Estimation of surface ice velocity of Chhota-Shigri glacier using sub-pixel ASTER image correlation

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This article presents results on surface ice velocity of the Chhota-Shigri glacier, Himachal Himalaya, deduced by applying sub-pixel image correlation technique (COSI-Corr software) on the ASTER time series data (2003–2009). The remote sensing-derived measurements are found to match quite well with the field measurements. In general, the surface ice velocity varies from ~20 m/yr to ~40 m/yr. Velocity variations occur in different parts of the glacier and also from year to year. In all the years considered for this glacier, the mid-ablation zone and the accumulation zone exhibit higher velocities and zones near the snout and equilibrium line altitude have relatively lower velocities. Further, the velocities are found to be relatively higher in the years 2005–2006 and 2007–2008 and lower in the years 2006–2007 and 2008–2009. These spatial and temporal variations in velocity, which could be related to the glacier morphology and hydro-metrological factors, need to be further studied.

Keywords: Glaciers, optical image correlation, remote sensing, sub-pixel images, surface ice velocity.

GLACIERS all over the world have been experiencing recession at varying rates[1–4], and the need of generating glacier inventory and dynamics data at global scale cannot be overemphasized. A comprehensive review on the Himalayan glaciers was made by Bolch *et al.*[5] emphasizing the need of their continued monitoring. Considering the vastness and inaccessible nature of mountain glaciers, and the various difficulties and limitations commonly associated with field glaciological studies, satellite remote sensing technology now offers a highly viable tool for various glaciological studies[6].

Glaciers move, or flow, downhill due to gravity and the associated internal deformation of ice. Also, ice can move as plastic material due to high pressure of thick accumulated ice/snow or due to basal sliding. Measurement of ice flow velocity can help in modelling the glacier dynamics. The surface ice velocity of a glacier is a measure of how fast the surface ice is flowing towards the terminus of the glacier. The flow can be fast or slow, depending on how much the glacier is melting. Fast-moving glaciers bring more ice towards the terminus for melting, which in turn is one of the important factors governing mass balance of the glacier. Another important aspect which is governed by the surface velocity is the load carrying capacity of a glacier. The denudational force exerted by the glacier and the transport of generated debris depend on the load carrying capacity. Therefore, it can be said that the surface ice velocity has a major impact on the health and fate of the glacier.

Conventionally, surface ice velocity is measured in the field by monitoring the position of stakes, which are installed by drilling into the glacier ice, by DGPS or total station. It is, however, difficult to obtain sufficient velocity data to investigate processes and the stability of glaciers with conventional glaciological techniques (field measurements) due to the frequent loss of stakes and difficulty in the handling of measuring instruments at the site. Glacier surface ice velocity can also be estimated from satellite data using SAR interferometry, SAR image data intensity tracking or feature tracking from optical data. Although SAR interferometry is a widely used technique for deformation and velocity mapping, it has limitations in highly rugged terrains like the Himalaya and especially for fast-moving glaciers. The visibility of the target glacier is affected in such rugged terrain conditions due to oblique viewing SAR images. Further, high incidence angle requires accurate Digital Elevation Models (DEMs) to correctly orthorectify the measurements[7].

Optical image correlation is another promising technique used to deduce deformation or displacement of a moving object. The principle involved in this technique is that two images acquired at different times are correlated to find out the shift in position of any moving object, which is then treated as displacement in this time interval. Surface velocity fields of glaciers and other moving ice bodies using optical satellite images have been studied since mid-1980s using manual tracking of features[8–10]. Different methods for correlating image to

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Table 1. Satellite remote sensing data used in the study

Sensor	Type of data	Resolution (m)	Image date and pair used for correlation
SRTM	DEM	90	2000
ASTER NIR band 3N	NIR band 3N	30	8 October 2003–17 September 2004
			17 September 2004–7 November 2005
			7 November 2005–17 November 2006
			17 September 2004–17 November 2006
			17 November 2006–20 November 2007
			20 November 2007–1 December 2008
			1 December 2008–1 October 2009

derive velocity have been developed and applied in glaciology, like normalized cross-correlation[11–16], cross-correlation operated in the Fourier domain[17], least squares matching[18], phase correlation[19–21] and orientation correlation (CCF-O)[22].

A few open source image processing software are available, e.g. CIAS, IMCORR, COSI-Corr, etc. which utilize the above principle, but their applications have been limited due to tedious and time-consuming processing. However, it has been reported that CCF-O and COSI-Corr are relatively more robust matching methods for global-scale mapping and monitoring of glacier velocities[8]. It may be mentioned that MIMC (multiple images/multiple chip sizes), and repeat-image feature-tracking (RIFT) algorithm have also been developed for measuring ice motion[23].

In this study, we have used COSI-Corr (an add-on module of ENVI) based on the algorithms described by Ayoub *et al.*[24] and Leprince *et al.*[25]. This software allows precise co-registration, orthorectification and sub-pixel correlation of remote sensing images, all in one package and in a more user-friendly environment. Final result largely depends on the precise co-registration and orthorectification of the two images being used in the pair. During processing (correlation), the errors from different sources tend to combine and lead to a relatively higher error in the final result. COSI-Corr includes different filtering algorithms to remove such errors. Precise orthorectification is obtained by applying the optimized model for registration and resampling[25]. An iterative unbiased processor that estimates the phase plane in the Fourier domain is also introduced in the COSI-Corr for image registration and correlation[25]. Scherler *et al.*[21] applied the COSI-Corr software to ASTER images to compute glacier ice velocities in the Khumbu and Gangotri glaciers in the Himalaya.

Here we have used ASTER images from 2003 to 2009 to estimate the velocity of Chhota-Shigri glacier. All the images used are almost of the same month from different years (Table 1). All the remote sensing data processing has been done in ENVI and COSI-Corr. Error removal and filtering have been done in COSI-Corr and ArcGIS.

Study area and data used

The Chhota-Shigri glacier is situated in the Lahaul-Spiti valley in Himachal Pradesh, India (Figure 1). It is a relatively small glacier with a length of around 9 km (lat. 32.08–32.29°N and long. 77.47–77.55°E) located on the northern slopes of the Pir-Panjal range. This glacier has been monitored in the field by several groups of glaciologists for quite some time[26–28] and some field data for glacier velocity are also available which have been used as reference data in this study.

We have used band 3N (nadir-viewing) near-infrared band image of ASTER images from 2003 to 2009. All the ASTER scenes have nearly similar incidence angles resulting in good correlation without requiring corrections for attitude. Details of ASTER image pairs used in this study are given in Table 1.

Methodology

The methodology of data processing followed is outlined in Figure 2. As mentioned earlier, sub-pixel level co-registration of optically sensed images and correlation (COSI-Corr) is a relatively new and advanced method developed by Leprince *et al.*[25] and this package is bundled and provided as add-on module for the ENVI software. The methodology for studying glacier dynamics is provided by Scherler *et al.*[21]. This methodology reduces the effect of inaccurate DEMs, errors due to satellite attitude during scanning and also increases the accuracy of co-registration of images.

Before correlation of images, raw satellite images were orthorectified and co-registered. For this, tie-points were manually selected from band 3N of AST14DMO (orthorectified image) with respect to the raw image (ASTER L1A). Then the GCPs were refined and used for automatic registration and orthorectification of the base image. The orthorectified image is now used as the base image for rectifying other images. After orthorectification, two selected time-series images are correlated to sub-pixel level using frequency correlator. The correlation gives horizontal displacement with two components

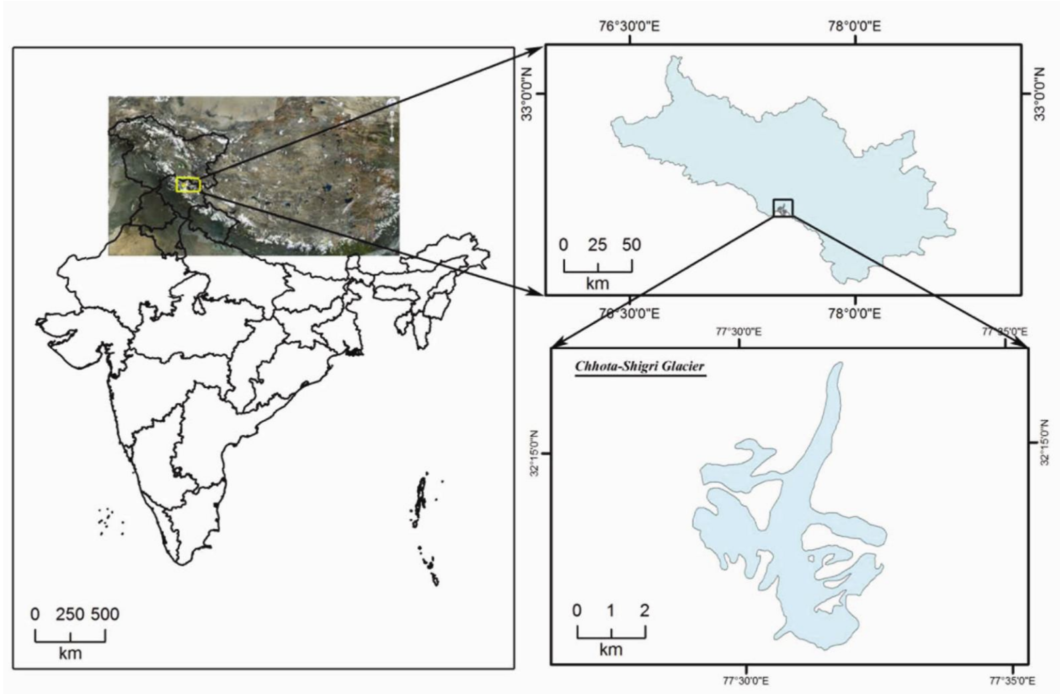

Figure 1. Location map showing Lahul-Spiti valley and the glacier under study.

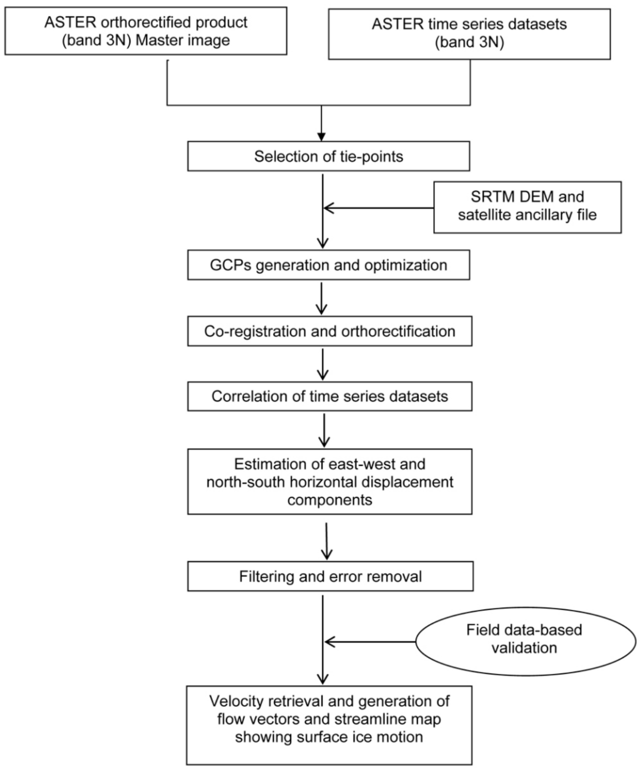

Figure 2. Overview of methodology.

(two images), i.e. east-west and north-south. Signal-to-noise ratio (SNR) is also calculated along with the displacement field defining the confidence of the results.

Now, an important step is the filtering of correlated results before any meaningful interpretation can be drawn. We have used three filters to refine our data processing involving SNR, direction and magnitude. The low SNR points are first filtered out to remove poorly correlated pixels. Then, a filter to check the direction of the general flow of the glacier is used to remove points that do not match with the general flow pattern. For this, flow vectors and streamlines showing general flow pattern are generated using computed horizontal displacement from the image pair. An example is given in Figure 3 for the image pair of 2003–2004. The last filter used is the magnitude filter. In case of glaciers, the movement rate may not change abruptly but gradually; this fact is used as a parameter for filtering. These filtering operations are done manually and have to be in small patches, and they also require some a-priori knowledge of the area.

The horizontal displacements (EW and NS components) which have been computed by feature tracking from a pair of images (different temporal coverage) are first converted into net displacements using Euclidean norm. All time-interval data have been normalized for 365 days interval (annual basis).

Results and discussion

We have used nadir-looking, near-infrared band of ASTER images of the period 2003–2009 to calculate the surface ice velocity. A total of seven image pairs have been used out of which six are separated by a year each

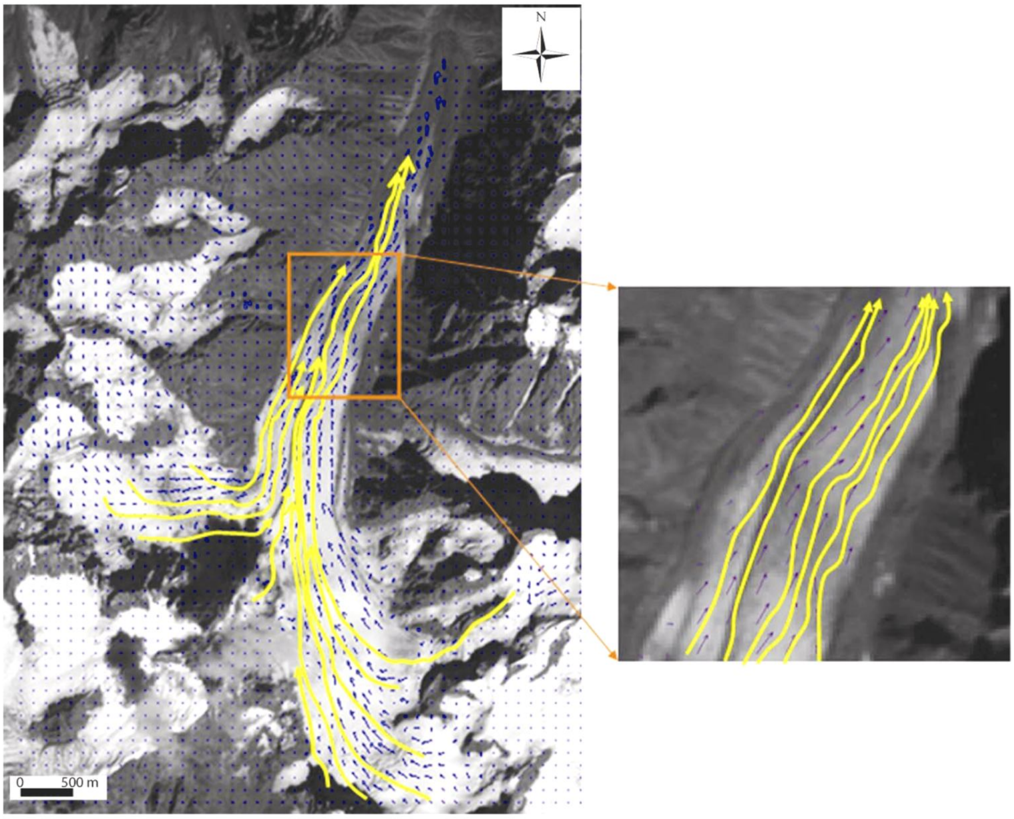

Figure 3. Example of velocity vectors derived from image pair 2003–2004. Streamlines are shown in yellow and have been constructed using the retrieved velocity vectors (vector length not to scale).

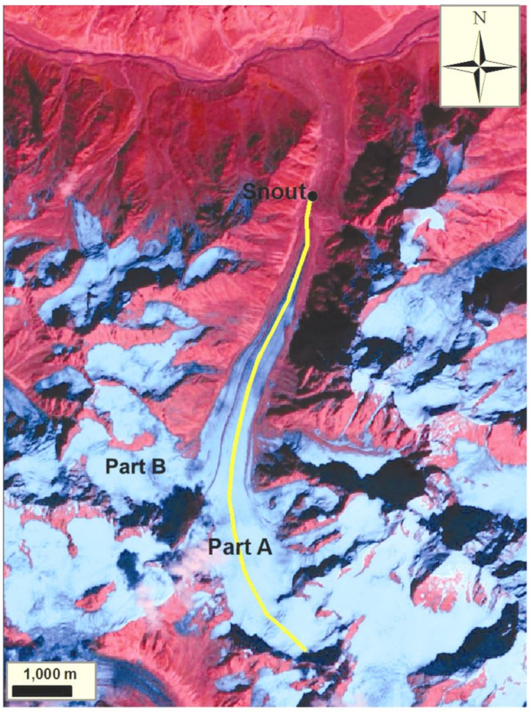

Figure 4. ASTER image false colour composite (R: band 4, G: band 3 and B: band 2; image dated 8 October 2003) of the Chhota-Shigri glacier. There are two main accumulation zones, part A and part B. All the data reported in this work are for part A. Location of the snout and the central profile line are also shown in the figure.

and one pair has a gap of two years. A comparison of the surface ice velocity derived from remote sensing and the published field data has also been made.

The Chhota-Shigri glacier has two main accumulation zones – parts A and B (terminology used by Wagnon *et al.*[28]; Figure 4). All the data reported in this work are for part A. The velocities have been taken pixel-wise along the central profile line, as most of the field measurements pertain to this part of the glacier.

Figure 5 shows a comparison of remote sensing-derived glacier surface ice velocities vis-à-vis field measurements for the years 2003–2004 and 2004–2005. The remote sensing-derived profile is a near-continuous profile line near the median glacier, whereas the field data are point data. It is obvious that there is a general agreement between the remote sensing estimates and the field data. It should be appreciated that field stake locations are selected on constraints of accessibility and therefore field data should be taken only as indicator for comparison. Further, it can be seen from Figure 5 that at several locations such as 2400, 3500, 4150, 6150 and 6600 m positions from the snout, correspondence between the field data and remote sensing estimates is good. Both sets of data indicate that the glacier surface ice velocity is relatively high at ~3 and ~6 km distances from the snout.

Table 2 shows the highest and the lowest glacier surface ice velocity data as derived from remote sensing

Table 2. Lowest and highest surface ice velocity measured using remote sensing and field-based method from 2003 to 2010 (part A)

	Lowest		Highest	
Year	Remote sensing estimates	Field-measured	Remote sensing estimates	Field-measured
2003–2004	20	24	41	45
2004–2005	19	22	38	42
2005–2006	19	NA	36	NA
2006–2007	21	NA	35	NA
2007–2008	20	NA	41	NA
2008–2009	16	NA	36	NA
2009–2010	NA	19	NA	35

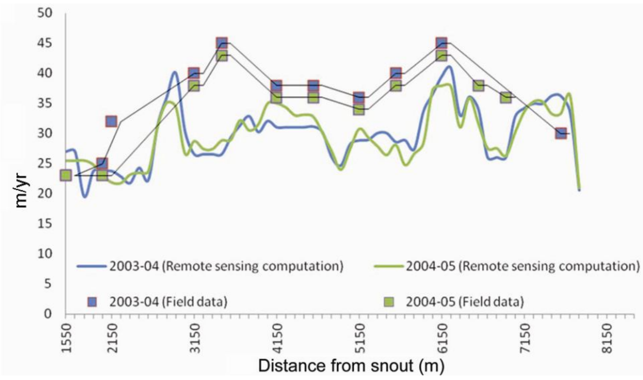

Figure 5. Comparison of remote sensing-derived glacier velocity vis-à-vis field measurements for the years 2003–2004 and 2004–2005 in part A of the glacier. The continuous curves show the remote sensing computation results; points pertain to field measurements (published data from Wagnon *et al.*[28]).

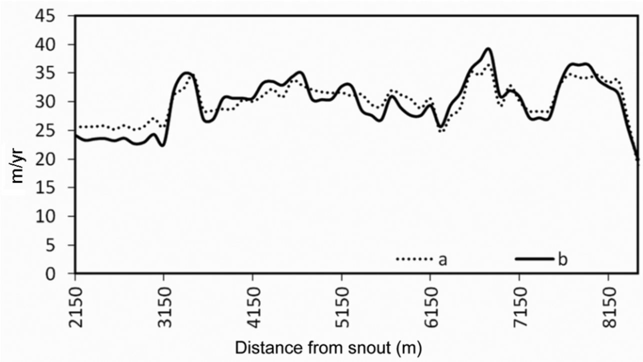

Figure 6. Comparison of velocity computation. (a) Velocity computed by averaging results of image correlation of 17 September 2004 versus 7 November 2005 and 7 November 2005 versus 17 November 2006; (b) Velocity from image correlation of 17 September 2004 versus 17 November 2006 (two-year difference). All computations are normalized for 365 days interval (one year).

processing and published field results. The highest and lowest velocities derived from remote sensing for the years 2003–2004 and 2004–2005 differ from field measurements by less than 10%. For the period 2005–2009, no published field data are available. For the year 2009–2010, we could not obtain any good remote sensing image pair for velocity estimation; however the field data giving velocities of 19 m/yr (lowest) and 35 m/yr (highest), appears to be quite close to the remote sensing estimates of 2008–2009.

It is important to mention a few words about error estimates. It should be appreciated that it is extremely difficult to generate field data for glacier studies and the published field data[28] used in this study for comparison do not include any error estimates. Regarding the remote sensing-generated computations, the image correlation accuracy is of the order of 1/20–1/10 of the pixel size[21], which would imply an error of about ±1.5 m/yr in image deduced velocity computations.

To check our image processing results, a separate exercise has been carried out in which we used images of 17 September 2004, 7 November 2005 and 17 November 2006. Velocities have been computed from the pairs (i) 17 September 2004 versus 7 November 2005, (ii) 7 November 2005 versus 17 November 2006 and (iii) 17 September 2004 versus 17 November 2006. Figure 6 shows the recomputed yearly surface ice velocity for the period 2004–2006. The result also shows similar trends in both cases, with residual error of ±2.5 m/yr.

Figure 7 shows the average velocity between 2003 and 2009 in different zones (distance from snout) as computed from remote sensing data. It is observed that the highest average velocity is in the 4000–5000 m zone, and therefore it can be said that this (mid-ablation zone) is the fastest moving part of the glacier. The slowest moving part is in the 5000–6000 m (distance taken from snout) zone. This inference is in correspondence with the field data (see Figure 5). The cause of this reduced velocity in the 5000–6000 m distance zone may be the topographic factor, as in this zone the glacier is forced to change its direction to follow the valley orientation. Further, the velocity is relatively high in the accumulation zone (Figure 7), which may be due to high topographic gradient and greater weight of the accumulated ice there.

Figure 8 is a plot indicating events in different years in different snout zones. Each line pertains to a distance zone from the snout. It can be said that the average velocity in all the zones ranges between ~20 and 40 m/yr. It can be also inferred that for all the zones, the velocity is higher for 2005–2006 and 2007–2008 and lower for

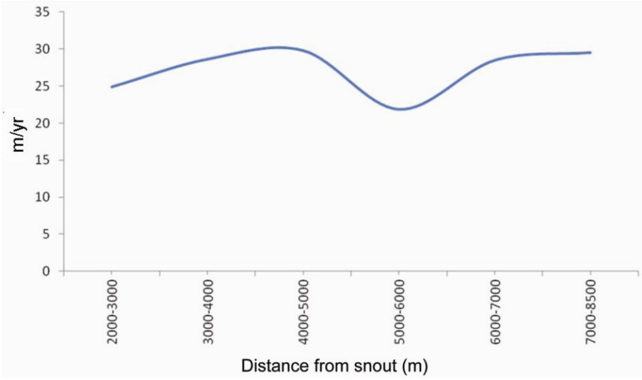

Figure 7. Average velocity of all the years in different distance zones from the snout. Average velocities pertain to average of all the years, i.e. 2003–2009.

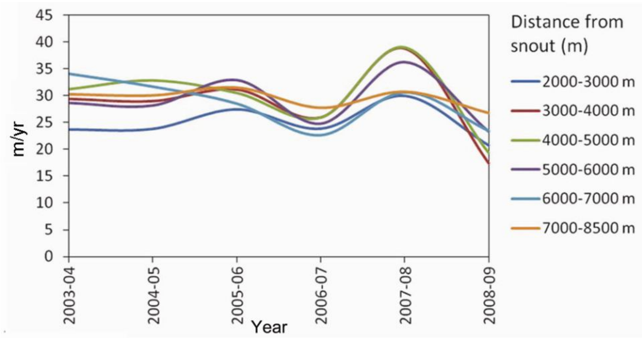

Figure 8. Year-wise variation of average velocity in different zones of the glacier. Each coloured line pertains to a distance zone from the snout.

2006–2007 and 2008–2009. Therefore, the velocity appears to exhibit a pulsating pattern, which may be due to the hydro-metrological parameters, including change in mass balance, variation in seasonal snowfall, etc.

Other possible causes of variation/source of error in computed results could be due to mismatch in image correlation, DEM-related error and minor difference in incidence angle of the two images of a pair. Another factor could be that we have used various images of different dates (17 September to 1 December) of different years and normalized all the vector displacements from image pairs to 365 days, based on the assumption that ice velocities are the same throughout the year, a generalization which may not be true. However, overall results from the image correlation by feature tracking technique appear to be acceptable.

Concluding remarks

In view of the general concern of global warming and glacier recession, it is important to monitor glacier dynamics on a global scale. COSI-Corr utilizes the method of feature tracking and is a powerful open-source software useful for such studies. We have generated velocity data of the Chhota-Shigri glacier applying COSI-Corr software using ASTER satellite images for the period 2003–2009. The image data were orthorectified, co-registered and adequately processed in COSI-Corr to generate displacement vectors. The results were compared with field data as available.

It is observed that the velocity data obtained from remote sensing images match well with the field measurements. In different parts of this glacier, the surface ice velocity appears to vary such that the mid-ablation zone and the accumulation zone are relatively fast-moving parts and the areas near the snout and equilibrium line altitude are slow-moving. This pattern of spatial variation in velocity is exhibited in all the years. Further, the glacier velocity also appears to vary from year to year, such that there are some years of higher velocity and some years of relatively lower velocity. This variation could be possibly related to hydro-meteorological factors.

The need of monitoring glaciers and their dynamics have already been well-outlined[5]. In view of the vastness and inhospitable terrain conditions in the Himalaya, the above approach of optical image correlation can be valuable in generating surface ice velocity data of the Himalayan glaciers.

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