

# Line-of-Sight Glacier Velocity Estimation of Transboundary Glaciers in the Eastern Himalayas Using High-Resolution TerraSAR-X Data <sup>†</sup>

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**Abstract:** Glacier velocity is one of the critical parameters for understanding the current health status of a glacier. According to the momentum law, mass is inversely proportional to velocity. A higher velocity may indicate a lower mass. Fifteen transboundary glaciers from the eastern Himalayas in the vicinity of India, Nepal, Bhutan, and China are chosen for the estimation of glacier velocity. These glaciers are Changshang, Rathong, South Lhonak, South Simvo, Talung, Tongshiong, Yalung, Zemu, Glacier 2, Glacier 3, Kaer, Ktr Gr 193, Middle Lhonak, North Lhonak, and Ktr Gr 171 (Lhonak Nepal), covering a total area of 440.92 km<sup>2</sup>. A remote sensing and GIS-based approach is considered for the study. High-resolution synthetic aperture radar data from TerraSAR-X were acquired from the German Aerospace Center (DLR) by the European Space Agency for the study area in the years 2020–2021. Satellite data were pre-processed using radiometric calibration and multi-look for speckle noise reduction. These datasets were co-registered using the SRTM Digital Elevation Model. Offset tracking was applied to estimate the glacier velocity. The maximum velocity in all glaciers ranged from 14.31 to 84.26 ma<sup>-1</sup>. The average velocity ranged from 1.78 to 7.09 ma<sup>-1</sup>. The glacier with the highest average velocity was the South Lhonak glacier. This glacier has been melting rapidly in the last few decades. Near the snout of this glacier lies a glacial lake made up of a moraine dam. For quality assessment, the latest field-based results of 2018 and the observed results of 2021 were compared. It was noticed that there is a variation of approximately 10%.

**Keywords:** glacier velocity; eastern Himalayas; transboundary region; offset tracking



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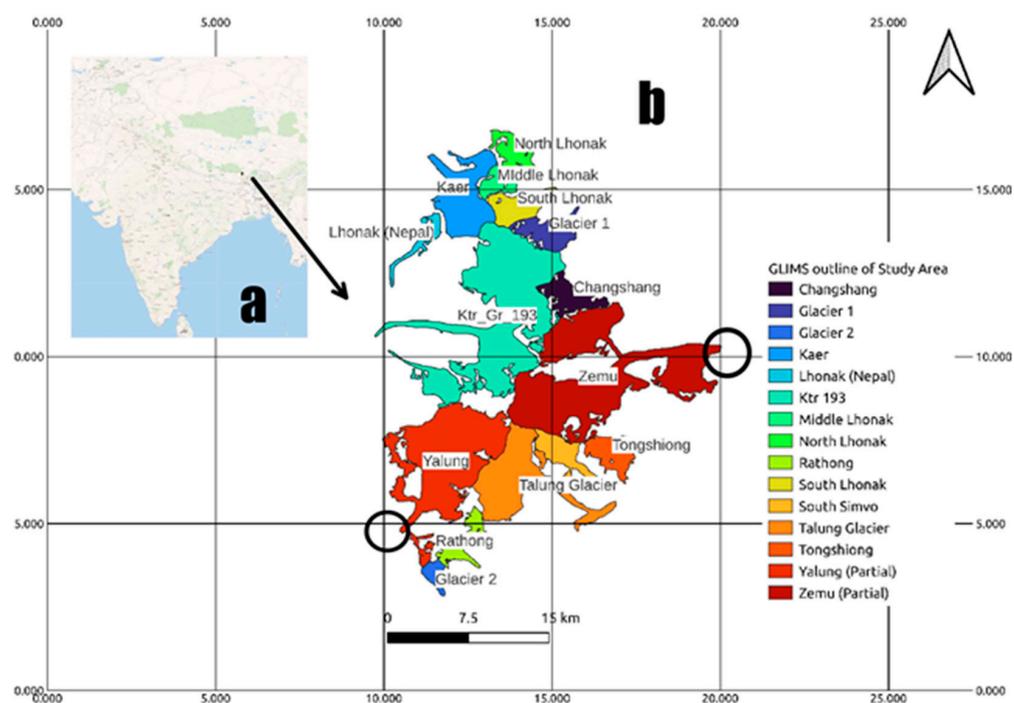
## 1. Introduction

The estimation of glacier velocity is very important since it is a parameter of glacier dynamics. It can help understand the health of a glacier because the momentum is directly related to the mass and the velocity is inversely related. As per the basic momentum law, a higher velocity could imply a decrease in mass; however, the slope parameters should be carefully considered before drawing any conclusions. The decrease in mass is a significant indicator of climate change. It is a general fact that climate change impacts cause natural hazards such as the formation of glacial lakes, which can cause glacial lake outburst floods (GLOFs). There are two approaches to the estimation of glacier velocity. One is the field-based method, and the other is the remote sensing-based method. Field-based estimation is not possible for all the glaciers in the world, since most of them are inaccessible due to various reasons. For example, in the Himalayan region, due to transboundary sensitivity and the rugged terrain structure, there are accessibility concerns. This problem is solved using satellite imagery.

In remote sensing-based methods, offset tracking is one of the most widely used tools. The offset tracking method works well in the Himalayan region. There has been a successful attempt at velocity estimation in the Chota Shigri and Bara Shigri glaciers [1]. The authors used SAR data from the Sentinel-1 satellite to estimate the glacier velocity using the offset tracking method. It has also been observed recently that there is a direct relationship between the mass balance and the glacier velocity [2]. Hence, it is very important to estimate the glacier velocity. It is a well-known fact that in the Himalayan glaciers, accessibility is a concern. In the eastern Himalayas, there are few studies related to glacier velocity estimation. In this study, we attempt to solve this problem through the use of high-resolution X-band SAR data from the TerraSAR-X. We use sub-pixel intensity-based offset tracking to estimate the glacier velocity of 15 transboundary glaciers in the eastern Himalayas. The peak of these glaciers forms the boundary of three nations, namely Nepal, India, and China.

## 2. Materials and Methods

The study area is mainly situated in Sikkim, India (Figure 1). It is the landlocked transboundary border state of Nepal, China, and Bhutan. In the western part of Sikkim lie Nepal and China. The bounding coordinates of the study area are 28°06′41.25″ N and 26°58′06.66″ N in the north and south, followed by 88°53′41.57″ E and 88°03′18.17″ E in the east and west, respectively. The above-sea-line altitude of the state ranges from 300 m to 8586 m at the Kanchenjunga peak. This peak is the 3rd highest mountain peak in the world.



**Figure 1.** Study area map, (a) Outline of Indian sub-continent (b) GLIMS outline of glaciers in study area. (Credits: Corresponding author and GLIMS database).

The fifteen glaciers of the study area are Changshang, Rathong, South Lhonak, South Simvo, Talung, Tongshiong, Yalung, Zemu, Glacier 2, Glacier 3, Kaer, Ktr Gr 193, Middle Lhonak, North Lhonak, and Ktr gr 171 (Lhonak Nepal). These glaciers cover a total area of 440.92 km<sup>2</sup>. Ktr Gr 193 is the largest glacier in this location, while Glacier 3 is the smallest. East Rathong glacier is the benchmark glacier for the field studies, while Zemu glacier is the origin of the Teesta River that flows till Bangladesh via Sikkim and West Bengal. The GLIMS outline is used to delineate the glacier boundary. In the whole region, due to the

swath limitation, Zemu and Talung cover 98% of the glacier area. The terminus portion is ignored for this reason.

### 2.1. Data

TerraSAR-X Stripmap products are acquired by the European Space Agency (Table 1). It is a sun-synchronous repeat-orbit satellite. The range and azimuth resolution are 1.36 m × 2.23 m, and it operates on a 31 mm wavelength and 9.6 GHz frequency. The chirp bandwidth is 150 MHz/300 MHz with the nominal acquisition direction on the right side. TerraSAR-X data are preferred because of their high resolution and better quality.

**Table 1.** Time series data for the study area.

S. No.	Date of Acquisition	Season	Polarisation	Range and Azimuth Resolution (m)	Pass	Incidence Angle (degree)
1	3 October 2020	Early Winter Accumulation	HH	1.36/2.23	ASCENDING	43.36–45.47
5	20 September 2021	Autumn Ablation	HH	1.36/2.23	ASCENDING	43.36–45.47

### 2.2. Pre-Processing and Offset Tracking

The data was acquired by the European Space Agency in slant-range format. For the line-of-sight velocity, the slant range information is not required (Prati, 1993). The conversion of the slant range product to the ground range product is the pre-processing required for the offset tracking. It is performed after applying radiometric calibration and speckle noise removal.

A radiometric calibration is applied for the conversion because ground-range products need backscatter conversion for understanding the characteristics of backscatter coefficients. The Sentinels Application Platform (SNAP) uses the following equation for the conversion:

$$i = \frac{DN_i}{A_i^2}$$

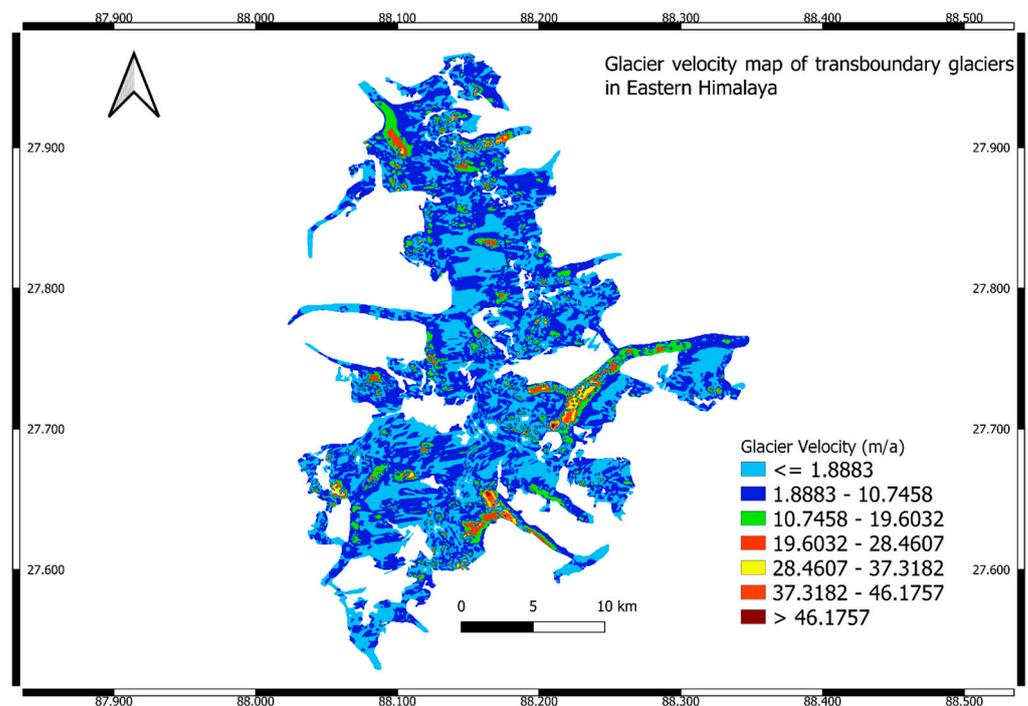
It is a well-known fact that SAR images contain speckle noise [3]. For the reduction of speckled noise, images are joined incoherently. This process is called multilooking. A major advantage of multilooked images is their interpretability and better visual appearance. SNAP software is used to create a warp polynomial of order 3 to map the ground range pixels to slant range pixels. Further, every pixel in the ground range computes the corresponding pixel position in the slant range image using the warp polynomial. In the final step, the pixel value is estimated using the nearest neighbour interpolation.

Offset tracking is used to track the offset in the slave image. A master image is the one that is being compared. A co-registration is performed on the master and slave images [4]. Offset tracking through the SAR data is most commonly used for the estimation of glacier velocity. As per various authors, this method is ideal for the estimation of glacier velocity across the glaciers of the world [5–7]. A 128-pixel window is chosen to track the offset in a master and slave image. The maximum velocity is set to be 0.25 m/day [8]. The last step is to geocode the offset tracking results. The topographical variations in the scenes, as well as the tilt of the sensor along with the distances, are sensitive to the distortion in SAR images. A terrain correction is applied to rectify the distortions in the SAR images [9].

## 3. Results and Discussion

The glacier velocity of the 15 transboundary glaciers is estimated through the offset tracking method (Figure 2). The maximum average velocity is observed in the South Lhonak lake (Table 2). The minimum average velocity is observed in Glacier 3. Near the snout of the south Lhonak lake, there is a glacier lake that is expanding at a rapid rate [10,11].

As per a study by [12], it is observed that high flow results in higher melting. The higher average velocity of the South Lhonak glacier could be one of the reasons for the increase in the size of the lake. The average annual velocity of the large glaciers, such as Ktr gr 193, Zemu, and Yalung, which have a surface area of more than 60 km<sup>2</sup>, is relatively lower than that of the South Lhonak glacier. The maximum velocity of the South Lhonak glacier is also relatively higher than that of glaciers having similar surface areas, such as Rathong, Middle Lhonak, South Lhonak, and Lhonak (Nepal). A study has observed that the maximum velocity of the glaciers in the western Himalayas ranges from 50 to 90 m/a [13]. We observe the maximum velocity of glaciers with a similar surface area to be ~52–84 m/a. A study observed a higher velocity trend [14] in slopy regions of the Himalayas. The velocity values in the slopy regions, as per this study, were greater. This study only used a time gap of 6 months. High velocity in regions with a higher slope is justifiable because of the gravity factor. In the line-of-sight approach, the analysis is completely based on the movement of the satellite sensor. The slope factor is not considered for this reason. There could be variations in the results based on different approaches.



**Figure 2.** Glacier velocity map of transboundary glaciers in the eastern Himalayas.

In the study area, field data on glacier velocity are available only for the benchmark outline of the East Rathong glacier. The last field-based survey was performed in the ablation season of 2018. The average velocity value of eight different points for a year in the benchmark outline was estimated to be 5.92 m/a (for the ablation season). It is compared with the average velocity value of the same points in the TerraSAR-X offset tracking estimates. The value is observed to be 6.61 m/a. A variation of approximately 10% was observed in the field value of the year 2018 (ablation season converted into a yearly scale) and direct yearly estimates of 2020–2021. This is not a direct validation of the results, but an estimate of variation from the latest available field data.

**Table 2.** Velocity estimates of 15 glaciers in transboundary eastern Himalayas.

Glacier Name	Mean Velocity	Maximum Velocity	Variance
Changshang	3.74	26.69	0.04
Glacier 2	3.62	25.43	0.03
Glacier 3	1.78	14.31	0.01
Kaer	5.94	33.69	0.08
Ktr gr 193	4.41	26.76	0.06
Ktr gr 171	2.77	12.40	0.01
Middle Lhonak	4.61	43.80	0.09
North Lhonak	4.03	30.04	0.04
Rathong	3.15	26.03	0.04
South Lhonak	7.09	55.03	0.16
South Simvo	3.48	20.72	0.04
Talung	5.99	51.80	0.18
Tongshiong	2.76	34.90	0.03
Yalung	3.62	39.15	0.05
Zemu	4.85	84.26	0.12

#### 4. Conclusions

A variation in glacier velocity could indicate significant changes in glacier health. As per the basic momentum and angular momentum laws, an increase in velocity is capable of decreasing the mass of a glacier. It is one of the most important parameters used to estimate the present flow conditions and mass of a glacier. There are many empirical relations that can be used to estimate overall glacier mass using shallow ice approximation methods [15,16]. Hence, it is important to create baseline data for future studies. This study creates a baseline average velocity and maximum velocity using high-resolution TerraSAR-X data. The chosen study area is the transboundary region of the Eastern Himalayas. This transboundary region is the border of four nations: India, Nepal, Bhutan, and China. The maximum velocity in all the glaciers ranged from 14.31 to 84.26 m/a. The average velocity ranged from 1.78 to 7.09 m/a. The glacier with the highest average glacier velocity is observed to be the South Lhonak glacier. This glacier has been melting rapidly in the last few decades. At the snout of this glacier lies a glacier lake made up of moraine dams. It is direct evidence of climate change for regional policy formation. For the quality assessment of the results, the latest field-based results of 2018 and the observed results of 2021 were compared. A variation of approximately 10% was observed.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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