Remote sensing analysis of changes in Chorabari glacier, Central Himalaya, India

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In this study, mass balance for Chorabari glacier of the Central Himalaya, India has been estimated. This glacier has been considered for the case study as it feeds the Mandakini River and was one of the reasons for flash floods in Rudraprayag district, Uttarakhand in 2013. The observations are based on glacier area/length change and rate of melting in the multi-decade (1976–2016) using Landsat data. The study estimates an overall decrease in area at 0.8% per year. Elevation change has been studied using geodetic method utilizing shuttle radar topography mission and TanDEM-X datasets, which have shown a decrease in elevation in 16 years (2000–16). From these remotely observed parameters, a negative mass balance for the decade 2000–11 indicates glacier retreat. This study highlights the applicability of optical and radar remote sensing for the Himalayan glaciers, for better disaster management and understanding glacier dynamics in response to climate change.

Keywords: Chorabari, elevation change, mass balance, remote sensing analysis.

Introduction

MOUNTAIN glaciers are widely accepted as indicators of climate change, and glacier dynamics provides an insight about its effects on (1) the water supply for people downstream in near future; (2) recent natural disasters linked to glaciers like glacial lake outburst floods (GLOF), and (3) sea-level rise[1]. Undoubtedly, it is imperative to have an in-depth knowledge about the glaciers as they control our life not only at the regional scale, but also at the global level.

The Himalayan glaciers comprise of the largest mountain glacier systems of the world, also sometimes called the 'third pole'[2]. These glaciers are divided into four zones: zone 1 (Mainly in Afghanistan), zone 2 (mostly stable glaciers, including the Karakorum which is advancing), zone 3 (mainly in India, consisting of the Central Himalaya) and zone 4 (mainly in Nepal)[3]. As most of the glaciers in zone 3 are reported to have a faster rate of retreat[4,5], the focus of the present study lies in this region for climate change analyses. Also, when one aims to study the effect of climate change, the best practice is to apply the bottom-up approach; local-scale studies (finer resolution) to global scale (coarser resolution), rather than the other way around.

Chorabari glacier, though reported to have a much slower retreat rate compared to other glaciers in this region[5], has gained attention in the recent past owing to the disaster that struck in June 2013. The glacial lake outburst led to the destruction of not only life and property, but it also changed the outlook of the glacier, viz. the snout position which could influence the course of the Mandakini River.

To understand the glacier dynamics, mass balance studies provide useful information. Changes in length, area, elevation and volume are the necessary parameters for mass balance estimation. For long-term studies, ground-based measurements are a challenge considering the difficult terrain of the Himalaya. Thus, remote sensing-based analysis serves as a useful alternative when continuous study needs to be performed. Here, using geodetic method, we have estimated the glacier mass balance with inputs from the above-said parameters utilizing different optical and radar remote sensing datasets.

Study area and datasets

Chorabari glacier (30°46′20.58″N, 79°2′59.38″E) is located in the basin of the Mandakini (Alaknanda catchment, a tributary of River Ganga) (Figure 1). The glacier is medium-sized with surface extent of ~6.7 sq. km, width of ~0.4 km and length of ~7.5 km with an altitude of 6420 m amsl at the head and 3800 m amsl at the terminus of the glacier[5]. The glacier is south-facing and has a total catchment of ~15 sq. km.

The general climate of the study area is humid temperate in summer and dry cold in winter. At 3820 m amsl, the annual daily average for the period 2007–2010 has been recorded as 3.4°C. Precipitation is influenced by the ISM (Indian summer monsoon) and the mid-latitude westerlies. The average wind speed is around 2.4 ms^{-1} and average daily sunshine around 190 min (ref. 6).

To estimate the changes in area and length of the glacier, Landsat images from 1976 till 2016 with an interval of a decade were used. The glacier area was delineated using visual interpretation method from the Landsat image for mass balance calculations for 2000–11. Landsat

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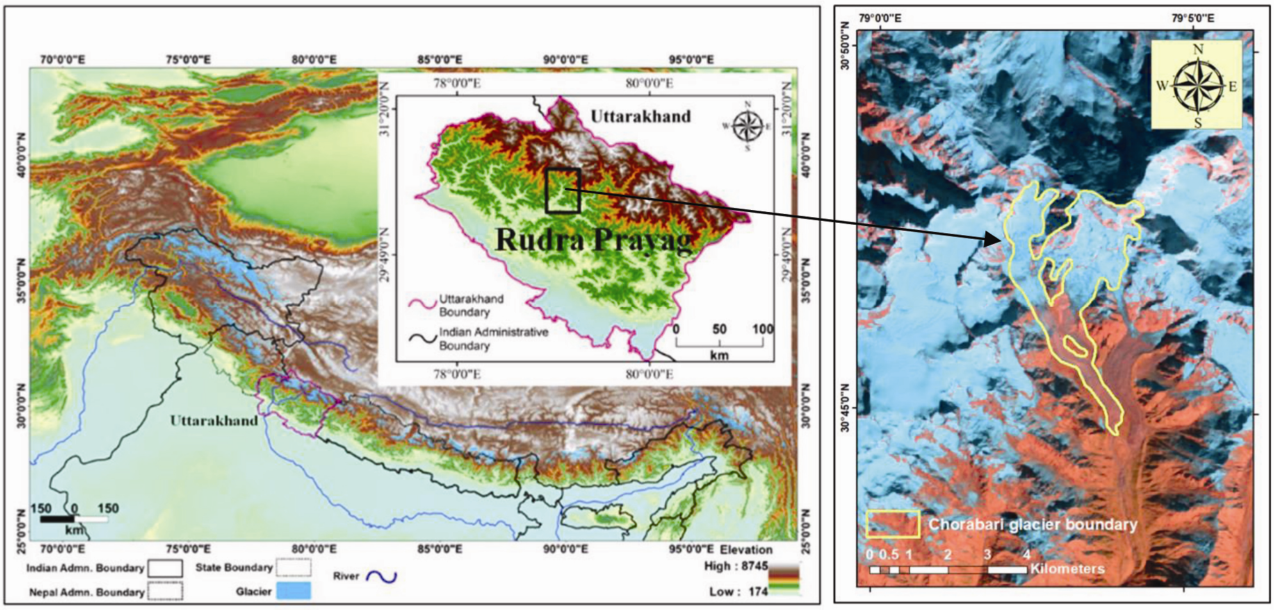

Figure 1. Overview of the extent and location of the study area (Chorabari glacier) in the Central Himalayan region.

Table 1. TanDEM-X data specifications

Parameter	8 September 2011	12 September 2016
Polarization/pass	HH/D	HH/D
Angle of incidence (degree)	36.8892	35.7084
Effective baseline (m)	101.4707	356.7470
Critical baseline (m)	3906.646	4239.754
Height of ambiguity (m)	60.1909	16.2858
Average coherence	0.6107	0.5832

legacy mission data were utilized for the study as they provide continuous coverage from 1972 till the present, having a moderate resolution of 30 m and are disseminated freely.

For elevation change studies, geodetic method requires digital elevation models (DEMs) of two different time-periods. For this, the available high-resolution DEM is the shuttle radar topographic mission (SRTM) version 4 DEM (1-Arc Second Global) of 30 m resolution. However, this dataset is for the year 2000. For continuous evaluation of mass balance studies, TanDEM-X data of very high resolution (9 m) with relative height accuracy of 2 m for flat region and 4 m for a steep terrain were utilized[7]. This accuracy has an edge over other datasets like SRTM 1-Arc Second[8] and Cartosat-1 DEM[9] which function with 15 and ~10 m vertical accuracy respectively. The DEMs were generated from TanDEM-X CoSSC products (data specifications for two years are mentioned in Table 1) but continuous data from 2011 to 2016 have been used for the study.

CoSSC (co-registered product) format of TanDEM-X need not be co-registered[10], which is an advantage for processing such datasets. The applicability of TanDEM data in the cryosphere is not only restricted to DEMs for elevation change, it can also be used for classification of various features (glacial lakes, moraine cover, crevasse mapping), and even glacier velocity mapping. This wide application is due to the all-weather, day–night capacity of microwaves. Despite these desirable qualities, TanDEM-X (CoSSC product) has unavoidable errors and hence uncertainties need to be accounted for, which have been deliberated here.

Methodology

For annual mass balance measurements of the Chorabari glacier, the geodetic method was used. This is a simple and useful tool when studies are done at a continuous decadal scale[11], especially for difficult terrains like the Himalaya. In this method, DEMs of two or more time-periods are generated and by DEM differencing, elevation change is estimated for the glacier. In this study, using TanDEM-X data, DEMs from 2011 to 2016 were generated (methodology followed as in Figure 2). Volume change was estimated by multiplying this height difference with the change in area. Using the visual interpretation technique, area of the glacier was calculated from Landsat data. Since the glacier boundary was delineated manually, mapping uncertainty was also calculated following the methodology of Basnett *et al.*[12].

Generation of TanDEM-X DEM

For generation of DEM, co-registered pairs of TanDEM-X were utilized and the standard InSAR technique used[13]. This method requires SRTM DEM as a reference to get a differential interferogram. The interferogram generated using the TanDEM interferometric pair was subjected to Goldstein filtering to reduce the noise introduced by temporal or baseline-related decorrelation. This interferogram phase needs to be unwrapped, for which the Delaunay minimum cost method (Delaunay MCF) was used. This method follows the same approach as MCF[14], however, the grid utilizes only those pixels which are above the unwrapping coherence threshold (in this case coherence >0.4). Also, Delaunay MCF utilizes the triangular grid rather than a square one. This process is especially useful to minimize phase jumps in the image. The next step included offset estimation and correction of the generated DEM using refinement and re-flattening. These algorithms generated DEMs close to realistic values (obtained using glaciological method). Interpolation method was applied to avoid NaN values in the DEM with a window size of (5 × 5). This resulted in a spatial resolution of ~10 m. Finally, the calibrated phase was recombined with the SRTM phase data and converted to height values. For accurate estimation of elevation change, it is necessary that error range is precisely stated for the DEMs that are generated. However, the quality of a DEM depends strongly on coherence as it summarizes various sources of errors[7] and as coherence is one of the prime input parameters while generating the interferogram, it is an absolute necessity that coherence standard deviation be properly estimated.

Precision analysis

For calculating the precision of the height, the following equation is used[9]

$$\sqrt{\frac{(1-\gamma^2)}{2\gamma^2}}\,\frac{\lambda R\sin\theta}{4\pi B_{\text{perp}}}, \tag{1}$$

where γ is the coherence of the image, R the range, θ the incidence angle and B_{perp} is the effective baseline of the satellite.

While processing the TanDEM-X data for DEM generation, a coherence image is generated, whose standard deviation can be estimated. The incidence angle, and perpendicular baseline for the product can be found from the metadata available with the dataset. All these values when incorporated in eq. (1) provide the precision of the generated DEM.

Mass balance estimation

For mass balance estimation, various parameters like accumulation area ratio (AAR), equilibrium line altitude (ELA), firn line altitude (FLA) estimation and DEM can be utilized. The methodology used here is visual interpretation for calculating area of the glacier and DEM differencing for elevation change. The dataset used for area change are Landsat satellite data and elevation change are TanDEM-X data. When elevation change and change in areal extent are combined, change in volume is obtained. Following the general assumption for ice density to be 0.85–0.90 g/cm^3 (ref. 15), the volume change is transformed into mass change for the glacier.

Results and discussion

To examine the extent of retreat in the glacier, the Landsat time series data from 1976 to 2016 were utilized. Figure 3 shows the changes in the glacier boundary at the terminus. Results indicate that in the past 40 years, the total terminus retreat of the glacier was ~320 m. This is comparable to the reported results for this glacier[5]. Also, the glacier retreat rate was estimated at 0.8 m a^{-1}. This rate of retreat for the Chorabari glacier is indicative of the fact that climate change has an impact on the melting of the glacier. Further, total area lost by the glacier in the past 40 years was approximately 3% with surface area reducing to 6.46 ± 0.38 sq. km in 2016. As observed in Figure 4, this loss accelerated in the past decade (2000–2016) for the glacier.

The elevation change was estimated from 2000 and 2016 (Figure 5). This elevation change map generated utilized SRTM of the year 2000 and TanDEM-X data of 2016. The error and biases were considered in the pre-processing steps of DEM generation. Hence, when elevation difference of 2016 TanDEM-X data was calculated from 2000 SRTM data, the elevation change was negative.

The precision in the estimation of height for the generated DEMs was found to be ±2.12 m (on an average),

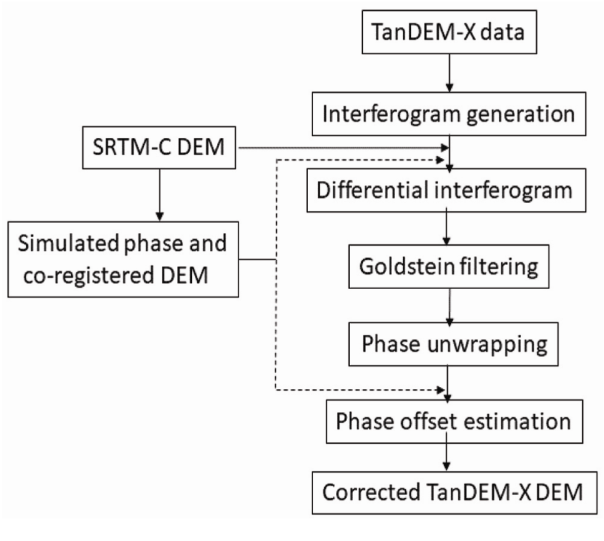

Figure 2. Methodology for digital elevation models (DEM) generation using TanDEM-X dataset.

which is in agreement with previously reported error range[7]. Table 2 shows the elevation change estimated along with the error range.

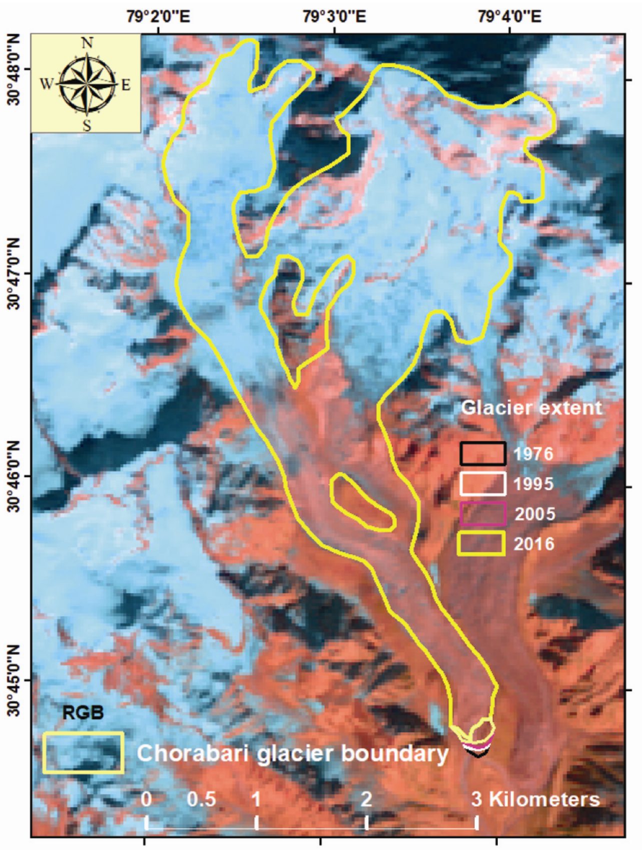

Figure 3. Glacier extent change from 1976 to 2016 using Landsat images.

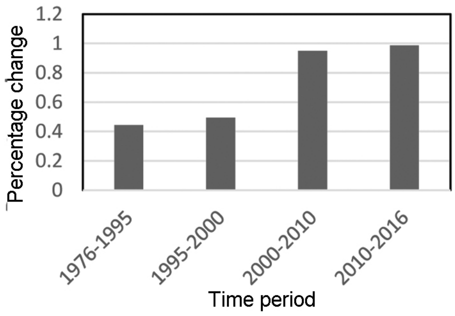

Figure 4. Percentage change in surface area (1976–2016).

Table 2. Elevation change from 2000 to 2016

Time-period	Elevation change for glacier in ablation zone (m)
2011–2012	–0.27 ± 1.97
2012–2013	–0.32 ± 2.32
2013–2014	–0.55 ± 2.05
2014–2015	–0.37 ± 2.11
2015–2016	–0.46 ± 2.19

The average annual height change of the entire glacier was found to be –5.10 ± 1.23 m for 2000–2016. For calculating change in volume, change in area from the Landsat data for 2000–2011, was multiplied with the estimated elevation change (from the generated DEMs). Further, for mass balance estimation, with assumed ice density of 0.85 g/cm^3, net mass balance for the entire Chorabari glacier from 2000 to 2011 (using SRTM and TanDEM-X DEM) was calculated as -4.39×10^6 m^3 w.e.a^{-1} and specific mass balance was –0.66 m w. eq. Reported values from ground data collection[12] for this glacier for 2003–2010 were -4.40×10^6 m^3 w.e.a^{-1} and –0.73 m w. eq. respectively. This minute discrepancy can be attributed to the difference in the duration of the estimates, i.e. reported mass balance is for a 7-year period (2003–2010), whereas estimated mass balance is for a 11-year time period (2000–2011). However, with comparative results, the accuracy of the DEMs can be further tested, and thus used for future analytical studies.

Conclusion

The present study suggests that the Chorabari glacier is retreating both in the overall areal extent as well as elevation. Field-based measurements are no doubt highly

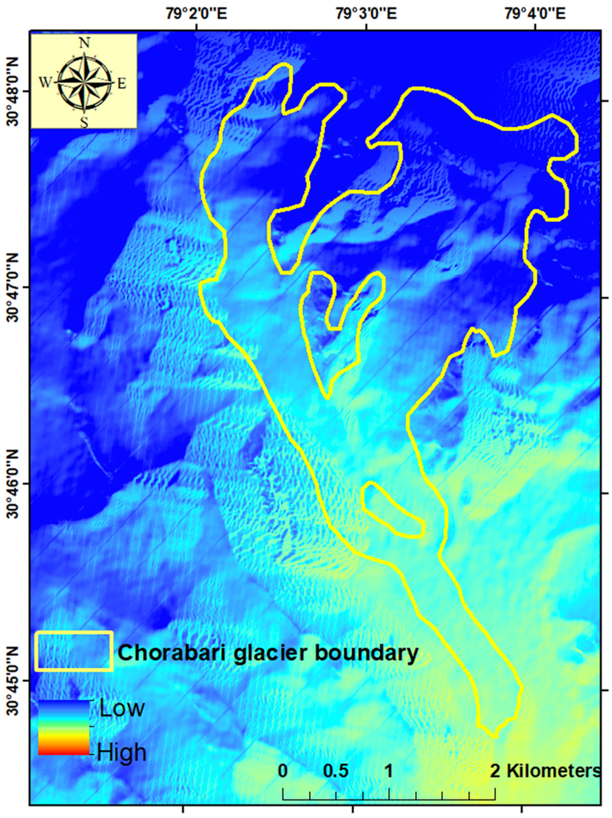

Figure 5. Elevation difference map for the decade 2000–2016; red colour signifies height change of ~10 m and blue color approx. –13 m elevation change.

reliable, but continuous ground studies in such terrains are difficult to perform. For this, remote sensing methods are the best option. Of the available tools, microwave remote sensing is increasingly becoming a preferable dataset owing to its all-weather properties and media penetration capabilities. Further, among the methods (glaciological, hydrological, ELA/AAR) available, the geodetic method (indirect method) provides easy and acceptable results. In this method, DEM generation being the prime aspect, its accuracy estimation is also important. TerraSAR-X/TanDEM-X dataset provides the first space-borne interferometric SAR pair with continuous single-baseline InSAR data which can be harnessed to generate accurate DEMs. These DEMs are utilized in this study, and the potential of TerraSAR-X/TanDEM-X data for glacier height change estimation is presented. The error sources in DEM generation are also discussed and a statistical technique for precision estimation is used to obtain a realistic value of the glacier height change. Further, with error estimates in a reasonable range, remote sensing-based techniques for continuous monitoring of the glacier parameters for better understanding of glacier dynamics, are good alternative.

This elevation change is further utilized to assess the net mass balance of the Chorabari glacier. With accurate elevation change estimates, we can conclude that the negative mass balance of the glacier is also within an acceptable limit, which has been confirmed with ground-based measurements[13]. A negative mass balance indicates that climate change has an impact on the health of the glacier, which in turn will affect us socio-economically. Hence, it is necessary that such studies utilize advanced remote sensing tools and techniques to monitor glaciers. This will not only help in continuous monitoring but predicts future scenarios and plan disaster management better.

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doi: 10.18520/cs/v114/i04/771-775