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Estimation of change in glacier ice thickness using ICESat laser altimetry data

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Abstract: Himalaya have the highest concentration of glaciers outside the polar regions and thus hold one of the most important natural resources in the form of frozen water. Himalayan glaciers also act as sensitive indicators of climate change. In view of above one needs to study and monitor the status of these glaciers. Present study deals with estimation of elevation change in the selected glaciers of the Himalaya using ICESat/GLAS data for the period 2003 to 2009. One glacier from Ganga basin and three glaciers from Indus basin have been taken for present study. ICESat data of the similar period have been analyzed using near-repeat track projection approach with the help of reference Digital Elevation Model (DEM). Average ice thickness change for the Gangotri glacier has been found to be +0.24 m/year while in Indus Basin, average rate of ice thickness change has been found to be +0.02 m/year, +0.44 m/year and -1.02 m/year for Siachin, Baltoro and Drenmarg glacier, respectively.

Keywords: ICESat, Himalaya, Glacier thickness

1. Introduction

Surface elevation and its variation remains an important parameter for studying the global environment and climate change. Till date a large number of earth observation satellites have been launched to retrieve surface elevation data. Satellite radar altimetry have been used for estimation of surface elevation and its change detection since late 1970s (Robin, 1966; Zwally et al., 1989, Wingham et al., 1998; Johannessen et al., 2005). Due to limitation of large footprint size, the satellite radar altimetry is mainly suitable to the region of low relief glaciers and ice sheets in cryosphere studies. Estimation of surface ice thickness change over high relief glaciers, requires high resolution altimetry datasets. In last few years, altimeters like Ice, Cloud and land Elevation Satellite (ICESat) laser altimeter (Zwally et al., 2002) have been providing high resolution elevation data sets. Cryosat-2 radar altimeter (Wingham et al., 2006) also provides high resolution datasets by employing advanced SAR interferometric altimeter techniques that are comparable to maps (Sauber et al., 2005; Muskett et al., 2008; Nuth et al., 2010).

ICESat, launched by NASA in January 2003, had the prime objective of estimating ice-elevation changes in Polar regions. Laser altimeter named Geoscience Laser Altimeter System (GLAS) on board ICESat with a high resolution footprint of 70m and along-track spacing of 170m provided elevation data. During 2003 to 2009 a large amount of data has been acquired by three laser sensors of GLAS. However, the utility of ICESat/GLAS data covered more aspects other than its main objective (Berthier et al., 2007; Kropacek et at., 2014; Kaab et al., 2015).

Glaciers, among the best indicators of terrestrial climate change, contribute importantly to water resources in many mountainous regions of the world. Himalayan glaciers cover an area of 71,182km2 (Arun et al., 2013) and monitoring changes in their thickness is a key issue as the melting of glaciers in central Asia may significantly contribute to sea level rise (Arun et al., 2013). In addition, runoff generated by the melting of the glaciers in the Himalaya is an important source of water for the people living in the plains. Given the size and remoteness of glaciers in Himalayas, in-situ measurements are sparse and thus satellite remote sensing is a viable alternative for comprehensive and frequent monitoring of this important resource (Berthier et al., 2006; Kasturirangan et Al., 2011; Bahuguna et al., 2014). The most commonly used technique for estimation of glacier ice thickness change is based on the subtraction of the two-time frame DEMs generated from satellite photogrammetry or interferometry (Gardelle et al., 2012).

Himalayan glaciers, however, generally have rougher surfaces and steeper regional slopes than the ice sheets for which ICESat was optimized (Sauber et al., 2005). Elevation changes (or ice thickness changes) over glaciers from satellite altimetry is computed directly using elevation difference at crossover points between ascending and descending satellite passes. This method gives coarse sampling for computation of elevation changes (Brenner et al., 2007). In this paper, an attempt has been made to explore the potential of repeat track ICESat to derive glacier elevation changes (glacier ice thickness change) for four glaciers; three in Indus basin (Siachin, Baltoro and Drenmarg) and one in the Ganga basin (Gangotri) of the Himalayan region.

2. Study area

Three glaciers from Indus basin, namely, Siachin, Drenmarg and Baltoro and one from Ganga basin (Gangotri), have been taken in this study. These four glaciers have been selected since GLAS/ICESat repeat track data was available over these glaciers. In addition, these four glaciers are among the largest glaciers in the

Indus and Ganga basin of the Himalaya. The glacier information and their attribute information is taken by the glacier inventory generated at Space Applications Centre (Arun et al., 2013) Figure 1 a and b shows the location of these four glaciers.

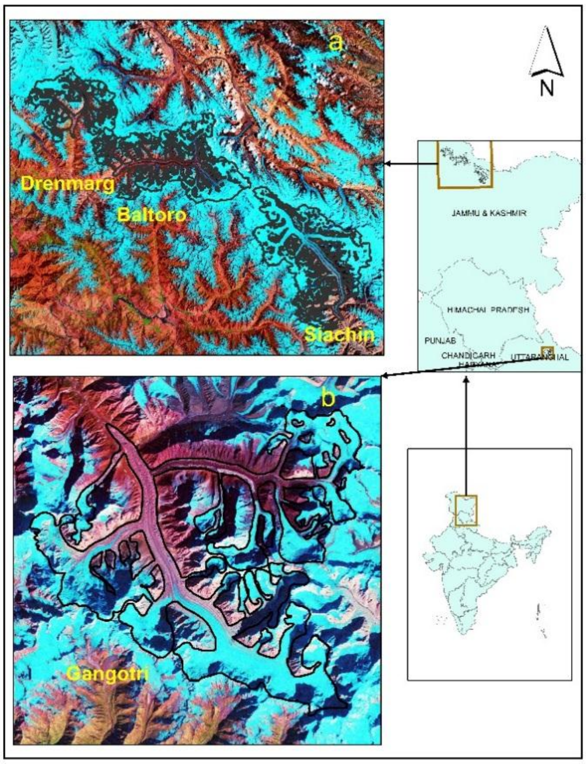

Figure 1: False Color Composite of Landsat TM image showing location of glacier a) Three glaciers (Drenmarg, Baltoro, Siachin in Indus basin) b) Gangotri glacier in Ganga basin of Himalayan region

- **Gangotri glacier**, one of the largest glaciers in the central Himalaya, is located in Uttarkashi district, Uttarakhand state of India. This valley type glacier is the source of a major river system Ganga in northern India. The glacier has an estimated ice volume of about 27 km3 (about 27 km long and 1 km wide). The orientation of the glacier is towards NW (North West).
- **Siachin glacier,** located in the eastern Karakoram range in the Himalayan mountains, is the longest glacier in the Karakoram and second-longest among the world's mountain glaciers. It lies between Saltoro ridge immediately to the west and the main Karakoram range to the east. Including all tributary glaciers, the Siachin glacier system covers about 700 km2 area and 1.3 to 3.2 km wide. The orientation of the glacier is towards SE (South East).
- **Baltoro glacier,** located in the Karakoram range, is the origin of Shigar river which is a tributary of the Indus river. The glacier is about 57.6 km long and 1.7 to 3 km wide with orientation towards SW (South West).
- **Drenmarg glacier** is located in the eastern Karakoram range in the Himalayan mountains. The glacier altitude varies from 5,467 m to 3,769 m above mean sea level. The glacier covers an area of 413.5 km2. It is about 25.31 km long with orientation toward SE (South East) and 0.8 to 1.5 km wide.

3. Data used

3.1 ICESat/GLAS

ICESat has an onboard laser altimeter system to collect surface elevations all over the globe with high precision. Since 2003 to the end of its operation in 2009, GLAS has been operating for three annual observation campaigns, each of approximately 35 days. This instrument combines a 3 cm precision 1064-nm laser altimeter with a laser pointing angle determination system (Sirota et al., 2005) and it is used to measure the Earth’s surface and it also measure the backscattering profile from thicker clouds, while those at 532-nm use photon-counting detectors and measure the height distributions of optically thin clouds and aerosol layers. A GPS receiver on the spacecraft provides data for determining the spacecraft position, and also the absolute time reference for the instrument measurements and altimetry clock (Abshire et al., 2005). It retrieves surface elevations within 70 m diameter footprints and along track spacing of 170 m. GLAS elevation accuracy is reported to be 15 cm over flat terrain (Zwally et al., 2002). Average error of 20 cm has been reported in estimating glacier ice thickness change in the Alps / Himalaya (Kropacek et al., 2014; Kaab et al., 2015; Kaab et al., 2012). In this study GLA06 product of ICESat has been used between 2003 and 2009 available from the National Snow and Ice Data Centre, (http://nsidc.org/data/icesat) in geographical co-ordinate system with WGS-84 datum (Zwally et al., 2008).

3.2 Digital Elevation Model (DEM)

CartoDEM and SRTM DEM have been used to project ICESat repeat tracks onto common locations and to extrapolate elevation changes to unmeasured locations. The thickness change has been computed by projecting the secondary track to reference track by using both SRTM DEM and CartoDEM.

3.2.1 Carto DEM : Cartosat-1 Digital Elevation Model (CartoDEM) is a National DEM developed by the Indian Space Research Organization (ISRO), derived from the Cartosat-1. Cartosat-1 has a pair of Panchromatic cameras having an along track stereoscopic capability to acquire two images simultaneously, one forward looking (Fore) at +26 degrees and another rear looking (Aft) -5 degrees with a base-to-height ratio of about 0.63. Its Absolute planimetric accuracy is 15 m and absolute vertical accuracy is 8 m and having 5 m relative vertical accuracy (Muralikrishnan et al., 2011). Cartosat derived DEM in the hilly terrain of Chamoli and Shimla districts of the Himalaya were validated (Agrawal et al., 2006) and reported the relative vertical accuracy of the DEM to be about 5 m. CartoDEM v1 data, available through Bhuvan portal (bhuvan.nrsc.gov.in) of NRSC in geographical projection and WGS-84 datum, were used.

3.2.2 SRTM DEM : The SRTM (Shuttle RADAR Topographic Mission) was the first mission using space-borne single pass interferometric SAR which was flown in 11 February 2000. The goal of the mission was to survey the Earth surface and to generate a homogeneous elevation data set of the world with a grid spacing of 3arcsec available from USGS (earthexplorer.usgs.gov). The digital topographic map products were expected to meet the Interferometric Terrain Height Data (ITHD)-2 specifications sampling with 16 m absolute vertical height accuracy, 10 m relative vertical height accuracy and 20 m absolute horizontal accuracy (Bamler, 1999). The horizontal datum is the World Geodetic System 1984 in geographical projection system. The vertical datum is mean sea level as defined by the Earth Gravitational Model (EGM-96) geoid. Most of the users commonly ignore the original vertical datum and use SRTM data as referenced to the WGS84 ellipsoid as geoid models (Markus, 2005). The problems can be resolved by use of the WGS-84 orthometric height correction calculated from EGM-96 to convert it in ellipsoidal height (Agrawal R et.al 2006).

4. Methodology

Researchers have used mainly three approaches for estimation of the elevation change using ICESat altimetry (Moholdt et al., 2010a). The first approach, which computes elevation changes at crossover points, has very high accuracy. Elevations at crossover points are linearly interpolated from the two closest footprints within 200 m in each track (Brenner et al., 2007). The main drawback of this approach is that the sampling is too coarse. The second approach uses a DEM to correct for the surface slope between the center points of overlapping footprints (Slobbe et al., 2008). This approach takes care of the slope-induced errors; however, it is constrained by the data availability for comparison. It is difficult to compare repeat track ICESat profiles due to the relatively large cross track separation between repeat profiles. In view of the limitations of the first two approaches, the third approach has been used in this study which utilizes near repeat ICESat tracks having small (up to 200 m) cross-track separation (Moholdt et al., 2010a) shown in figures 2 and 3.

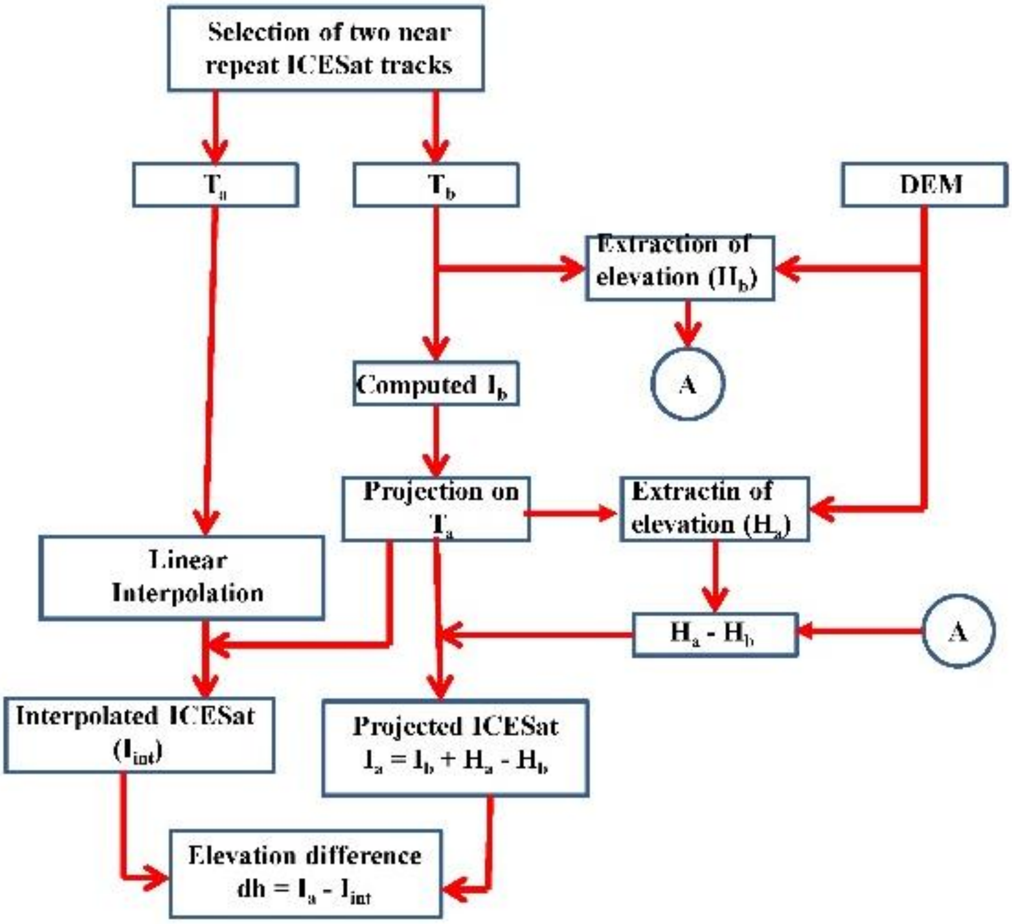

Figure 2: Flowchart showing the near repeat track methodology for elevation change estimation.

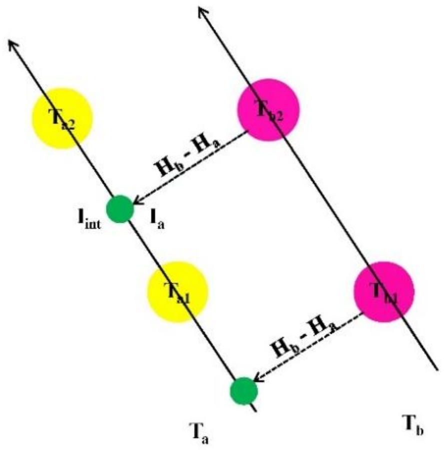

Figure 3: Projection of near repeat tracks on common locations using DEMs. Green dots represent projected location, Pink dots represent secondary track and Yellow dots represent reference track

In this approach, two near repeat ICESat tracks (T_a and T_b) pertaining to different years and same month have been taken for computing the glacier ice thickness change. For every pair of ICESat repeat tracks, one track is considered as the reference track and other one as secondary track. The track T_a which is older in time sequence, is chosen as the reference track. The secondary track is projected on the reference track and surface elevation change at these two locations can be estimated by the change in elevation values of these locations using DEM. The elevation information H_a and H_b have been extracted from the DEM at the ICESat footprints on track T_a and T_b, respectively. The difference ($H_a – H_b$) of this elevation information (H_a & H_b) is represented as the unmeasured topography between the near repeat tracks. Here the utility of DEM implies along-track interpolation to restrict the DEM slope correction to the cross-track distance between two repeat-tracks (Moholdt et al., 2010b). Now each footprint on track T_b is projected perpendicularly on track T_a using CartoDEM or SRTM DEM. The ICESat elevation on the projected points (I_a) over reference track (I_a) can be computed as in equation (1).

$$I_a = I_b + H_a - H_b \qquad (1)$$

At the same projected points on the reference track T_a, ICESat elevation (I_{int}) is estimated through linearly interpolating the neighboring footprints (T_{a1} and T_{a2}) along the track. The elevation difference at the projected points (dh) is the change in the elevation between the projected (I_a) and interpolated ICESat elevation (I_{int}) and it can be computed as in equation (2):

$$dh = I_a - I_{int} \qquad (2)$$

where,

dh= elevation difference of two different periods;

I_a = ICESat elevation at projected location on track T_a;

I_{int}= interpolated ICESat elevation on track T_a

I_b= ICESat elevation on track T_b;

H_a= extracted elevation from DEM on track T_a;

H_b= extracted elevation from DEM on track T_b.

5. Results and discussion

The ICESat altimetry data of near repeat tracks (T_a and T_b) have been used to estimate the surface elevation changes in the glaciers and thus change in glacier ice thickness. In this study, track T_a is considered as the reference track and track T_b as secondary track. The mean elevation changes and mean track separation, computed from the repeat passes of the ICESat for the four selected glaciers, are given in Table 1. Different tracks over Gangotri glacier show the variations in the thinning / thickening rate in the range of 0.01 to 0.71 m/year by utilizing CartoDEM for projecting secondary track over the reference track. Similar ice thickness changes (-0.20 to 0.84 m/year) have been observed while using SRTM DEM.

There has been significant positive change in the ice thickness (0.71 m/year) for Gangotri glacier during the period 2005-07. However, ice thickness change during the period of 2004-08 has been found to be negligible (Table 1).

For Siachin glacier, mean separation between the ICESat near repeat tracks (T_a and T_b) has been found to be 14.5 m. The mean thicking rate during 2004-09 has been found to be 0.23 m/year and 0.27 m/year by using CartoDEM and SRTM respectively. The positive ice thickness change (thickening) has been observed during the period 2004-09. There has been a very small negative ice thickness change during the period 2003-05 (Table 1).

For Baltoro glacier, the near repeat track has a temporal separation of six years (2003-09). The mean ice thickness change (thickening) during this period have been found as 0.44 m/year and 0.66 m/year using CartoDEM and SRTM respectively for projecting secondary track over the reference track.

The mean ice thickness change in the case of Drenmarg glacier, during the period (2003-07) are found to be -1.02 m/year and -1.05 m/year using CartoDEM and SRTM respectively. Figure 4 shows the average annual rate of ice thickness change along the ICESat reference track for all the four glaciers. It is observed that the thinning / thickening rate computed using SRTM and CartoDEM are almost similar.

Table 1: Mean elevation change along the ICESat tracks of Gangotri, Siachin, Baltoro and Drenmarg glacier

S. No.	Glacier name	ICESat Tracks		Mean Track Separation (m)	Elevation change rate (m/year)	
		Track T_a (Ref.)	Track T_b		Carto-DEM	SRTM
1.	Gangotri	Mar-04	Mar-08	273.77	0.01 ± 2.83	-0.20 ± 2.85
		Mar-05	Apr-07	34.67	0.71 ± 3.24	0.84 ± 4.25
		Feb-04	Feb-08	15.06	0.02 ± 2.54	0.04 ± 2.39
2.	Siachin	Oct-04	Oct-09	5.14	0.23 ± 0.60	0.27 ± 0.56
		Oct-03	Oct-05	24.03	-0.19 ± 1.70	-0.38 ± 0.95
3.	Baltoro	Oct-03	Oct-09	277.95	0.44 ± 1.27	0.66 ± 1.20
4.	Drenmarg	Oct-03	Oct-07	182.68	-1.02 ± 2.21	-1.05 ± 2.64

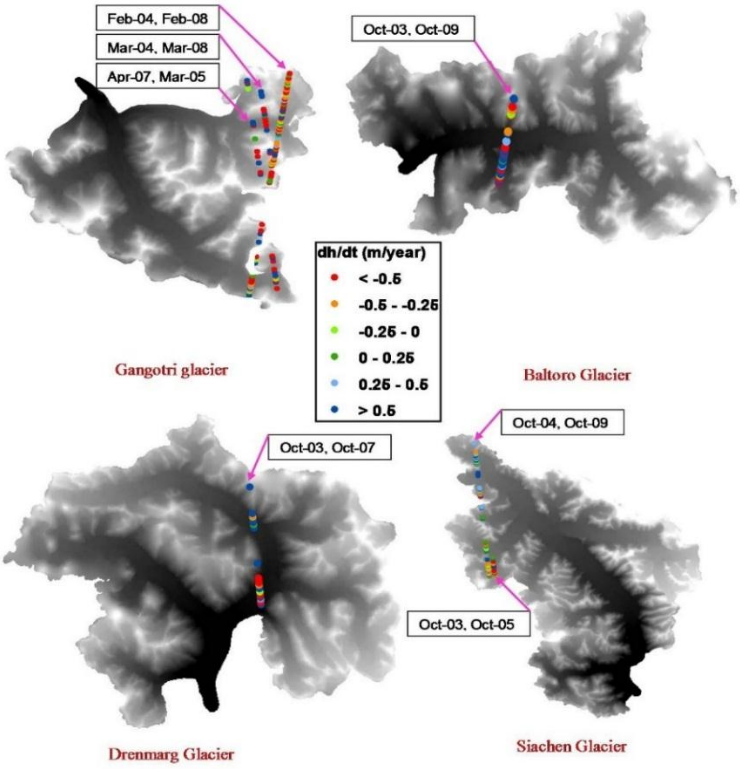

Figure 4: The Elevation change rate along ICESat tracks for Siachin, Gangotri, Baltoro and Drenmarg glaciers of the Himalayan region.

6. Conclusion

In this study four large glaciers of the Himalaya have been taken up for the estimation of ice thickness change using ICESat altimetry data and DEMs (CartoDEM and SRTM). ICESat laser altimetry has proved to be a highly valuable dataset for computing elevation / thickness changes and thus mass change for larger glaciers with mountainous topography. In this study the near repeat track approach has been used to compute ice thickness changes by estimating unmeasured variation in local topography with the consideration of reference DEM. This approach takes care of the slope induced error but the relative error in the DEM may play an important role for change detection. To minimize the relative inaccuracies in DEM the near repeat track separation should have minimum value. To get the better accuracy it is important to use the near repeat datasets which is closer as much as possible with the utilization of the DEM having better relative accuracies in the mountainous regions.

For Gangotri glacier, ice thickness change has been found to be negligible during the period 2004-08. Positive thickness changes (thickening) have been observed for the Siachin and Baltoro glaciers during the period 2004-09 and 2003-09 respectively. Negative thickness change (thinning) at the rate of about 1 m/year has been observed for the Drenmarg glacier during the period 2003-07. Similar values of thickness change have been found while using CartoDEM and SRTM DEM for projecting the secondary tracks over the reference tracks. This procedure can be used for estimation of glacier surface elevation (or ice thickness) change for large number of glaciers in the Himalayan region with the availability of data from future ICESat-2 mission, which will have close coverage with close spacing and dense point coverage using six laser beam configuration.

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