Glacier Velocity Changes in the Himalayas in Relation to Ice Mass Balance

Yu Zhou ¹, Jianlong Chen ^{1,2} and Xiao Cheng ^{3,*}

¹ Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), School of Earth Sciences and Engineering, Sun Yat-sen University, Zhuhai 519000, China; zhouyu36@mail.sysu.edu.cn (Y.Z.); chenjl25@mail2.sysu.edu.cn (J.C.)

² Guangdong Geological Survey Institute, Guangzhou 510062, China

³ Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), School of Geospatial Engineering and Science, Sun Yat-sen University, Zhuhai 519000, China

* Correspondence: chengxiao9@mail.sysu.edu.cn

Abstract: Glacier evolution with time provides important information about climate variability. Here, we investigated glacier velocity changes in the Himalayas and analysed the patterns of glacier flow. We collected 220 scenes of Landsat-7 panchromatic images between 1999 and 2000, and Sentinel-2 panchromatic images between 2017 and 2018, to calculate surface velocities of 36,722 glaciers during these two periods. We then derived velocity changes between 1999 and 2018 for the early winter period, based on which we performed a detailed analysis of motion of each individual glacier, and noted that the changes are spatially heterogeneous. Of all the glaciers, 32% have sped up, 24.5% have slowed down, and the rest 43.5% have remained stable. The amplitude of glacier slowdown, as a result of glacier mass loss, is significantly larger than that of speedup. At regional scales, we found that glacier surface velocity in winter has uniformly decreased in the western part of the Himalayas between 1999 and 2018, while increased in the eastern part; this contrasting difference may be associated with decadal changes in accumulation and/or melting under different climatic regimes. We also found that the overall trend of surface velocity exhibits seasonal variability: summer velocity changes are positively correlated with mass loss, i.e., velocity increases with increasing mass loss, whereas winter velocity changes show a negative correlation. Our study suggests that glacier velocity changes in the Himalayas are spatially and temporally heterogeneous, in agreement with studies that previously highlighted this trend, emphasising complex interactions between glacier dynamics and environmental forcing.

Keywords: glacier velocity changes; Himalayas; Landsat-7; Sentinel-2; ice mass balance

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1. Introduction

Glaciers are sensitive to climate variability and are a major contributor to global sea level rise [1–7]. It is of great importance to understand glacier evolution with time because it provides direct evidence for climate change [2,8,9]. The Himalayas host the largest volume of glaciers outside the polar regions, which also contribute importantly to water resources for the Indus and Ganges basins [10–12]. Due to the difficult accessibility of high mountain areas, remote sensing has been a powerful tool for studying the Himalayan glaciers. Researchers have used satellite altimetry (e.g., [2,13,14]) and optical satellite stereo imagery (e.g., [7,15,16]) to quantify glacier mass balance in the Himalayas. Although the estimates derived from different techniques vary, they consistently show that the Himalayan glaciers are experiencing significant thinning and mass loss, thereby affecting ice fluxes and river discharge. The thinning rate is also suggested to have accelerated in the past 40 years, which is possibly driven by atmospheric warming and associated energy fluxes [15–17]. Recently, Dehecq et al. [9] investigated the response of glacier flow to mass changes at regional scales. They estimated time-series glacier velocities from 2000 to 2016,

using Landsat-7 optical satellite images [18], and found that the variability in velocity changes within a large region can be explained solely by changes in ice thickness, i.e., ice mass balance [9]. Their study provides a novel way for estimating ice mass balance in the Himalayas as glacier velocity changes can be easily measured with satellite images.

Glacier surface velocity in summer has been heavily exploited, e.g., [9,18]. Velocity estimates in [9] show that glaciers in the Himalayas have experienced significant slowdown in the past two decades. However, seasonal variability of regional glacier motion remains unclear. The aim of this study is to explore the long-term winter velocity and its changes. We first derived glacier velocities for two periods, early winter in 1999–2000 and 2017–2018, using Landsat-7 and Sentinel-2 image pairs, respectively. High-resolution satellites provide a powerful tool for monitoring ice and snow [19,20]. We chose Sentinel-2 over Landsat-7 for mapping the present glacier motion because it has been tested to have a better geometric and radiometric quality [21]. By differencing the Landsat-7 and Sentinel-2 derived velocities, we map velocity changes over nearly two decades, and, combining the data with glacier mass balance, we show the complex patterns of glacier flow in the Himalayas.

2. Study Area

The Himalaya front (Figure 1) stretches over 3000 km from the west to the east, containing more than 36,000 glaciers of different sizes (Randolph Glacier Inventory, RGI 6.0). The topography increases rapidly across the front, from 200 m in the south to over 5000 m in the north, entering the Tibetan Plateau. Evolution of glaciers in different parts of the Himalayas is affected by different climatic regimes. In the western part, snow accumulation is controlled by westerly atmospheric circulations, so Hindu Kush, Spiti Lahaul and Karakoram receive most accumulation during winter. In the eastern part, the Indian summer monsoon dominates the accumulation in West Nepal, East Nepal, Bhutan and Nyainqentanglha [2,12,22–24]. The extreme topography creates additional complexity; precipitation at high-altitude regions has been suggested to be 2–10 times higher than that at low-altitude regions [25,26]. As a result, glaciers in the Himalayan front exhibit contrasting variabilities in evolution and mass balance [2,7,9]. Shaded relief of the Himalaya region generated from the 3 arc second Shuttle Radar Topography Mission (SRTM) DEM [27] is shown in Figure 1.

3. Data and Methods

In this study, we focused primarily on surface velocity changes of the Himalayan glaciers at decadal scales. Satellite optical images were used to generate glacier velocity maps at different times. We collected 40 pairs of Landsat-7 Level-1T data between 1999 and 2000 to calculate glacier velocity during this period. Each panchromatic Landsat-7 Level-1T image covers an area of 185 km × 170 km, with a spatial resolution of 15 m. A total of 70 panchromatic Sentinel-2A/B Level-1C image pairs were obtained to calculate glacier velocity between 2017 and 2018. Each Sentinel-2 Level-1C image has a footprint of 100 km × 100 km and a spatial resolution of 10 m. Dehecq et al. [9] analysed velocity changes in summer. We are interested to explore whether glacier velocities exhibit seasonal variations, so all the 110 pairs of Landsat-7 and Sentinel-2 images used in this study were acquired during winter, centred around December. We also collected glacier geometry data including length, area, slope and thickness from RGI 6.0 and [28], along with satellite-derived glacier elevation changes from [7], for a comprehensive analysis of glacier velocity changes and the possible driving factors.

We estimated glacier velocities by applying cross-correlation using the COSI-Corr software package. Optical correlation is implemented in the frequency domain with an accuracy $\sim 1/10$ of the input pixel size [29,30]. We used a correlation window of 64 pixels × 64 pixels as a first step, followed by 32 pixels × 32 pixels for a second run, with a step of 16 pixels × 16 pixels (160 m) for Sentinel-2A/B data and 10 pixels × 10 pixels (150 m) for Landsat-7 data. The resulting east-west and north-south components of the

displacement were filtered using the non-local means algorithm [30]. The purpose of filtering is to use the correlation to excluded snow-covered regions where the correlation is relatively low. We then used RGI 6.0 to mask out the non-glacial areas and generated two annual velocity fields for 1999–2000 and 2017–2018, for all the 36,722 glaciers within the Himalayas, as shown in Figure 2.

The velocity uncertainty was estimated from the overlapping areas between adjacent pairs. As shown in Figure 3, the Landsat-7 and Sentinel-2 derived velocities have a measurement error of $-3.4 \pm 11.6 \text{ m yr}^{-1}$ and $0.4 \pm 4.6 \text{ m yr}^{-1}$, respectively. Since all the image pairs are centred around December with little interannual fluctuations, the uncertainty depends largely on radiometric quality and image resolution, indicating that Sentinel-2 imagery has a better radiometric quality than Landsat-7 imagery [21], and higher resolution improves pixel matching [20], hence yielding more consistent results.

Figure 1. Glaciers are highlighted in light blue. The total number of glaciers in each subregion is labelled. Black box marks the location of Figure 2. We calculated the mean value of velocity changes of each subregion and compared our estimates to [9]. (a–g) shows examples of velocity changes in subregions. See Table 1 for details.

To calculate velocity changes, we re-sampled the Landsat-7 and Sentinel-2 derived velocity maps onto the same grid with a spacing of 160 m, and then differenced the two velocities on a pixel basis (Figure 1). Unlike [9], who based their analysis of glacier velocity changes mainly on regions, we conducted our analysis based on individual glacier. For each glacier, we computed its velocity and the associated change by averaging all the pixel values that cover the glacier.

Figure 2. Deriving glacier surface velocity using optical correlation. The Sentinel-2 optical data were provided by the European Space Agency (ESA). See Figure 1 for location.

Figure 3. Velocity uncertainties. The Landsat-7 and Sentinel-2 derived velocities have a measurement error of $-3.4 \pm 11.6 \text{ m yr}^{-1}$ and $0.4 \pm 4.6 \text{ m yr}^{-1}$, respectively.

4. Results

A total of 36,722 glaciers were included in our study (from the RGI 6.0 database). As shown in Table 1, 43.5% of the glaciers had a stable velocity during 1999–2018 (the difference between Landsat-7 and Sentinel-2 velocities is no more than 3 m yr^{-1}), 32.0% sped up (velocity changes $> 3 \text{ m yr}^{-1}$) and 24.5% slowed down (velocity changes $< -3 \text{ m yr}^{-1}$). Although speedup glaciers outnumber slowdown glaciers, the average amplitude of glacier speedup (6.3 m yr^{-1}) is much smaller than slowdown (-12.3 m yr^{-1}). At regional scale, more glaciers in the east of the Himalayas, i.e., West Nepal (33.4%), East Nepal (56.2%), Bhutan (34.1%) and Nyainqentanglha (41.3%), have experienced speedup than the west in Hindu Kush (22.6%), Spiti Lahaul (19.6%) and Karakoram (17.3%). Karakoram has seen the largest proportion of glacier slowdown (31.5%), followed by West Nepal (29.1%), Hindu Kush (28.3%), Bhutan (22.1%), Nyainqentanglha (21.9%), East Nepal (19.6%) and Spiti Lahaul (18.7%). The greatest speedup (about 130 m yr^{-1} in RGI60-14.04875) and slowdown (about -250 m yr^{-1} in RGI60-14.0300) also occurred in Karakoram.

We analysed glacier surface velocity in combination with glacier geometry data including area, length, slope and thickness. We used Sentinel-2 derived velocities in the analysis, given the smaller measurement uncertainties. The results (Figure 4) showed that small glaciers (area $< 20 \text{ km}^2$), regardless of non-surge and surge types, exhibit complex flow velocities, which are poorly correlated with area ($R = 0.13$ for non-surge type and $R = 0.22$ for surge type), length ($R = 0.12$ and $R = 0.21$), slope ($R = -0.08$ and $R = 0.02$) and thickness ($R = -0.01$ and $R = 0.09$). Flow velocities of large (area $\geq 20 \text{ km}^2$), non-surge-type glaciers show a positive correlation with both area ($R = 0.69$) and length ($R = 0.78$), i.e., the size of glaciers, suggesting faster motion with increasing sizes, as glacier flow laws would predict. Surge-type glaciers do not show an evident correlation with any of the factors. We also noted that glacier velocities appear to be independent of, or at least not linearly correlated with, both slope and thickness. Similarly, we analysed the relationship between glacier velocity changes and glacier size and thickness. As shown in Figure 4, velocity changes of both non-surge- and surge-type glaciers are completely independent of glacier geometry, indicated by the very low correlation ($R \approx 0$).

Table 1. Statistics of glacier velocity changes in the Himalayas. Stable glaciers are defined as the amplitude of differences between Landsat-7 and Sentinel-2 velocities, i.e., velocity changes between 1999 and 2018, $\leq 3 \text{ m yr}^{-1}$. Velocity changes $> 3 \text{ m yr}^{-1}$ are regarded as speedup and $< -3 \text{ m yr}^{-1}$ as slowdown. The overall changes were calculated by averaging all the glaciers within each subregion, in order to be comparable with the results in [9].

	Number of Glaciers	Speedup	Slowdown	Stable	Speedup (m yr^{-1})		Slowdown (m yr^{-1})		Overall ($\text{m yr}^{-1} \text{ dec}^{-1}$)	
					Average	Maximum	Average	Maximum	This Study	[9]
Hindu Kush	4206	22.6%	28.3%	49.1%	5.2	29.6 (RGI60-14.24088)	−11.5	−186.0 (RGI60-14.22312)	−1.0	−1.4
Karakoram	12,822	17.3%	31.5%	51.2%	6.6	127.7 (RGI60-14.04875)	−13.7	−256.7 (RGI60-14.03000)	−1.6	0.8
Spiti Lahaul	7796	19.6%	18.7%	61.7%	6.4	81.5 (RGI60-14.19261)	−12.1	−179.0 (RGI60-14.17193)	−0.4	−4.6
West Nepal	3906	33.4%	29.1%	37.5%	5.5	27.2 (RGI60-14.12426)	−9.7	−51.4 (RGI60-15.05231)	−0.5	−2.2
East Nepal	3563	56.2%	19.6%	24.2%	6.3	55.8 (RGI60-15.09859)	−12.3	−62.0 (RGI60-15.09861)	0.7	−1.8
Bhutan	1547	34.1%	22.1%	43.8%	6.6	39.5 (RGI60-15.02102)	−8.5	−61.3 (RGI60-15.01907)	0.2	−2.1
Nyainqentanglha	2882	41.3%	21.9%	36.8%	6.9	95.9 (RGI60-15.12714)	−12.4	−135.6 (RGI60-15.12081)	0.2	−6.4
Total	36,722	32.0%	24.5%	43.5%	6.3	127.7 (Karakoram)	−12.3	−256.7 (Karakoram)	−0.3	/

Figure 4. Glacier velocity and velocity changes versus area, length, slope and thickness. Dots and triangles stand for glaciers with an area of smaller than 20 km^2 and over 20 km^2 , respectively. Non-surge- and surge-type glaciers are separated by blue and red. Lines show the linear regression analysis of the corresponding group of data.

5. Discussion

5.1. Regional Patterns of Surface Velocity Changes

Dehecq et al. [9] calculated time-series velocity anomalies for 11 subregions in the Himalayas. An analysis of glacier changes at regional scales allows us to explore cryospheric responses to climatic forcing. Here, we followed their line of analysis and focused on the 7 subregions that stretch along the range front. In order to compare our estimates to theirs, we averaged the velocity differences of all glaciers in each subregion and calculated the rate of change (velocity differences divided by 1.8 decades). Velocity changes (Table 1) show that, on average, glaciers in Hindu Kush ($-1.0 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 4206 glaciers), Karakoram ($-1.6 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 12,822 glaciers), Spiti Lahaul ($-0.4 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 7796 glaciers) and West Nepal ($-0.5 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 3906 glaciers) have slowed down from 1999 to 2018, whereas a slight acceleration has occurred in the east: East Nepal ($0.7 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 3563 glaciers), Bhutan ($0.2 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 1547 glaciers) and Nyainqentanglha ($0.2 \text{ m yr}^{-1} \text{ decade}^{-1}$ for 2882 glaciers). Our results differ from [9]’s,

who found that all subregions have experienced a slowdown between 2000 and 2017, with a changing rate varying from $-6.4 \text{ m yr}^{-1} \text{ decade}^{-1}$ in Nyainqentanglha to $-1.4 \text{ m yr}^{-1} \text{ decade}^{-1}$ in Hindu Kush, except for Karakoram, which experienced a small speedup ($0.8 \text{ m yr}^{-1} \text{ decade}^{-1}$). The inconsistency is likely to be resulted from seasonal changes in glacier flow. The images used in our study were collected in December, so our estimates are velocities during winter, while [9]'s velocity estimates are centred around June. Past studies (e.g., [31–33]) have shown that, during summer, when melting occurs, glaciers flow much faster with stronger temporal and spatial variations. Velocity changes during winter ($0 \sim 1 \text{ m yr}^{-1} \text{ decade}^{-1}$) are considerably smaller than the changes during summer ($1 \sim 6 \text{ m yr}^{-1} \text{ decade}^{-1}$) (see Figure 1 and Table 1), possibly due to strong spatio-temporal variations in melting in the Himalayas. From the winter velocity changes, we also observed a contrasting difference between the western (slowdown) and eastern (speedup) parts of the Himalayan front, indicating heterogeneous changes in accumulation and/or melting under different climatic regimes.

5.2. Linking Surface Velocity Changes with Glacier Mass Balance

To further investigate the driving factors of glacier velocity changes, we use the empirical power law relation between glacier surface velocity V and driving stress τ [34–37]:

$$V = A\tau^m \quad (1)$$

where A and m are positive constants, related to ice rheology, bed topography and flow mechanisms (ice deformation and basal sliding) [34,35]. m has been estimated to vary from 1 (flow over soft sediments, [38]) to 4 (high subglacial pressure, [9]) under different circumstances.

Taking the derivative of V with respect to τ , we have:

$$dV = Am\tau^{(m-1)}d\tau \quad (2)$$

Combining Equations (1) and (2), we have:

$$\frac{dV}{V} = m \frac{d\tau}{\tau} \quad (3)$$

Assuming that changes in the driving stress ($d\tau$) are induced by mass balance (dM) and ignoring other factors, as proposed by [9], i.e., $d\tau = C_1dM + C_2$, we have:

$$\frac{dV}{V} = \frac{m}{\tau}C_1dM + \frac{m}{\tau}C_2 \quad (4)$$

where C_1 and C_2 are assumed constant, relating the driving stress and mass balance. Dehecq et al. [9] analysed velocity changes and mass balance data and found that, at regional scales, summer velocity changes are positively correlated with mass balance: $\frac{dV}{V} \sim 1.25dM$ (see Figure 5).

To test whether velocity changes exhibit any seasonal variability, we applied Equation (4) to analyse the winter velocity estimates. We calculated the average values of velocity V and its change dV for each of the glaciers, based on which we determined the overall dV and V for each subregion. The measurements of glacier mass balance (dM) were taken from [7]. Although estimates of glacier mass balance in Brun et al. [7] did not take seasonal variability into account, an earlier study in [2] has shown that the long-term trend of dM is consistent between seasons (the amplitude differs slightly). Therefore, using the average long-term trend of dM should not affect the linear relationship between dV and dM . As shown in Figure 5, glacier velocity changes $\frac{dV}{V}$ are negatively correlated with mass balance ($\frac{dV}{V} \sim -0.96dM$), suggesting that ice mass loss promotes glacier motion in winter. This is in contrasting difference with summer velocity changes in the study by [9], which states that mass loss drives glacier slowdown. Such seasonal variability indicates

different mechanisms of glacier mass loss in the Himalayas. Increased melt conditions in the early winter period, November and December, could enhance velocity, as noted by Bocchiola et al. [39], Pelto et al. [40] in the eastern Himalaya. During summer, mass losses are more likely to be resulted from increased ablation zone melting, given that precipitation has not been significant [41,42]. The result suggests that velocity changes in the Himalayas are temperature driven, rather than accumulation process driven.

Figure 5. Glacier surface velocity changes versus mass balance. Mass balance data were taken from [7]. Shaded bands indicate 68% confidence interval. Winter velocity changes (filled circles, in this study) are negatively correlated with mass balance, with a correlation of $R = -0.87$. Summer velocity changes (filled triangles, [9]) are positively correlated with mass balance.

6. Conclusions

In this study, we used Landsat-7 and Sentinel-2 optical imagery to investigate glacier surface velocity and the associated changes in the Himalayas. We analysed flow patterns of individual glacier along the Himalayan mountain front and found that glacier velocity changes exhibit an evident heterogeneity at different spatial scales. Of all the 36,722 glaciers, 32% have experienced speedup, 24.5% have slowed down, and the rest, 43.5%, have remained stable. At regional scales, the amplitude of velocity changes is significantly larger in summer [9] than that in winter (this study). The decreasing velocities in winter between 1999 and 2018 in the western part of the Himalayas, in contrast to the increasing velocities in the eastern part, may be caused by changes in accumulation and/or melting under different climatic regimes. Accelerated flow in Eastern Nepal may be impacted by melting conditions, where more melting has been observed. We also observed that glacier velocity changes in winter are controlled by mass balance, as suggested by [9]; however, unlike summer velocity changes that are positively correlated with mass balance, winter velocity changes show a negative correlation. Our study suggests that glacier velocity changes in the Himalayas are more spatially and temporally heterogeneous than what

was previously thought, emphasising complex interactions between glacier dynamics and environmental forcing.

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