Mass balance estimation using geodetic method for glaciers in Baspa basin, Western Himalaya

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Himalayan glaciers, which contribute to water security for almost 1.3 billion people in Asia, are now under threat due to climate change. Assessment of glacier mass balance changes is crucial to determine the implications of climate change, but *in situ* measurements are limited due to rugged terrain and harsh climate of the Himalaya. Remote sensing-based geodetic method is therefore important for studying the evolution of Himalayan glaciers at a large scale. In this study, the mass balance of glaciers located in Baspa basin (Western Himalaya) is estimated for a period of 11 years between 2000 and 2011, using geodetic method. Out of 89 glaciers in the basin, 42 glaciers (greater than 1 km^2) covering an area of ~72% (215 km^2) of the total glaciated area were selected for the study. A mean thinning of ~50 ± 11 m and mean accumulation of ~35 ± 11 m was observed during the study period, with the cumulative mass balance varying between –36.9 ± 1.98 and 6.47 ± 1.98 m.w.e. A mean annual mass loss of –1.09 ± 0.32 m.w.e.a^{-1} was observed for the entire basin, suggesting that the glaciers in Baspa basin are losing mass at higher rate compared to the glaciers in central and eastern Himalayas. This study demonstrates the utility of geodetic method to estimate mass balance of glaciers at basin scale, which will be useful to assess future changes in glacial extent and stream run-off.

Keywords: Baspa basin, geodetic method, mass balance, Western Himalaya.

HIMALAYAN glaciers play a vital role in providing the melt water for hydropower generation, irrigation and domestic purposes to almost 1.3 billion people[1]. Consequently, the rapid shrinkage of Himalayan glaciers over the past few decades, due to the changing climate, has become a topic of considerable public and scientific interest[2–5]. The effect of climate change on a glacier's health can be best assessed by mass balance, which is a more relevant parameter than glacier length and area especially for debris-covered Himalayan glaciers[6]. However, the harsh topographic and weather conditions in the Himalayas are not favourable for detailed ground-based glaciological studies[1,7,8]. Due to limitations in field investigations[9–12], remote sensing techniques such as the Accumulation Area Ratio (AAR) and Equilibrium Line Altitude (ELA) methods have been used to study the mass balance of glaciers in the Himalayas[13–15]. In addition, geodetic method (comparison of multi-temporal digital terrain models) has been used to estimate the glacier mass balance at basin and regional scales in the Himalayas[2,6,16,17]. This method can also be used to supplement field measurements for wide temporal and spatial coverage[18]. Mass balance estimates using the geodetic method suggest that glaciers in Western Himalaya (–0.53 ± 0.16 m.w.e.a^{-1}) are losing mass rapidly compared to the Eastern (–0.22 ± 0.12 m.w.e.a^{-1}) and Central Himalaya (–0.33 ± 0.14 m.w.e.a^{-1})[6]. However, owing to the varying topography and climate regimes, individual glaciers within a region tend to behave differently and therefore it is necessary to study basin level mass balance in the regions where no field measurements are available[18]. The aim of this study is to present the geodetic mass balance estimates for a large sample of glaciers in Baspa basin, Western Himalayas which are influenced by drop in albedo, warmer temperatures and precipitation deficiency[3,15,19,20].

Baspa is a major tributary of Sutlej River, located in Kinnaur district of Himachal Pradesh, India (Figure 1). The river originates at Arsomang and travels 72 km through the valley before joining Satluj River at Karcham[21]. The basin is influenced by both westerlies and monsoon precipitation, with altitude varying from 1800 to 6400 m.a.s.l. The total area covered by the basin is 1050 km^2, out of which ~22% (238.65 km^2) is covered by 89 glaciers in the altitude range varying between 3720 and 5900 m.a.s.l (ref. 22). For the present study, 42 glaciers covering 72% of the basin glaciersed area was selected (Figure 1), considering their respective glacier area (>1 km^2) and coarse resolution of the elevation datasets (30 m). Among the 42 glaciers, 14 glaciers are south facing and 28 glaciers are north facing. However, among the 42 glaciers, only Baspa Bamak and Jorya Garang glaciers have extensive areas covered by the accumulation zone. Glacier equilibrium line altitudes (ELAs) are roughly estimated to 5270 m.a.s.l (ref. 19). Almost all of the selected 42 glaciers are covered by supra-glacial debris (Figure 1), which was estimated to be ~37 km^2 (ref. 15).

In this study, the elevation models from Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), with a spatial resolution of 30 m were considered for geodetic mass balance estimation. SRTM DEM was acquired in February 2000 and ASTER DEM on 23 October 2011. The SRTM V3 was obtained from USGS earth explorer (http://earthexplorer.usgs.gov/) and ASTER DEM (AST14DMO) from NASA Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/dataset_discovery/aster/aster_products_table/ast14dmo_v003).

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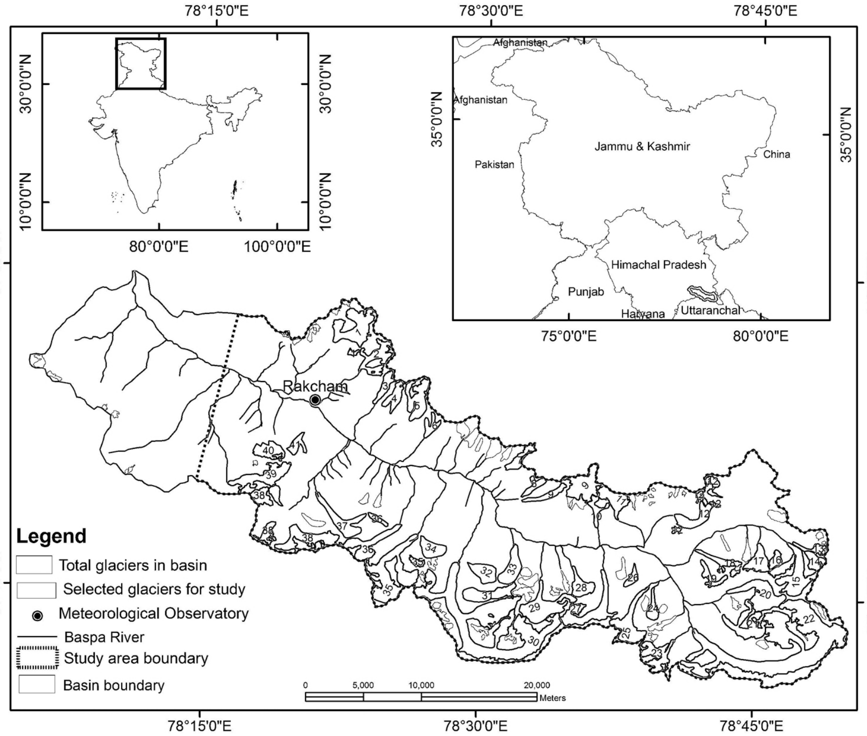

Figure 1. Geographical location of the study area. A total of 42 glaciers (marked with solid line and number) were selected for mass balance estimation. The basin area considered for the study is highlighted with dotted boundary line.

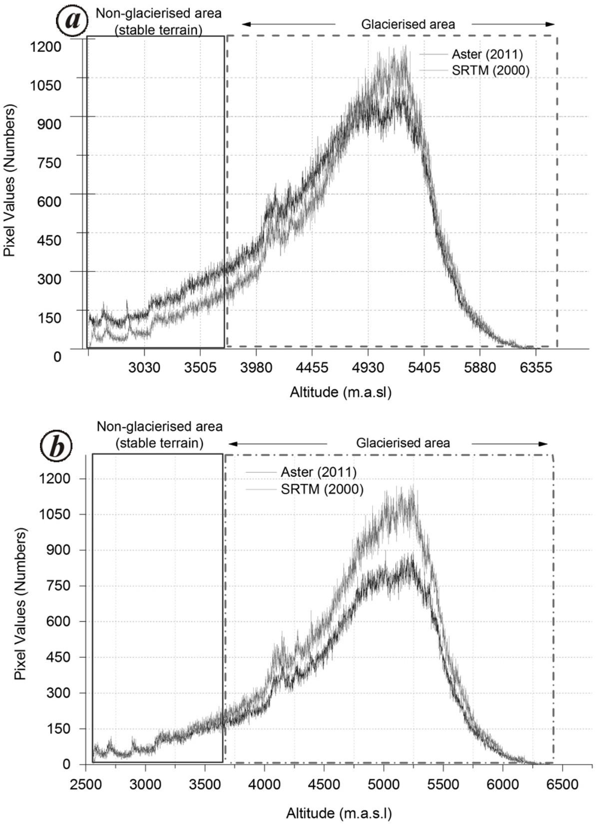

Figure 2. Pixel distribution of non-glacierzed and glacierzed areas in Aster and SRTM images, before and after the co-registration process, along-across track and elevation dependent corrections.

In addition, meteorological data (daily temperature (°C), snow water equivalent (mm) and rainfall (mm)) obtained from Rakcham observatory (3050 m.a.s.l), was also considered to study the climatic impact on mass balance in long term.

As these DEMs were obtained from two different sources employing different image acquisition techniques (SAR interferometry and stereo photogrammetry), horizontal and/or vertical offsets may exist. Hence, coregistration, along/across track and elevation dependent corrections of these DEMs are required to minimize the mis-registration errors. For this, the non-stable terrain (glaciers and river with 50 m buffer) was removed from both the images. Then, the universal coregistration algorithm was used to perform co-registration (planimetric adjustment) of DEM's for non-glaciated terrain[23,24]. After planimetric adjustment, the SRTM image was shifted according to positional vectors (Δx, Δy) and the bias in elevation (Δz) reduced to 0.85 m for non-glaciated terrain. Further, the azimuth of ASTER ground track was used to rotate the coordinate system of AST14DMO DEM and then the elevation differences along and across the satellite track was computed for stable/non-glacierized areas. The bias during this process was minimized using a 4th order polynomial fit[17,25]. Field control points obtained in the basin were also used during this process to minimize the error in elevation-dependent bias. The histogram/pixels distribution of non-glacierized (stable) and glacierized areas are plotted for both the ASTER and SRTM images, to identify the elevation difference (Figure 2) before and after the corrections listed above. The SRTM image obtained after applying the corrections was considered further to estimate the glacier elevation changes (d*h*), at an interval of 100 m altitude bins. Elevation changes greater than +100 m and lower than –100 m were generally treated as outliers as these values usually represent the data gaps and DEM edges[2,25]. In addition to the outlier threshold, pixels representing the absolute elevation difference more than three standard deviations from the mean, in each altitude bin were discarded[24]. After these changes, the elevation differences are observed to be varying between –50 and +50 m.

The SRTM DEM acquired in February (winter season), 2000 using C-band (~5.6 cm wavelength) has an average penetration of 2.4 ± 0.4 (m) over the accumulation zone of glaciers in the Lahaul–Spiti region[17,24]. Hence the accumulation areas of 42 glaciers were corrected for radar penetration by considering the mean ELA as 5270 m (ref. 14). In addition, ASTER DEM was also acquired in winter season (late October). Hence, the possible mass changes during this 5-month period (seasonality correction) were derived from the mean winter mass balance of three glaciers (Gor Garang, Shaune Garang and Naradu) in the same basin for a period of 11 years between 2000 and 2011 (ref. 26), which is estimated to +1.53 $\mathrm{m.w.e.a}^{-1}$ (corresponding to +0.30 m.w.e. per month). The estimated average winter mass balance is in good agreement with the modelled winter mean mass balance in Western Himalaya (Chhota Shigri glacier) during 2000–2009 (+1.17 $\mathrm{m.w.e.a}^{-1}$) and 1969–2012 (+1.08 ± 0.34 $\mathrm{m.w.e.a}^{-1}$)[27–29]. Thereafter, the average elevation changes among various altitude bins were analysed and integrated throughout the glacier surface to estimate the volume change (m3), followed by mass balance estimation by approximating the density of ice as 850 ± 60 kg. m^{-3} (refs 30–33).

The uncertainties in volume (eq. (1)) and mass balance (eq. (2)) were estimated by considering the error sources such as radar wave penetration (Δp in meters), relative vertical accuracy NMAD (normalized median absolute derivation) ($\sigma_{\delta h}$ in meters, which is resilient to outliers) and uncertainty in ice density ($\Delta\rho$ in $\mathrm{kg/m^3}$)[27,33,34].

$$U_V = \sqrt{\Delta p^2 + \sigma\delta h^2}, \tag{1}$$

$$U_M = \sqrt{\Delta p^2 + \sigma\delta h^2 + \Delta\rho^2}. \tag{2}$$

Elevation changes and mass loss were estimated for 42 glaciers in Baspa basin, for a period of 11 years between 2000 and 2011. The SRTM image exhibited large distortions (*X*: 48.8″, *Y*: 6.6″ and *Z*: 8.8 m), compared to ASTER image and the elevation changes estimated before co-registration was between –180 m and +180 m, which are outliers. After the co-registration process, along/across track and radar penetration corrections and removal of outliers, the elevation differences (d*h*; Figure 3) were estimated. Out of 42 glaciers, accumulation was observed only for 17 glaciers whereas thinning was observed for all considered glaciers. The thinning was observed in ablation regions of glaciers (below ELA) and thickening in accumulation areas (above ELA). The mean maximum thinning was estimated to –50 m, whereas the mean maximum accumulation was ~+35 m, during the study period (Figure 3). However, small glaciers have shown higher thinning compared to large size glaciers. Baspa Bamak (Glacier ID 22) is one of the largest glaciers in the basin with a glacierized area of 32.65 km^2. Its tongue is heavily covered by supraglacial debris, with 2 lakes existing as of 2001 (22–09–2001; Earth explorer). During the study period, this glacier experienced rapid thinning because of higher rise in temperatures, and a negligible accumulation due to precipitation deficiency[15]. As a result, 12 new lakes (of different sizes) were formed in the ablation zone of Baspa Bamak glacier, which strongly suggests that debris covered glaciers react faster to ongoing climate change, if associated with lakes[35]. Higher changes in elevation were also observed at steep zones and in the regions having sudden change in slope (Figure 4).

Negative mass balance was estimated for 40 glaciers during the observation period (Table 1). In contrast, positive mass balance was observed for two glaciers (Glacier ID 9 and 27). This is possibly due to the large accumulation area (glacier no 27) and high altitude/geographical location (where the mid-altitude >5800 m.a.s.l). For the remaining glaciers, the mass balance varies from –3.35 to –0.41 $\mathrm{m.w.e.a}^{-1}$ (Table 1). The mean annual geodetic balance for the glaciers at basin level is –1.09 $\mathrm{m.w.e.a}^{-1}$, with an estimated uncertainty of 0.32 m.w.e (eq. (2)). Glaciers located at lower altitude (where mid-altitude is less than 5200 m.a.s.l) have shown higher mass loss (Figure 5), probably due to warming at lower altitudes. To evaluate the accuracy of the geodetic method, comparative analysis was carried out using mass balance measurements of three glaciers namely Gor Garang, Shaune Garang and Naradu glaciers, derived using geodetic and temperature index melt methods[26] (Table 2). It was found that the mass balance estimated using geodetic method was in good agreement with that derived using temperature index method[26]. Also, to analyse changes in mass balance characteristics in long-term, the glaciological mass balance measurements available for past and present decades were compared (Table 3) and it strongly suggests that the glaciers have experienced higher mass loss in the present decade, possibly due to the temperature rise and precipitation deficiency. The meteorological data obtained from the Rakcham observatory support such scenarios (Figure 6)[15]. Finally, it was observed that the mass loss in Baspa basin (–1.09 ± 0.32 m.w.e.) was higher compared to other parts of the Himalayas like Hindukush (–0.49 ± 0.14 $\mathrm{m.w.e.a}^{-1}$), West Nepal (–0.43 ± 0.09 $\mathrm{m.w.e.a}^{-1}$)[28]. In addition, the estimated mass balance was also more

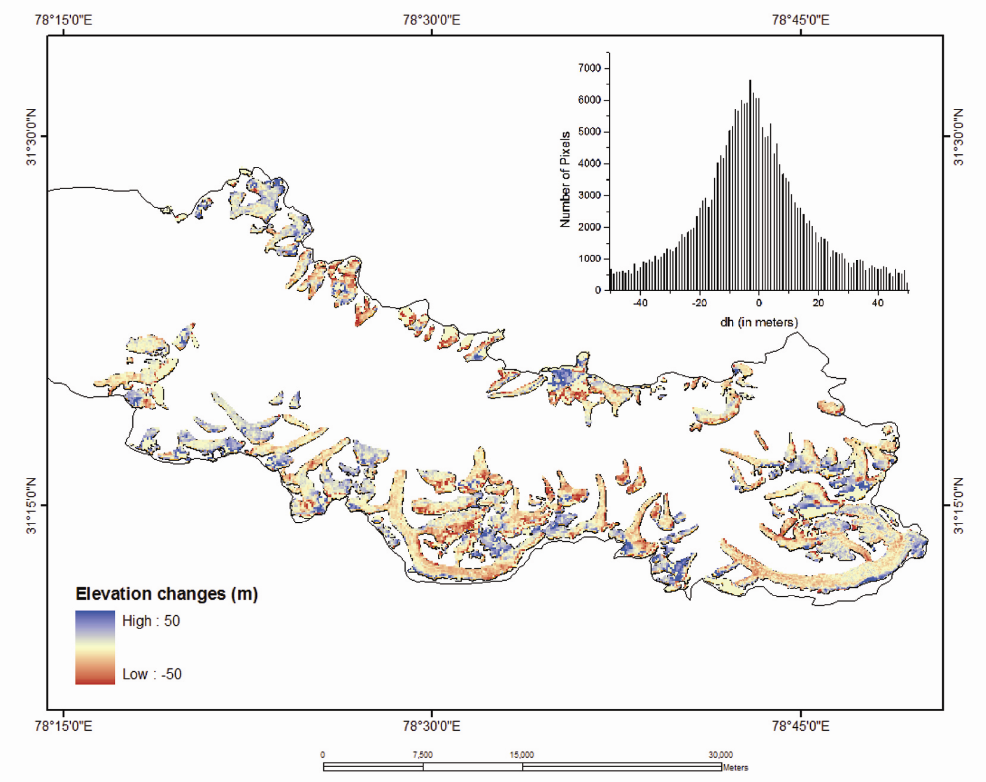

Figure 3. Observed elevation changes (d*h*) between 2000 and 2011. The negative values represent the thinning/ablation, whereas the positive values represent the accumulation during the observation period.

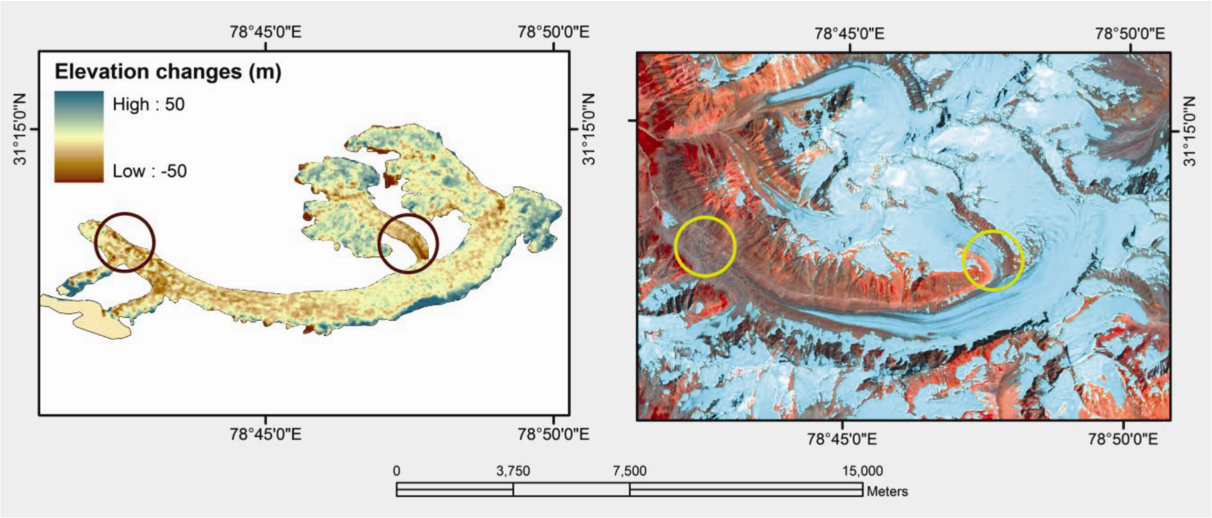

Figure 4. Elevation changes observed for Baspa Bamak (Glacier ID: 22). Maximum thinning was observed at steep slopes and in the lake areas.

negative compared to the mass balance of glaciers in Lahaul–Spiti region (-0.53 ± 0.16 m.w.e.a^{-1}), in the western Himalaya for the same study period[6].

Regional mass balance studies are required to assess the water availability for various domestic and industrial activities. However, the mass balance estimation using glaciological method at a wide temporal and spatial coverage is highly difficult in Indian Himalayas. Thus, we estimated the glacier's mass balance using geodetic method, which has an advantage in evaluating the mass balance of large sample of glaciers. The study strongly suggests that the glaciers are thinning and losing mass in long term. Higher mass loss was observed for glaciers, located at lower altitudes (i.e., where the mid-altitude of

Table 1. Glacier area, total mass balance (m.w.e), annual specific mass balance (m.w.e.a^{-1}) and uncertainty for individual glaciers in Baspa basin using geodetic method between 2000 and 2011

Glacier ID	Area (km^2)	Mid-altitude (m.a.s.l)	Cumulative mass balance (m.w.e)	Annual mass balance (m.w.e.a^{-1})	Uncertainty (m.w.e)
1	8.0	5200	–18.68	–1.70	0.56
2 (Gor Garang)	3.8	5200	–10.74	–0.98	0.26
3	1.9	5100	–5.10	–0.46	0.21
4	2.1	5100	–8.02	–0.73	0.35
5	3.8	5200	–15.06	–1.37	0.37
6	1.2	4800	–15.29	–1.39	0.02
7	1.9	5250	–9.74	–0.89	0.11
8	1.3	5000	–15.95	–1.45	0.20
9	7.2	5400	6.47	0.59	0.17
10	1.5	5150	–6.37	–0.58	0.23
11	3.2	5550	–16.37	–1.49	0.26
12	5.2	5350	–13.71	–1.25	0.07
13	1.3	5400	–11.06	–1.01	0.02
14	1.7	5550	–10.33	–0.94	0.25
15	7.4	5550	–36.86	–3.35	0.31
16	1.1	5550	–9.63	–0.88	0.02
17	2.9	5500	–9.78	–0.89	0.05
18	2.2	5250	–10.75	–0.98	0.03
19	1.5	5200	–10.47	–0.95	0.10
20	6.2	5600	–9.95	–0.90	0.52
21	4.6	5600	–17.39	–1.58	1.37
22 (Baspa Bamak)	32.4	5150	–19.65	–1.79	0.43
23	2.2	5050	–16.14	–1.47	0.13
24	1.5	5150	–8.21	–0.75	0.27
25	4.4	5200	–6.14	–0.56	0.21
26	1.0	5100	–13.07	–1.19	0.09
27	5.4	5250	2.85	0.26	0.26
28	2.6	5200	–14.03	–1.28	0.52
29	4.3	5450	–17.41	–1.58	1.41
30	31.5	5200	–20.22	–1.84	1.20
31	4.0	5350	–5.94	–0.54	0.41
32	2.8	5150	–4.48	–0.41	0.31
33	3.5	4950	–5.02	–0.46	0.35
34	2.6	4950	–12.95	–1.18	0.21
35	9.7	5050	–24.13	–2.19	0.23
36 (Naradu)	3.7	5100	–9.13	–0.83	0.28
37	2.0	4850	–15.04	–1.37	0.35
38 (Shaune Garang)	6.0	5050	–10.84	–0.99	0.35
39	9.7	5050	–15.54	–1.41	0.39
40	5.1	5100	–12.56	–1.14	0.03
41	2.8	4350	–9.63	–0.88	0.18
			Average	–1.09	0.32

Table 2. Comparison of mass balance estimates derived using geodetic and temperature index methods during the study period (2000–2011)

	Geodetic method (m.w.e)	Uncertainty (m.w.e)	Temp Index method (m.w.e)	Uncertainty (m.w.e)
Gor Garang	–0.98	0.26	–0.73	0.24
Naradu	–0.83	0.28	–0.61	0.23
Shaune Garang	–0.99	0.35	–1.09	0.33

Table 3. Observed changes in glaciers mass balance on a long term scale in Baspa basin

	Glaciological method		Geodetic method	
Name of the glacier	Period of observation	Mean mass balance (m.w.e)	Period of observation	Mean mass balance (m.w.e)
Gor Garang	1977–1986	–0.38	2000–2011	–0.98
Naradu	2000–2003	–0.40	2000–2011	–0.83
Shaune Garang	1982–1992	–0.42	2000–2011	–0.99

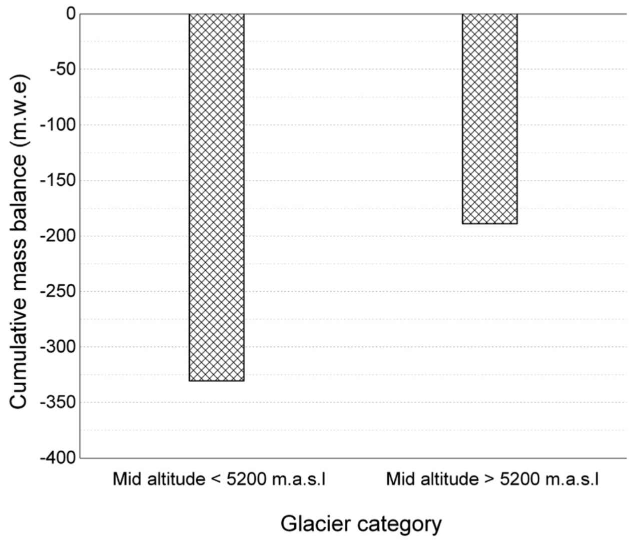

Figure 5. Cumulative mass balance of the studied glaciers between 2000 and 2011. Glaciers with mid altitude less than 5200 m.a.s.l are losing more mass than the glaciers, located at higher altitudes.

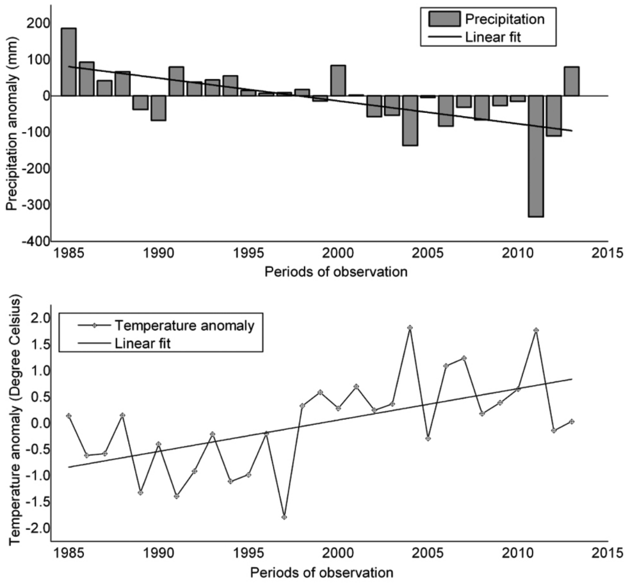

Figure 6. The meteorological data obtained from Rakcham observatory (located at 3050 m.a.s.l in the basin; around 100 km from Shaune Garang glacier) suggests a rise of 1.65°C in mean annual temperature between 1984 and 2013. A significant decrease (102 mm) in precipitation (rainfall and snowfall) is observed between 1984 and 2015.

glaciers is less than 5200 m.a.s.l). Also, the study suggests that glaciers in this basin are losing mass at a higher rate compared to glaciers in the other regions of the Himalayas. From the above observations, it is strongly evident that the glaciers in Baspa basin may melt faster due to ongoing climatic change and could lead to the severe water scarcity in the near future.

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Luminescence dating of Neolithic pottery in North East India

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Imprecise chronological data have long been affecting archaeological studies in Assam and Meghalaya, North East India. Relative dating methods have been used to study the antiquity of stone tools and ceramics found in the archaeological sites of these two areas. Both the areas are important as the eastern Asiatic Neolithic complex of double-shouldered celts and cord-marked pottery was first reported in India from Daojali Hading, Assam (1961), Garo Hills, Meghalaya has the highest concentration of prehistoric sites found in North East India. Optically stimulated luminescence dating offered an excellent opportunity for dating the ceramic samples recovered during the first excavations in 1961 (Daojali Hading in Dima Hasao district Assam) and 1999 (Gawak Abri, Garo Hills), as the method provided a direct age estimate of the time of last exposure of quartz or feldspar minerals to light or heat, and the purity of the etched quartz (i.e. any feldspar contaminations) can be confirmed by infrared stimulated luminescence technique. Date obtained from Daojali Hading is 2.7 ± 0.3 ka (LD1728) and that from Gawak Abri is 2.3 ± 0.2 ka (LD1727).

Keywords: Cord marked, dating, hypothesis, neolithic, pottery.

NEOLITHIC sites have been reported from all the eight states of North East India. Excavated Neolithic sites from the region are Daojali Hading[1] and Saru Taro[2] from Assam; Gawak Abri[3] and Law Nongthroh[4] from Meghalaya; Napachik and Nongpok Keithelmanbi from Manipur[5,6] Parsi Parlo from Arunachal Pradesh[7] and Ranyak Khen from Nagaland[8]. Daojali Hading, excavated in 1961, is the first stratified Neolithic site discovered in NE India (Figure 1). This site has put NE India in the Neolithic map of the world because of the recovery of the double-shouldered celt and cord-marked pottery which till then was considered as a character of the Neolithic of 'East Asia'[1]. After this discovery, the boundary of the East Asiatic 'Corded ware' Neolithic culture was extended to include NE India[9–11].

For the first time in India, the shouldered celts were put into a stratigraphical context and the presence of quadrangular adzes and square-shouldered celts at the site suggest that the culture belonged to a Late Neolithic phase, the date of which is most probably linked to the late Neolithic cultures of southwest China and Southeast Asia. As there were no absolute dates, these observations

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