Long-term spatiotemporal variability in the glacier surface velocity of Eastern Himalayan glaciers, India

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Abstract: Investigation of spatiotemporal variation in glacier velocity is imperative to comprehend glacier mass and volume loss as a function of their sensitivity to climate change. The long-term glacier velocity record for Eastern Himalayan region is of utmost importance owing to its data scarcity and climate sensitivity. Here, we present a long-term dataset spanning over more than two decades (1994-2020) of glacier surface velocity for the entire Sikkim Himalaya by applying image correlation method on the multi-temporal Landsat images. Our result demonstrates an average glacier surface velocity decline from 15.7±5.69 (1994/96) to 12.88±2.09 m yr^{-1} (2018/2020) i.e. decline by ~15% during the period of investigation. Trend analysis shows decreasing trend in median velocity (32.2%) at a rate of 0.25 m yr^{-1}. Despite the general decline in average glacier velocity, rate of slowdown of individual glaciers is extremely heterogeneous (3.6-20 m yr^{-1}). Our study shows that up to 32% of the observed heterogeneity in velocity variation can be explained by the variation in glacier size. The present study highlights that large glaciers with thick ice cover move faster as compared to small glaciers (even those situated on the steep slopes). The findings are significant and have direct implications for assessing future water availability scenarios and modeling glacio-hydrology in the region.

Keywords: Eastern Himalaya, Glacier Surface Velocity, and Remote sensing.

1. Introduction

Glacier-fed rivers of the High Mountain Asia (HMA) supply water to the most densely populated regions (~20% world population) of South and Central Asia [1]. This cryosphere region acts as the lifeline to the population living in the downstream regions by supporting fresh water supply, hydropower generation, environmental services, and eco-tourism. Thus, largely influencing the socio-economic activities of the region [2]. Therefore, the HMA cryosphere has attracted considerable attention from the global glaciology community in recent years [3,4]. Moreover, the cryosphere region of HMA has experienced unprecedented and non-uniform behavior in response to the changing climate [4-6]. Several studies have highlighted notably imbalanced state of the glaciers in HMA, which has resulted in a general glacier mass loss [4,7,8], slowdown [3] and lake expansion [9,10]. However, the Kunlun and Karakoram region glaciers show anomalous behavior where glaciers are either stable or advancing [11,12]. Information of glacier velocity is imperative in order to understand glacier mass [3], ice volume [13], surge event of glacier [14], topography [15] and response to climate change [16,17]. Additionally, glacier flow bears significance in terms of concomitant supraglacial and proglacial lake formation and expansion [18]. As ice flow within the glacier system is a combined effect of ice deformation, mass flux and basal movement [3], the glacier velocity is considered one of the most important glaciological parameter to understand overall dynamics of glacier system and hazard assessment. The proliferation of satellite imagery and improved spatial resolution provide vast potential to study glacier flow dynamics at regional and global scales. To derive accurate glacier velocity fields, various feature tracking algorithms are available [19-22]. In general, feature tracking algorithms compute pixel displacement between two remotely sensed images acquired over the same area but at two different times. Initially, several studies utilized normalized cross-correlation to derive glacier velocity [14,19,20,23]. Later, cross-correlation [21] and phase correlation [5,22] in the frequency domain were extensively used for glacier velocity estimation. Despite a particular relevance of studying long-term spatio-temporal variability in glacier velocity, such studies have either concentrated on western Himalaya or localized glaciers but rarely in the Eastern Himalaya region (Fig. 1A & Table 1).

The spatially heterogeneous glacier slowdown in the entire Hindu Kush-Himalaya (HKH) region is evident from previous studies [3,5,16,24-26]. Notably, the available literature highlights a scarcity of glacier velocity data for a significant part of Eastern Himalaya (Sikkim Himalaya in particular). Specifically, only two studies have attempted to investigate glacier velocity in Sikkim Himalaya [3,16]. These studies made notable contribution to the existing knowledge of glacier flow in the Eastern Himalayan region. Garg et al. [16] provides velocity information at glacier scale during 1990-2015. Dehecq et al. [3] report glacier flow trends across the HMA during 2000-2017. Although these studies suffer from several limitations such as Garg et al. [16] analyzed only 23 of the larger glaciers in the region and glacier velocity was estimated only for three epochs (i.e. 1990±3 years, 2000±3 years, and 2015±3 years) leaving gaps to our understating of glacier flow in the region. These observations are not enough to comprehend the entire Sikkim Himalaya's glacier velocity pattern at higher temporal resolution. The results of Garg et al. [16] were extracted along the center flow line where a higher signal of glacier velocity is expected, owing to the converging ice flow and higher glacier thickness. In contrast, Dehecq et al. [3] presented the glacier velocity trend analysis for the glaciers larger than 5 km^2. It is noteworthy that Dehecq et al. [3] does not take into account smaller glaciers wherein about 75% glaciers in the Sikkim Himalaya are smaller than 5 km^2 [27]. Additionally, accumulation zones have been excluded from the analysis presented in Dehecq et al. [3] owing to large measurement uncertainties. Therefore, large parts of the Eastern Himalaya including Sikkim have not been reasonably examined. This part is even more important as several studies have demonstrated how quickly smaller glaciers tend to respond to the changing climate [5,16]. In particular, the Eastern Himalaya is responding faster than any other Himalayan region [3,9]. This, in turn, has ensued in a higher rate of terminus retreat [28], mass loss [7], expansion of high-altitude lakes [29,30], and slowdown and down wasting [16]. Thus, there is ample scope for the presented investigation from the Sikkim Himalaya (at least as a representative of the Eastern Himalaya). Such an investigation can be unique for the region in studying the relationship between glacier flow and surface topography and improving our knowledge of the topographic control on glacier flow. To this end, our objective are – (1) to assess long-term spatiotemporal (1994-2020) glacier velocity of the entire Sikkim Himalaya (Fig. 1B) using optical remote sensing data, and (2) to analyze topography and debris as possible controls on glacier motion in the Sikkim Himalaya.

2. Materials and Methods

2.1. Study site

The presented study focuses on Sikkim, a state in northeastern India (Fig. 1). This is the second smallest state of India (7096 km^2) and shares a border with Nepal in the west, Bhutan in the east, West Bengal in the south, and Tibet in the north. The spatial extent of study region varies from 27 to 28° N latitude and 88 to 89° E longitude (Fig. 1B). The study region receives high annual precipitation (2000-4000 mm); major source of precipitation (>80%) for this region is the Indian Summer Monsoon [31]. Long-term meteorological observation at Gangtok station reveals increasing trend in minimum temperate (0.036º C yr^{-1}) and decreasing trend (0.027º C yr^{-1}) in maximum temperature during 1961-2017 [32]. Almost 35-40% of study region remained snow-capped even during the summer season [33]. Sikkim Himalaya hosts the third highest peak on Earth (i.e. Mt. Kanchenjunga) and harbors the typical summer accumulation-type glaciers. Sikkim is one of India's ecological hotspots with a wide variety of alpine, tropical, temperate and tundra plant species. This ecological diversity is closely dependent on the freshwater availability in the region owing to glacier-melt. Sikkim state has steep slopes (> 43% of area) and escarpments with rugged terrain. The state's topographic relief ranges from ~300 m above sea level at the valley floor to 8586 m asl at Mt. Kanchenjunga summit.

Hydrologically, numerous streams have carved out river valleys in the west and south Sikkim. These streams collectively make two major river systems, namely, Tista and Rangit originating from the high-altitude glacierized region.

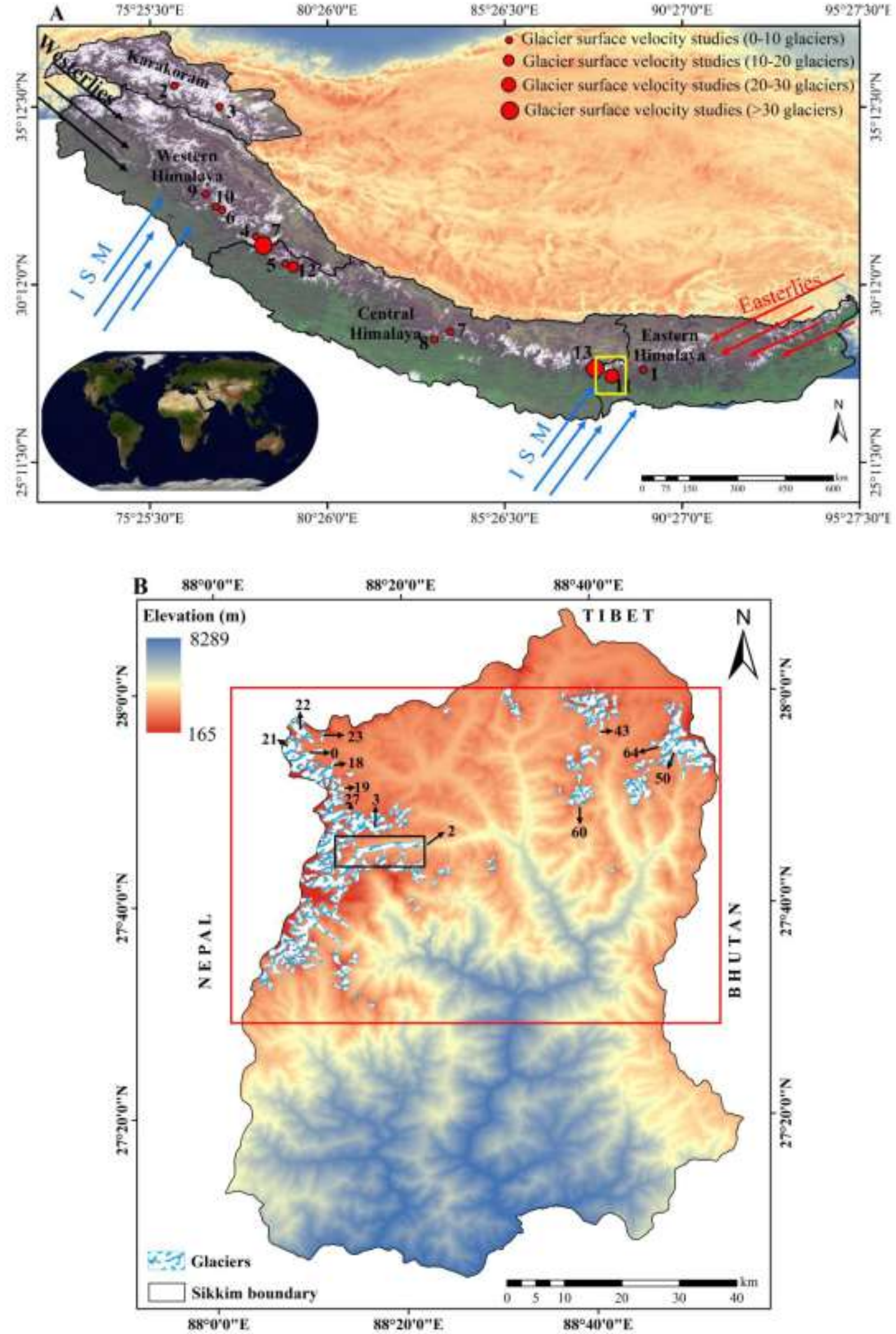

Fig. 1. (A) Map of some significant glacier velocity studies carried out in the Himalaya and Karakoram. This map does not include study reported by Dehceq et al. [8] which provides a regional assessment of glacier velocity concentrated only on large (>5 km^2) glaciers. Yellow box shows location of study area, (ISM - Indian Summer Monsoon). Inset map shows location of Himalaya and Karakoram on world map. The boundary of the Himalayan region is taken from Bolch et al. [34]. (B) Map of study area showing studied glaciers and topography. The glacier boundaries are taken from Randolph Glacier Inventory Version 6 (RGI V6) and Advanced Land Observing Satellite (ALOS) - Phased Array type L-band Synthetic Aperture Radar (PALSAR) (12.5 m) DEM is used for displaying topography. Fastest flowing glacier (ID 2, Zemu) and all other marked glaciers such as ID0 = South Lohnak, ID21 = Middle Lohnak, and ID22= North Lohnak, provide contextual information for Fig. 6 and 7. The red and black box provides a contextual overview of figures 4 and 5.

Table 1. Overview of some significant glacier velocity studies shown in figure 1A.

S.No.	Author	Study area	Observations
1.	Kääb et al. [35]	Bhutan Himalaya	*220 m yr^{-1} **20 m yr^{-1}
2.	Quincey et al. [36]	Central Karakoram	***~2000 m yr^{-1}
3.	Kumar et al. [37]	Siachen glacier, Karakoram	*43 cm day^{-1} **5 cm day^{-1}
4.	Sam et al. [38]	Baspa Basin	*25.93 m yr^{-1} **0.025 m yr^{-1}
5.	Satyabala et al. [25]	Gangotri glaciers	*~70 m yr^{-1} **~5 m yr^{-1}
6.	Garg et al. [39]	Chandra basin, Western Himalaya	*~5 m± 4.9 m yr^{-1} *~60 m± 4.9 m yr^{-1}
7.	Sam et al. [15]	Baspa Basin	*~321.4 m yr^{-1} **0.15 m yr^{-1}
8.	Kraaijenbrik et al. [40]	Lirung Glacier, Central Himalaya	*6 , yr^{-1} *~1.5 m yr^{-1}
9.	Robson et al. [41]	Mansalu region, Central Himalaya	*~200 m yr^{-1} **~0 m yr^{-1}
10.	Bhushan et al. [42]	Zaskar basin, Western Himalaya	*~90±5.58 m yr^{-1} *<10±5.58 m yr^{-1}
11.	Yellal et al. [26]	Chandra basin, Western Himalaya	*28.11 m yr^{-1} **1.76 m yr^{-1}
12.	Garg et al. [16]	Sikkim Himalaya	*124.77 ± 2.51 m yr^{-1} **3.24 ± 2.51 m yr^{-1}
13.	Shukla et al. [24]	Central Himalaya	*56.84± 1.6 m yr^{-1} **6.97± 1.4 m yr^{-1}
14.	Zhao et al. [17]	Kanchenjunga region	*1752 m yr^{-1} **0.01 m yr^{-1}

Note: * = Maximum velocity, ** = Minimum velocity, *** = Surge event

2.2. Satellite data

The present study uses Landsat TM, ETM+, and OLI imagery acquired over the period of 1994 to 2020 (https://earthexplorer.usgs.gov). The Landsat imagery are orthorectified and radiometrically corrected (L1T and L1TP). Available satellite imageries of the ablation season with minimal cloud and seasonal snow coverage are used. The glaciers of Sikkim Himalaya fall under the category of monsoon-fed glaciers and thereby, the images from November and December are preferred. However, in the absence of cloud-free November and December images, ± 1-month images are used. The list of Landsat satellite data used for glacier velocity estimation is given in Table 2. The years with insufficient coverage of the study area owing to the significant cloud or seasonal snow-covered images have been excluded from this analysis. In order to extract the topographic information this study used (SRTM) Digital Elevation Model version-3 (DEM v-3) (https://earthexplorer.usgs.gov/).

Table 2. List of Landsat satellite data used to estimate glacier velocity

Scene ID	Spatial resolution (m)	Date of acquisition
LT05139041199412020 1	30	02-12-1994
LT05139041199611050 1	30	05-11-1996
LT05139041199812290 1	30	29-12-1998
LT05139041200012020 1	30	02-12-2000
LE71390412000361SGS00	30, 15 PAN	26-12-2000
LE71390412001363BKT00	30, 15 PAN	29-12-2001
LE71390412002350SGS00	30, 15 PAN	16-12-2002
LT05139041200402130 1	30	13-02-2004
LT05139041200412290 1	30	29-12-2004
LT05139041200511140 1	30	14-11-2005
LT05139041200612030 1	30	03-12-2006
LT05139041200812080 1	30	08-12-2008
LT05139041200911250 1	30	25-11-2009
LT05139041201012300 1	30	30-12-2010
LT05139041201101310 1	30	31-01-2011
LC81390412013340LGN01	30, 15 PAN	06-12-2013
LC81390412014311LGN01	30, 15 PAN	07-11-2014
LC81390412015362LGN02	30, 15 PAN	28-12-2015
LC81390412016365LGN01	30, 15 PAN	30-12-2016
LC81390412017047LGN00	30, 15 PAN	16-02-2017
LC81390412017351LGN00	30, 15 PAN	17-12-2017
LC81390412018338LGN00	30, 15 PAN	04-12-2018
LC81390412020360LGN00	30, 15 PAN	25-12-2020

2.3. Glacier velocity and topographic control estimation

The standard Co-registration of Optically Sensed Images and Correlation (COSI-Corr) method was adapted to estimate glacier velocity [43]. In the past several studies have successfully demonstrated the capabilities of this tool to assess glacier velocity [5,22,24]. This image correlation algorithm uses a phase correlation method that depends on the Fourier shift theorem. The relative displacement between image pairs of similar characteristics is retrieved through an iterative, unbiased process that estimates their Fourier Transform phase difference [43]. COSI-Corr estimates surface displacement using variable window size (initial and final). Initial window size is typically a large-scale window which maximizes the correlation between image pair whereas the final window size looks for the finer details. The standard COSI-Corr algorithm gives an output in the form of East-West (EW) displacement, North-South (NS) displacement and signal-to-noise ratio (SNR). The typical COSI-Corr process allows estimation of horizontal displacement with an accuracy of sub-pixel resolution (i.e. 1/20–1/10 of the spatial resolution) [22].

The Landsat image pair were directly correlated using 32×32 pixels window as the initial window and 16×16 pixels window as final search window. The step size of 8 and 4 pixels for 15 m Pan and 30 m TM, respectively, between adjacent correlations, resulted in glacier velocity maps sampled at 120 m. In the post-processing steps, we adopted the methodology proposed by [44], using primarily four filters (i.e., cloud mask, low Signal to Noise Ratio pixel, replace/discard image-specific values, Gaussian filtering and median filtering) to filter/discard noise present in the derived velocity field. Firstly, manually delineated cloud mask is used to remove the anomalous velocity field owing to cloud cover. Signal to Noise Ratio values <0.9 were discarded in both East/West and North/South directions to remove poorly correlated pixels. The displacement images (NS and EW) resulting from image correlation were used to estimate absolute glacier velocity using Euclidean distance (Fig. 2). All the obtained velocity pixels were normalized to 365 days (m yr^{-1}). As the third post-processing step magnitude filter was used, this filter considers that the glacier motion may evolve gradually, not abruptly [22]. The abrupt changes in the glacier flow were excluded from the results after careful observation of each glacier. Afterwards, we applied Gaussian filtering to circumvent the noise present in each velocity map. The parameter set for the Gaussian filter was, width $\sigma = 1.6$ and search window of 3×3 pixels. As the final step median filter with window size of 3×3 pixels was applied to all the derived results, which proved significant in removing isolated pixels and filling small gaps. All the glacier boundaries were derived using scene-adjusted RGI V6 glacier boundaries. Finally, the average of common pixels presented in each image pair was considered to estimate glacier velocity trends in the entire Sikkim Himalaya. Unlike the previous studies for the region, the present study does not assess glacier velocity only along the central line, and it is also not limited only to the ablation zones of the glaciers. Therefore, the resulting velocity trend is well-distributed over entire altitudinal zones and small glaciers, with unprecedented temporal coverage of the region. All glaciers larger than 0.5 km^2 (133) were considered for the analysis, keeping in mind the spatial resolution limitations of Landsat data. Further, non-parametric Man-Kendall and Sen's slope tests were applied at 95 %

confidence interval to estimate the glacier velocity data trend. Correlation coefficient and regression analysis were performed to estimate glacier velocity dependency on glacier size, slope and debris cover.

To assess the impact of glacier size on glacier velocity, glaciers were classified as small (<5 km^2), medium (5-10 km^2), and large-sized glaciers (>10 km^2). To assess the impact of slope correlation analysis is performed between surface slope and average velocity. Further, to investigate the relationship between surface slope and glacier velocity, we have estimated velocity and slope along the glacier central flow line for selected glaciers of different size and debris cover. The slope and velocity values are resampled at every 120 m. The debris cover map provided by Herreid and Pellicciotti [45] were used to assess velocity trend over debris cover part and clean ice glaciers. We classified glaciers as Clean Ice Glaciers (CIG; debris cover <10%), Sparsely Debris Covered (SDCG; debris cover >=10 and <=25%) and Debris Covered Glaciers (DCG; debris cover >25%).

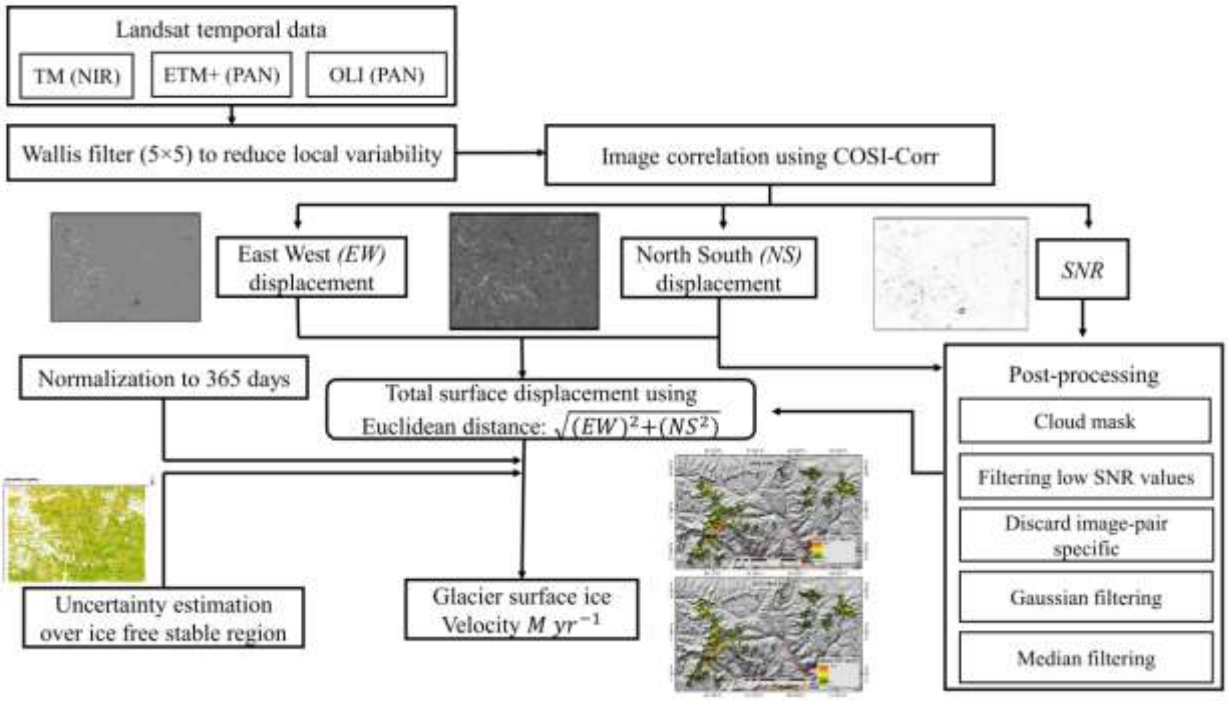

Fig. 2. Flow chart of overall methodology.

2.4. Uncertainty estimation

Field-based glacier velocity studies are entirely missing for the Sikkim Himalaya. The absence of such studies directly hampers the evaluation of remote sensing-based glacier velocity measurements. The estimation of glacier velocity using remotely-sensed data is largely influenced by scene characteristics (e.g., cloud cover, shadow, and poor visual contrast), preprocessing steps (e.g., image co-registration and orthorectification), image correlation algorithm, and evolution of the surface between the two image acquisitions [21,22,46] . In order to reduce any errors, imagery with minimum cloud and seasonal snow cover were used. The image co-registration error in the Landsat imageries is acceptable for glaciological studies [47,48]. The error introduced due to orthorectification may result into some minor horizontal shift. However, in case of imageries for same path and row, the resulted error is negligible in the estimated glacier velocity [21]. Finally, the total uncertainty in the glacier velocity was measured using the root mean square error (RMSE) of the displacement measurements attained over off-glacier pixels (Fig. S1 and Fig. S2) [13]. Ice-free ground outside the glacier boundary was assumed to be stable. The uncertainty estimated for each image pair is given in Table 3.

Table 3. Estimated uncertainty in velocity for each Image pair and average for the entire period.

Image pair	Sensor used	Estimated uncertainty (± m yr^{-1})
1994-1996	TM	5.69
1996-1998	TM	3.86
1998-2000	TM	4.81
2000-2001	ETM+	3.55
2001-2002	ETM+	3.33
2003-2004	TM	4.76
2004-2005	TM	5.45
2005-2006	TM	4.97
2006-2008	TM	5.00
2008-2009	TM	4.57
2009-2010	TM	4.95
2013-2014	OLI	3.60
2014-2015	OLI	3.41
2015-2016	OLI	2.70
2016-2017	OLI	2.66
2017-2018	OLI	2.62
2018-2020	OLI	2.09

Note: TM = Thematic Mapper; ETM+ = Enhanced Thematic Mapper+; OLI = Operational Land Imager

3. Results

3.1. Spatiotemporal variation in glacier velocity

The results show an overall decrease from 15.17±5.69 m yr^{-1} to 12.88±2.09 m yr^{-1} (~15%) in glacier average velocity over the period of 1994-2020 (Fig. 3A). However, the results are not monotonic as a slight velocity increase in comparison to previous years can be seen in the years of 2001, 2002, 2005, 2006, 2014, 2015, and 2020 (Fig. 3A). The lowest average glacier velocity is observed from 2015 to 2016. However, trend analysis demonstrates no statistically significant trend in the average glacier velocity data of Sikkim Himalaya (Table 4). Trend analysis and percentage change (32.2%) exhibit a significant decreasing trend with a rate of 0.25 m yr^{-1} in the median glacier velocity of Sikkim Himalaya during the entire observation period (Table 4). The result of individual glaciers is summarized in Table S1. The heterogeneity in the rate of glacier flow is summarized in Fig. 3B, which explicitly shows that 75% of glaciers in the Sikkim Himalaya have ~<13 m yr^{-1} glacier velocity during the entire period of observation. However, the maximum average glacier velocity is found to be ~30 m yr^{-1} during 1994-1996 (Fig. 3B).

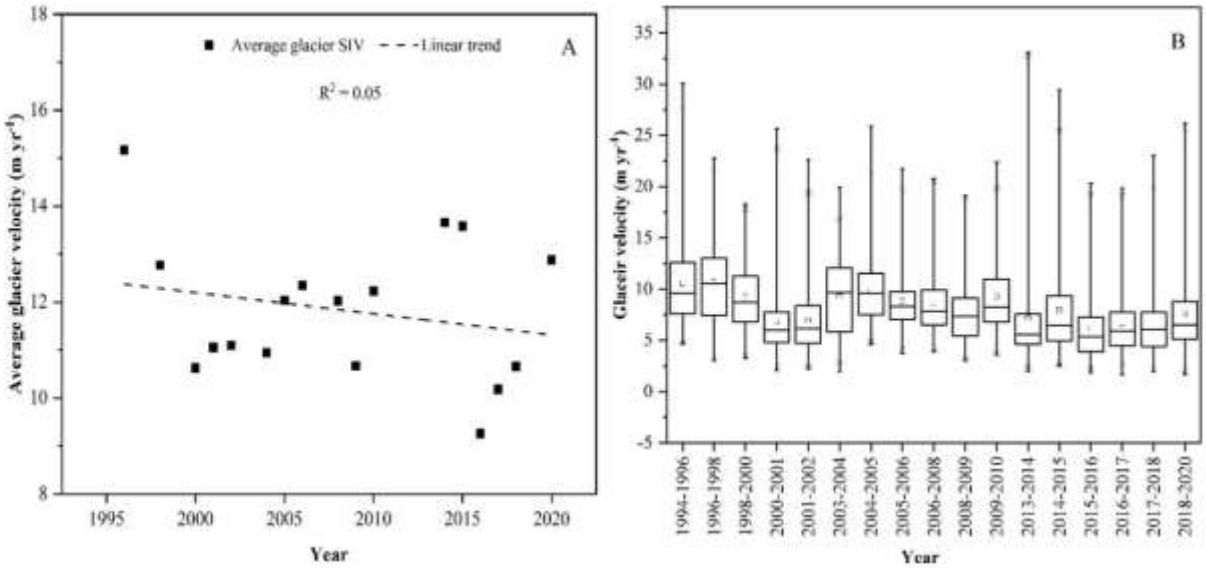

Fig. 3. Trend in glacier velocity of Sikkim Himalaya. Linear trend, the deviance bar shows the estimated uncertainty in velocity for the particular image pair (A), Box plot showing heterogeneity in glacier velocity in the Sikkim Himalaya (B). The uncertainty associated with particular image pair is given in table 3.

The fastest flowing glacier of the Sikkim Himalaya is Zemu glacier with an average velocity of ~20 m yr^{-1} during 1994-2020 (Fig. 4 and Fig. 5). However, it shows a slowdown where the glacier velocity is reduced from 27.6±5.69 m yr^{-1} to 22.3±2.09 m yr^{-1} during 1994-2020 (Fig. 4 and Fig. 5). The rate of change is non-monotonic throughout observation for Zemu glacier. Trend analysis shows no significant trend in the glacier velocity of Zemu glacier. In terms of average glacier velocity during the entire observation period (Table 4), the slowest moving glacier (ID 60; Fig. 1) in the region has an average velocity of 3.6 m yr^{-1}. The results show a heterogeneous pattern of glacier velocity within the same climatic setting of Sikkim Himalaya. The regions around the transient snow lines and icefalls usually show the highest velocity, whereas snout regions show the lower velocity signal [15].

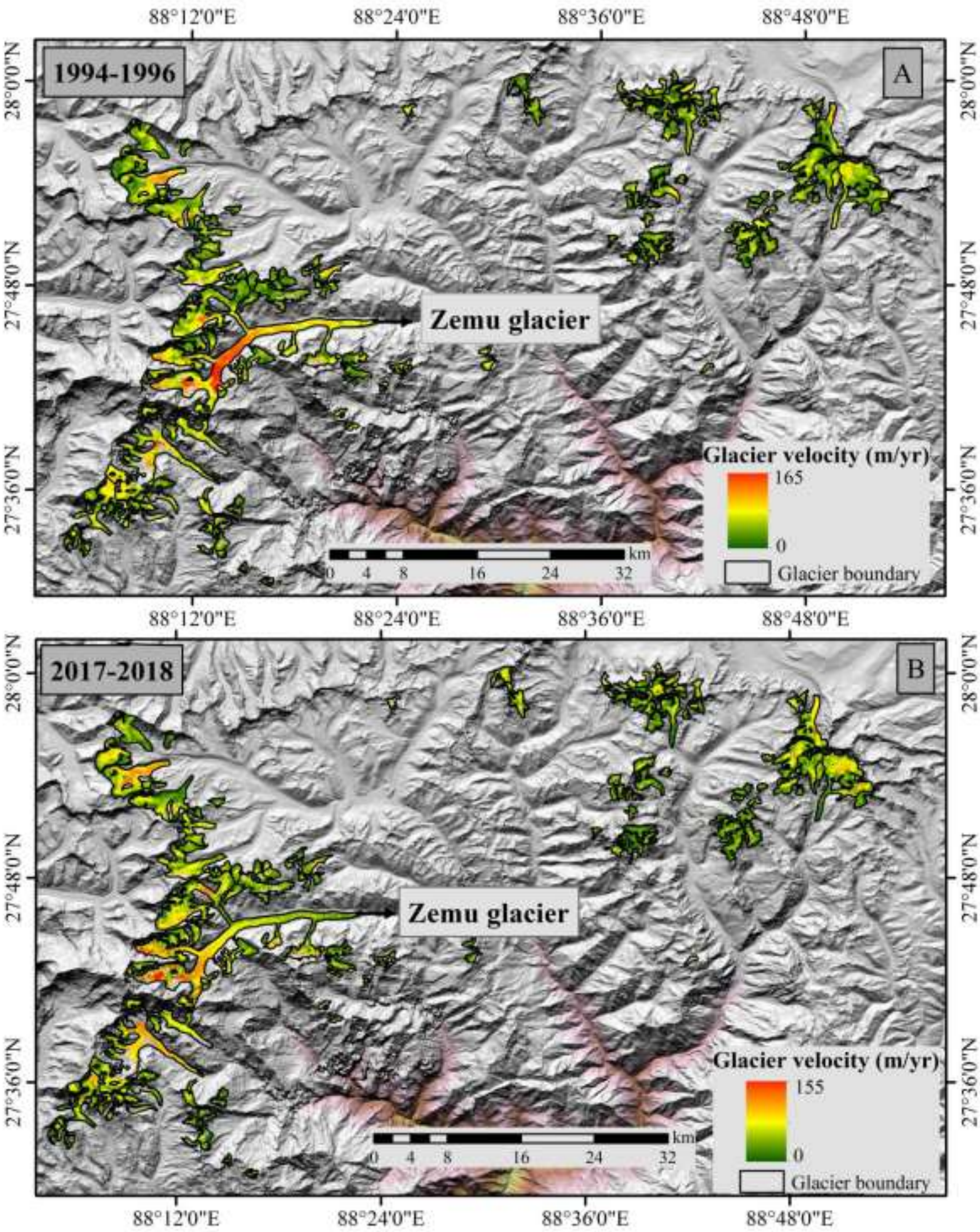

Fig. 4. Spatiotemporal variability in glacier velocity across Sikkim Himalaya. A) Glacier velocity estimated during 1994-1996 and B) Glacier velocity estimated during 2017-2018. Notice clear slowdown in the Zemu glacier.

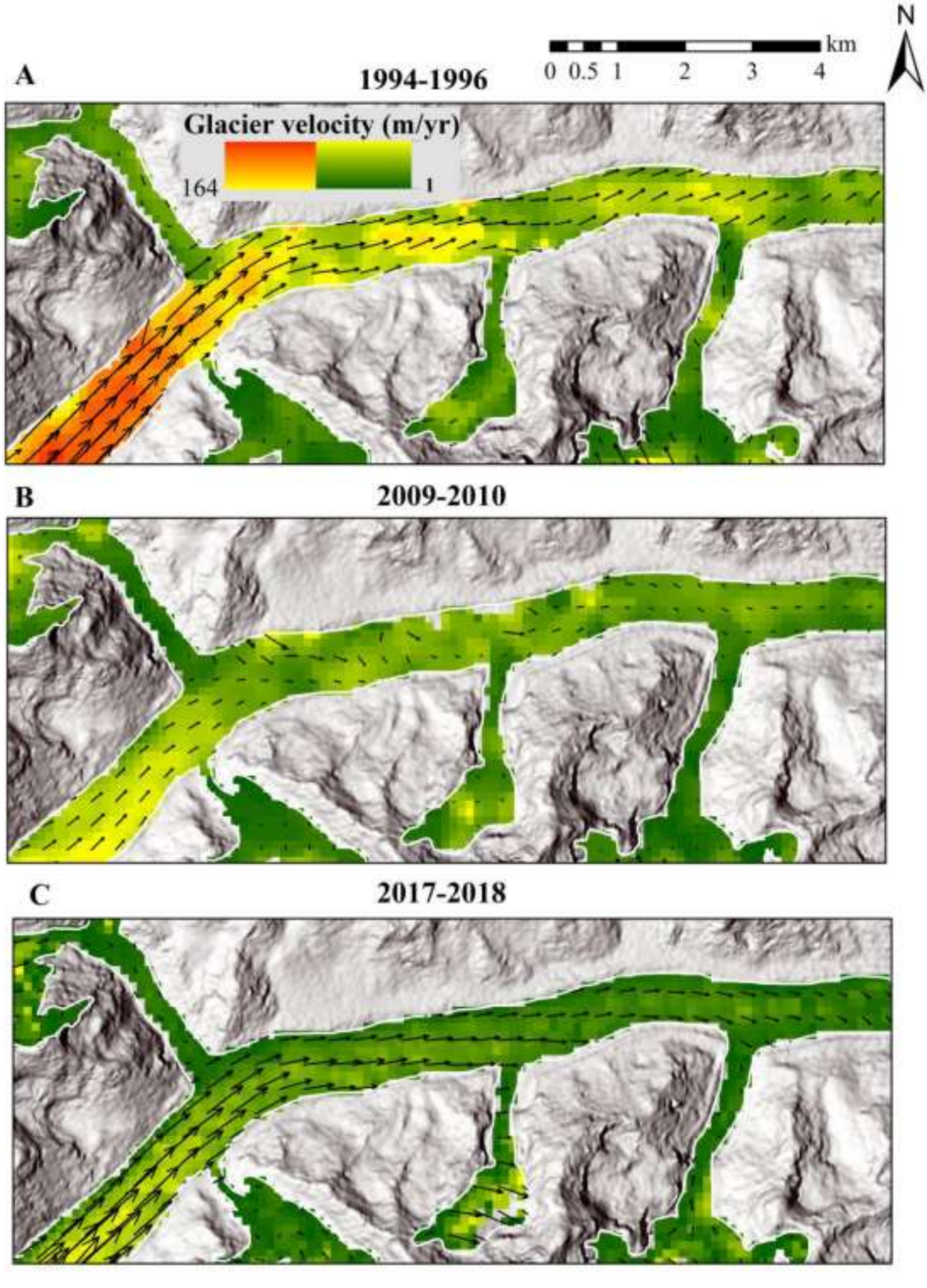

Fig. 5. Temporal snapshots of glacier slowdown in the Zemu glacier. A) velocity estimation during 1994-1996, b) velocity estimation during 2009-2010 and c) velocity estimation during 2017-2018. The glacier velocity is derived from image pairs of Landsat using COSI-Corr. Notice clear slowdown in up glacier.

3.2. Impact of glacier size and debris cover on velocity

The results show strong association of glacier size and average velocity (Fig. 6A) where larger glaciers (> 10 km^2) show higher velocities whereas medium (5-10 km^2) and small glaciers (< 5 km^2) show decreasing velocities in that order (Fig. 6A). During the period of investigation (1994-2020), the minimum glacier velocity of 5.58±2.70 m yr^{-1} is observed for a small glacier (<5 km^2) during 2015-2016, whereas the highest average glacier velocity (10.49±3.89 m yr^{-1}) for the small glaciers is recorded during 1996-1998 (Fig. 6A). The trend analysis shows a significant decreasing trend with a rate of 0.2 m yr^{-1} in the average velocity of small glaciers over the entire observation period (Table 4). In terms of percentage small glaciers have experienced 32.7% reduction in the average velocity. In contrast, no trend is observed for medium (5-10 km^2) and large glaciers (>10 km^2) (Table 4). The average velocity for small, medium, and large glaciers are 7.73±4.0, 10.43±4.0 and 16.14±4.0 m yr^{-1}, respectively, during the entire period of observation. The coefficient of correlation and regression analysis shows a strong association between glacier size and velocity. Correlation analysis shows a positive association between glacier size and average velocity (r=0.57) during the entire observation period. The regression analysis (r^2=0.32) signifies that 32% variability in glacier velocity can be explained by glacier size changes (Fig. S3 and Fig. S4).

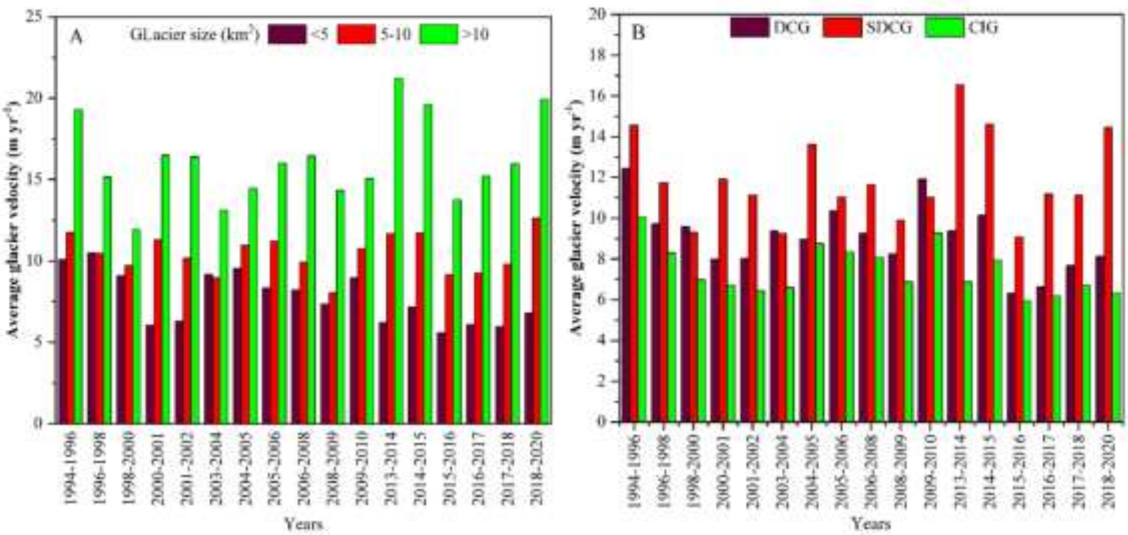

Fig. 6. Impact of glacier size and debris cover on glacier velocity in the Sikkim Himalaya during 1994-2020. A) Velocity variation among the different sizes of Glaciers. B) Velocity variation among different debris cover extent glaciers. DCG; Debris Cover Glacier (debris cover >25%), SDCG; Sparsely Debris Cover Glacier (debris cover >10 and <25%) and CIG; Clean Ice Glacier (debris cover < 10%).

The present study results show higher glacier velocity over sparsely debris cover glacier (SDCG) than clean ice glacier (CIG) and debris cover glacier (DCG) (Fig. 6B). During the period of observation (1996-2020), the average velocity for SDCG, DCG and CIG glaciers is 11.88±4.0, 9.06±4.0 and 7.43±4.0 m yr^{-1}, respectively. The highest average glacier velocity for DCG (12.43±5.6 m yr^{-1}) is observed during 1994-1996 whereas DCG account lowest velocity (6.33±3.89 m yr^{-1}) during 2015-2016 (Fig. 6B). Trend analysis exhibits no significant trend in any class of debris cover glacier (Table 4). The presence of debris cover exerts strong control over glacier mass flux [45,49], melting [50,51], thus significantly influence glacier flow. The higher glacier velocity over SDCGs shows strong evidence of surface melting, as few centimeter-thick debris increase surface albedo, thus promoting basal sliding resulting higher velocity signal [17,24]. Contrary to this, thick debris cover acts as an insulator and significantly reduces surface albedo, decreasing ice ablation and basal sliding [24]. This is notable that velocity observation is computed only over selected glaciers (> 1 km^2), which may result in bias toward small glaciers (<1 km^2).

3.3. Impact of slope on glaciers velocity

To assess the impact of surface slope on glacier velocity correlation analysis has been carried out. Although the overall results show no direct impact (r=0.04) of surface slope on glacier velocity (Fig. 7A), there is an improved positive correlation (r=0.32) between surface slope and glacier velocity for medium and large size glaciers (>5 km^2) (Fig. 7B). These results are in line with the previous studies [17,24], where several glaciers show anomalous behavior with respect to surface slope. It may be noted that present study incorporated 134 glaciers of different sizes (0.5 - 68 km^2), unlike previous studies, which only focused on large and medium-sized glaciers.

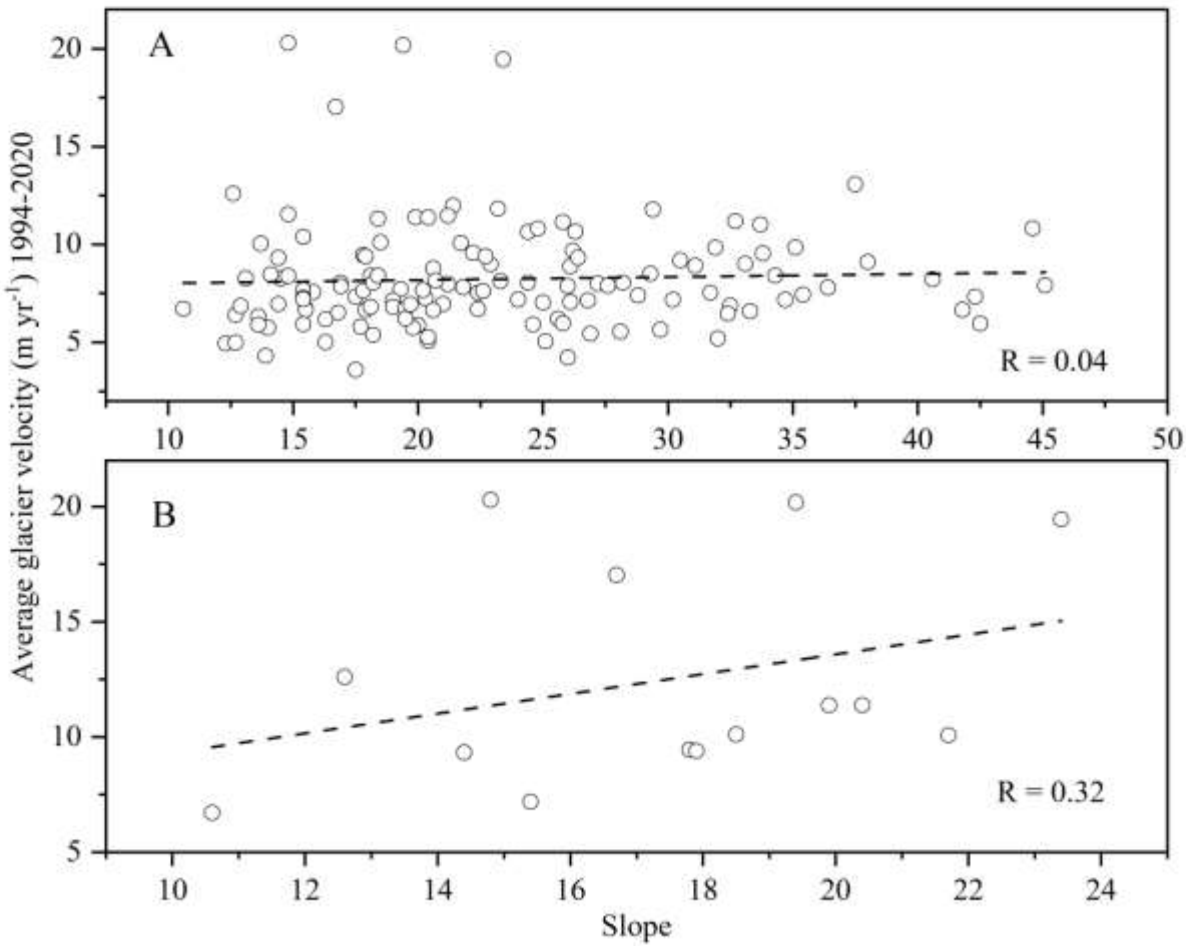

Fig. 7. Impact of slope on glacier velocity in the Sikkim Himalaya. (A) Relationship between slope and glacier velocity considering all glaciers. (B) Relationship between slope and glacier velocity for medium and large glaciers.

Our observations along the central flowlines reveal that glaciers have lower velocity near the terminus, which gradually increases with distance and altitude from the snout (Fig. 8). The selected glaciers are of different characteristics in terms of size (Fig. 8 large; G0, G18, G2, medium; G19, G21, G50, small; G3, G23), lake terminating (Fig. 8 G0, G19), clean ice (Fig. 8 G3, G50) and debris cover (Fig. 8 G2, G18, G19, G21) as a representation of the heterogeneity of study region. Overall, the lowest glacier velocity is observed at the glacier terminus. The velocity tends to increase with distance from terminus and reaches its maximum velocity values near the icefall and transient snow line, followed by higher reaches (Fig 8, Fig. S5). Our data shows the highest velocity for large glaciers (Fig. 5; Fig. 8 G2) near the transient snowline where the highest ice thickness is expected. The selected smaller glaciers (Fig. 8; G3, G23) shows lowers most glacier velocity among all glaciers. At the same time both glaciers show anomalously higher glacier velocity is observed in the terminus region. The G3 glacier falls under the category of CIG and consistent velocity could be observed for the same whereas G 23 is a small glacier and careful inspection of high resolution google earth data reveal the development of proglacial lake which might have accelerated the ice flow in the terminus region [52]. The development of supraglacial or proglacial lake causes percolation of water into glacier sub-system concomitant with increased pressure at the glacier bed thus, resulting higher basal sliding and glacier velocity [52,53]. Our observations demonstrate that glaciers with long tongues covered with debris (Fig. 8; G2, G18) have much lower velocity (~ 10 and 5 m yr^{-1}) in the terminus region compared to CIGs with higher velocity(~ 12 and 10 m yr^{-1}) (Fig. 7 G3, G50). The long glacier tongues with gentle slope promotes debris cover accumulation over time which in turn accelerated downwasting and ice mass loss, resulting in lower velocity signal. The G19 shows some deviance from this observation particularly owing to its lake-terminating characteristic. The velocity estimation along the central flowline for lake terminating glaciers (Fig. 8; G0, G19 and G21) shows a comparatively higher glacier velocity signal (~ 17, 13 and 16 m yr^{-1}) at the terminus region than land terminating glaciers (Fig. 8 G18; ~5). The lake ice interaction at calving front has probably promoted ice flow in the lower terminus region, resulting in higher velocity; these observations align with previous studies of the lake-terminating glacier in the Himalaya [54,55]. This behavior of Sikkim Himalayan glacier directly corresponds to typical valley-type glaciers.

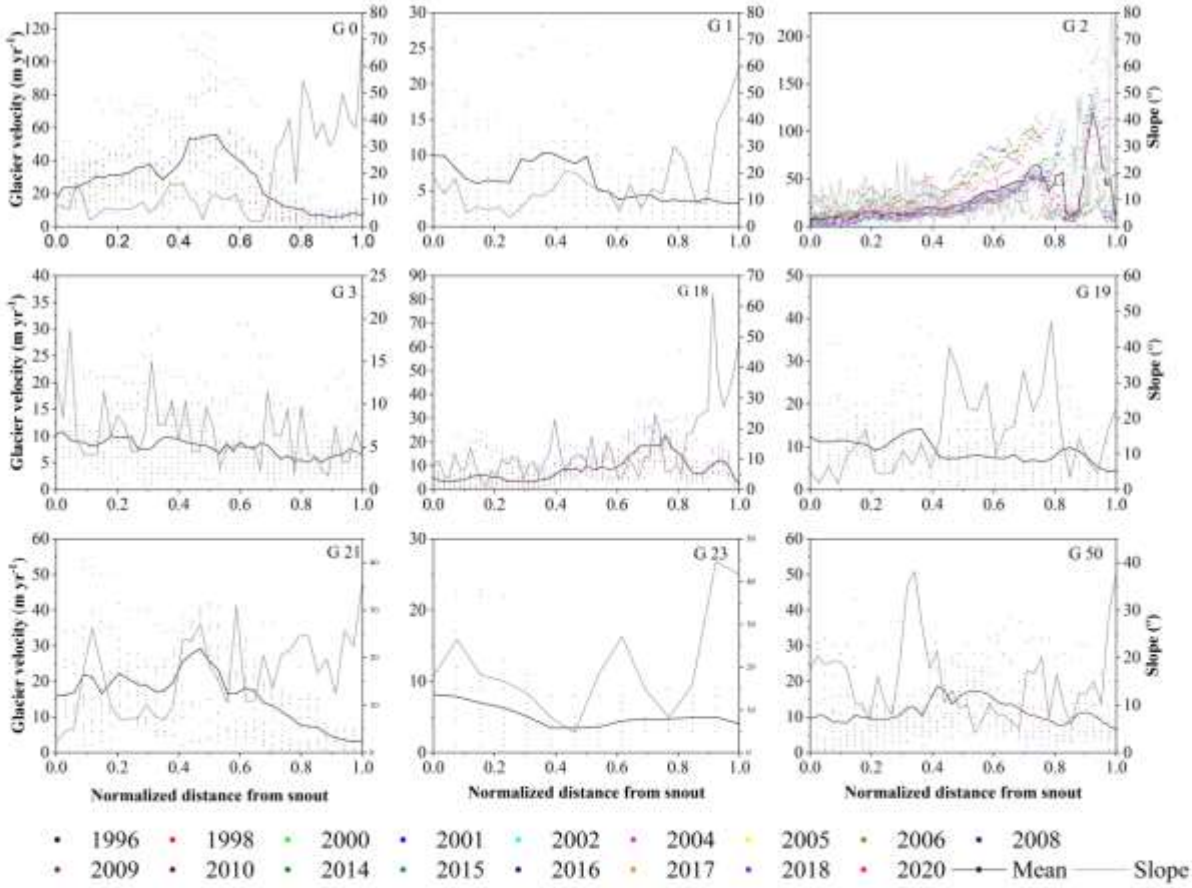

Fig. 8. Computed Glacier velocity and surface slope along the central flow line for the selected glaciers (G0, G1, G2, G3, G18, G19, G21, G23 and G50) during (1994-2020). The glacier velocity and surface are resampled at every 120 m.

Table 4. Statistical results of Sikkim glacier velocity trend analysis (Mann-Kendall and Sen's slope).

	Glacier velocity (1994-2020)			
	Z_s	Q_s	P-value	Trend
Average velocity	-0.45	-0.039	0.65	No trend
Median velocity	-2.67	-0.25	0.007	Decreasing
Zemu glacier (G 2)	-0.45	-0.10	0.65	No trend
Large glaciers	0.70	0.11	0.48	No trend
Medium glaciers	-0.04	-0.006	0.96	No trend
Small glaciers	-2.84	-0.24	0.004	Decreasing
Debris cover glaciers	-1.68	-0.14	0.09	No trend
Sparsely debris cover glaciers	-0.04	-0.004	0.96	No trend
Clean ice glaciers (CIGs)	-1.85	-0.08	0.06	No trend

Note: Z_s = Mann–Kendall Z statistic; Q_s= Sen's slope, test is applied at 95% confidence interval.

4. Discussion

4.1. Understanding spatiotemporal variability in glacier velocity

The assessment of Sikkim Himalayan glacier velocities is not a routine task owing to the paucity of field-based observation accompanied with complex topography and climate. The present study demonstrates the spatiotemporal variation in glacier velocity in Sikkim Himalaya over the period of 1994-2020. Our investigation demonstrates non-monotonic nature of glacier velocity at regional scale. However, a slight increase in the glacier velocity compared to the previous year could be primarily attributed to seasonal snow and data unavailability in the same month. As in the present study, increase in glacier velocity during 2004/05, 2005/06, 2013/14 and 2014/15 is directly associated with the presence of seasonal snow in the satellite imagery acquired during the month of November (Table 2). This seasonal snow might have resulted in higher velocity signal during the particular year. This importance of snow accumulation owing to seasonal precipitation in promoting rapid ice flow has been reported for several coastal glaciers in Alaska [56] and in Western Himalaya [15]. The longer glaciers in the study area display higher and larger accumulation zones, which govern faster ice flow regime in the lower reaches of these glaciers. Similar type of control of climate regime on glacier flow has been reported from the middle and the Western Himalaya [57]. The deformational flow generated by the accumulated seasonal snow loading might be vital in controlling seasonal glacier movements in the region. Thus, we could not observe any significant trend in the average glacier velocity of Sikkim Himalaya during the observation period (Fig 3A). Unlike previous studies [3,16,24], our velocity estimation is not restricted to only large glaciers, to the ablation zones, and only along the central flow line (Fig. 4). Incorporating results along the central flow line and only ablation region may result in the overestimation of glacier velocity [3,24]. Therefore, our study attempts to incorporate all the well-correlated pixels covering the glaciers to avoid this bias. Glacier flow velocity is primarily controlled by the driving stress, which promotes ice deformation (creep) and sliding over or deformation of the bed [58]. Driving stress is a weight of horizontal component of the ice per unit area (Equation 3), which generally increases with an increase in the accumulation in upper reaches and decreases with depth. Previous studies have demonstrated that velocity due to creep is a function of the glacier ice thickness and gravitational driving stress, which in turn is dependent on accumulation [58].

$$t(x) = pgH(x)\frac{\partial s}{\partial x}(x) \quad (3)$$

Where, t(x) = driving stress, p=ice density, g= gravitational acceleration, H(x) = ice thickness and S(x) the ice surface position x along a given flow line.

Dehecq et al. [3] demonstrate that up to 94% of spatiotemporal variability in glacier flow across HMA can be demonstrated by variations in driving stress, which in turn is mainly regulated by changes in ice thickness. The ultimate cause of driving stress and glacier flow is mass accumulation in the upper reaches (due to precipitation and windblown snow) and ablation in their lower zone (due to melting and calving). Our results explicitly show higher glacier velocity over the thickest zone of glacier (Fig. 4, 5, and 7). The present study highlights that large glaciers with thick ice cover move fast as compared to small glaciers situated even on the steep slopes. These observations exhibit the dominant control of ice thickness on glacier flow at the regional scale. The mass loss-driven glacier slowdown is reported in previous study [3]. A study [7] demonstrated mass loss of -0.34±0.09 m w.e. yr^{-1} over the period of 2000-2016 in Eastern Nepal covering the Sikkim Himalaya. Recently, [59] investigated mass balance and elevation change for entire Himalayan range. The Sikkim Himalaya experienced decreasing rate (-0.48 ± 0.33 m yr^{-1}) of elevation change and cumulative mass loss of -2.86±3.03 Gt over the period of 2000-2014. Similarly, mass loss of -30±0.12 m w.e.yr^{-1} is observed for the Sikkim Himalaya during mid 1970s-2000 [60]. These studies show strong evidence of negative glacier mass balance and reduced ice thickness in the Sikkim Himalaya under the influence of climate change. These studies support the finding of the present study which explicitly shows glacier slowdown. The glacier slowdown trend in

Sikkim Himalaya has direct implications for formation and expansion of glacial lakes within a suitable topography.

Thereby, Sikkim Himalaya host 466 high latitude and glacial lakes [30] which have become emblematic of climate change. A recent investigation found that Eastern Himalaya serves as a hot spot of GLOF comparably three times higher than other parts of Himalaya [9]. The present study investigates underlying impact of controlling factors such as glacier slope, size and debris on the velocity in the study region. Among these factors, glacier size proves to be the most controlling factor, as the decreasing trend (0.2 m yr^{-1}) is found only for the smaller glaciers (<5 km^2). This phenomenon can be explained in terms of response time of glaciers. The smaller glaciers tend to respond faster to climate change, resulting in quick and notable mass loss. The lowermost region has experienced the lowest average glacier velocity which is mainly attributed to reduced ice in the glacier tongue region. The higher reaches of glaciers which represent dry accumulation zone have experienced higher velocity than tongue regions but lower than transitional snow line zones (Fig. 7). This region usually experiences higher ice thickness and driving stress, which in turn increases glacier velocity [15]. These observations are in agreement with a previous study for the Western Himalaya [15]. The impact of slope on glacier velocity for the study region could not be directly correlated owing to heterogeneity in glacier size. Additionally, our observations are insensitive toward surface slope evolution in response to mass loss and subsequent impact on glacier velocity owing to unavailability of time-series DEMs for the region. However, glaciers (> 5km^2) show a positive correlation between surface slope and glacier velocity (Fig.7A). Our slope and velocity observation, along with the central flow line, highlight characteristics of typical valley type glaciers. The difference between velocity values at the glacier tongue and near the transitional snow line is comparatively higher for glaciers having long and narrow tongue with debris cover (Fig. 7 G2).

4.2. Comparison with other studies

In general, the trends of glacier velocity in the Sikkim Himalaya correspond to those of typical valley-type glaciers [16,17]. However, the results exhibit a heterogeneous pattern of glacier velocity in the Sikkim Himalaya, as average glacier velocity varies from 3.6 m yr^{-1} to ~20 m yr^{-1}. The absence of field-based glacier flow velocity measurements hampers any direct evaluation of the present remote sensing-based study. However, two studies [3,16] attempt to study Glacier velocity in Sikkim Himalaya using remotely-sensed data. A study by Dehecq et al. [3] estimated glacier velocity of the entire HMA. In this study, Sikkim Himalaya is covered within Eastern Nepal region. Regional analysis by Dehecq et al. [3] has shown the slowdown of 28.9% during 2000 and 2017 in eastern Nepal, covering the present study area (i.e. Sikkim

Himalaya). Interestingly, the results of the present study deviate with Dehecq et al. [3], which reports strong slowdown of glaciers with area >5 km^2. However, it is noteworthy that Dehecq et al. [3] estimated glacier velocity over only ablation zone. Since, ablation zone of the glacier experience maximum ice mass loss thereby, decreasing trend of velocity are expected. The Sikkim Himalaya has presence of 129 glaciers which are <5 km^2 and >0.5 km^2. Therefore, these poorly constrained glaciers (10 glaciers could not be correlated due to cloud cover) are studied in the present study. Recently, Garg et al. [16] adopted a multi-parametric approach to comprehend poorly constrained glaciers of Sikkim Himalaya during 1991-2015. Their study incorporates 23 glaciers as representative of the Sikkim Himalaya. The results show that the terminus of the glacier retreated (17.78±2.06 ma^{-1}), loss of glacier area (5.44±0.87%) and observed a significant increase in the snow line altitude (~7 ma^{-1}). Moreover, glaciers slowed-down (by 24.90%) during 1991-2016. Our results are comparable to Garg et al. [16] in terms of overall slowdown (~29.7% during 1994-2018) in Sikkim Himalaya. The methodology adopted for glacier velocity estimation are distinct for both studies. The significant difference lies in the extraction of velocity values along the central flow line, spatiotemporal coverage and statistical analysis. Our results explicitly show that relying only on the percentage change in velocity may give an ambiguous interpretation as it is only dependent on two-time observations and overlooks the intermediate spatiotemporal variation. For example, if we compare mean annual velocity from 1994/96 to 2015/16 slowdown of ~38% could be observed. Contrarily, we have observed ~15% decrease in the average velocity during 1994-2020. The long-term glacier velocity was found to be of non-monotonic nature, similar to previous study [3]. Therefore, statistical trend analysis test (e.g. Mann Kendall) over long-term velocity observation may provide a comprehensive picture of glacier flow. Moreover, this study explicitly highlights that a significant difference lies in the velocity estimation along the central flow line and including all correlated pixels (Fig. 9). We recommend velocity estimation incorporating all pixels, as estimation over a particular zone (i.e ablation zone) or along the central line may provide bias. The significant difference could be observed for glaciers having long debris cover tongue (Fig 8; G2, G0, G22, G31), whereas this difference is minimum in case of clean ice glaciers (Fig. 8; G1, G3). Here, we observe significant decrease in glacier velocity at the margin and higher signal at the center, which further highlight the control of ice thickness on glacier flow at regional scale.

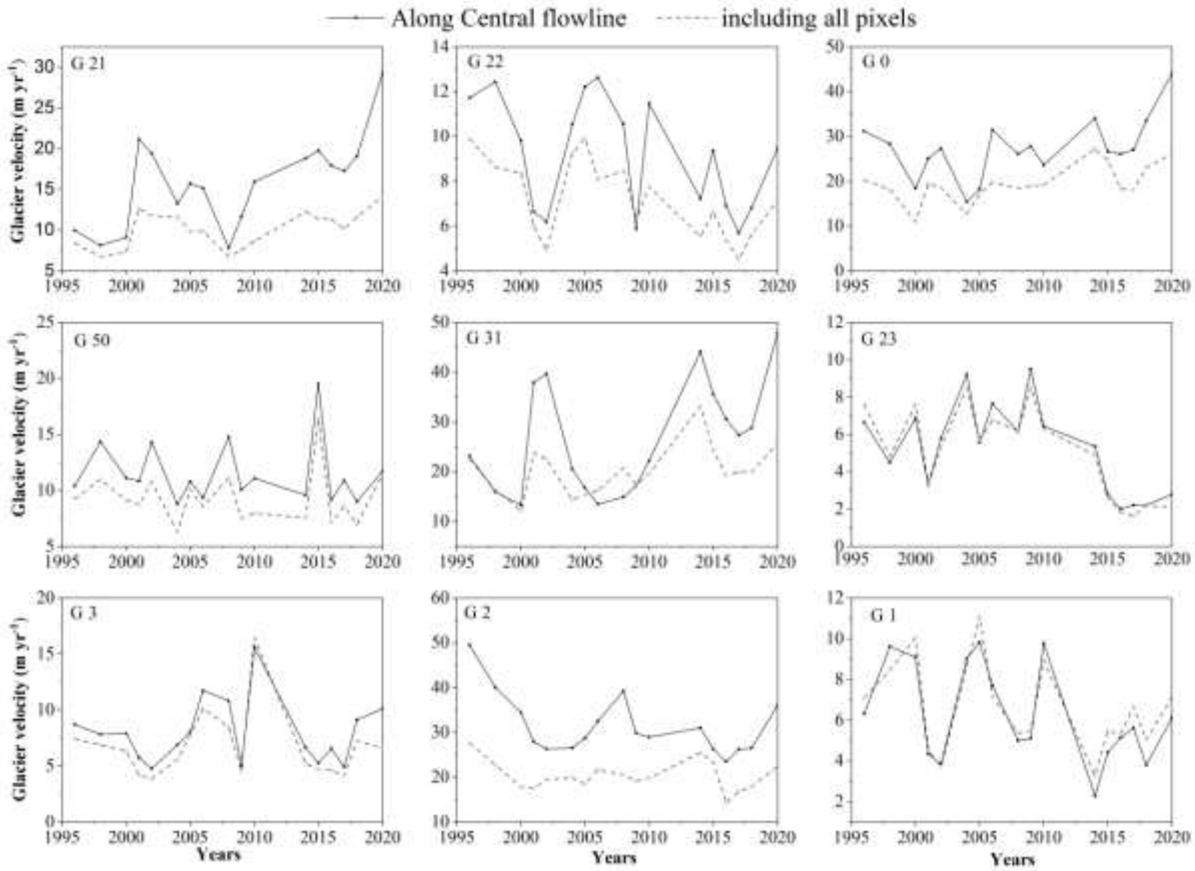

Fig. 9. Comparison between glacier velocity estimated along central flowline and including all pixels for selected glaciers in the study region. Glacier velocity estimated along central flowline exhibits higher velocity signal.

Recently, integrated multi-parametric approach is adopted to report the status of 429 glaciers of Kanchenjunga region [17]. This study demonstrated decreasing glacier area and elevation with a rate of -0.18 ± 0.07% yr^{-1} and-0.32 ± 0.02 myr^{-1}, respectively, during 1975-2015. As velocity increases from 25.55 m yr-1 to 29.2 m yr^{-1} during 2004-2015 [22], anomalous behavior is observed with respect to glacier velocity. This increasing glacier velocity is mainly attributed to the impact of seasonal snow, as satellite data during the summer season (i.e. June and August) were used to estimate glacier velocity. The glacier of this region falls under the category of summer accumulation-type (i.e. receiving precipitation in summer season); thereby higher velocity signal is expected during June and August. Thus, anomalies can be observed due to fast-changing snow scenarios. The other parts of HMA show similar trends of decreasing glacier velocities as study by Heid and Kääb [23] demonstrated glacier slowdown in the Pamir region with a rate of 43% per decade during 2000-2010. Sugiyama et al. [61] have found 70% slowdown in Yala glacier of Nepal Himalaya during 1982-2009. However, Karakoram and Kunlun regions have shown anomalous behavior with increasing glacier flow trends [3,20,62]. Scherler et al. [5] reported spatial heterogeneity in glacier velocity during 2000-2008 by observing 286 glaciers well-distributed over the Himalaya except the eastern region. Scherler et al. [5] showed strong evidence of stagnant glaciers in Hindu Kush (16%) and in the northern (10%) and southern (28%) Himalaya. However, stagnant glaciers are scarce in the Western Himalaya (~1.5%) and nonexistent in the Karakoram ranges. A study by Satyabala et al. [25] demonstrates long-term spatiotemporal variation in glacier flow of Gangotri glacier, showing an overall ~30% slowdown during 1992-2007. Thakuri et al. [18] studied the interrelationship between expansion of Imja Tsho (lake) and dynamics of Imja Glacier. Their result shows a decrease in glacier velocity from 37±30 m yr^{-1} during 1992/93 to 23±15 m yr^{-1} during 2013-2014. Apart from glacier flow, it is evident from previous studies that glaciers of Sikkim in Eastern Himalaya are worse affected by climate change in respect of glacier mass loss [7], expansion of glacier lakes [9,30], and increasing snow line altitude [16]. This adverse effect of climate change is usually attributed to the summer accumulation type of glaciers.

5. Conclusions

Our study provides a new avenue to address a key question of ice dynamics in Himalaya under the influence of climate change. We investigate spatiotemporal variation of Sikkim Himalayan glaciers; total 134 glaciers were studied, and the results show an overall ~15% slowdown and the trend analysis (Mann-Kendall and Sens slope test) shows a decreasing trend of glacier median velocity at a rate of 0.25 m yr^{-1} during observation period (i.e. 1994-2020). Our investigation demonstrates pronounced slowdown in average velocity of smaller glaciers (@0.2 m yr^{-1}) in the Sikkim Himalaya during 1994-2020. The Sikkim Himalaya shows heterogeneous rate of slowdown, average velocity varies from 3.6 to ~20 m yr-1 during 1994-2020. The heterogeneity in glacier velocity can be explained by glacier size (32%) which emerges to be the most important parameter in controlling glacier velocity in the region. The strongly imbalance state of Sikkim Himalayan glaciers is alarming for regional water security. The present study has two-fold implications to 1) the future water availability and 2) overall strategic plan to mitigate the anticipated risk of GLOF in the downstream region. Further, the study also provide important inputs for modelling glacio-hydrology in the region (e.g. snowmelt run-off and GLOF modelling). Additionally, the present study improves our understanding of the glacier flow in this one of the least explored Himalaya regions. Sikkim Himalaya has data paucity in terms of long-term spatiotemporal velocity and our study forms the baseline velocity data for the region.

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