Chapter 13

A GEO-INTELLIGENCE BASED APPROACH TO INVESTIGATE TEMPORAL CHANGES IN THE LENGTH, SURFACE AREA AND ICE VELOCITY OF SAKCHUM GLACIER

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ABSTRACT

The Himalayan-Karakoram (HK) region is often referred as the 'Water Tower of Asia', as the melt water from the glaciers and snow cover of this mountainous region provide a continuous supply of water to the major rivers of South Asia, notably the Indus, Ganga, and Brahmaputra. Recent studies reveal that climate change has altered the accumulation of snow and the snowmelt processes of the region, leading to changes in the size and mass of glaciers, with potential impacts on the river flow downstream and the ecosystems and livelihoods depending on it. Consequently, mapping and monitoring glaciers, mainly through estimates of their spatial extent, recession rate, debris cover extent and surface velocity, are integral parts of water resource management. Because of the rugged topography and harsh climatic conditions of the HK region, estimating these parameters based on traditional techniques is tedious and challenging. The

exploitation of geospatial data and information through Geo-intelligence (GI) has thus emerged as a data collection and processing method in the study of glaciers. It processes images from satellites and airborne vehicles with high-end mathematical and statistical algorithms. This chapter demonstrates the effectiveness of GI techniques to map and monitor the Sakchum Glacier of the HK region with the results suggesting that these techniques could potentially contribute to long-term planning and management of water resources in regions whose water supply depends on the melt water of glaciers.

Keywords: Geo-intelligence (GI), remote sensing, Sakchum Glacier, temporal changes

13.1 INTRODUCTION

The Himalaya–Karakoram (HK) region is a mountainous region covering a surface area of 40,800 km^2 and comprises the largest glacier area outside of the polar region. In the Himalayan region of India alone, there are approximately 9600 glaciers of varying lengths and shapes (Singh and Ramanathan, 2017; Raina and Shrivastava, 2008). The melt water from the glaciers and snow cover of the HK region provides a continuous supply of water to the major rivers of South Asia, notably the Indus, Ganga, and Brahmaputra (Immerzeel et al., 2010; Bolch et al., 2012), thereby supporting ecosystems and the livelihoods of approximately 1.3 billion people. The HK region is highly susceptible to global climate change. Temperatures in the region are increasing at a faster rate than the global average (Singh et al., 2015a), with researchers predicting that this trend will continue into the future (Kraaijenbrink et al. 2017; Singh et al., 2015b). In addition to this rise in temperature, there is evidence of changes in the accumulation and melting of snow (Tawde et al. 2019), affecting the size and mass of glaciers (Maurer et al. 2019), which could potentially impact on river flow downstream (Rai et al., 2019; Singh et al., 2015c). For this reason, the monitoring of glaciers and regular mapping are an integral part of water resource management in regions depending on the melt waters of glaciers such as the HK region.

The influence of climate change on glaciers can be assessed by studying long-term changes in their spatial area, retreat rate, debris cover extent and surface velocity (Bhambri and Bolch, 2011; Chand and Sharma, 2015; Bhambri et al., 2017; Sahu and Gupta, 2019a; Shukla and Garg, 2020). These parameters have traditionally been estimated using field-based methods, but because of the harsh climatic conditions and the difficulty of access to many areas of the Himalayas, regular monitoring of many glaciers using *in situ* measurements is difficult. Hence, Geo-intelligence (GI), which combines the collection of remotely sensed images and their analysis in a Geographical Information System (GIS), has emerged as an alternative and complementary approach to field-based techniques. GI processes images from satellites and airborne vehicles with high-end mathematical and statistical algorithms. Satellite images are available at a spatial resolution varying from 10 to 30m from various sensors, for instance, Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) carried on board the Landsat missions from the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board the Terra satellite, a collaborative mission between the United States of America and Japan, and the MultiSpectral Instrument (MSI) on board of the Sentinel-2 satellite of the European Space Agency (ESA). Higher resolution satellite images at a 2-12 m spatial resolution are also available from declassified images from the CORONA satellite operated by the Central Intelligence Agency and the U.S. Air Force during the period 1959-1972, and the KeyHole (KH)-9 Hexagon satellite operated between 1971 and 1986 by the National Reconnaissance Office. Both missions had for purpose to spy on Soviet military capabilities. These satellite images have previously been used to examine temporal changes in a glacier of the Himalayan region (Chand et al., 2017).

Several studies have used remote sensing to investigate changes in glaciers in the HK region, notably their recession, retreat as well as changes in their surface velocity (Bhambri et al., 2013; Bhushan et al., 2018; Garg et al,. 2017a; Garg et al., 2017b; Kaushik et al., 2018; Sahu and Gupta, 2019b; Shukla et al., 2019). Within the Western Himalaya section of the HK region is Chandra Basin, an important basin with a total of 395 glaciers covering a surface area of 703.3 ± 20.4 km^2 (Sahu and Gupta, 2020b). Chandra Basin is the source of the Chenab River, a major river of the Punjab region flowing in both India and Pakistan, and a tributary of the Indus River. However, few studies have examined temporal changes in the characteristics of the glaciers of Chandra Basin. Pandey and Venkataraman (2013) analysed temporal changes in the surface area and the length of 15 glaciers in that basin during the period 1980-2010 using satellite data from Landsat Multispectral Scanner (MSS) and TM, and the Linear Imaging Self-Scanning Sensor 3 (LISS III) and the Advanced Wide-Field Sensor (AWiFS) from the Indian Space Research Organisation (ISRO). Similarly, Garg et al. (2017b) analysed changes in the surface area and the length of Chhota Shigri, Bara Shigri and Sakchum glaciers from 1993 to 2015 using Landsat TM, ETM+ and ASTER images, but also changes in their surface velocity over the shorter 1999-2015 period. In a study covering a larger geographical area, Sahu and Gupta (2020b) investigated changes in the surface area of 169 glaciers in Chandra Basin, including the Chhota Shigri, Bara Shigri, Gepang Gath, Samudra Tapu and Hamtah glaciers, during the period 1971 to 2016, using images from Corona KH-4, Landsat ETM+ and Sentinel-2. Singh et al. (2020) estimated the seasonal and annual surface velocity of glaciers for 2009-2010 and 2015, respectively. However, Sakchum Glacier in Chandra Basin has not yet been investigated for long term changes in its surface area, length, and surface velocity as a result climate change. Hence, the present study examines changes in the recession rate of the surface area of Sakchum Glacier, as well as its changes in its length and debris cover extent during the period 1971-2019. Moreover, changes in the surface velocity of Satchum Glacier are investigated for the period 1990-2018, although a shorter period is used for this parameter, it is still significantly longer than the previous study focusing on this glacier. This will provide insights on dynamics of the Sakchum Glacier.

13.2 STUDY AREA

Sakchum Glacier is located in Chandra Basin between latitudes 31°10'45"N and 32°14'45"N and longitudes 77°24'0'' E and 77°28'0''E in Lahaul and Spiti district of the northern Indian state of Himachal Pradesh in the Western Himalayas (Figure 13.1). It is a valley type glacier located at 4356 to 5741 m above sea level; it is north-facing and has debris on its surface. Sakchun Glacier is located in the monsoon–arid transition zone and has a tundra climate given its altitude. Although there is no *in situ* weather observation taken on Sakchum Glacier, there is an Automatic Weather Station (AWS) situated near the study area within Chandra Basin at an altitude of approximately 4860 m, with data available for the 7-year period extending from 2009 to 2016. According to these data, mean annual temperature is 5.4°C, with average winter and summer temperature of -11.3°C and 0.5°C, respectively. The weather station also indicated that the region receives precipitation from the Indian Summer Monsoon (ISM), but also from Western Disturbances (WD) in winter (~70%) (Bajpai, 1995). Thus, the basin is completely covered by snow in winter when it becomes isolated and unreachable (Sahu and Gupta, 2020a).

13.3 MATERIALS AND METHODS

This section describes the sources of the satellite data and the methods used to process them. Satellite images were obtained from the CORONA KH-4B (spatial resolution: 3m), Landsat-7 ETM+ (spatial resolution: 30m for bands 1 to 7 and 15m for panchromatic band 8) and Sentinel-

2 MSI (spatial resolution: 10m) missions (Table 13.1), which were used to calculate the recession rate of Sakchum Glacier from 1971 to 2019. Elevation was estimated from the ASTER Global Digital Elevation Map Version 2 (GDEM V2) database, which provides data at a spatial resolution of 30m with a vertical accuracy of 20m. The satellite data were downloaded from the website of the USGS (http://earthexplorer.usgs.gov/). They were obtained at the beginning of the accumulation period (end of the ablation period), as there is minimum snow and cloud cover during that period.

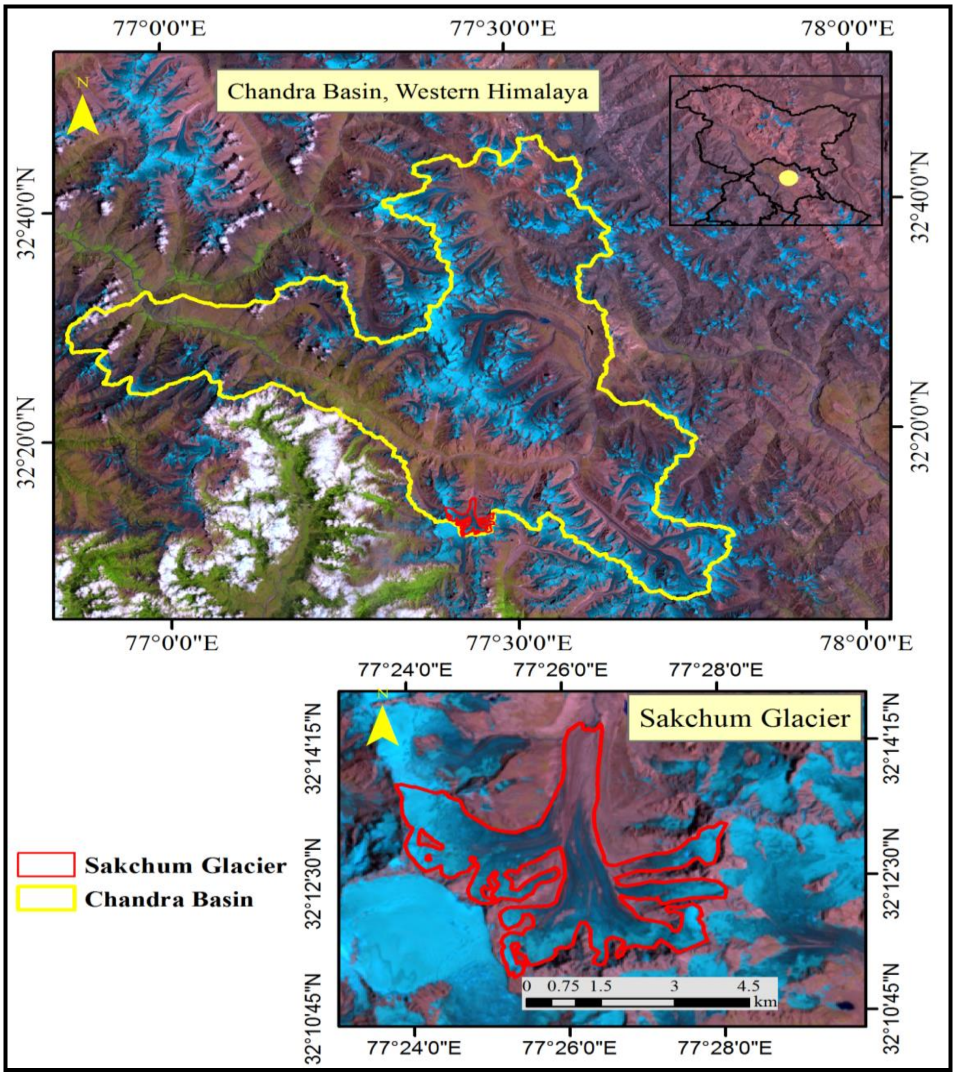

Figure 13.1: Location of study area

The satellite images were checked for geometric and radiometric errors using the software ERDAS Imagine 2016 and ArcGIS 10.3. This analysis found that the CORONA KH-4B image lacked spatial reference. The image was thus co-registered with respect to the georeferenced Landsat-7 imagery using 20 common ground control points, which were visible on both images, and the spline adjustment method. There are three methods available to delineate the boundaries of a glacier on the satellite image: automatic, semiautomatic and manual. Sahu and Gupta (2018) suggested that when analysing only one glacier, the manual method based on visual interpretation is the most suitable, as it provides high positional accuracy. For this reason, the boundary of Sakchum Glacier was delineated through visual interpretation. A centre flow line was drawn within the glacier to estimate changes in the length of the glacier from 1971 to 2019.

Table 13.1: Satellite data used to calculate temporal changes in surface area and length of Sakhum Glacier

Sensor	Date of acquisition	Spatial Resolution (m)	Scene ID	RMSE[1] X,Y (m)
CORONA KH-4B	27-09-1971	3	DS1115-2282DF064	<6
Landsat 7/ ETM+	02-08-2002	30/15 (PAN)	LE07_L1TP_147037_20020802_20170130_01_T1	<15
Sentinel-2 MSI	17-09-2019	10	L1C_T43SGR_A022124_20190917T053926	<10

[1] Root-mean-square error

For the determination of changes in the surface velocity of the glacier, data from the Inter-mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE) project (https://nsidc.org/apps/itslive/), with data available for the period 1990-2018 at a spatial resolution of 240m, were used (Gardner et al., 2018, Gardner et al., 2019). In addition, climate data were obtained from the Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded dataset, available at a 0.25°x0.25° spatial resolution (http://aphrodite.st.hirosaki-u.ac.jp/products.html), to investigate annual and seasonal climate viability over the study area.

13.4 UNCERTAINTY ANALYSIS

Errors or uncertainties inevitably arise when estimating the various glacier parameters, i.e., its boundary, surface area, length, and surface velocity. The uncertainty associated with the estimation of the boundary of a glacier was calculated using the buffer method, which consists of creating a buffer area half the image resolution along the glacier boundary. Accordingly, a buffer of 15m, 5m and 2.5 m was drawn along the glacier boundary on the Landsat-7 ETM+, Sentinel-2, and CORONA KH-4B images, respectively. Errors associated with the estimation of the surface area (Bhambri et al., 2013) and length (Chand et al., 2017) of the glaciers were, for their part, calculated using Eq. 13.1 and 13.2:

$$E_a = \sqrt{b_1^2 + b_2^2} \qquad (13.1)$$

$$E_l = \sqrt{e_1^2 + e_2^2} + R \qquad (13.2)$$

where E_a and E_l represent errors in in the surface area and length of the glacier, respectively; b_1 and b_2 are errors in the mapping of the glacier for individual years; e_1 and e_2 represent the spatial resolution of the first image and the second image, respectively; and R denotes the co-registration error. Errors in surface velocity were obtained directly from the ITS_LIVE product file, which stores uncertainties in the measurements of surface velocity in a separate image file. The study area was cropped from the image and the mean value of all pixels was averaged over study area to estimate the error in surface velocity. These uncertainties are considered in the next section when describing the results of this study

13.5 RESULTS

13.5.1 Analysis of Changes in the Surface Area, Debris Covers Extent and Length of the Glacier

Table 13.2 and Figure 13.2 show the temporal change in the surface area of Sakchum Glacier for three time-periods: 1971-2002, 2002-2019 and 1971-2019, revealing that the surface area of the glacier decreased considerably between 1971 and 2019. In 1971, the glacier had a surface area of 14.32 ± 0.14 km^2 and decreased in spatial extent to 13.84 ± 0.27 km^2 by 2019, representing a decline of 0.49 ± 0.30 km^2 or 3.4 ± 2.1% in the surface area of the glacier over 48 years.

Table 13.2: Temporal changes in the surface area, debris cover extent and length of Sakchum Glacier

Year/time-period	Surface area of the glacier / change in the surface area of the glacier (km^2)	Debris cover extent / Change in debris cover extent (km^2)	Change in the length of the glacier (m)	Recession rate of the glacier (m/yr.)
1971	14.32 ± 0.14	1.78 ± 0.14	-	-
2002	14.03 ± 0.40	2.47 ± 0.40	-	-
2019	13.84 ± 0.27	3.12 ± 0.27	-	-
1971-2002	-0.29 ± 0.43	0.69 ± 0.43	-644 ± 27.09	-20.77 ± 0.87
2002-2019	-0.20 ± 0.48	0.65 ± 0.48	-125 ± 28.01	-7.35 ± 1.64
1971-2019	-0.49 ± 0.30	1.34 ± 0.30	-769 ± 21.44	-16.02 ± 0.45

The rate at which the surface area of the glacier decreased was higher during the more recent 2002-2019 period in comparison to the earlier 1971-2002 period. The surface area of the glacier decreased by 0.29 ± 0.43 km^2 between 1971 and 2002 (31 years), representing a receding rate of 0.065% per year, while it recorded a loss of 0.20 ± 0.48 km^2 during the 17-year period extending from 2002 to 2019, a 0.083% decrease per year. The areal extent of the debris cover area of the glacier substantially increased during the 1971-2019 period. In 1971, it was estimated at 1.78 ± 0.14 km^2, and increased by 75.3% to 3.12 ± 0.27 km^2 by 2019. Given the relationship between an increase in the debris cover area of a glacier and its recession rate (Mal et al., 2019), it is not surprising to observe a recession of Sakchum Glacier. It was found that the length of the glacier decrease by 769 ± 21.44m over the 48-year period extending from 1971 to 2019, representing a recession rate of 16.02 ± 0.45m per year

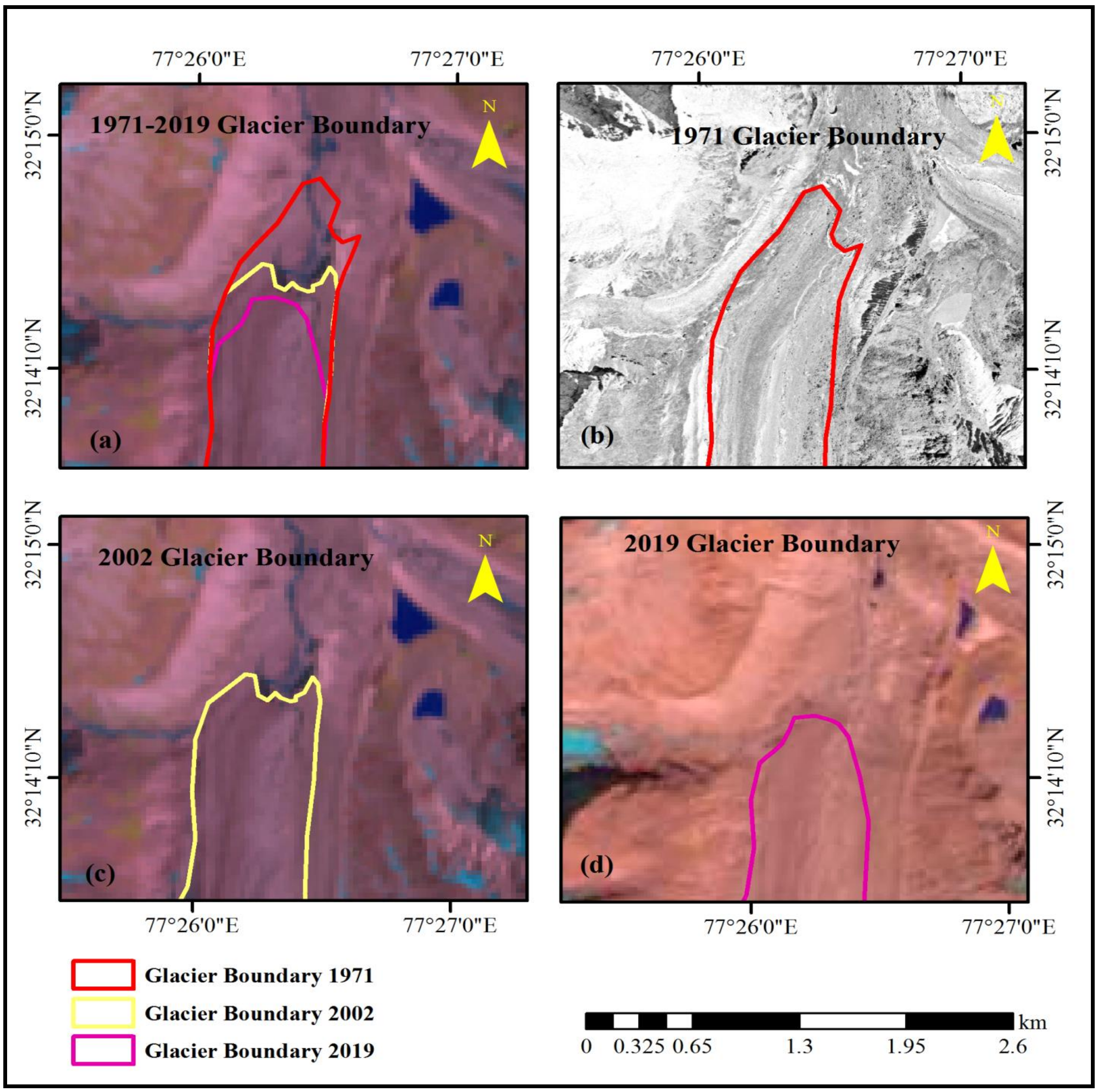

Figure 13.2: Changes in the surface area of Sakchum Glacier during the period 1971-2019 (a) and boundaries of the glaciers during the years 1971 (b), 2002 (c) and 2019 (d).

13.5.2 Changes in the Surface Velocity of the Glacier

The surface velocity data from Sakchum Glacier show high spatial variability in patterns of change across the glacier between 1990 and 2018 (Figure 13.3). Variation in annual surface velocity along the centre flow line of the glacier was also investigated. The highest surface velocity was observed in 1990 when it reached 14.2 ± 4.3m/yr., while it was the lowest in 2017 at 5.0 ± 2.7m/yr. (Table 13.3).

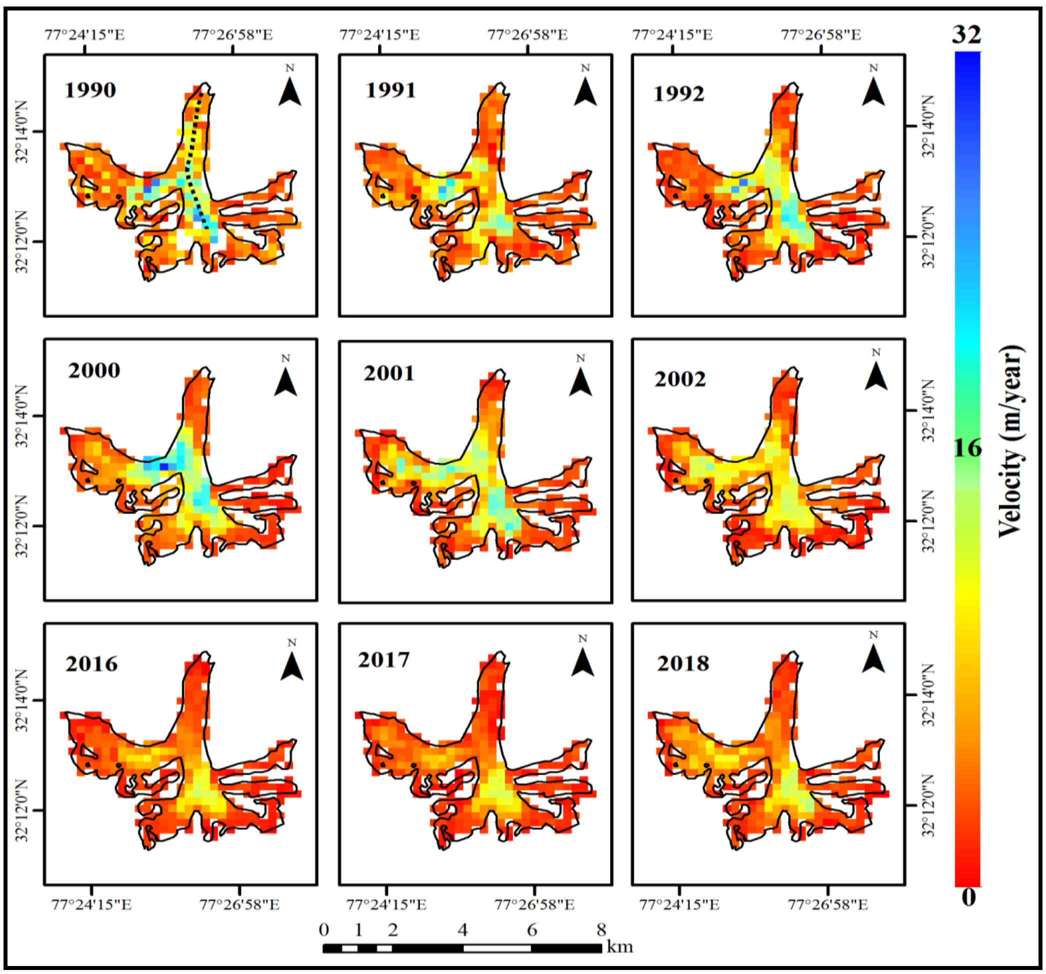

Figure 13.3: Changes in the surface velocity of Sakchum Glacier during the periods 1990-1992, 2000-2002 and 2016-2018

Table 13.3: Surface velocity of Sakchum Glacier during the period 1990-2019

Year / time-period	Glacier surface velocity	Year / time-period	Glacier surface velocity	Year / time-period	Glacier surface velocity
1990	14.2 ± 4.3	2000	12.0 ± 3.7	2016	5.9 ± 3.1
1991	7.8 ± 4.1	2001	10.6 ± 3.2	2017	5.0 ± 2.7
1992	10.9 ± 3.8	2002	8.2 ± 3.4	2018	6.3 ± 3.2
1990-1992	11.0 ± 5.7	2000-2002	10.3 ± 5.0	2016-2018	5.7 ± 4.8

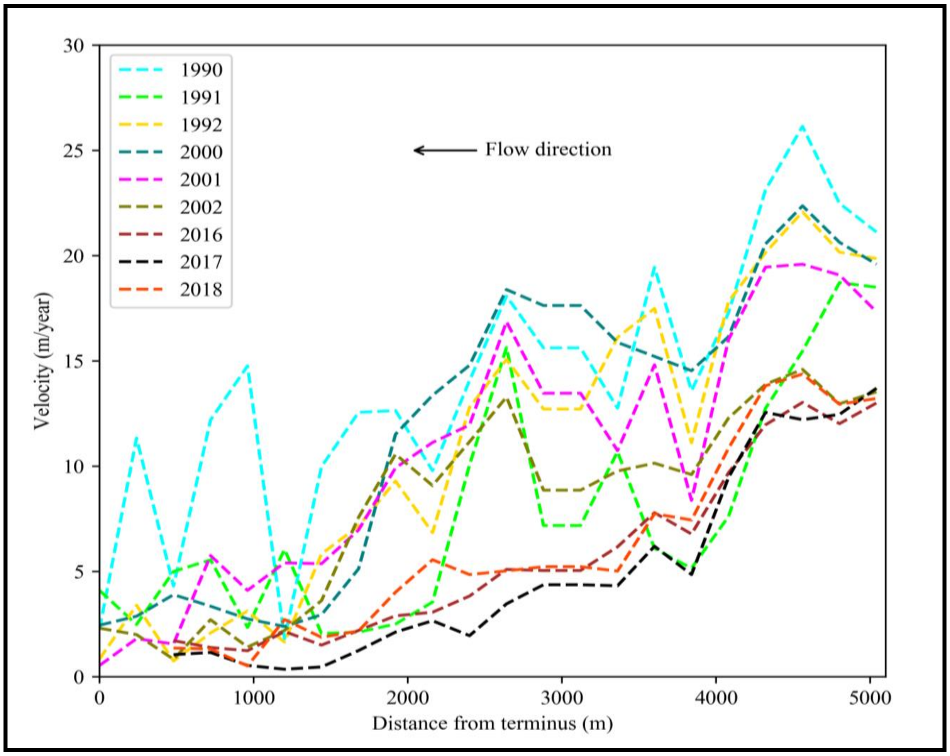

Figure 13.4: Surface velocity of Sakchum Glacier for individual years during the periods 1990 to 1992, 2000 to 2002 and 2016 to 2018 along the centre flow line

A decrease in annual surface velocity of Sakchum Glacier was observed from 1990-1992 to 2016-2018 (Figure 13.4). The average annual surface velocity during the period 1990-1992 was 11.0 ± 5.7m/yr., but this decreased to 5.7 ± 4.8 m/yr. during the more recent 2016-2018 period, representing a 48.2% decline in surface velocity of the glacier. A comparison of the average surface velocity of the glacier and elevation reveals that as the elevation increases, the surface velocity of the glacier also increases. However, no clear relationship is seen between the average surface velocity and the slope of the glacier (Figure 13.5). These results are in agreement with Garg et al. (2017b), when considering the uncertainty in the measurements, as they found that the surface velocity of Sakchum Glacier varied between 13.53 ± 4.5m/yr. and 10.63 ± 4.5 m/yr. during the period 2003-2004 and 2013-2014, respectively.

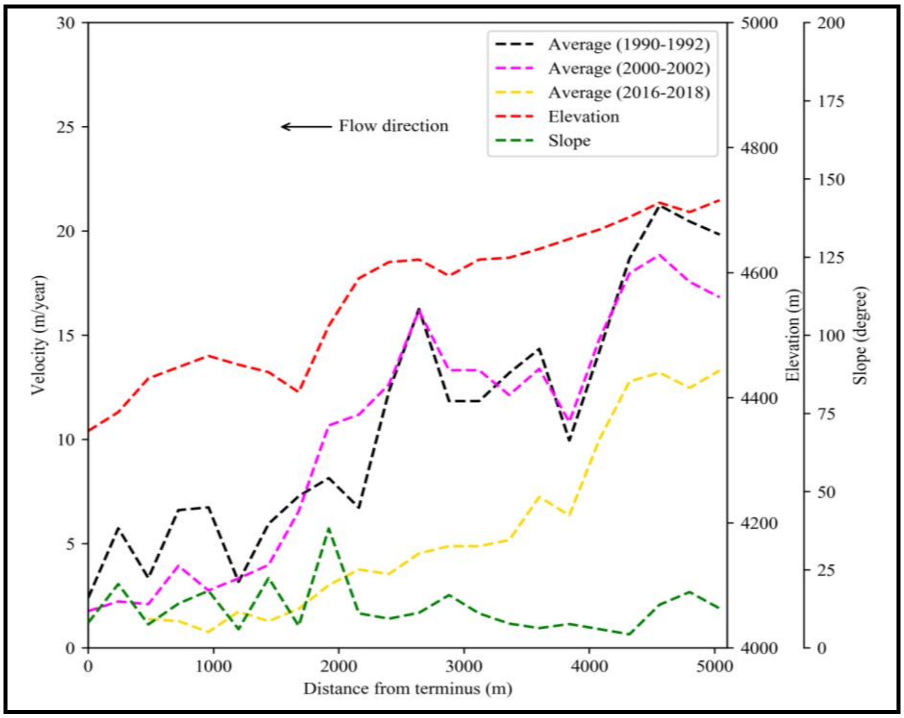

Figure 13.5: Average surface velocity of Sakchum Glacier from 1990 to 1992, 2000 to 2002 and 2016 to 2018 along the centre flow line and the elevation and slope of the glacier

13.6 DISCUSSION

The decrease in the surface area, length and surface velocity of Sakchum Glacier calculated in this study could be attributed to temporal changes in climate. A trend analysis on annual temperature and precipitation data reveals that temperature has increased and that precipitation decreased during over the period 1950-2015 (Figure 13.6).

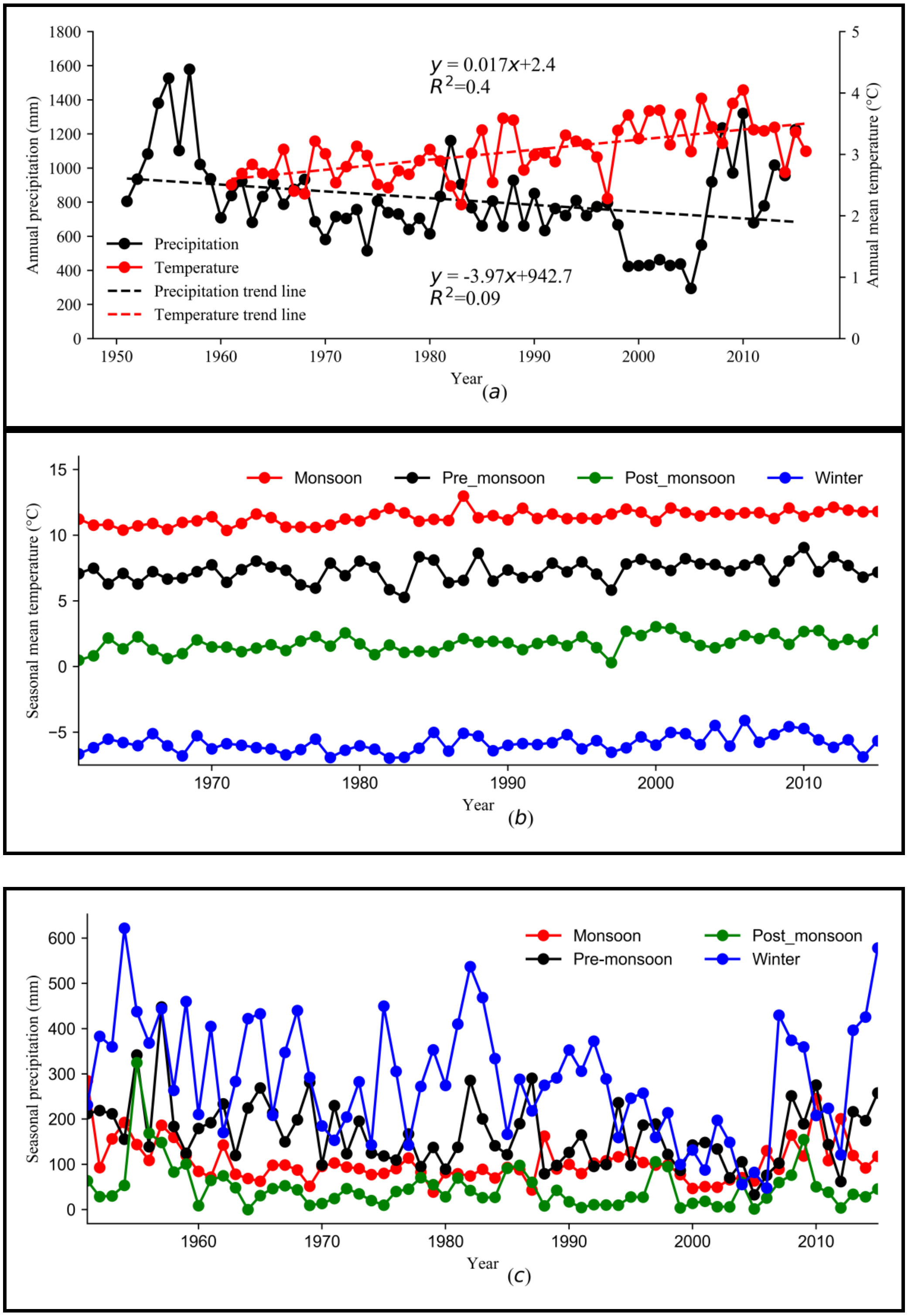

Figure 13.6: (a) annual temperature and precipitation, (b) seasonal temperature and (c) seasonal precipitation

Similar patterns of change are also seen for temperature and precipitation at the seasonal timescale. Although temperature gradually increased during the study period, an abrupt decrease in precipitation is observed between 1997 and 2006. This might be the reason for the reduced surface velocity of the glacier between 2016 and 2018, as it has increased melting rate resulting in the loss of glacier mass, changes in surface gradients and increased in the debris cover area (Sahu and Gupta, 2019b; Shukla and Garg, 2020). The findings of this study are also supported by those of Mukherjee et al. (2018) and Azam et al. (2014). Mukherjee et al. (2018) previously conducted a study in Lahaul and Spiti district, reporting that the glacier melting rate increased in the year 2000, which they associated with an increase in mean summer temperature and a decrease in winter precipitation. Azam et al. (2014) observed variability in winter precipitation at Bhuntar near Chhota Shigri Glacier. Thus, in the late of 20th and early of 21st century, the rise in temperature, and decrease (including seasonal variability) in precipitation are the most important factors controlling rates of glacier recession, retreat, and surface velocity in the HK region.

13.7 CONCLUSION

In the present study, changes in the area, length and debris covered ice were examined for Sakchum Glacier for the period 1971-2019 using satellite data from CORONA KH-4B, Landsat 7 and ETM+, and Sentinel-2 MSI, while changes in surface velocity were estimated using ITS_LIVE surface velocity product from 1990 to 2018. This analysis reveals that in 1971 the glacier area was 14.32±0.14 km^2, which decreased to 14.03 ± 0.4 km^2 in 2002 and then to 13.84 ± 0.27 km^2 in 2019. The loss in total glacier area was thus 0.49 ± 0.3 km^2 (3.41 ± 2.98%) during period 1971-2019. The retreat rate of Sakchum Glacier was calculated to be 20.77 ± 0.87 m/yr. during the period 1971-2002, but with a less pronounced retreat rate of 7.35 ± 1.64 m/yr. during the more recent 2002-2019 period. On the other hand, the debris covered glacier ice increased from 1.78 ±0.14 km^2 in 1971 to 3.12 ± 0.27 km^2 in 2019.

The calculation of changes in the length of Sakchum Glacier was performed along the centre flow line in the ablation zone. It was estimated that during the period 1971-2019, the glacier retreated by 769 ± 21.44 m, representing a retreat rate of 16.02 ± 0.45 m/yr. A 48.2% decrease in average surface velocity of Sakchum Glacier was also observed when comparing data from the period 1990-1992 to the period 2016-2018. Such a reduction in surface velocity has occurred as a result of a decrease in the mass of the glacier, which changes the surface gradient and increases the debris-covered area.

REFERENCES

Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, A., Linda, A., & Singh, V. B. (2014). Reconstruction of the annual mass balance of Chhota Shigri glacier , Western Himalaya , India , since 1969. *Annals of Glaciology*, *55*(66), 1–12. doi:10.3189/2014AoG66A104

Bajpai, S. C. (1995). “Lahaul-Spiti: A Forbidden Land in the Himalayas” (pp. 1−9)., 3rd ed., New Delhi: Indus Publishing Company.

Bhambri, R., & Bolch, T. (2011). Mapping of debris-covered glaciers in the Garhwal Himalayas using ASTER DEMs and thermal data. *International Journal of Remote Sensing*, *32*(23), 8095–8119. doi:10.1080/01431161.2010.532821

Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D. P., Srivastava, D., & Pratap, B. (2013). Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. *The Cryosphere*, *7*, 1385–1398. doi:10.5194/tc-7-1385-2013

Bhambri, R., Hewitt, K., Kawishwar, P., & Pratap, B. (2017). Surge-type and surge-modified glaciers in the Karakoram. *Scientific Reports*, *7*(1), 1–14. doi:10.1038/s41598-017-15473-8

Bhushan, S., Syed, T. H., Arendt, A. A., & Kulkarni, A. V. (2018). Assessing controls on mass budget and surface velocity variations of glaciers in Western Himalaya. *Scientific Reports*, (may), 1–11. doi:10.1038/s41598-018-27014-y

Bolch, T., A. V Kulkarni, A. Kääb, C. Huggel, F. Paul, Cogley, H. Frey, et al. 2012. “The State and Fate of Himalayan Glaciers.” *Science* , 336: 310–314.

Chand, P., & Sharma, M. C. (2015). Glacier changes in the Ravi basin , North-Western Himalaya (India) during the last four decades (197 –2010/13). *Global and Planetary Change*, *135*, 133–147. doi:10.1016/j.gloplacha.2015.10.013

Chand, P., Sharma, M. C., Bhambri, R., Sangewar, C. V., & Juyal, N. (2017). Reconstructing the pattern of the Bara Shigri Glacier fluctuation since the end of the Little Ice Age, Chandra valley, north-western Himalaya. *Progress in Physical Geography*, *41*(5), 643–675.

doi:10.1177/0309133317728017

Gardner, A. S., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., van den Broeke, M. & Nilsson, J. (2018). Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years, *The Cryosphere, 12(2)*: 521–547, doi:10.5194/tc-12-521-2018.

Gardner, A. S., Fahnestock, M. A. & Scambos, T. A. (2019). ITS_LIVE Regional Glacier and Ice Sheet Surface Velocities. Data archived at National Snow and Ice Data Center; doi:10.5067/6II6VW8LLWJ7.

Garg, P. K., Shukla, A., & Jasrotia, A. S. (2017a). Influence of topography on glacier changes in the central Himalaya, India. *Global and Planetary Change*, *155*(July), 196–212. doi:10.1016/j.gloplacha.2017.07.007

Garg, P. K., Shukla, A., Kamal, R., & Singh, A. (2017b). Assessing the status of glaciers in part of the Chandra basin , Himachal Himalaya : A multiparametric approach. *Geomorphology*, *284*, 99–114. doi:10.1016/j.geomorph.2016.10.022

Immerzeel, W. W., Beek, L. P. H. V, & Bierkens, M. F. P. (2010). Climate Change Will Affect the Asian Water Towers. *Science*, *328*, 1382–1385. doi:10.1126/science.1183188

Kaushik, S., Dharpure, J. K., Joshi, P. K., Ramanathandand, A., & Singh, T. (2018). Climate change drives glacier retreat in Bhaga basin located in Himachal Pradesh, India. *Geocarto International*. doi:10.1080/10106049.2018.1557260

Kraaijenbrink, P., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, *549*(7671), 257–260. doi:10.1038/nature23878

Maurer, J. M., Schaefer, J. M., Rupper, S., & Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. *science advance*, *5*(6).

Mukherjee, K., Bhattacharya, A., Pieczonka, T., Ghosh, S., & Bolch, T. (2018). Glacier mass budget and climate reanalysis data indicate a climatic shift around 2000 in Lahaul-Spiti, western

Himalaya. *Climatic Change*, *148*(1–2), 219–233. doi:10.1007/s10584-018-2185-3

Pandey, P., & Venkataraman, G. (2013). Changes in the glaciers of Chandra – Bhaga basin , Himachal Himalaya , India , between 1980 and 2010 measured using remote sensing. *International Journal of Remote Sensing*, *34*(15), 5584–5597. doi:10.1080/01431161.2013.793464

Patel, A., Dharpure, J. K., Mani, S., & Ganju, A. (2019). Estimating Surface Ice Velocity on Chhota-Shigri glacier from Satellite data using Particle Image Velocimetry (PIV) technique. *Geocarto International*, *34*(4), 335–347. doi:10.1080/10106049.2017.1404142

Pratap, B., Sharma, P., Patel, L. K., Singh, A., Gaddam, V. K., Oulkar, S., & Thamban, M. (2019). Reconciling High Glacier Surface Melting in Summer with Air Temperature in the Semi-Arid Zone of Western Himalaya. *Water*, *11*(8), 18. doi:https://doi.org/10.3390/w11081561

Sahu, R., & Gupta, R. D. (2018). Conceptual Framework of Combined Pixel and Object-based Method for Delineation of Debris-Covered Glaciers. In *ISPRS TC V Mid-term Symposium "Geospatial Technology – Pixel to People"* (pp. 173–180).

Rai, S. P., Singh, D., Jacob, N., Rawat, Y. S., & Arora, M. (2019). Identifying contribution of snowmelt and glacier melt to the Bhagirathi River (Upper Ganga) near snout of the Gangotri Glacier using environmental isotopes. *Catena*, *173*, 339-351.

Sahu, R., & Gupta, R. D. (2019a). Surface Velocity Dynamics of Samudra Tapu Glacier, India from 2013 to 2017 Using Landsat-8 Data. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(5/W2), 75–81. doi:10.5194/isprs-annals-IV-5-W2-75-2019

Sahu, R, & Gupta, R. D. (2019b). Spatiotemporal variation in surface velocity in Chandra basin glacier between 1999 and 2017 using Landsat-7 and Landsat-8 imagery. *Geocarto International*. doi:10.1080/10106049.2019.1659423

Sahu, R., & Gupta, R. D. (2020a). Snow cover area analysis and its relation with climate variability in Chandra basin, Western Himalaya, during 2001–2017 using MODIS and ERA5 data. *Environmental Monitoring and Assessment*, *192*(8), 1–16. doi:10.1007/s10661-020-08442-8

Sahu, R., & Gupta, R. D. (2020b). Glacier mapping and change analysis in Chandra basin, Western Himalaya, India during 1971–2016. *International Journal of Remote Sensing*, *41*(18), 6914–6945. doi:10.1080/01431161.2020.1752412

Shukla, A., & Garg, P. K. (2020). Spatio-temporal trends in the surface ice velocities of the central Himalayan glaciers, India. *Global and Planetary Change*, *190*(May). doi:10.1016/j.gloplacha.2020.103187

Shukla, A., Garg, S., Mehta, M., Kumar, V., & Shukla, U. K. (2019). Temporal inventory of glaciers in the Suru sub-basin, western Himalaya: Impacts of the regional climate variability. *Earth System Science Data*, *122*(August).

Shukla, S. P., Mishra, R., & Chitranshi, A. (2015). Dynamics of Hamtah Glacier , Lahaul & Spiti district , Himachal Pradesh. *Journal of indian geophysics union*, *19*(4), 414–421.

Singh, G., Nela, B. R., Bandyopadhyay, D., Mohanty, S., & Kulkarni, A. V. (2020). Discovering anomalous dynamics and disintegrating behaviour in glaciers of Chandra-Bhaga sub-basins, part of Western Himalaya using DInSAR. *Remote Sensing of Environment*, *246*. doi:10.1016/j.rse.2020.111885

Singh, D., Gupta, R. D., & Jain, S. K. (2015a). Statistical analysis of long term spatial and temporal trends of temperature parameters over Sutlej river basin, India. *Journal of Earth System Science*, *124*(1), 17-35.

Singh, D., Jain, S. K., & Gupta, R. D. (2015b). Statistical downscaling and projection of future temperature and precipitation change in middle catchment of Sutlej River Basin, India. *Journal of Earth System Science*, *124*(4), 843-860.

Singh, D., Gupta, R. D., & Jain, S. K. (2015c). Assessment of impact of climate change on water resources in a hilly river basin. *Arabian Journal of Geosciences*, *8*(12), 10625-10646.

Tawde, S. A., Kulkarni, A. V, & Bala, G. (2019). An assessment of climate change impacts on glacier mass balance and geometry in the Chandra Basin, Western Himalaya for the 21st century. *Environmental Research Communications*, *1*(4), 1–9. doi:10.1088/2515-7620/ab1d6d

Tiwari, R. K., Gupta, R. P., & Arora, M. K. (2014). Estimation of surface ice velocity of Chhota-Shigri glacier using sub-pixel ASTER image correlation. *Current Science*, *106*(6), 853–859.