m/y. The band-
3 3N of ASTER 2004 was orthorectified using SRTM GDEM-v3, which served as the master
4 image for tie point collection. Scherler et al. (2008) discussed two systematic artefacts viz. (i)
5 residual error because of satellite geometry, and (ii) DEM-related errors that may affect
6 computed displacements and finally the SIV. In our case, we did not find the first one, but the
7 latter might have been translated from the DEM used (SRTM GDEM-v3) during the
8 orthorectification of the correlated images. These DEM-related errors were estimated on stable
9 grounds (considered pixels ~1142) following the standard procedure (Scherler et al., 2008) and
10 suitably corrected. Further, a directional filter was applied on the computed displacement that
11 efficiently removes the miscorrelations/distortions. Additionally, during post-processing,
12 velocity of more than 100 m/y (not expected in the study area) was also excluded from the
13 computations.

14 To estimate the glacier surface elevation changes, we used the ‘DEM differencing
15 method’ (popularly known as the geodetic method), which involves measuring the elevation
16 changes over time ($\delta h/\delta t$) by comparing temporal DEMs on a pixel-by-pixel basis (Racoviteanu
17 et al., 2008b).

18 The DEMs for the year 2002 and 2014 were generated from ASTER stereo pair bands 3N
19 (nadir looking) and 3B (backward looking) using ENVI 5.1 software. Quasi-simultaneous
20 acquisition of both bands (3N and 3B) offers alike weather conditions by eliminating time lag
21 and base to a height ratio of 0.6, making it ideal for automatic elevation modeling (Kamp et al.,
22 2005; Toutin, 2008). Also, if the GCPs are accurate and well-distributed, a DEM with 30 m
23 spatial resolution can be easily achieved in mountainous region (Eckert et al., 2005). In order to
24 generate epipolar images, 8 and 10 GCPs (latitude, longitude, and elevation) collected from SOI
25 toposheets were provided manually, while 99 and 134 tie points were colocated interactively
26 from stereo pairs of 2002 and 2014, respectively. As the region is devoid of road networks and
27 other land use features, river confluences, first-order streams and lake-stream junctions were
28 used for GCP collection, considering them stable (Racoviteanu et al., 2009). The model
29 computes Y parallax to be 0.9 and 1.2 for 2002 and 2014 stereo pairs, respectively. In the next
30 step, DEMs were generated from epipolar images with high terrain details (level 4) and 30-m

spatial resolution, which is recommended to minimize the noise (Eckert et al., 2005; Toutin, 2008). Because the generated DEMs contain missing data, unnatural peaks, sinks, and sometimes mismatching, appropriate post-processing measures were undertaken to remove these errors. For generated DEMs, we created shaded reliefs to identify unnatural peaks and sinks on the glaciated area. The same were removed using the spline method. Furthermore, to improve the quality of resulting DEMs, they were smoothened using a low-pass filter (kernel window size of 5*5; Racoviteanu et al., 2009). Finally, the DEM of 2002 was subtracted from the 2014 DEM over glacier areas on a cell-by-cell basis to estimate surface elevation change.

Snowline altitude (SLA) at the end of melting season is generally regarded as the ELA (Pandey et al., 2013). Equilibrium lines for 1993, 2000, and 2014 were delineated manually from Landsat images of a respective period by virtue of high reflectance of perennial snow cover representing the accumulation areas of the glaciers at the end of the ablation period, using different false color composites (FCC). Then a total buffer size of 30 m (15 m either side of the lines), equivalent to pixel resolution of Landsat images, was created. Finally, mean elevation of equilibrium lines (along with buffers) was extracted from the SRTM GDEM-v3.

3.3. Source of errors and uncertainties

As the present study focuses on assessing multiple glacier parameters from multiple data sets of different time periods, evaluation of uncertainty is of utmost importance (Racoviteanu et al., 2008a). The uncertainty in extraction of glacier parameters from remote sensing data may arise from various sources, which includes (i) locational/positional errors (geocoding), (ii) processing errors, (iii) classification/methodological errors, (iv) conceptual/interpretation error (Racoviteanu et al., 2008a, 2009; Paul et al., 2013a), (v) correlation error in SIV estimation (Leprince et al., 2007; Scherler et al., 2008; Tiwari et al., 2014), and (vi) error associated with elevation models. In this study, we estimated the uncertainty associated with each monitored glacier parameter separately by using various well-established methods which are discussed below.

Multiple methods were performed for estimating the uncertainty related with area and length measurements viz. (i) interpretation dependent (Paul et al., 2013a), (ii) data dependent (Hall et al., 2003; Granshaw and Fountain, 2006), and (iii) validation of results from high resolution data.

In the first method, the boundaries of all three glaciers were digitized on a 2000 ETM image several times (>5 times) by the same analyst with sufficient time gaps to ascertain the interpretational biases affecting the mapping estimates. Resultant boundaries were compared and an average variability was computed to be 3.52%, 3.80%, and 7.98% for Sakchum, Chhota Shigri, and Bara Shigri glacier, respectively. The second method, i.e., data dependent uncertainty analysis, includes the buffer method (Granshaw and Fountain, 2006) and the method proposed in Hall et al. (2003). In the buffer method, buffers equal to registration errors were created in and outside of the delineated glacier area. For all three analysis periods (1993, 2000, and 2014), errors in glacier boundaries were calculated to be $\pm 0.43 \text{ km}^2$, $\pm 0.51 \text{ km}^2$, and $\pm 2.72 \text{ km}^2$ for Sakchum, Chhota Shigri, and Bara Shigri, respectively. Further, uncertainty in length measurement was calculated from the following equation given by Hall et al. (2003):

$$U_{\text{retreat}} = \sqrt{a^2 + b^2} + \sigma \quad (1)$$

where U_{retreat} is uncertainty in retreat estimation, a and b represent spatial resolution (pixel size) of temporal images, and σ is the error in coregistration. Accordingly, snout fluctuations (length change) were estimated with an accuracy of $\pm 51.43 \text{ m}$ for 1993-2000 and $\pm 52.93 \text{ m}$ for 2000-2014 periods. Uncertainty in areal extent change was computed using the following formula (Hall et al., 2003; Wang et al., 2009):

$$U_{\text{area}} = 2 * U_{\text{retreat}} * V \quad (2)$$

where U_{area} is uncertainty in areal change estimation, and V is the image pixel resolution. Thus, changes in the areal extent of the glaciers were measured with an accuracy of $\pm 0.0031 \text{ km}^2$ for 1993-2000 and $\pm 0.0032 \text{ km}^2$ for 2000-2014.

The third method, i.e., comparison of results from coarse and moderate resolution satellite data with high resolution data, is the most widely accepted method of validation amongst the glaciological community. The glacier boundary of Chhota Shigri, digitized on Landsat 2014 OLI (area = 15.03 km^2), was validated from the boundary digitized on Worldview image (area = 15.13 km^2), which showed good agreement with a slight difference in area of 0.1 km^2 . Difference in length measurement was found to be $< \sim 20 \text{ m}$ only. Our reported locational

1 and mapping uncertainties are comparable with earlier studies (Hall et al., 2003; Wang et al.,
2 2009; Bhambri et al., 2013).

3 We computed uncertainties in image-deduced SIV computations as per Scherler and
4 Strecker et al. (2012) in which mean and standard deviation of displacement over stable ground
5 are summed up and divided by temporal separation of the correlated image pair. A total number
6 of ~1100 pixels were considered and uncertainty was calculated to be ~4.9 m/y for both time
7 periods. Also, SIV of the Chhota Shigri glacier has been compared with published field results
8 for coinciding time periods (discussed in section 4.3), yielding a standard deviation of ± 4.78 m/y.
9 Further, the Worldview image could not be used to evaluate the accuracy of debris cover
10 classification because of the presence of temporary snow cover; therefore, the ASTER VNIR
11 image (2014) was utilized for this. A total of 200 sample points, 100 each for debris cover and
12 nondebris cover class, were selected via stratified random sampling. These check points were
13 visually inspected overlaying them on the ASTER VNIR image of 2014, which gave an overall
14 accuracy of ~92% for debris cover classification.

15 Careful evaluation of DEMs is important in glaciology because changes in surface
16 elevation over time can be an indicator of mass balance changes (Racoviteanu et al., 2008b). We
17 evaluated errors in the vertical coordinate (Z) of generated ASTER DEMs against SRTM
18 GDEM-v3 by comparing them over nonglaciaded areas. Previous studies have reported that
19 SRTM DEM is fairly suitable for glaciological applications (Racoviteanu et al., 2007; Berthier et
20 al., 2007). Moreover, availability of recently released SRTM GDEM-v3 with 30-m spatial
21 resolution enabled us to take it as a reference to validate our DEMs. As a first step, the 2002
22 DEM and 2014 DEM were coregistered with SRTM GDEM-v3 as per Nuth and Kaab (2011) to
23 ensure congruence in X , Y , and Z coordinates. The estimated shift in X , Y , and Z directions of
24 coregistered DEM was 3.4, 3, and 0.2 m for the 2002 DEM and -5.9, -9.5, and 1.2 m for the
25 2014 DEM, respectively. Then, the standard error (SE) and relative uncertainties (e) of the
26 DEMs were computed based on snow/ice-free areas relative to SRTM GDEM-v3 as per Bolch et
27 al. (2011). Table 2 presents the complete statistics of uncertainty estimation. Accordingly, the
28 uncertainty in our glacier surface elevation change estimations was computed to be ± 3.05 m,
29 which is in accordance with earlier studies (Racoviteanu et al., 2007; Bolch et al., 2011).

Error in ELA estimations may arise from various sources such as seasonal snow cover, glacier surface elevation changes between the dates of image acquisition, and DEM generation and inaccuracies associated with the DEM used (Wu et al., 2014; Shukla and Qadir, 2016). Uncertainty in ELA was also estimated in X , Y , and Z directions. However, the error in the X and Y coordinates should equal the registration errors of the images used to delineate them; but because we have created a buffer size of 15 m on either side of the equilibrium lines prior to ELA result computations, therefore, error in the X , Y directions may be regarded as ± 15 m. The uncertainty in the Z direction is similar to that of SRTM GDEM-v3 (± 17 m), which was used to extract the elevations (Shukla and Qadir, 2016).

4. Results

4.1. Length/area variation

Glacier snout position monitoring in this study reveals a nonuniform trend of retreat for the chosen glaciers (Fig. 2). During the last 21 years (1993-2014), Bara Shigri showed a maximum retreat of 325.74 m followed by Sakchum (which retreated by 223.58 m), while Chhota Shigri retreated by just 85.19 m (which is noticeably less than the other two). Total associated uncertainty in retreat measurement for the 21-year period is estimated to be ± 52.93 m. Observing the variations in retreat rates, Bara Shigri and Sakchum retreated at a faster rate compared to Chhota Shigri, which retreated at a much slower rate (Table 3). We also assessed the retreat variations on a decadal time scale for two time frames, i.e., 1993-2000 (7 years) and 2000-2014 (14 years). During 1993-2000, Sakchum retreated at a faster pace compared to Bara Shigri, whereas Chhota Shigri also exhibited a noteworthy retreat rate (Table 3). In the subsequent decade (2000-2014), Bara Shigri continued to retreat at a nearly similar pace to the previous one; however, the retreat rates of Sakchum and Chhota Shigri drastically reduced (Table 3).

Comparing our findings with previous studies carried out in this region (Table 3), we found that our results are in good agreement up to 2000 (1993-2000 period), but tend to be slightly less afterward. For the 2000-2014 period, retreat rates of Bara Shigri are still comparable but those estimated for Chhota Shigri differ slightly from the reported ones. This discrepancy may be because previous studies averaged out the retreat rates for large time spans. However, the

uncertainties associated with retreat measurements complicate an accurate comparison (Table 3). Kulkarni et al. (2007) reported a retreat of 800 m (53.33 m/y) during 1988-2003 for Chhota Shigri, which is much higher than any other study and questionable (Wagnon et al., 2007; Pandey and Venkataraman, 2013).

Temporal boundaries of glaciers were compared for estimation of changes in the glacier area. Table 4 shows the area change in studied glaciers during 1993-2014. The total glaciated area (composite of the studied glaciers) has been reduced from 158.46 to 156.60 km², exhibiting a loss of 1.86 ± 0.0032 km² or deglaciation of 1.78% during 1993-2014. However, the rate of change varied from glacier to glacier: Sakchum and Bara Shigri lost their area with an almost similar rate in both investigated decades. Further, results show that the collective share of Sakchum and Bara Shigri in deglaciation was ~94% and ~87% during 1993-2000 and 2000-2014, respectively, suggesting that while Sakchum and Bara Shigri lost area, Chhota Shigri remained nearly stagnant (in terms of deglaciation) during the study period (Table 4).

Comparison of results of this study with previous studies show good agreement (Table 4). However, Kulkarni et al. (2007) reported a change in area of 12% for glaciers >10 km² in size for the Chenab basin from 1962 to 2001, which is much higher than the results of the present study. This discrepancy may be attributed to error in the boundaries of glaciers in the topographic maps used in the previous study (Pandey and Venkataraman, 2013).

4.2. Debris cover variation

Monitoring of debris cover is not only important for its influence on glacier health (Shukla et al., 2009) but also because it can be used as a proxy for regional mass balance guesstimates (Herreid et al., 2015). Studied glaciers exhibit varying amounts of supraglacial debris cover on them (Table 5). Sakchum glacier has the maximum percentage of debris-covered area followed by Bara Shigri and Chhota Shigri (Table 5). We observed that Sakchum and Bara Shigri have extensive debris covers on their ablation zone as compared to the Chhota Shigri glacier. Considering the total study period of 21 years, debris cover has been increased on all the glaciers. However, maximum percentage increase in debris cover was observed in Chhota Shigri (33.33%) followed by Sakchum (29.09 %) and Bara Shigri (24.12 %). This is in agreement with studies conducted elsewhere that report that debris cover increase on relatively cleaner glaciers

has increased manifold in comparison with their debris-covered counterparts (Shukla and Qadir, 2016; Racoviteanu et al., 2014). Investigation of decadal variations in debris cover reveals that while Bara Shigri showed maximum debris cover increase during 1993-2000, Sakchum and Chhota Shigri showed maximum debris cover expansion during 2000-2014 (Table 5).

Previous studies conducted in the Chenab basin also reported an increase in debris cover with time (Kulkarni et al., 2007; Shukla et al., 2009). Kulkarni et al. (2007) observed that debris cover over Chhota Shigri glacier increased during 1988-2003 but did not quantify the change.

4.3. Surface ice velocity variation

In the debris-covered Himalayan glaciers where length changes may not represent actual glacier health and mass balance data is limited, flow rates become vital to ascertain their dynamics (Luckman et al., 2007; Quincey et al., 2009). We assessed the SIV along respective central flow line of the glaciers (Figs. 3, 4A-C). Average SIV of Sakchum and Chhota Shigri were computed for every 500 m (0.5 km) distance, while for Bara Shigri (which is comparatively very long), SIV were calculated for every 1 km distance from snout. Further, for carrying out a detailed assessment of variations in SIV, the glaciers were divided into three distinct zones: accumulation zone (ACZ), upper ablation zone (UAZ) and lower ablation zone (LAZ). First, the glaciers were divided into an ACZ and ablation zones based on the ELA of 2014 (discussed in section 4.5). Then, the ablation zones were further divided into UAZ and LAZ by following the contour line of 4600 m (derived from SRTM GDEM-v3) irrespective of clean and debris-covered ice. Table 6 shows the elevation range of different zones for studied glaciers for the year 2014, which was used for the estimation of zonal statistics of the SIV and surface elevation changes.

Surface ice velocity results show that Sakchum has been the slowest, while Bara Shigri was the fastest moving glacier during the period of study (Figs. 3, 4A-C). Results show that average SIVs of all three glaciers have decreased significantly during the study period; however, the impact is seen more prominently in Chhota Shigri and Bara Shigri as compared to Sakchum, probably because it was already the slowest. We found a dropdown of 21.43%, 23.52%, and 22.15% in a glacier-wide average SIV of Sakchum, Chhota Shigri, and Bara Shigri, respectively. Moreover, a pulsating trend in SIV with respect to distance from snout is observed (Fig. 4).

1 Zonal analysis reveals that slowdown was not that significant (considering the associated
2 uncertainties) in ACZ as compared to UAZ of the glaciers (Fig. 4; Table 7). Observed
3 differential slowdown in LAZ shows that while Chhota Shigri registered significant deceleration
4 in LAZ, Sakchum and Bara Shigri exhibited minimal slowdown probably because of already
5 existing stagnant zones on these glaciers, which constitute a major part of their LAZ. Figure 5
6 shows the velocity vectors calculated for the Bara Shigri glacier for the year 2003/04. Vectors
7 displayed in Figure 5 are, however, not to scale; but their relative sizes indicate a higher SIV in
8 UAZ than LAZ. Further, maximum decrease in SIV was observed in UAZ of Sakchum (34.48%)
9 and Bara Shigri (37.36%), whereas Chhota Shigri showed maximum SIV reduction in LAZ
10 (29.33%).

11 In Sakchum glacier, an abnormally high SIV peak (22.17 m/y) is seen at 5 km in 2013/14
12 (Fig. 4C), which is probably because of some temporary phenomenon (e.g., avalanche) caused
13 by steep sidewall located in the southwestern side at this point (Fig. 1). Further, the debris-
14 covered lower part of Sakchum (up to ~1 km upstream) and Bara Shigri (up to ~6 km upstream)
15 moved with similar rates in both observation periods with no temporal variation (Figs. 4A, C).

16 We compared our remotely deduced SIVs of Chhota Shigri glacier with previous
17 measurements of the same glaciers. Dobhal et al. (1995) reported the maximum flow rate of ~46-
18 52 m/y in UAZ (4600-4800 m asl in their study) for Chhota Shigri in 1987-1989. In LAZ and
19 ACZ, they reported a flow rate of ~31-39 and ~32-38 m/y, respectively. These estimates are
20 higher than the present study, which may be because of large difference in observation period
21 (15 years). During this period, probably SIV would have slowed down as per the existing trend.
22 However, excellent agreement was found when SIV of 2003/04 of Chhota Shigri was compared
23 with field measurements for a similar study period (Azam et al., 2012; Fig. 4D) yielding a
24 standard deviation of only ± 4.78 m/y (6%). This discrepancy is well within the range of
25 uncertainties associated with our SIV estimations (section 3.3). Moreover, Tiwari et al. (2014)
26 also remotely estimated slightly lower SIV (variation of ~10%) for Chhota Shigri than field data.
27 There is no complete published SIV data for Bara Shigri and Sakchum to compare; however,
28 Berthier et al. (2007) remotely measured flow rate for the debris-covered tongue of Bara Shigri
29 to be <20 m/y, which confirms our results.

4.4. Surface elevation change

Glacier surface elevation changes are of crucial concern because instead of reducing in length, the glaciers may be downwasted in response to climate change (Berthier et al., 2007). Here, the results of elevation changes observed in the studied glaciers from 2002 to 2014 are presented (Figs. 6, 7). Similar to SIV, the results of surface elevation change have also been analyzed along the central flow line (Fig. 6, 7). Results show significant elevation changes in glaciers during the study period (Table 8). Sakchum (-1.22 m/y) and Bara Shigri (-1.21 m/y) showed maximum and nearly similar glacier-wide average elevation change rates, while minimum elevation change rate is observed in the Chhota Shigri glacier (-0.91 m/y; Table 8). Zonal observations show that the ACZ of all the glaciers did not reveal a significant elevation change considering the associated uncertainties. However, the UAZ of Sakchum (-1.9 m/y) and Chhota Shigri (-1.25 m/y) lowered with maximum pace, whereas maximum downwasting in Bara Shigri is observed in LAZ. Further, an average thickening of 1.3 m (maximum up to 13 m in a few points) is observed near the snout region of Chhota Shigri glacier (up to 0.5 km from snout) between 2002 and 2014 (Figs. 6, 7).

The results of surface elevation change of this study were thoroughly compared with the earlier studies performed in the same region. Vincent et al. (2013) remotely deduced a surface thinning of -8.9 to -9.2 m on Chhota Shigri for the glacier part between 4700 and 5100 m asl during 1999-2010, which is comparable with our results. However, from 1988 to 2010 (22 years) they reported a glacier-wide average thinning of -5.6 m, which is lower than our estimates. This difference is, however, within the range of uncertainty (section 3.3), possibly because they have averaged out the thickness change for a large time period and meanwhile they also reported a shift in glacier dynamics during the 1990s. Further, Vincent et al. (2013) computed a thickening of up to ~22 m near the snout (4050-4300 m asl) of Chhota Shigri for 1988-2010, which matches with our results. Our results are also in line with Berthier et al. (2007) who calculated a thinning of 2-3 m/y in debris-covered tongues of the glaciers in the same region for 1999-2004. Kumar and Dobhal (1997) found a thinning of 3 m during 1987-1988 (2 years) in the middle part of the Chhota Shigri glacier, showing similar rates to that of the present study.

4.5. ELA variation

The ELA is an important parameter, useful in defining the relation between local climate and distribution of glacier mass (Hanshaw and Bookhagen, 2014; Guo et al., 2014) as well as the overall state of the glacier (Shukla and Qadir, 2016). However, ELA is dynamic in nature and, in general, varies year to year; this study reports ELA changes as a proxy for the mass fluctuations in studied glaciers on the decadal scale. Results show that ELA of the studied glacier raised-up significantly during the study period of 21 years (Table 6). The ELA of Sakchum, Chhota Shigri, and Bara Shigri shifted up by 106, 141, and 85 m, respectively, from 1993 to 2014. Decadal observation shows that ELA of Chhota Shigri shifted with the same rate in both decades; while in Sakchum and Bara Shigri, maximum ELA rise was seen during 1993-2000.

Earlier studies reported that ELA of Chhota Shigri has varied year to year. Wagnon et al. (2007) estimated the ELA of Chhota Shigri as 5180 m asl for 2002/03 and 2005/06, and 4855 m asl for 2004/05. Wagnon et al. (2007) also reported that ELA at 4960 m asl represents the zero mass balance for the Chhota Shigri glacier. Dobhal et al. (1995) reported the ELA of Chhota Shigri to be 4600 and 4840 m asl for the years 1987 and 1998, respectively. Considering the dynamic nature of ELA, we stress that the comparison of our ELA estimates to published estimates is complicated by the fact that, generally, they do not correspond to the same years. Moreover, Pandey et al. (2013) estimated the ELA for the Chhota Shigri and Bara Shigri glaciers to be 4783 m asl (standard deviation (SD) 26 m) and 5204 m asl (SD 133 m), respectively, for the year 2000. However, our results for Bara Shigri match well with these estimates, but a large discrepancy for the Chhota Shigri glacier was found which may be attributed to the difference in the date of image acquisitions (not mentioned in Pandey et al., 2013) and the data sets used to deduce the ELA.

5. Discussion

All investigated parameters clearly indicate toward negative health of the three glaciers for the study period; however, their pattern varies considerably from one to another. Previous studies have amply highlighted that climate change is the main driving force behind adverse variations in vital glacier parameters observed in recent decades (Kulkarni et al., 2007, 2011; Wagnon et al., 2007; Shukla et al., 2009; Scherler et al., 2011; Bolch et al., 2012; Vincent et al., 2013). Climatic factors mainly include the variation in the meteorological parameters, i.e., temperature and precipitation plus the change in form of precipitation from solid to liquid. For

the last century, a rise in temperature ranging from 0.6°C to 1.6°C has been reported in the Himalayan region (Shrestha et al., 1999; IPCC, 2007; Bhutiyani et al., 2010). Further, monsoon precipitation has also exhibited a substantial decreasing trend in the last century (Bhutiyani et al., 2010). Kulkarni and Alex (2003) found that this climatic variation had started affecting the stability of Himalayan glaciers. Moreover, most of the studies conducted in WH, including this study, reported heterogeneous response of glaciers even if they are sharing similar climatic and geographical settings (Kulkarni et al., 2007; Brahmbhatt et al., 2012; Bhambri et al., 2013; Negi et al., 2013), which indicates the role of nonclimatic factors.

Results show that the Sakchum glacier had been retreating, losing area, slowing, and thinning down; while Chhota Shigri showed negligible reduction in length and area, but exhibited comparable drop in SIV and surface elevation change and highest increase in debris cover percentage. Bara Shigri glacier experienced the highest amount of retreat and deglaciation, considerable slowdown, and obvious surface thinning, which was accompanied by a commensurate increase in debris cover. In this section, the above-mentioned response of these glaciers have been reassessed, considering the possible control of the nonclimatic factors (debris cover, slope gradient, size of accumulation area, hypsometry, and altitudinal range) and mutual relation between various glacier parameters.

Results of retreat measurements show that Sakchum experienced enhanced retreat during 1993-2000 (20.37 ± 7.35 m/y) when it had relatively less amount of debris cover (23.34%). However, during the next decade (2000-2014) as the debris-covered area increased (30.25%), its retreat rate decreased substantially (5.79 ± 3.78 m/y) but it continued to ablate via thinning (Fig. 7). So possibly increased extent of debris cover slowed down the recession rate of the glacier. On the contrary, the Bara Shigri glacier retreated at a faster pace in both decades (1993-2000: 16.00 ± 7.35 m/y; 2000-2014: 15.27 ± 3.78 m/y). The increased retreat of Bara Shigri may be because of the presence of supraglacial lakes ranging in diameter from 20 to 170 m (Tiwari et al., 2012) and an increase in their number and dimensions in recent years. Schauwecker et al. (2015) reported ~60-70 supraglacial lakes (area >500 m²) on the lower ablation zone of Bara Shigri glacier. Glaciers with supraglacial lakes deglacierate rapidly (Basnett et al., 2013) because melt rates around these lakes are, in general, higher (1 to 2 times more) than melt rates beneath debris cover (Benn et al., 2012). Moreover, the debris cover on such glaciers is frequently redistributed, which results in large spatial and temporal differences in debris thickness. This changing spatial

distribution of debris cover would differently enhance or inhibit the ablation and encourage topographic inversion (Thompson et al., 2016). Despite a maximum debris cover increase (33.12%), Chhota Shigri exhibited comparatively lesser terminus change, probably because of the deep shadow cast by surrounding steep slopes of the narrow valley (Wagnon et al., 2007). However, the associated uncertainties with retreat rates of Chhota Shigri make them negligible (Table 3). Another possible reason behind differential retreat of the studied glacier may be their flow patterns. We observed that slower flow rates over LAZ of Sakchum and Bara Shigri (Figs. 4A,C; Table 7) were associated with higher retreat (Table 3); whereas higher SIV in similar zones of Chhota Shigri managed to make it recede by a lesser amount. Ultimately, lesser surface lowering (which translates to lower mass loss in the case of the Chhota Shigri glacier) seems to be the main cause behind the differential retreat and associated flow patterns (Table 8).

The total areal changes were also found to be more in Sakchum ($0.49 \pm 0.0032 \text{ km}^2$) and Bara Shigri ($1.18 \pm 0.0032 \text{ km}^2$) than Chhota Shigri ($0.19 \pm 0.0032 \text{ km}^2$) glacier. This comparatively rapid areal change of Bara Shigri may again be linked with the enhanced melting because of the presence of supraglacial lakes and ice cliffs on this glacier (Thompson et al., 2016). Moreover, the altitudinal ranges of main trunks of Sakchum, Chhota Shigri and Bara Shigri glaciers are found to be ~4380-5360, ~4107-5480, and ~4005-6180 m asl, respectively. This suggests that Bara Shigri had the highest altitudinal range (i.e., ~2180 m), which may be an important factor behind its maximum deglaciation ($1.18 \pm 0.0032 \text{ km}^2$) and retreat ($325.74 \pm 52.93 \text{ m}$). Ideally, Sakchum should have retreated and deglaciated the least according to the altitudinal range, but the possible influence of other factors (e.g., hypsometry) altered its response. Given the absence of supraglacial lakes on Sakchum, hypsometry of this glacier may explain its higher deglaciation/retreat.

Hypsometry of glaciers can reveal ample information about their behavior if analyzed together with the position of the ELA (Rivera et al., 2011). If a large portion of the glacier is at an elevation similar to the ELA, a small change in the elevation of the ELA might result in a significant change in the areas of accumulation and ablation. We found that Sakchum, Chhota Shigri, and Bara Shigri have 73%, 58%, and 39% (respectively) of their areas at elevations similar to that of ELA (Fig. 8). As the Sakchum glacier has maximum percentage of its area similar to ELA and the ELA of this glacier has also migrated up by 106 m during 1993-2014

(Table 6), this might have been one of the major reasons behind its higher retreat and deglaciation.

Assessment of debris cover variation shows varying amounts of debris on the studied glaciers, which may be the result of (i) topography of the valley (e.g., slope gradient), (ii) change in various glacier parameters (e.g., deglaciation, SIV), and (iii) extra-glacial processes (e.g., rock avalanche) resulting from steep sidewalls, etc. Scherler et al. (2011) reported that if the accumulation zone has vast areas of steeper slope ($>25^\circ$) and ablation zone has a more gentle slope ($<8^\circ$), the probability of debris cover accumulation over a glacier surface is higher. We found that Sakchum, Chhota Shigri, and Bara Shigri have ~38%, ~22%, and ~25% steeper slope area in ACZ and ~49%, ~40%, and ~54% gentle sloping area in LAZ; while they have ~30.25%, ~11.96%, and ~19.61% debris-covered area, respectively. This indicates that slope gradient may be one of the major reasons behind higher amounts of debris in Sakchum and Bara Shigri glaciers. Further, the areal shrinkage in Sakchum and Bara Shigri (Table 4) have been accompanied by increased debris cover (Table 5), suggesting that the deglaciation and debris cover in the study area are linked with a positive feedback mechanism (Benn et al., 2012; Herreid et al., 2015). Also, the released meltwater, as a consequence of glacier downwasting, tends to drain-out, dumping the debris load behind and resulting in increased debris cover. Therefore, the observed increase in debris cover (Table 5) may also be linked with the rapid glacier surface lowering in the studied glaciers (Table 8). Moreover, higher SIVs in the upper reaches of Sakchum and Bara Shigri (Figs. 4A,C) are another possible reason for extensive debris cover in their lower tongues because higher SIV may bring more debris downglacier (Tiwari et al., 2014). We observed that the average decrease in SIV in UAZ of Chhota Shigri is relatively less (18.88%) than Sakchum (34.48%) and Bara Shigri (37.35%) and that this glacier also experienced maximum percent expansion in debris cover (33.33%). This is probably because continuous higher SIV favored debris movement downward. However, the maximum SIV decrease in LAZ of Chhota Shigri (29.33%) seems to encouraging debris accumulation here.

The SIV is the sum of glacier flow as a result of (i) shear deformation and (ii) basal sliding (Scherler and Strecker, 2012). Basal sliding has been reported to be the major movement mechanism in Chhota Shigri glacier as the lower part of this glacier rests on unconsolidated morainic debris or till (>50 - 100 m thick) deposited by glacier movement (Kumar and Dobhal,

1997). Also, slope gradient, bedrock characteristic, and meltwater availability can also affect the movement of the glaciers to varying extents. The SIV may vary intraannually (seasonally) as well as interannually. In general, as the ablation period sets in, released meltwater enhances the basal sliding and hence the SIV. For instance, in Chhota Shigri glacier, Kumar and Dobhal (1997) found that meltwater significantly contributed to its movement. Thus, the maximum SIV may be found during the peak ablation period, which again decreases as the ablation period ends (Scherler and Strecker, 2012). Because our correlated ASTER images are of nearly similar months (Table 1), the estimated results present only interannual SIV and are expected to be free from any seasonal bias (Table 7). To assess the influence of slope gradient on SIV variations, we computed the slope gradient along the central flow line and plotted it against the SIV of 2003/04 and 2013/14 (Figs. 4A-C). We observed that SIV variations closely followed the slope gradient. The maximum SIV is observed over higher slope gradients. Further, we found that, in both observed periods, the LAZ of Chhota Shigri has relatively higher average SIV as compared to Sakchum and Bara Shigri (Table 7), probably because of steep slope gradient near its snout (Fig. 4B). A relatively lesser amount of surface lowering (Table 8) may be another possible reason for its relatively higher SIV in LAZ. Further, despite the fact that percent steep sloping areas in ACZ of Bara Shigri (25%) are comparable to Chhota Shigri (22%) and even less than Sakchum (38%), SIV of this glacier is relatively very high in its ACZ and UAZ (Table 7). When we translate steep sloping area from percent to square kilometers, the actual figure corresponds to ~2.13, ~1.65, and ~17.36 km² for Sakchum, Chhota Shigri, and Bara Shigri, respectively. It shows that the steeper sloping area (km²) in ACZ of Bara Shigri is ~8-10 times more than the other two. Therefore, the higher SIV in ACZ and UAZ of Bara Shigri seems to be associated with its vast ACZ and consequential large mass supply. Moreover, the influence of glacier size is also observed in maximum and minimum glacier velocities. Bara Shigri has the highest SIV (>57 m/y in UAZ) compared to the other two, owing to its larger size (126.45 ± 2.7 km²) and greater mass.

In debris-covered parts of Sakchum (up to ~1 km upstream) and Bara Shigri (up to ~6 km upstream), only slight or no temporal variation in SIV is observed (Figs. 4A,C) during the study period, suggesting that these parts of the glaciers are stagnant (in terms of SIV). This may again be linked with the supraglacial lakes, ice cliffs, and gentle slope gradient that may have decelerated the horizontal movement of glacier. However, in the case of Chhota Shigri glacier, a decrease in SIV even in the snout region (Fig. 4B; Table 7) signifies that its ablation is

completely active with no stagnant zones. Further, the maximum drop of SIV in the UAZ of Sakchum and Bara Shigri (Figs. 4A,C; Table 7) clearly indicates that the current stagnant zones in their lower ablation areas may extend farther up (Benn et al., 2012). Further, the most likely cause of glacier stagnation and decreasing velocity is the reduction of ice thickness and surface gradient over the last few decades (Benn et al., 2012). Reduced ice thickness and surface gradient reduce the driving stress τ_D given by

$$\tau_D = \rho_i g H \tan \varphi \quad (3)$$

where ρ_i is ice density, g is gravitational acceleration, H is ice thickness and φ is surface slope. We found that as the surface elevation changed (discussed in the next paragraph), slope gradient of the glaciers has also been changed. Average slope gradient in ablation zones (LAZ+UAZ) of Sakchum, Chhota Shigri, and Bara Shigri has reduced by 16.07%, 1.81%, and 8.80%, respectively, during 2002-2014. Thus, the observed reduction in SIV of the three glaciers may be because of glacier thinning (Benn et al., 2012) or perhaps the accelerated surface thinning may be a result of decreasing SIV (Quincey et al., 2009).

The surface elevations of all three studied glaciers have changed significantly from 2002 to 2014. Though maximum elevation change was observed in UAZ (-1.13 to -1.89 m/y), a substantial surface lowering was also found in extensive debris-covered LAZ (-0.93 to -1.6 m/y) during 2002-2014. Previously, Berthier et al. (2007) estimated a thinning of 2-3 m/y for debris-covered tongues of glaciers of the same study region. Bolch et al. (2011) also reported enhanced elevation change in thickly debris-covered parts (0.39 ± 0.07 m/y) in the glaciers of the Mt. Everest region from 1970 to 2007. These results are contrasting with those from other studies, which state that debris cover may reduce glacier melting as a function of its thickness (Zhang et al., 2011; Fujita and Nuimura, 2011). Schauwecker et al. (2015) estimated a debris thickness of up to ~0.3 m in the lower part of Bara Shigri; still it lowered at the maximum rate of -1.21 m/y from 2002-2014 (Table 8). This is because the ablation processes in the lower stagnant debris-covered parts of glaciers with a substantial number of supraglacial lakes and ice cliffs bordering them are quite complicated and less explored. Recently, Thompson et al. (2016) attempted to compute the relative contribution of various processes, such as subdebris melt, ice cliff melting and backwasting, perched lakes bathymetry etc. in ablation of the heavily debris-covered

1 Ngazumpa glacier, Nepal, which is akin to the Bara Shigri glacier. They report that the major
2 contribution (40%) to mass loss was caused because of the melting and retreat of ice cliffs, even
3 though they occupy only a small area (5%) of the glacier. Similarly, though we were not able to
4 decouple the relative contribution of the above processes in the stagnant zone of the Bara Shigri
5 glacier because of the limitation of data resolution, but assuming that the same processes are
6 active here as well, we found that the mean surface lowering of the stagnant zone (up to ~6 km
7 upstream) was ~32% higher than glacier-wide thinning. This can clearly be attributed to the
8 enhanced melting around supraglacial lakes and retreat of ice cliffs present on this glacier.

9 Unlike Bara Shigri, despite high downwasting (-1.22 m/y; Fig. 7; Table 8), no such
10 prominent supraglacial lakes were identified on Sakchum glacier, which indicate that an efficient
11 englacial or subglacial drainage is existent here (Bolch et al., 2008). Moreover, Reynold (2000)
12 suggested that on debris-covered glaciers with slope $<2^\circ$, large supraglacial lakes may form,
13 while slope between 2° and 6° facilitated development of supraglacial ponds on a sufficiently
14 large area. However, these may be transient in nature. Our analysis reveals that Bara Shigri and
15 Sakchum have 12.81% and 2.76% of their ablation areas with slope $<2^\circ$ and 60.88% and 40.82%
16 of the ablation areas $<6^\circ$, respectively. This gradient analysis shows that Bara Shigri has the most
17 suitable and favorable conditions for development of supraglacial lakes. Nevertheless,
18 continuous downwasting in Sakchum may lower its gradient and break the existing subglacial
19 drainage system, indicating the possibility of development of supraglacial ponds in the future
20 (Benn et al., 2012).

21 Therefore, on the basis of the observed heterogeneous response of the analyzed glaciers,
22 they can be designated to three distinct regimes/stages of glacier evolution as proposed by Benn
23 et al. (2012) in their conceptual model:

- 24 • Chhota Shigri represents regime 1 where all parts of the glacier are completely active
25 (Fig. 4B) and ablation takes places mainly by melting beneath surface debris.
- 26 • Sakchum may be categorized into regime 2 where the mid-ablation zone experiences
27 increased mass loss (Fig. 7A) and reduced ice flux (Fig. 4A). Another characteristic
28 of regime 2 is enhanced slowdown and progressive stagnation (section 4.3).
- 29 • Bara Shigri exhibits typical characteristics of regime 3 where base-level lakes are
30 expected to form and more melting occurs around the exposed ice cliffs bordering

these lakes. Here, the transition of supraglacial lakes to full-depth lakes is another important aspect.

As discussed above, the variations in different glacier parameters are found to be intimately interlinked with each other via active positive and negative feedback mechanisms. Deglaciation has been accompanied by debris cover increase that, in turn, affected glacier retreat and thinning. Reduced SIVs caused stagnation, favored increased accumulation of debris cover, and enhanced surface elevation change (surface lowering). Surface lowering is again linked with slope gradient decrease, SIV dropdown, and debris cover increase. This shows that different glacier parameters exercise great controls on mutual variations and, thus, the response of glacier to changing climatic environment.

6. Summary and conclusions

The present study investigates the multidimensional response of three valley glaciers (namely Sakchum, Chhota Shigri, and Bara Shigri) located in the Chandra River basin by assessing multiple glacier parameters, their mutual control on each other, and nonclimatic factors controlling the overall glacier response. The status and variation of all investigated parameters during the last one or two decades indicate that these glaciers are shrinking, downwasting, and exhibit considerable heterogeneity in their response. The following major inferences may be drawn from the results:

- In spite of being located in close proximity to each other (similar climatic zone), retreat rate and deglaciation varied significantly among the glaciers being higher for Sakchum (retreat rate: 10.65 ± 2.52 m/y; area loss: 0.49 ± 0.0032 km²) and Bara Shigri (retreat rate: 15.51 ± 2.52 m/y; area loss: 1.18 ± 0.0032 km²) and lower for Chhota Shigri (retreat rate: 4.06 ± 2.52 m/y; area loss: 0.19 ± 0.0032 km²) from 1993 to 2014. The total glaciated area reduced by 1.78% during the study period.
- High retreat/deglaciation of Bara Shigri is possibly linked with the presence of numerous supraglacial lakes on it and its higher altitudinal range. Higher retreat/deglaciation of Sakchum may be because of its morphology as hypsometry shows that this glacier has almost one-third of its area at elevations similar to ELA.

1 Relatively lower retreat rates of Chhota Shigri may be because of the higher SIV in
2 its LAZ.

- 3 • Total debris cover is maximum in Sakchum (30.25%) and Bara Shigri (19.61%),
4 while Chhota Shigri has minimum debris cover (11.96%). Sakchum and Bara Shigri
5 have large steep sloping areas in ACZ and more gentle sloping areas in LAZ, which is
6 a probable reason behind their extensive debris cover. Conversely, maximum debris
7 cover increase on Chhota Shigri (33.33%) can be attributed to the rapid glacier
8 surface lowering and lesser SIV reduction in its UAZ than LAZ, whereas debris cover
9 increase in Sakchum (29.09%) and Bara Shigri (24.12%) may be the result of
10 observed deglaciation and surface lowering.
- 11 • In terms of movement, Sakchum is the slowest (10.63 m/y) and Bara Shigri is the
12 fastest (23.30 m/y) moving glacier. A significant dropdown in SIV of 21.43%,
13 23.52%, and 22.15% were observed in Sakchum, Chhota Shigri, and Bara Shigri
14 glacier, respectively. Slope is the main driving factor of SIV, whereas reduction in
15 SIV is likely because differential surface elevation change causes change in surface
16 gradient. The higher SIV in ACZ and UAZ of Bara Shigri may be attributed to its
17 vast ACZ. Further, the lower zones of Sakchum (up to ~1 km upstream) and Bara
18 Shigri (up to ~6 km upstream) are found to be stagnant, while the maximum
19 dropdown of SIV in their UAZ indicate that these stagnant zones are extending
20 farther up.
- 21 • A significant and differential surface lowering is observed in Sakchum (-14.62 m),
22 Chhota Shigri (-10.87 m), and Bara Shigri (-14.52 m). Also, changes in surface
23 gradients of Sakchum glacier, which are linked to surface elevation change and SIV
24 dropdown, indicate possible development of supraglacial lakes on it in the future.
- 25 • Uneven distribution of debris cover, presence of supraglacial ponds, and exposed ice
26 cliffs around these supraglacial ponds were found to increase melting in the stagnant
27 part of Bara Shigri as the mean surface lowering of this part (<6 km upstream) was
28 ~32% higher than mean glacier-wide thinning.
- 29 • The studied glaciers represent different regimes of glacier evolution (ablation
30 patterns) in a homogenous climatic setting, which further emphasizes the importance
31 of nonclimatic factors governing the glacier health.

- Analysis of the mutual influence of glacier parameters reveals a clear interdependency amongst nearly all glacier parameters. Debris cover extent and its variation is the most influential glacier parameter as well as major controlling factor that alters glacier response.

Moreover, evaluation of variation in two-dimensional attributes of Chhota Shigri showed it to be stable with slight or no dimensional changes (deglaciation and retreat); but assessment of other parameters simultaneously revealed comparable surface elevation change and dropdown in SIV, suggesting that glacier mass wasting process is active here. This reiterates the importance of multiparametric monitoring of glaciers to ascertain comprehensive glacier response. Further, in spite of the limited data, our results help in building a more holistic picture about the status of the glaciers in this region. Thus, we recommend a similar approach to be adopted for other Himalayan glaciers to ensure complete understanding of their response.

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References

- Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., Aizen, E.M., 2007. Glacier changes in the Tien Shan as determined from topographic and remotely sensed data. *Global and Planetary Change*, 56(3), 328-340.
- Albert, T.H., 2002. Evaluation of remote sensing techniques for ice-area classification applied to the tropical Quelccaya Ice Cap, Peru. *Polar Geography*, 26(3), 210-226.

- 1 Aniya, M., Sato, H., Naruse, R., Skvarca, P., Casassa, G., 1996. The use of satellite and airborne
2 imagery to inventory outlet glaciers of the Southern Patagonia Icefield, South
3 America. *Photogrammetric Engineering and Remote Sensing*, 62(12), 1361-1369.
- 4 Azam, M.F., Wagnon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A.,
5 Pottakkal, J.G., Chevallier, P., Singh, V.B., Berthier, E., 2012. From balance to imbalance:
6 a shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India. *Journal*
7 *of Glaciology*, 58(208), 315-324.
- 8 Azam, M.F., Wagnon, P., Vincent, C., Ramanathan, A.L., Favier, V., Mandal, A., Pottakkal,
9 J.G., 2014. Processes governing the mass balance of Chhota Shigri Glacier (western
10 Himalaya, India) assessed by point-scale surface energy balance measurements. *The*
11 *Cryosphere*, 8(6), 2195-2217.
- 12 Bahuguna, I.M., Rathore, B.P., Brahmabhatt, R., Sharma, M., Dhar, S., Randhawa, S.S., Kumar,
13 K., Romshoo, S., Shah, R.D., Ganjoo, R.K., 2014. Are the Himalayan glaciers retreating.
14 *Current Science*, 106(7), 1008-1013.
- 15 Bajpai, S. C., 1995. Lahaul-Spiti: A forbidden land in the Himalayas (3rd ed.). New Delhi: Indus
16 Publishing Company, pp. 1–9.
- 17 Basnett, S., Kulkarni, A.V., Bolch, T., 2013. The influence of debris cover and glacial lakes on
18 the recession of glaciers in Sikkim Himalaya, India. *Journal of Glaciology*, 59(218), 1035-
19 1046.
- 20 Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D.,
21 Thompson, S., Toumi, R., Wiseman, S., 2012. Response of debris-covered glaciers in the
22 Mount Everest region to recent warming, and implications for outburst flood
23 hazards. *Earth-Science Reviews*, 114(1), 156-174.
- 24 Berthier, E., Arnaud, Y., Baratoux, D., Vincent, C., Rémy, F., 2004. Recent rapid thinning of the
25 “Mer de Glace” glacier derived from satellite optical images. *Geophysical Research*
26 *Letters*, 31(17), L17401.
- 27 Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., Chevallier, P., 2007. Remote
28 sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya,
29 India). *Remote Sensing of Environment*, 108(3), 327-338.

- 1 Bhambri, R., Bolch, T., Chaujar, R.K., 2011. Mapping of debris-covered glaciers in the Garhwal
2 Himalayas using ASTER DEMs and thermal data. *International Journal of Remote*
3 *Sensing*, 32(23), 8095-8119.
- 4 Bhambri, R., Bolch, T., Chaujar, R.K., 2012. Frontal recession of Gangotri Glacier, Garhwal
5 Himalayas, from 1965 to 2006, measured through highresolution remote sensing
6 data. *Current Science*, 102(3), 489-494.
- 7 Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D.P., Srivastava, D., Pratap, B., 2013.
8 Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. *The*
9 *Cryosphere*, 7(5), 1385-1398.
- 10 Bhutiyani, M.R., Kale, V.S., Pawar, N.J., 2010. Climate change and the precipitation variations
11 in the northwestern Himalaya: 1866–2006. *International Journal of Climatology*, 30(4),
12 535-548.
- 13 Bolch, T., Buchroithner, M., Pieczonka, T., Kunert, A., 2008. Planimetric and volumetric glacier
14 changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER
15 data. *Journal of Glaciology*, 54(187), 592-600.
- 16 Bolch, T., Pieczonka, T., Benn, D.I., 2011. Multi-decadal mass loss of glaciers in the Everest
17 area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere*, 5 (2), 349-358.
- 18 Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S.,
19 Fujita, K., Scheel, M., Bajracharya, S., 2012. The state and fate of Himalayan glaciers.
20 *Science*, 336(6079), 310-314.
- 21 Bookhagen, B., Burbank, D.W., 2010. Toward a complete Himalayan hydrological budget:
22 Spatiotemporal distribution of snowmelt and rainfall and their impact on river
23 discharge. *Journal of Geophysical Research: Earth Surface*, 115(F03019), 1-25.
- 24 Brahmabhatt, R.M., Bahuguna, I., Rathore, B.P., Kulkarni, A.V., Shah, R.D., Nainwal, H.C.,
25 2012. Variation of snowline and mass balance of glaciers of Warwan and Bhut Basins of
26 Western Himalaya using remote sensing technique. *Journal of the Indian Society of*
27 *Remote Sensing*, 40(4), 629-637.
- 28 Burns, P., Nolin, A., 2014. Using atmospherically-corrected Landsat imagery to measure glacier
29 area change in the Cordillera Blanca, Peru from 1987 to 2010. *Remote Sensing of*
30 *Environment*, 140, 165-178.

- 1 Cogley, J.G., 2011. Present and future states of Himalaya and Karakoram glaciers. *Annals of*
2 *Glaciology*, 52(59), 69-73.
- 3 Deota, B.S., Trivedi, Y.N., Kulkarni, A.V., Bahuguna, I.M., Rathore, B.P., 2011. RS and GIS in
4 mapping of geomorphic records and understanding the local controls of glacial retreat from
5 the Baspa Valley, Himachal Pradesh, India. *Current Science*, 100(10), 1555-1563.
- 6 Dobhal, D.P., Kumar, S., Mundepi, A.K., 1995. Morphology and glacier dynamics studies in
7 monsoon-arid transition zone: An example from Chhota Shigri glacier, Himachal-
8 Himalaya, India. *Current science*, 68(9), 936-944.
- 9 Dobhal, D.P., Gergan, J.T., Thayyen, R.J., 2008. Mass balance studies of the Dokriani Glacier
10 from 1992 to 2000, Garhwal Himalaya, India. *Bulletin of Glacier research*, 25, 9-17.
- 11 Dyurgerov, M.B., Meier, M.F., 1998. Year-to-year fluctuations of global mass balance of small
12 glaciers and their contribution to sea-level changes. *Oceanographic Literature Review*,
13 6(45), 902-903.
- 14 Dyurgerov, M.B., Meier, M.F., 2005. *Glaciers and the changing Earth system: a 2004 snapshot*.
15 Boulder: Institute of Arctic and Alpine Research, University of Colorado. Occasional Paper
16 No. 58.
- 17 Eckert, S., Kellenberger, T., Itten, K., 2005. Accuracy assessment of automatically derived
18 digital elevation models from ASTER data in mountainous terrain. *International Journal of*
19 *Remote Sensing*, 26(9), 1943-1957.
- 20 Fujita, K., Nuimura, T., 2011. Spatially heterogeneous wastage of Himalayan
21 glaciers. *Proceedings of the National Academy of Sciences*, 108(34), 14011-14014.
- 22 Ghosh, S., Pandey, A.C., 2013. Estimating the variation in glacier area over the last 4 decade and
23 recent mass balance fluctuations over the Pensilungpa Glacier, J&K, India. *Global*
24 *Perspectives on Geography*, 1(4), 58-65.
- 25 Granshaw, F.D., Fountain, A.G., 2006. Glacier change (1958–1998) in the north Cascades
26 national park complex, Washington, USA. *Journal of Glaciology*, 52(177), 251-256.
- 27 Guo, Z., N. Wanga., N. M. Kehrwald, R. Mao, H. Wua, Y. Wu, X. Jiang. 2014. Temporal and
28 spatial changes in Western Himalayan firn line altitudes from 1998 to 2009. *Global and*
29 *Planetary Change*, 118, 97–105.

- 1 Hall, D.K., Bayr, K.J., Schöner, W., Bindschadler, R.A., Chien, J.Y., 2003. Consideration of the
2 errors inherent in mapping historical glacier positions in Austria from the ground and space
3 (1893–2001). *Remote Sensing of Environment*, 86(4), 566-577.
- 4 Hanshaw, M.N. and Bookhagen, B., 2014. Glacial areas, lake areas, and snow lines from 1975 to
5 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central
6 Andes, Peru. *The Cryosphere*, 8(2), 359-376.
- 7 Herreid, S., Pellicciotti, F., Ayala, A., Chesnokova, A., Kienholz, C., Shea, J., Shrestha, A.,
8 2015. Satellite observations show no net change in the percentage of supraglacial debris-
9 covered area in northern Pakistan from 1977 to 2014. *Journal of Glaciology*, 61(227), 524-
10 536.
- 11 IPCC (2007). *Climate change 2007: The physical science basis*. In S. Solomon, D. Qin, M.
12 Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.),
13 *Contribution of working group I to the fourth assessment report of the intergovernmental*
14 *panel on climate change*. Cambridge, United Kingdom and New York, NY, USA:
15 Cambridge University Press 996 pp.
- 16 Iturrizaga, L., 2011. Trends in 20th century and recent glacier fluctuations in the Karakoram
17 Mountains. *Zeitschrift für Geomorphologie, Supplementary Issues*, 55(3), 205-231.
- 18 Jóhannesson, T., Raymond, C., Waddington, E.D., 1989. Time-scale for adjustment of glaciers to
19 changes in mass balance. *Journal of Glaciology*, 35(121), 355-369.
- 20 Kamp, U., Bolch, T., Olsenholler, J., 2005. Geomorphometry of Cerro Sillajhuay, Chile/Bolivia:
21 comparison of DEMs derived from ASTER remote sensing data and contour
22 maps. *Geocarto International*, 20(1), 23-34.
- 23 Kargel, J.S., Cogley, J.G., Leonard, G.J., Haritashya, U., Byers, A., 2011. Himalayan glaciers:
24 The big picture is a montage. *Proceedings of the National Academy of Sciences*, 108(36),
25 14709-14710.
- 26 Kaul, M. K., Puri, V. M., Singh, R. K., Srinivasan, D., Sangeawr, C. V., Swaroop, S., Gautam,
27 C. K., 1999. *Inventory of the Himalayan Glaciers*. Geological Society of India, Special
28 Publication No. 34.
- 29 Kulkarni, A.V., Alex, S., 2003. Estimation of recent glacial variations in Baspa Basin using
30 remote sensing technique. *Journal of the Indian Society of Remote Sensing*, 31(2), 81-90.

- 1 Kulkarni, A.V., Bahuguna, I.M., Rathore, B.P., Singh, S.K., Randhawa, S.S., Sood, R.K., Dhar,
2 S., 2007. Glacial retreat in Himalaya using Indian Remote Sensing satellite data. *Current*
3 *science*, 92(1), 69-74.
- 4 Kulkarni, A.V., Rathore, B.P., Singh, S.K., Bahuguna, I.M., 2011. Understanding changes in the
5 Himalayan cryosphere using remote sensing techniques. *International journal of remote*
6 *sensing*, 32(3), 601-615.
- 7 Kumar, S., Dobhal, D.P., 1997. Climatic effects and bedrock control on rapid fluctuations of
8 Chhota Shigri glacier, northwest Himalaya, India. *Journal of Glaciology*, 43, 467–472.
- 9 Leprince, S., Barbot, S., Ayoub, F., Avouac, J.P., 2007. Automatic and precise orthorectification,
10 coregistration, and subpixel correlation of satellite images, application to ground
11 deformation measurements. *Geoscience and Remote Sensing, IEEE Transactions on*, 45(6),
12 1529-1558.
- 13 Luckman, A., Quincey, D., Bevan, S., 2007. The potential of satellite radar interferometry and
14 feature tracking for monitoring flow rates of Himalayan glaciers. *Remote sensing of*
15 *Environment*, 111(2), 172-181.
- 16 Mandal, A., Ramanathan, A.L., Angchuk, T., 2014. Assessment of Lahaul-Spiti (western
17 Himalaya, India) Glaciers-An Overview of Mass Balance and Climate. *Journal of Earth*
18 *Science & Climatic Change*, 2014, 1-9.
- 19 Naito, N., Nakawo, M., Kadota, T., Raymond, C. F., 2000. Numerical simulation of recent
20 shrinkage of Khumbu Glacier, Nepal Himalayas, *IAHS Publ.* 264, pp. 245–254.
- 21 Nakawo, M., Fujita, K., Ageta, Y., Shankar, K., Pokhrel, A.P., Tandong, Y., 1997. Basic studies
22 for assessing the impact of the global warming on the Himalayan cryosphere, 1994 - 1996.
23 *Bulletin of Glacier research*, 15, 53-58.
- 24 Negi, H.S., Saravana, G., Rout, R., 2013. Monitoring of great Himalayan glaciers in Patsio
25 region, India using remote sensing and climatic observations. *Current Science*, 105 (10),
26 1383-1392.
- 27 Nuth, C., Kääb, A., 2011. Co-registration and bias corrections of satellite elevation data sets for
28 quantifying glacier thickness change. *The Cryosphere*, 5(1), 271-290.
- 29 Pandey, P., Venkataraman, G., 2013. Changes in the glaciers of Chandra–Bhaga basin, Himachal
30 Himalaya, India, between 1980 and 2010 measured using remote sensing. *International*
31 *journal of remote sensing*, 34(15), 5584-5597.

- Pandey, P., Kulkarni, A.V. and Venkataraman, G., 2013. Remote sensing study of snowline altitude at the end of melting season, Chandra-Bhaga basin, Himachal Pradesh, 1980–2007. *Geocarto International*, 28(4), 311-322.
- Paul, F., Kääb, A., Haeberli, W., 2007. Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies. *Global and Planetary Change*, 56(1), 111-122.
- Paul, F., Barrand, N.E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S.P., Konovalov, V., Bris, R.L. and Mölg, N., 2013a. On the accuracy of glacier outlines derived from remote-sensing data. *Annals of Glaciology*, 54(63), 171-182.
- Paul, F., Bolch, T., Kääb, A., Nagler, T., Nuth, C., Scharrer, K., Shepherd, A., Strozzi, T., Ticconi, F., Bhambri, R., Berthier, E., 2013b. The glaciers climate change initiative: Methods for creating glacier area, elevation change and velocity products. *Remote Sensing of Environment*, 162, 408-426.
- Quincey, D.J., Luckman, A., Benn, D., 2009. Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking. *Journal of Glaciology*, 55(192), 596-606.
- Racoviteanu, A.E., Manley, W.F., Arnaud, Y., Williams, M.W., 2007. Evaluating digital elevation models for glaciologic applications: An example from Nevado Coropuna, Peruvian Andes. *Global and Planetary Change*, 59(1), 110-125.
- Racoviteanu, A.E., Arnaud, Y., Williams, M.W., Ordonez, J., 2008a. Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. *Journal of Glaciology*, 54(186), 499-510.
- Racoviteanu, A.E., Williams, M.W., Barry, R.G., 2008b. Optical remote sensing of glacier characteristics: a review with focus on the Himalaya. *Sensors*, 8(5), 3355-3383.
- Racoviteanu, A.E., Paul, F., Raup, B., Khalsa, S.J.S., Armstrong, R., 2009. Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA. *Annals of Glaciology*, 50(53), 53-69.
- Racoviteanu, A., Arnaud, Y., Williams, M.W., Manley, W.F., 2014. Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern Himalaya. *The Cryosphere*, 9, 505-523.

- 1 Raina, V.K., 2009. Himalayan Glaciers - A State-of-Art Review of Glacial Studies, Glacial
2 retreat and Climate Change. Ministry of Environments and Forests. Discussion Paper, 60
3 pp.
- 4 Reynolds, J.M., 2000. On the formation of supraglacial lakes on debris-covered glaciers. IAHS
5 publication, 264, pp. 153-164.
- 6 Rivera, A., Cawkwell, F., Rada, C., Bravo, C., 2011. Hypsometry. In: Singh, V.P., Singh, P.,
7 Haritashya, U.K. (Ed.), Encyclopedia of Snow, Ice and Glaciers. Springer Netherlands, pp.
8 551-554.
- 9 Sangewar, C. V., Shukla, S. P., 2009. Inventory of the Himalayan Glaciers: A Contribution to the
10 International Hydrological Programme. Special Publication, Geological Survey of India,
11 34: An Updated Edition 594 pp.
- 12 Schauwecker, S., Rohrer, M., Huggel, C., Kulkarni, A., Ramanathan, A.L., Salzmann, N.,
13 Stoffel, M., Brock, B., 2015. Remotely sensed debris thickness mapping of Bara Shigri
14 Glacier, Indian Himalaya. Journal of Glaciology, 61(228), 675-688.
- 15 Scherler, D., Leprince, S., Strecker, M.R., 2008. Glacier-surface velocities in alpine terrain from
16 optical satellite imagery—Accuracy improvement and quality assessment. Remote Sensing
17 of Environment, 112(10), 3806-3819.
- 18 Scherler, D., Bookhagen, B., Strecker, M.R., 2011. Spatially variable response of Himalayan
19 glaciers to climate change affected by debris cover. Nature geoscience, 4(3), 156-159.
- 20 Scherler, D., Strecker, M.R., 2012. Large surface velocity fluctuations of Biafo Glacier, central
21 Karakoram, at high spatial and temporal resolution from optical satellite images. Journal of
22 Glaciology, 58(209), 569-580.
- 23 Shrestha, A.B., Wake, C.P., Mayewski, P.A., Dibb, J.E., 1999. Maximum temperature trends in
24 the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the
25 period 1971-94. Journal of climate, 12(9), 2775-2786.
- 26 Shukla, A., Qadir, J., 2016. Differential response of glaciers with varying debris cover extent:
27 evidence from changing glacier parameters. International Journal of Remote Sensing,
28 37(11), 2453-2479.
- 29 Shukla, A., Yousuf, B., 2016. Evaluation of Multisource Data for Glacier Terrain Mapping: A
30 Neural Net Approach. Geocarto International, 1-45.

- 1 Shukla, A., Gupta, R.P., Arora, M.K., 2009. Estimation of debris cover and its temporal variation
2 using optical satellite sensor data: a case study in Chenab basin, Himalaya. *Journal of*
3 *Glaciology*, 55(191), 444-452.
- 4 Shukla, A., Arora, M.K., Gupta, R.P., 2010a. Synergistic approach for mapping debris-covered
5 glaciers using optical–thermal remote sensing data with inputs from geomorphometric
6 parameters. *Remote Sensing of Environment*, 114(7), 1378-1387.
- 7 Shukla, A., Gupta, R., Arora, M.K., 2010b. Delineation of debris-covered glacier boundaries
8 using optical and thermal remote sensing data. *Remote Sensing Letters*, 1(1), 11-17.
- 9 Thompson, S., Benn, D.I., Mertes, J. and Luckman, A., 2016. Stagnation and mass loss on a
10 Himalayan debris-covered glacier: processes, patterns and rates. *Journal of Glaciology*,
11 62(233), 467-485.
- 12 Tiwari, R.K., Gupta, R.P., Gens, R., Prakash, A., 2012, July. Use of optical, thermal and
13 microwave imagery for debris characterization in Bara-Shigri glacier, Himalayas, India.
14 In *Geoscience and Remote Sensing Symposium (IGARSS)*, 2012 IEEE International (pp.
15 4422-4425). IEEE.
- 16 Tiwari, R.K., Gupta, R. P., Arora, M.K., 2014. Estimation of surface ice velocity of Chhota-
17 Shigri glacier using sub-pixel ASTER image correlation. *Current Science*, 106(6), 853-859.
- 18 Tiwari, R.K., Garg, P.K., Shukla, A., Ahluwalia, R.S., Singh, N., Chauhan, P., 2016. A
19 geomorphic and morphometric analysis of surface ice velocity variation of different valley
20 type glaciers. In *SPIE Asia-Pacific Remote Sensing*, 98771I-1-98771I-9.
- 21 Toutin, T., 2008. ASTER DEMs for geomatic and geoscientific applications: a review.
22 *International Journal of Remote Sensing*, 29(7), 1855-1875.
- 23 Vincent, C., Ramanathan, A., Wagnon, P., Dobhal, D.P., Linda, A., Berthier, E., Sharma, P.,
24 Arnaud, Y., Azam, M.F., Gardelle, J., 2013. Balanced conditions or slight mass gain of
25 glaciers in the Lahaul and Spiti region (northern India, Himalaya) during the nineties
26 preceded recent mass loss. *The Cryosphere*, 7(2), 569-582.
- 27 Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J.G.,
28 Berthier, E., Ramanathan, A., Hasnain, S.I., Chevallier, P., 2007. Four years of mass
29 balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the
30 western Himalaya. *Journal of Glaciology*, 53(183), 603-611.

- 1 Wang, Y., Hou, S., Liu, Y., 2009. Glacier changes in the Karlik Shan, eastern Tien Shan, during
2 1971/72–2001/02. *Annals of Glaciology*, 50(53), 39-45.
- 3 Wu, Y., He, J., Guo, Z., Chen, A., 2014. Limitations in identifying the equilibrium-line altitude
4 from the optical remote-sensing derived snowline in the Tien Shan, China. *Journal of*
5 *Glaciology*, 60(224), 1093-1100.
- 6 Zhang, Y., Fujita, K., Liu, S., Liu, Q., Nuimura, T., 2011. Distribution of debris thickness and its
7 effect on ice melt at Hailuoguo glacier, southeastern Tibetan Plateau, using in situ surveys
8 and ASTER imagery. *Journal of Glaciology*, 57(206), 1147-1157.

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Table 1

List of satellite data used in the study; length, area and debris cover (DC) were retrieved using Landsat data while ASTER images were used for surface ice velocity (SIV) and surface elevation change estimations (PAN = Panchromatic and MX = multispectral)

Purpose	Satellite and sensor	Spatial resolution	Scene ID	Date of acquisition	Band used
Length/area, DC	Landsat- 5 TM	30 m	LT51470381993277ISP00	04-10-1993	1-5
Length/area, DC	Landsat-7 ETM	30 m	LE71470382000289SGS00	15-10-2000	1-5
Length/area, DC	Landsat-8 OLI TIRS	30 m	LC81470382014271LGN00	28-09-2014	2-6,7
Surface elevation change	Terra ASTER	15 m	AST_L1A_00310302002053633_20100826060508_10691	30-10-2002	3N, 3B
SIV	Terra ASTER	15 m	AST_L1A_00310082003054128_20100826060508_10698	08-10-2003	3N
SIV	Terra ASTER	15 m	AST_L1A_00309172004053444_20100826060518_10840	17-09-2004	3N
SIV	Terra ASTER	15 m	AST_L1A_00310282013053510_20151106010214_21801	28-10-2013	3N
Surface elevation change, SIV	Terra ASTER	15 m	AST_L1A_00310312014053542_20150825235422_20969	31-10-2014	3N, 3B
Elevation reference	SRTM GDEM version 3	30 m	SRTM1N32E077V3	February, 2000	DEM
Accuracy assessment	Worldview-2	0.52 m PAN 2.4 m MX	Order No. 052481379060_01	13-10-2010	PAN, 1-8

Table 2

Uncertainty estimates of the DEMs, for years 2002 and 2014, generated from ASTER stereo images of the respective years

DEMs	Mean elevation difference (<i>MED</i>) (m)	Standard deviation (<i>STDEV</i>) (m)	Number of pixel considered (<i>n</i>)	Standard error ($SE = \frac{STDEV}{\sqrt{n}}$) (m)	Uncertainty ($e = \sqrt{SE^2 + MED^2}$) (m)
SRTM GDEM-v3 – 2002 DEM	-2.44	32.68	19205	0.24	2.45
SRTM GDEM-v3 – 2014 DEM	1.11	32.01	19461	0.23	1.13
2002 DEM – 2014 DEM	-3.05	16.53	22776	0.11	3.05

Table 3

Retreat of the Sakchum, Chhota Shigri, and Bara Shigri glaciers during 1993, 2000, and 2014 (table also compares the results of this study with previous studies)

Glacier name	Retreat (this study) (m/y)			Retreat (previous studies) (m/y)			
	1993-2000	2000-2014	1993-2014	Pandey and Venkataraman (2013), 1980-2010	Azam et al. (2012), 1988-2010	Dobhal et al. (1995), 1962/63-1989	Kulkarni et al. (2007), 1988-2003
Sakchum	20.37 $\pm$ 7.35	5.78 $\pm$ 3.78	10.65 $\pm$ 2.52	-	-	-	-
Chhota Shigri	7.81 $\pm$ 7.35	2.18 $\pm$ 3.78	4.06 $\pm$ 2.52	7.73 $\pm$ 1.0	7.05	7.5	53.33
Bara Shigri	16.00 $\pm$ 7.35	15.27 $\pm$ 3.78	15.51 $\pm$ 2.52	18.67	-	-	-

Table 4

Area change in the Sakchum, Chhota Shigri, and Bara Shigri glaciers during 1993, 2000, and 2014 (table also compares the results of this study with previous studies)

Glacier name	Area change (this study)				Area change (previous studies)
	Area 1993, km ²	Loss in area (1993- 2000), km ²	Loss in area (2000-2014), km ²	Total loss in area (1993-2014), %	Pandey and Venkataraman (2013) (1980-2010), %
Sakchum	15.61 ±0.43	0.19 ±0.0031	0.31 ±0.0032	3.17	-
Chhota Shigri	15.22 ±0.51	0.04 ±0.0031	0.15 ±0.0032	1.26	0.47
Bara Shigri	127.63 ±2.7	0.46 ±0.0031	0.72 ±0.0032	0.92	1.50

Table 5

Debris cover area variations on the Sakchum, Chhota Shigri, and Bara Shigri glaciers during 1993, 2000, and 2014

Glacier name	Debris cover (km ²)			Debris cover (% of glacier area)		
	1993	2000	2014	1993	2000	2014
Sakchum	3.54	3.79	4.57	22.64	24.60	30.25
Chhota Shigri	1.35	1.47	1.80	8.87	9.67	11.96
Bara Shigri	19.98	23.75	24.80	15.66	18.67	19.61

Table 6

Equilibrium line altitudes (ELA) for the Sakchum, Chhota Shigri, and Bara Shigri for the year 1993, 2000, and 2014 along with the standard deviations (SD); standard deviations of ELA represent the elevation range of individual glacier ELAs and not the associated uncertainties (table also shows the elevation range of different glacier zones of the Sakchum, Chhota Shigri, and Bara Shigri glaciers; these were used in extracting the zonal estimates of surface ice velocities (SIV) and surface elevation changes in the glaciers)

Glacier name	ELA (m asl)						Elevation range of glacier zones based on 2014 ELA (m asl)		
	1993		2000		2014		LAZ	UAZ	ACZ
	Mean	SD	Mean	SD	Mean	SD			
Sakchum	4925	213	4978	223	5031	200	<4600	4600 - 5031	> 5031
Chhota Shigri	4968	130	5091	172	5109	111	<4600	4600 - 5109	> 5109
Bara Shigri	5158	180	5232	199	5243	180	<4600	4600- 5243	> 5243

Table 7

Surface ice velocity (SIV) variations of the Sakchum, Chhota Shigri, and Bara Shigri glaciers during 2003/04 and 2013/14 (ACZ= accumulation zone, UAZ= upper ablation zone, LAZ= lower ablation zone); SIV reported here was computed along the central flow line of the respective glaciers (note the significant slowdown of SIV in the UAZ of all the glaciers; the associated uncertainties with SIV measurements are ± 4.9 m/y)

Glacier name	Glacier-wide averaged SIV (m/y)		Zone-wise averaged SIV (m/y)						Minimum SIV (m/y)		Maximum SIV (m/y)	
			2003/04			2013/14						
	2003/04	2013/14	ACZ	UAZ	LAZ	ACZ	UAZ	LAZ	2003/04	2013/14	2003/04	2013/14
Sakchum	13.53	10.63	11.11	16.56	12.91	11.68	10.85	9.37	6.66	5.13	19.41	22.16
Chhota Shigri	27.33	20.90	29.12	33.79	19.09	21.81	27.41	13.49	9.87	7.71	42.75	37.70
Bara Shigri	32.50	25.30	36.95	47.75	12.81	35.33	29.91	10.68	5.39	4.78	57.01	43.16

Table 8

Surface elevation changes in Sakchum, Chhota Shigri, and Bara Shigri glaciers between 2002 and 2014; note the prominent surface lowering in UAZ of Sakchum and LAZ of Bara Shigri glaciers (ACZ= accumulation zone, UAZ= upper ablation zone, LAZ= lower ablation zone); surface elevation change reported here was computed along the central flow line of the respective glaciers from the DEMs generated using the ASTER stereo images; the associated uncertainties with surface elevation change measurements are ± 3.05 m

Glacier name	Glacier-wide averaged surface elevation change (m)	Zone-wise averaged surface elevation change (m)			Minimum surface elevation change (m)	Maximum surface elevation change (m)
		ACZ	UAZ	LAZ		
Sakchum	-14.62	-9.91	-22.80	-11.15	-6.83	-26.40
Chhota Shigri	-10.87	-4.51	-14.94	-13.16	1.35	-23.69
Bara Shigri	-14.52	-10.76	-13.51	-19.28	-1.19	-24.35

List of Figures Captions

Fig. 1. Location map of study area. Glacier boundaries shown by blue polygons are overlain on false color composite (FCC) of Landsat-8 OLI image of 28 September 2014 with band combination R=near infrared band, G= red band and B= green band.

Fig. 2. Retreat of studied glaciers during 1993, 2000, and 2014. ‘A’, ‘B’ and ‘C’ are corresponding zoomed-in views of snouts of the Sakchum, Chhota Shigri, and Bara Shigri. Note the higher retreat in Sakchum and Bara Shigri glaciers in comparison to Chhota Shigri. Main panel background is a false color composite (FCC) of ASTER image of 31 October 2014 (R=near infrared, G= red and B= green). Inset panel background is an FCC of Worldview image of 13 October 2010 (R=near infrared, G= red and B= blue).

Fig. 3. Spatial distribution of surface ice velocity (SIV) for (A) 2003/04 and (B) for 2013/14 derived from respective ASTER images using Cosi-Corr technique. Black lines overlain on glaciers represent the central flow line along which respective SIV and slope (Fig. 4) and surface lowering (Fig. 5) were computed.

Note: Some areas in the upper reaches of Sakchum and Chhota Shigri have partial cloud cover in 2004 ASTER image which resulted in miscorrelation, therefore, these areas were masked out.

Fig. 4. Surface ice velocities of the three glaciers along the central flow line. Panels (A), (B), and (C) display the average SIV for 2003/04 and 2013/14 along with average slope for Sakchum, Chhota Shigri, and Bara Shigri, respectively. Average surface ice velocity (SIV) and average slope for every 1 km distance (for Bara Shigri) and 0.5 km (for Sakchum and Chhota Shigri; calculated along the central line) from the snout have been plotted. (D) Comparison of remote-sensing-derived (from this study) glacier velocity of Chhota Shigri glacier vis-à-vis field measurements (Azam et al., 2012) for the years 2003/04.

Fig. 5. Velocity vectors derived from ASTER image pair of 2003–2004 for Bara Shigri glacier (vector lengths not to scale). Panels ‘A’ and ‘B’ represent the slowest (lower ablation zone) and highest (upper ablation zone) moving parts of the glacier, respectively. Background is an orthorectified ASTER band 3N image of 31 October 2014.

Fig. 6. Spatial distribution of surface elevation change on Sakchum, Chhota Shigri, and Bara Shigri glaciers, deduced by differencing 2014 digital elevation model (DEM) from 2002 DEM. Black lines overlaid on glaciers represent central flow line along which surface lowering has been computed.

Fig. 7. Surface elevation change on the studied glaciers between 2002 and 2014. Panels (A), (B), and (C) display the average elevation change along the central flow line (starting from snout to upper most point of glacier, shown in Fig. 3) for Sakchum, Chhota Shigri, and Bara Shigri, respectively. Average elevation change of Sakchum and Chhota Shigri were computed for every 500 m (0.5 km) distance while for Bara Shigri, surface elevation change were calculated for every 1 km distance.

Fig. 8. Hypsometric curve and integrals (area under the hypsometric curve) for the Sakchum, Chhota Shigri, and Bara Shigri glacier computed from SRTM GDEM-v3. ELA_{SC} , ELA_{CS} and ELA_{BS} represent the normalized equilibrium line altitude (ELA) for the Sakchum (0.4), Chhota Shigri (0.53), and Bara Shigri (0.52), respectively. Notice the maximum area of Sakchum (73%) at an altitude similar to ELA, which makes it most vulnerable to the ongoing climatic variations.