Measuring Thickness and Area change using Old DEM, SRTM DEM and Landsat Images of Parbati and Pin Glaciers in Himachal Pradesh, India

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Abstract
Temporal change in Digital Elevation Models observed in 1962 and 1999 were used to determine the elevation change over Pārbati and Pin glacier. The results suggest that the average - area thickness decreased over Parbati and Pin glacier with rate of 0.39m /yr and 0.22 m/y. Thickness loss resulted in extreme retreat of snout of Parbati glacier from 4157amsl to 4205 amsl and snout of Pin glacier retreat 4452 amsl to 4582 amsl during 1962 - 2005. The comparative areal coverage of glaciers in 1962 and 2005 suggests the areal shrinkage of 17% and 13% for Pārbati and Pin glacier. Thickness losses, areal shrinkage in lower and middle ablation accompanied with rapid snout retreat consequently resulting in the formation of the hummocky type of terminal moraine and fragmentation of the tributary glaciers from main valley glacier in recent times.

1. Introduction

The snow and ice cover in the Himalaya is an important source of water in Indian continent. Snow and ice melting in summer and spring leads to constant water supply in major rivers of Asia and fulfill water demand of the biggest population of the world. In recent years, the glacier and snow fields are shrinking in Himalayas due to increasing atmospheric temperature, which will lead to high discharges in rivers in early years and later depleted discharges (Lutz et al., 2013). The change in hydrological characteristics may cause a major disruption in an economy of the region in near future. Therefore, it is necessary to study the rate of depletion of this water resource to adopt a suitable strategy for future planning. For evaluating the rate of glacier depletion, field based glacier mass balance studies in the Himalaya were started since 1950s and continued by various researchers (Ageta et al., 1984, Dhobal et al., 1995, Raina, 2009, Raina and Srivastava, 2008 and Wagnon et al., 2007). All these studies suggested that the glacier at present predominant under negative mass balance with accelerating mass loss in last half century (Bolch et al., 2012 and Thakuri et al., 2014). The glaciological based mass balance studies were conducted on a small glacier in the Himalaya due to the logistic problem. Other indirect methods such as AAR technique, hydrological balance have also been used to determine the glacier mass balance (Rabatel et al., 2005 and Bhutiyani, 1999). The AAR (Accumulation Area Ratio) method is based on empirical relationship between altitude and mass balance information. These AAR values are site specific, therefore AAR methods may not implement on a regional scale.

However, hydrological approaches are full of inaccuracies due to unavailability of hydro-meteorological data in remote Himalaya. But recent developments in remote sensing technologies provide an opportunity to detect the change in big glacier area using images of two different dates. These studies show that significant size of the glaciers has been reduced in last few decades (Hasnain et al., 2000 and Kulkarni et al., 2000). All these studies are related to change in surface area of glaciers, but the determination of thickness change of glacier surface was not possible from these remote sensing images. Although, it is possible to compare the glaciers DEM (Digital Elevation model) of two dates and evaluate the glacier thickness change. While conventional method to prepare repeated topographic DEM in remote areas are not economic suitable for these studies. Now the advancement in stereo mapping through satellite technology in last ten year provides an opportunity to extract the DEM frequently from satellite sensors e.g.; IRS, SPOT, ASTER. In an area of limited access, the DEMs derived from satellite images have been extensively used for geomorphological and hydrological application by Arendt et al., (2002). The satellite-based DEM and SRTM DEM have also been used to evaluate the glacier thickness

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changes by comparing old topographic DEM (based on old topographic contour map) and SRTM DEM, SPOT DEM, ASTER DEM (Rignot et al., 2000, Berthier et al., 2007 and Surazakov and Azien, 2006). This method enables an increase in glacier mass balance data of glaciers in the Himalaya (Bolch et al., 2011, Kaab et al., 2012, Nuimura et al., 2012 and Pieczonka et al., 2013).

In the present study, the suitability of topographic map and SRTM DEM is assessed for thickness change study over Parbati and Pin glacier in Himachal Pradesh. The change in thickness associated with the change in an area since 1962 has used in calculating total glacier mass loss and specific mass balance rate during 1962 - 2005. The consequences of the high melting rate on glacio-geomorphological features were also discussed by field campaign in the area.

2. Study Area

Pārbati and Pin glacier situated in the Parbati valley, Kullu district of Himachal Pradesh. The Parbati River is the main river which initiated from Parbati snout which is known as Beas in Kullu district (Figure 1). The climate condition ranging from mild moist in the valley to cool temperature at higher altitude, the climate become progressively colder until an extreme polar type is reached at the higher altitude on glacier. The temperature in winter goes below the freezing point where the maximum temperature is around 30° C in summer.

2.1 Glaciers change Mapping

A survey of the de-glaciations pattern of Parbati and Pin glacier is conducted using topographic sheets constructed by ariel photograph taken in 1962 and present day remote sensing images of 2000 and 2005. The glacier surface areas in the Parbati and Pin glaciers have been mapped using Survey of India topographic sheets on 1:50,000 scales published by survey of India in 1962 (53E/5, 53E/9, 53E/10. 53E/13). Information given on topographic sheets were used in geo-referencing the topographic sheets. After geo-referencing the glaciers boundaries were mapped using Geomatica 9.1.2. These glaciers were mapped as individual exited on the 1962 topographic sheets.

The new glacier inventory has also been prepared using LANDSAT ETM $^{+}$ images acquired in October 2000 and 2005 for the Parbati and Pin area (granule Path 147, 146 and Row 38, 39). Glaciers on remote sensing images can be mapped by supervised classification (Sidjak and Wheat, 1999), thresholding of ratio images (Paul and Andreassen, 2009) and NDSI (Normalise difference snow index) have been used by Racoviteanu et al., 2008. These methods were tested for glacier delineation and found that these methods are reasonable useful for delineation of clean-ice glaciers. However, glaciers in the present study area are covered with debris and it is not easy to differentiate debris from undifferentiated sediments around glaciers (Bolch et al., 2008). Bhamri and Bloch (2009) have also observed that NDSI and Band ratio method are not appropriate for discriminating the boundary of Himalayan glaciers. Therefore, the manual digitization has been adopted as recommended for glacier boundary mapping in this study. Numerous challenges were encountered for mapping i.e., the ice divide and boundary near the terminal position of the glaciers. The new glacier boundary was prepared from FCC (False Color Composite) image along with high-resolution 8th gray band image and enhancement techniques were also used for accurate mapping of the glacier boundaries.

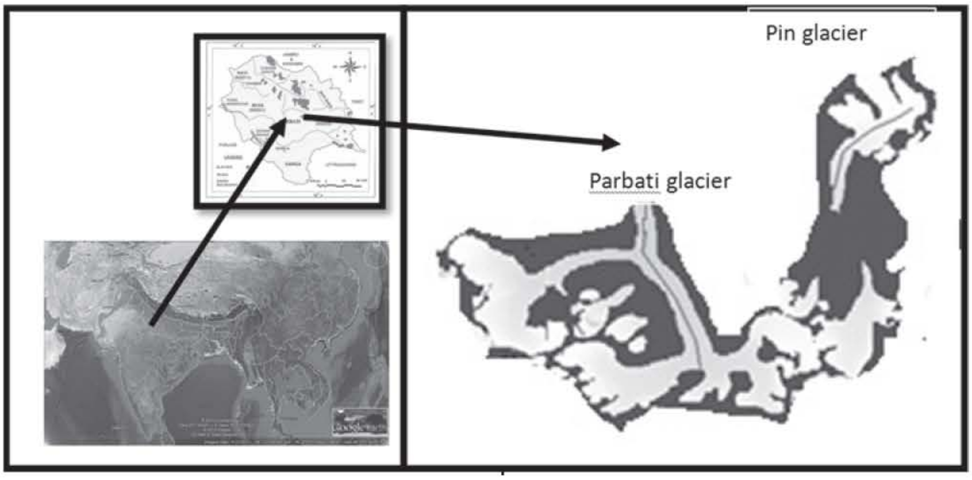

Figure 1: Location map of the Parbati and Pin glacier

The glacier area cover in 1962, 2000 and 2005 were analyzed under GIS environment. This study involves the data of two different sources with different spatial resolution, uncertainties are expected to be involved in measuring area calculations. Hence, it is necessary to compute the error introduced in our study. The error in manual digitization of glacier boundaries was considered to be one pixel. The error estimation for individual glacier based on buffer method suggested by Granshaw and Fountain (2006) and Bloch et al., (2010) has been utilized in present study. Parbati and Pin glacier area was 38 ± 1.01 sq km and 12.66 ± 0.46 km sq on topographic sheets in 1962. The area of glaciers on remote sensing images of 2005 was 29 ± 1.16 sq km and 11.1± 0.45 sq km. The error ranges 2.9 - 3.99% of area measuring error were also found by Bhambri et al., (2011) for glacier change study conducted in Garhwal Himalaya using remote sensing images and these uncertainties are well in matched with the studies carried out by Racoviteanu et al., 2008 and Bolch et al., 2010.

2.3 Glacier Elevation change Mapping

Numerous studies have assessed the thickness change of glaciers using change in two dates DEMs (Berthier et al., 2006, Berthier et al., 2007 and Bloch et al., 2013). In the present study, we compared the old topographic sheets based glacier DEM of 1962 and SRTM DEM of 1999 over Parbati and Pin glacier in Himachal Pradesh. The topographic sheets based on ariel survey of 1962 at 1:50,000 scales were used in generating DEM (Digital Elevation Modal) of the Parbati and Pin glaciers. All the contour lines of the glacier were digitized and saved as separate vector line file with altitude attribute. Using the vector line file and attribute, the glaciers' DEMs were prepared based on extrapolation techniques using Orthoengine module of PCI Geomatica 9.1.2. This DEM is named as Topographic DEM and used for comparing the glaciers surface elevation existed on topographic sheets in 1962. In the second step the SRTM DEM of glaciers were downloaded from the NASA website. It is available at 1- degree tile with WGS 84 datum. The SRTM is freely available global digital elevation data set over 80% of the globe. This data is 3 arc second about spatial resolution of 90 meter with vertical accuracy of 16 meter (Marschalk et al., 2004).

The changes in surface elevation information on the glacier surface were obtained by subtracting Topographic DEM of 1962 and Shuttle Radar Topography Mission (SRTM DEM of 1999). Comparison of two DEMs acquired on two different periods and methodology requires the standardization processes to detect the significant level of elevation change. To minimize the error, we analyzed the elevation difference on stable terrain outside the glacier boundaries. These errors are related due to mismatch of x, y and z data and elevation, slope and aspect dependent bias. In the present study, the individual error is determined analyzed to understand individual term so it can be used with extra care in elevation change study (Peduzzi et al., 2010).

The co-registraion error due to mismatching of x, y has been determined by comparing the re-sampling of old topographic DEM to newest SRTM DEM. Both DEM were compared on stable terrain off to the glaciers using migration of grids command of MICRODEM-32. The results indicated the shifting of 1.02 ± 5.01m in x-direction and 0.80 ± 6.13 m in y-direction. It indicates that the SRTM DEM is well geo-located with respect to Topographic DEM. The statistical report of both DEMs is given in Table 1 and correlation between elevation values on Topographic DEM and SRTM DEMs indicate that both DEMs are suitable co-registered (Figure 2). The x, y and z data shift between two DEMs results in an aspect dependency for bias in elevation differences studies (Nuth and Kaab, 2011). In the present study, the aspect and elevation bias (Topographic DEM elev. – SRTM DEM elev.) show a sinusoidal relationship (Figure 3). But normalization of difference elevation (Topographic DEM elev. – SRTM DEM elev.) with slope and aspect relations does not show any sinusoidal relationship (Figure 4). This indicates that both the DEMs are well geolocated and aspect – elevation bias relationship is related to looking of SRTM C- band radar antenna on the different aspect. In present study, the strong biasness coincides with North West direction.

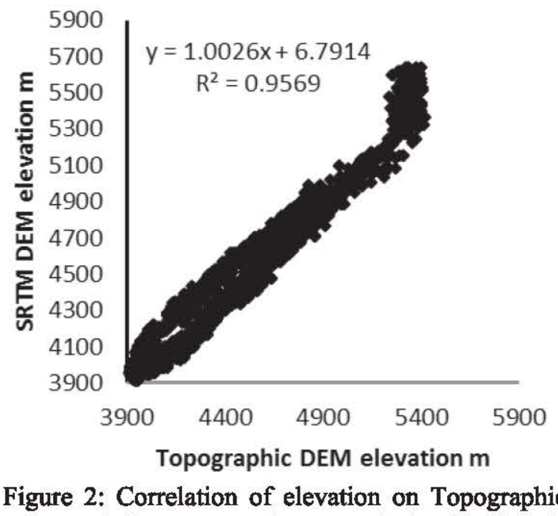

Figure 2: Correlation of elevation on Topographic DEM and SRTM DEM in non- glaciated region in study area

Table 1: Comparative characteristics of Topographic DEM and SRTM DEM in non-glaciated region in study area

	SRTM DEM	Topographic DEM
Elevation n	257266	257266
Elevation mean in m	4307.05	4271.16
Elevation avg. dev m	264.88	256.23
Elevation std dev	314.71	306.02
Elevation skewness	0.6925	0.7768
Elevation Kurtosis	-0.4473	-0.3227
Elevation min m	3898	3913.4
Elevation max m	5242	5285.19
Elevation median m	4241.5	4197.54

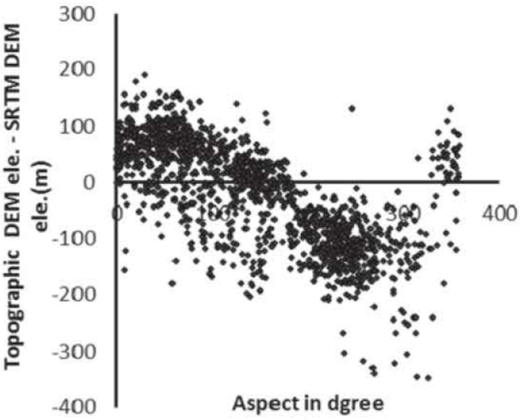

Figure 3: Relationship between Topographic DEM - SRTM DEM and aspect in non- glaciated region in study area

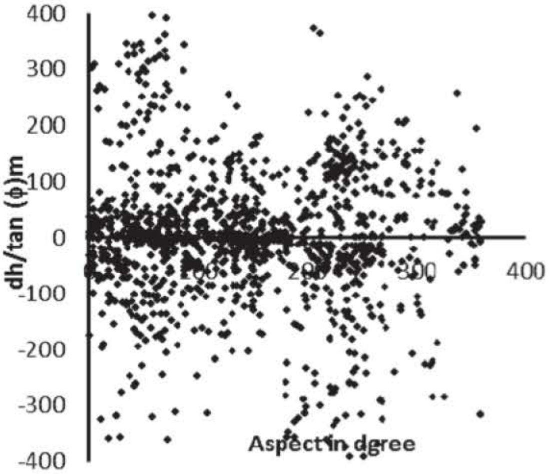

Figure 4: Relationship between Topographic DEM - SRTM DEM/tan ϕ(m) and aspect in non- glaciated region in study area

Glacier surface elevation change studies have indicated that the vertical accuracy of the SRTM DEM exceeds the 16-m in rugged terrain (Eineder and Holzner, 2000). To determine the error on glacier surface change, we compared the SRTM DEM and the Topographic DEM over glacier-free areas. The DEM differences were calculated for over about 18000 elevated points on glacier-free area near to Parbati and Pin Glacier. The relationship between elevation difference with elevation / slope is established in the glacier-free area (Table 2 and Figure 5). The slope does not show any systematic relation with elevation difference, whereas the elevation shows a systematic relationship. Therefore, in present study the biasness in the topographic data is applied based on elevation band.

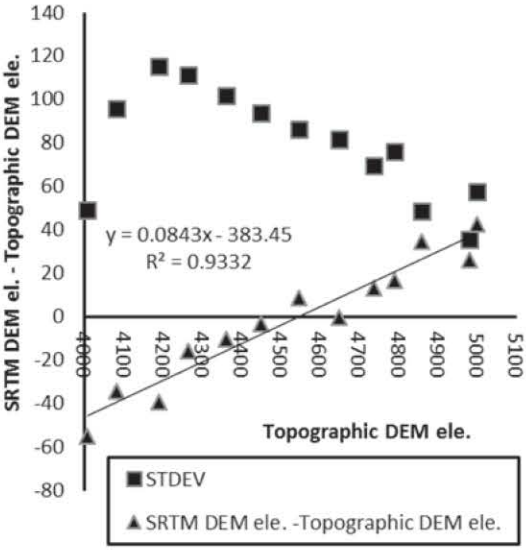

Figure 5: Bias of elevation (SRTM DEM - Topographic DEM) and altitude relationship on Non- glaciated in study area

It is observed that lower elevation points are located mainly in shadow region of valley and underestimated the elevation on SRTM DEM. But at higher the elevation on Topographic DEM has been underestimated due to poor contrast in ariel photographs of 1962 or interpolation of the lower elevation data in glacier accumulation area (Raina and Srivastava, 2008, Bhambri et al., 2011 and Bhambri et al., 2012). The studies conducted by Zhang et al., (2013) suggested correcting methods the old Topographic DEM using SRTM DEM. Therefore, the Topographic DEM has been corrected using gradient of biasness about 8.4 m per 1000 m elevation calculated by the calibrating the SRTM DEM and Topographic DEM over non glacier area near to Parbati and Pin glaciers.

Table 2: Bias of elevation on SRTM DEM – Topographic DEM in non- glaciated region in study area

Slope in degree	Bias mean in m	Maxi. Ele. M	Min. Ele. M	Stand. Dev.	Counts
0-5	4	3956	3952	6	342
5-10	8	3967	3959	20	1402
10-15	4	4270	4266	29	983
15-20	21	4070	4049	40	1002
20-25	-21	4510	4550	80	2000
25-30	6	4062	4056	37	2549
30-35	8	4365	4357	41	3542
35-40	-13	4447	4460	102	2504
> 40	-20	4621	4641	95	2647
All	-18			41	16971

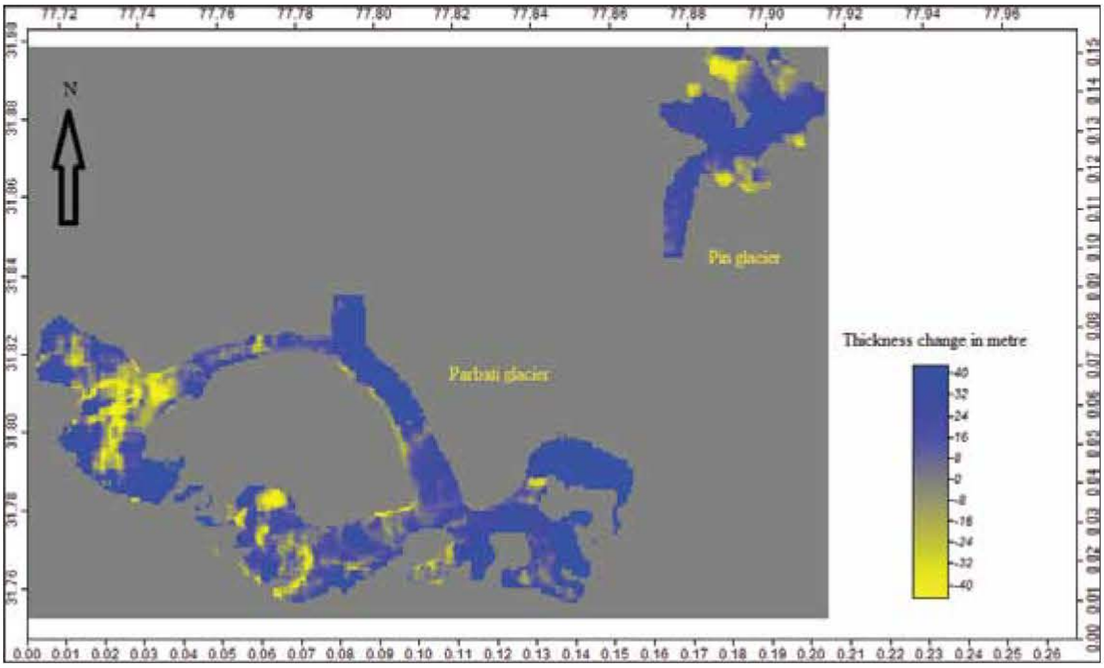

Figure 6: Difference image of corrected Topographic DEM 1962 and SRTM DEM 1999

Moreover, the under estimation of the SRTM DEM at lower attitude in shadow region of the glacier has been corrected using Topographic DEM values. The accuracy studies of SRTM DEM also suggested that elevations are showed underestimation on glacier surface because of penetration of C band radar wave into snow and ice. A comparative analysis of penetration of C-band wave suggested that depth of penetration depends on the physical conditions of snowpack (Rignot et al., 2001). Hence, the C- band penetration depth very with hydro-meteorological condition of glacier surface. The assessment conducted by Kaab et al., 2012 determined that C-band penetration in Himalayan region vary from 2.5 ± 1.2m in Karakoram region and 1.5± 0.1 m in Central Himalayan region. The recent assessment by Gardelle et al., (2013) over various locations on glacier surface in the Himalaya also showed that the penetration depth varies from 3.4 m in the Karakoram, to 1.4 m in the Everest region. Due to lack of knowledge of real ground condition of glacier surface and unavailability of data, such C-band penetration depth correction rarely applied to interferometric DEMs (Nuth and Kaab, 2011). The present study site is near to the test site of Gardelle et al., 2013 and Kaab et al., 2012), therefore we accounted for a bias of 1.4 m bias in our SRTM data in snow and ice region of the glaciers.

3. Results and Discussion

The difference image obtained by subtracting Topographic DEM from SRTM DEM over the Parbati and Pin glacier (Figure 6).

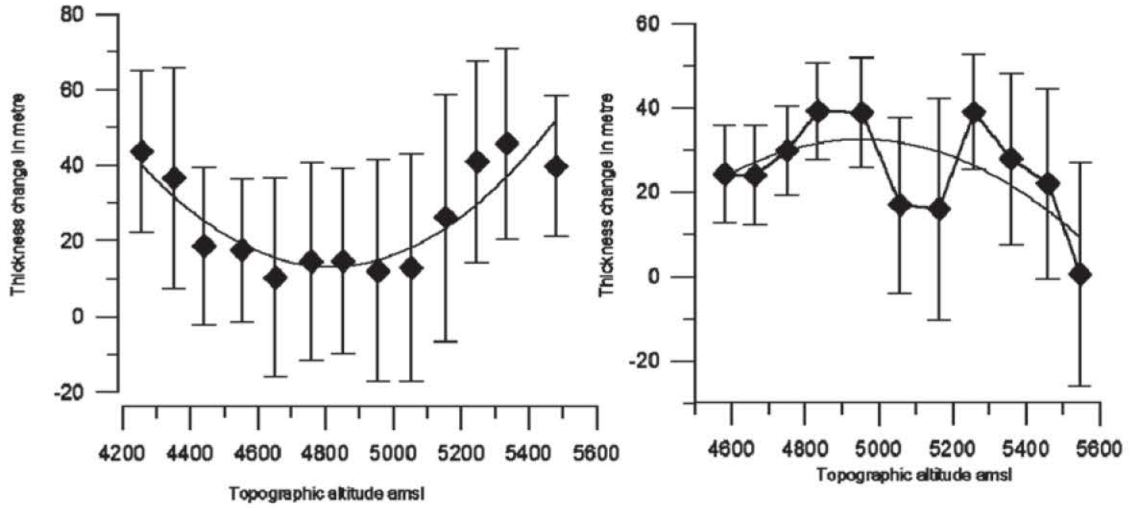

Figure 7: Relationship of thickness change (Corrected Topographic DEM 1962 - Corrected SRTM DEM 1999) and altitude over Parbati and Pin glacier surface

It indicated considerable thickness changes over glaciers and observed that highest thickness losses are mainly in lower and middle portion of the glaciers due to availability of stable clean ice surface and supraglacial melt water calving impact. The debris over the snout inhibits the glacier melting, while, more thinning in middle of the ablation is likely to be effected by high melt water production and stagnation at low slope middle ablation part of the glacier (Owen et al., 2016). The mean of thickness change was plotted along fixed contour line altitudes over the Parbati and Pin glaciers (Figure 7). It shows an inverse relation with the thickness loss and topographic altitude. However, after a certain topographic altitude the thickness loss increases with altitude. This phenomenon is contrast to field and modeling based glaciological observation. Hence, it is assumed that the high-altitude contours over glacier were drawn based on simple interpolation of lower elevation. Furthermore, the DEM based on topographic sheets also develop inaccuracy because of optical saturation by seasonal snow/ice on ariel photographs of the glacier region and results in erroneousness at high altitude in snow region (Raina and Srivastava, 2008, Raina, 2009, Bhambri et al., 2011 and Bhambri et al., 2012). These inaccuracies result in underestimation of the elevation on higher altitude over the glacier, hence altitude at which thickness lowering is minimum can be considered as good indicator of the permanent snowline altitude over glacier (Nuth et al., 2007). Therefore, in our calculation the thickness change information up to permanent snowline altitude is only considered. The permanent snowline altitude over Parbati and Pin is approximately 5100 amsl in present study and observed also by Azam et al., 2014, Berthier et al., 2007 in Chandra –Bhaga valley in the North of the study area.

The results show a mean of 20 ± 25m thickness loss at the glacier surface for the altitude ranging between 4200- 5200 msl for the Parbati glaciers (Figure 7). The glacier area under these elevation ranges comprises about 88% of the glaciers. Applying the thickness loss gradient all over the glacier shows that average –area glacier surface (Topographic DEM – SRTM DEM) is thinned by 14.54 ± 26.2 m. The total volume change of 0.528 km ^{3} was calculated by multiplying the thickness change and surface area change from 1962 and 2005. The standard error of volume change of 0.0113km^3 was calculated by dividing the product of surface change error and glacier area by square root of the number of measurements SRTM DEM pixel used in the study. The Pin glacier is located on higher altitude and thickness loss of the glacier surface ranging from 24 ± 11.6m for the altitude 4500 -4600 amsl and 16 ± 20.8m for the altitude 5000-5100 amls (Figure 7). It shows that the thickness change information above the 5100 amsl become irrelevant. The area-average thinning over Pin glacier is about 8.1 ± 18 m determined using elevation – area histogram and thickness loss at particular altitude. Total volume loss of 0.0972 km^3 ± 0.0012 km^3 is calculated for the Pin glacier by multiplying the surface area change and thickness change from 1962 and 2005.

The thickness loss rate per square meter over the Parbati and Pin glacier from 1962 and 1999 is estimated about – 0.39 ± 0. 71 m/y and -0.22 ± 0.52m/y. The lesser thickness loss over Pin glacier is due to its comparative higher altitude and location in rain shadow region. Recent glaciological mass balance studies on Chhota Shigri glacier in this region reported about - 1.4 m/y in 2002/03 (Wagnon et al., 2007). For the same Chhota shigri glacier the geodetic mass balance was of -0.41 ± 0.11 m per year during 1999-2011(Gardelle et al., 2013). In present study, the geodetic glacier mass balance is similar to observed values for Parbati and Pin glacier. It indicated that glaciers in this region have gone high negative value in recent time. The geodetic glacier mass balance of the glacier mass balance in North Nepal Himalaya suggested that lowering of 0.80 ± 0.35 m/y and 0.62 ± 0.37 m /y over ablation zones in Dudh Koshi and Tama Koshi catchments.

While, ablation zones of glaciers flowing onto the Tibetan Plateau lowered by 0.95 ± 0.30 m/y on average during 2000-2014/15 (Owen et al., 2016).

In Baspa and Chandra valley, Himachal Pradesh (Bahuguna and Kulkarni 2005 and Brethier et al., 2007) estimated the reduction in thickness of ice 35 m and 10 m thickness in deglaciated valley respectively in different period of time interval. The study conducted by (Kulkarni et al., 2007) in the same area indicated high rate of snout Pārbati glacier about 52 m/year retreated for the period of 1990 to 2001. High rate of thinning of the glaciers resulted in 17% and 13% areal shrinkage for Parbati and Pin glacier from 1962 to 2005 (Figure 8).

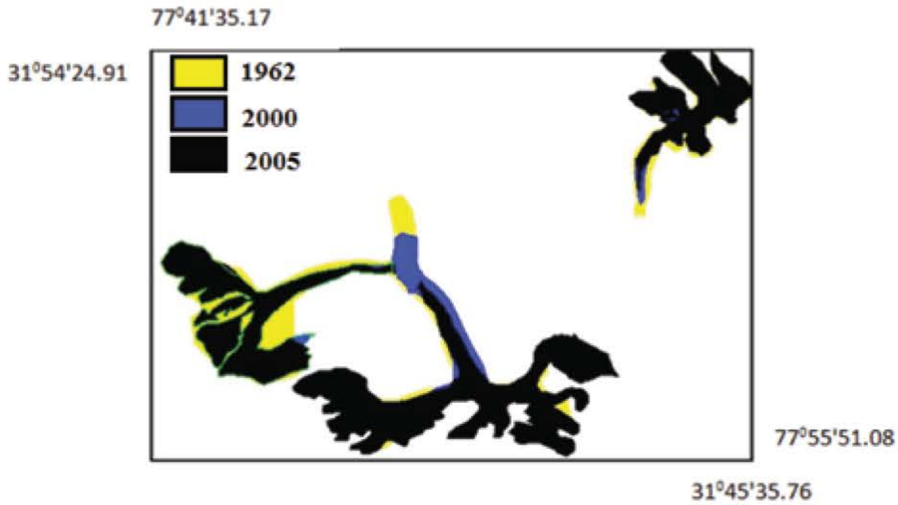

Figure 8: Fragmentation of the Parbati and Pin glacier (1962 -2005)

Figure 9: Hummock morain and dead ice near Parbati glacier

Major impact of glacier shrinkage is observed in snout region and fragmentation of tributaries glaciers is also observed commonly. It resulted in extreme snout retreat of Parbati glacier from 4157amsl to 4205 amsl and snout of Pin glacier retreat 4452 amsl to 4582 amsl during 1962 – 2005. The snout of Parbati glacier has been retreated 3000 meter from 1962 with rate of 23m per year for the period between1962-2005. Rapid snout retreat resulted in formation of hummocky type of terminal moraine and dead ice witnessed in field campaign in 2013 (Figure 9). Thickness loss over lower and middle ablation region resulted in potential increase in height of side moraines and mobilization of big boulder on glacier surface. Thinning of the glaciers, uneven moraine mobilization and rapid glacier backward movement generate highly uneven surface, which results in drainage development over glacier surface. High drainage density of the supraglacier channels development results in deep gullies formation and leads to dead ice mass in lower ablation region and hummock terminal in de-glaciated valley (Figure 8).

At the junction of tributary glacier with main valley glacier shows a slope difference all along the main glacier valley. The difference in slope provides a potential for mass movement of tributary glacier downstream quickly and responsible for high retreat rate. Therefore, tributary glaciers show heavy thickness loss than the main valley glaciers at tributary junction. A comparison of relationship between thickness loss and altitude of the main valley glacier and tributary glacier indicated that main valley glacier shows a glaciological thickness change and altitude relationship, while this relationship is not followed by tributary glaciers. The major area of the tributary glacier is located in higher altitude and only small glacier portion in linked with the main glacier. The vanishing of tributary glacier leads to limit it into cirque region.

4. Conclusions

The average elevation change over Pārbati and Pin glacier is -0.38 m/year and -0.22 m/y for the period of 1962 to 1999 year. Thickness changes over glaciers are mainly in lower and middle ablation portion of the glaciers. The availability of stable clean ice surface and calving due to supraglacier meltwater over low slope of middle ablation part of the glacier is responsible for high thickness loss in this portion. Heavy thickness loss resulted in 17% and 13% shrinkage of Parbati and Pin glacier area from 1962 to 2005. The substantial thickness losses in lower ablation resulting in rapid snout retreat, consequentially the hummocky type of terminal moraine are prominent feature near the snout of valley glacier. Tributary glaciers have been dissociated from main valley glacier and Pārbati glacier area is fragmenting in recent time due to difference in slope of main valley and tributary glaciers.

The thickness change studies over glaciers must involve the possible correcting factors before comparing the old topographic based DEM with SRTM DEM or other Remote Sensing Satellite based DEMs. Because of interpolation of lower elevation over high altitude accumulation region of glacier basin and optical saturation of snow/ice on ariel photograph resulted in inaccuracies in elevation on topographic sheets based DEMs at higher.

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