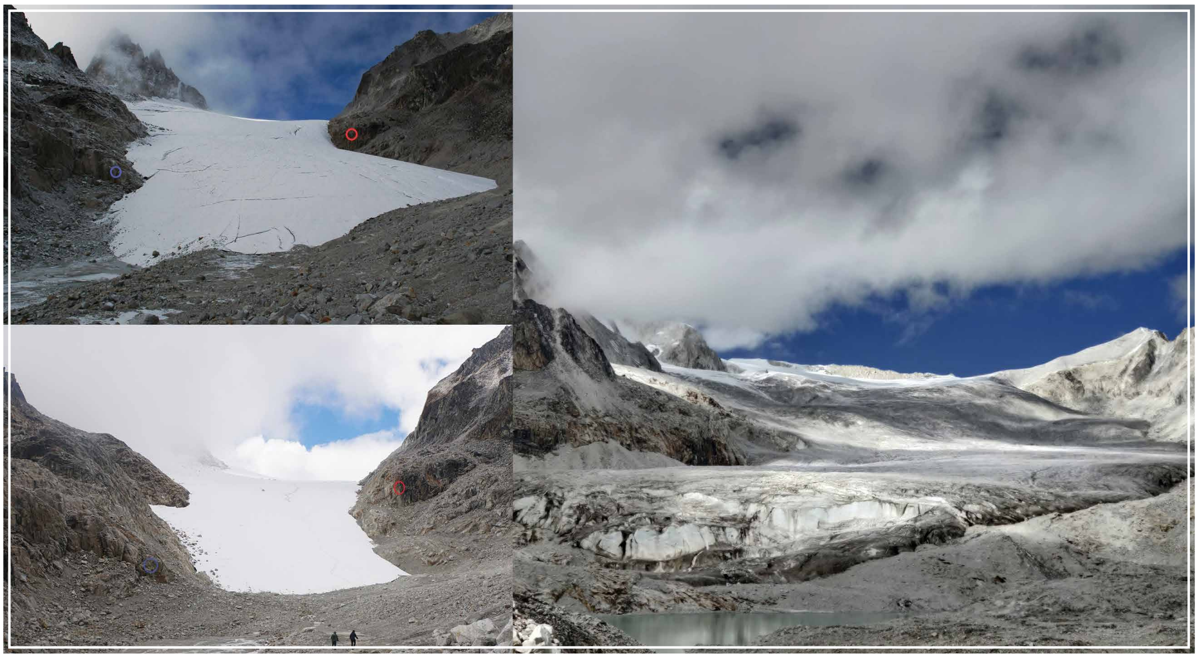
Mass Balance Status of Glaciers of Bhutan Himalayas

As observed on Gangju La and Thana Glacier



Cryosphere Services Division
National Center for Hydrology and Meteorology
2021

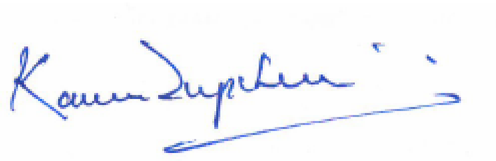
FOREWORD

Glaciers all over the world are retreating at an accelerated rate. Bhutan is no exception to this phenomenon. It is also evident from various studies that mountain glaciers play an important role in regulating and maintaining the hydrological regime in the region. Fresh water is a life line to all forms of life and glaciers are one of the main sources of freshwater. However, the cryosphere is impacted drastically with the advent of climate change which is an undeniable truth. Bhutan located in the eastern part of the Himalayas, the glaciers in Bhutan are known to be summer accumulation type on which major accumulation occurs during summer when the monsoon is in active phase. A slight change in the air temperature can have a drastic impact on the nature of accumulation on the glaciers in Bhutan.

Mass balance study is a way of monitoring the status of a glacier. Information on mass balance study is generated by collecting data from the glaciers on annual basis which provides vital information on the behavioral characteristics of glaciers such as whether the glacier is advancing (gaining mass), retreating (losing mass) or at equilibrium (mass loss due to melting equals to mass gain through accumulation). Such scientific information is necessary and can play a vital role in the socio-economic development of a country. This science-based information can also serve as a tool for our planners and decision makers to take prompt decisions and action on all development related programs.

National Center for Hydrology and Meteorology (NCHM) as a scientific and technical autonomous agency was created bringing in all related fields under one umbrella. At present the center is mandated to conduct research and provide scientific services through dissemination of information in the field of weather, climate, hydrology and cryosphere to all the end users. Based on the mandates of the center, two benched marked glaciers were identified for long term mass balance observation in Bhutan. Thana glacier is located in the headwaters of Chamkhar Chu and Gangju la glacier is located in the headwaters of Pho Chu. Mass balance monitoring program on Thana and Gangju la glaciers was initiated in 2015 and 2004 respectively.

NCHM takes plight in publishing this scientific report on mass balance studies on the two bench marked glaciers in Bhutan. The findings in this report provide a general idea on the current status of the glaciers in Bhutan which was achieved through extensive data collection field work and meticulously analyzing the data set. It is hoped that the report will be of value to individuals and organizations involved in related fields.



Karma Dupchu
DIRECTOR

Acknowledgement

The National Center for Hydrology and Meteorology would like to express our gratitude to the following individuals and organizations for enabling us to complete this report a success.

We would like to thank European Space Agency (ESA) for making freely available Remote Sensing data (Sentinel imageries) which were used for various analyses during the preparation of this report.

The Center also would like to acknowledge the financial support received from UNDP, Bhutan for printing and publication of this important scientific report.

We remain grateful to the teams who carried out earlier surveys and made the data sets available for reproduction of maps and results and made easier for comparison for detecting changes taken place over time on the glaciers.

Lastly, we acknowledge all the contribution made by individuals and agencies either directly or indirectly towards achieving our goal of publishing this report very successfully.

Executive Summary

Himalayan range holds the world's second largest ice mass outside the polar regions and its melt water feeds some major river systems in Asia supporting lives of about two billion people in the South Asian region. Global climate change is a fact and such ice reserves worldwide are melting fast. The glaciers in the High Mountain Asia are often referred to as the Pulse of the Planet as they react more sensitively to global climate change. Bhutan, as part of the Himalaya is not an exception. The insufficient studies and knowledge gap on know-how regarding their response towards rising global temperature hampers the planners and decision makers across the region. In order to better understand the status of Himalayan glaciers, numerous researches have been carried out.

Bhutan lies in the eastern part of the Himalaya and glaciers located in such regime are more sensitive to climate change. Many of studies have been conducted on glaciers in other parts of the Himalayan region but so far, only few studies have been conducted on glaciers in Bhutanese. In an attempt to understand the behavior of glaciers of Bhutan in the context of global climate change, two benchmark glaciers were identified; one, centrally located in the headwater of Chamkhar Chhu (Thana glacier) and the other (Gangju La glacier), in the headwater of Pho Chhu, a sub basin of Punatsangchu for annual glacier mass balance monitoring. Observations on Gangju La glacier started as early as 2003 by group of Japanese researchers, later continued by NCHM from 2011 while research activities on Thana glacier was initiated in 2012 through a collaborative work by erstwhile Department of Hydro-Met Services. Since then, annual monitoring of those two glaciers have been continued.

So far, the findings reveal that both the glaciers are found to shrink and lose mass annually. Gangju La glacier exhibits negative mass balance values ranging from -1110 to -2390 mm w.e. with area shrinkage of about 30% leading to 1.7 million tons of ice loss from 2004 to 2020. Since 2004 till date, it accounts to cumulative net balance of -28,500 mm w.e. Similarly, Thana glacier also exhibits negative mass balance values ranging from -660 to -2910 mm w.e. with area shrinkage of about 7%, leading to 24 million tons of ice loss from 2016 to 2020. The cumulative net mass balance of Thana glacier is about -6530 mm w.e. Holistically applying the cumulative net balance of Gangju La glacier from 2004 to 2020 to other glaciers covering an area of 630 km^2, Bhutan has lost 17 gigatons of glacier ice from 2004 till date.

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1. Introduction

Himalayan range is referred to as the third pole owing to the huge reserve of glacier ice next to the polar ice caps. In the recent times due to global climate change, ice caps and mountain glaciers worldwide have been losing mass drastically. Moreover, glaciers across the Himalayan region have exhibited more ice loss in the past 40 years (J. M. Maurer et al., 2019). In this context, the Himalayan glaciers which feed water resources to about two billion people, are often referred to as the Pulse of the Planet as glaciers located in such environment react more sensitively to global climate change.

Glaciers of Bhutan are located in the eastern part of the Himalayas and are fed by the summer monsoon from Bay of Bengal. Such glaciers, including glaciers in Nepal Himalaya are known to be summer accumulation type and are more sensitive to global climate change (Y. Ageta; K. Higuchi, 1984) mainly driven by precipitation phase shift, meaning, a slight change in temperature in the region changes the form of precipitation from solid (snow) to liquid (rain) and/or vice versa. While there are many studies carried out over the Himalayan glaciers adopting *in-situ* measurements (Yao et al., 2012; Azam et al., 2018; Tshering & Fujita, 2016) as well as airborne satellites or remotely sensed technologies (Gardelle et al., 2012; Rupper et al., 2012; Joshua M. Maurer et al., 2016; Brun et al., 2018), there had been no or only few studies conducted regarding the Bhutanese glaciers until the early 2000s. In a latest inventory (BGI, 2018) published by National Center for Hydrology and Meteorology (NCHM) using the latest freely available high resolution sentinel satellite imageries, 700 glaciers (including both debris covered and clean ice type) were reported covering an area of approximately 629.55±0.02 km^2 in Bhutan.

In an attempt to understand the behavior of those glaciers in the context of global climate change, two benchmark glaciers were identified; one, centrally located in the headwater of Chamkhar Chhu (Thana glacier) and the other (Gangju La glacier), in the headwater of Pho Chhu, a sub basin of Punatsangchu for annual glacier mass balance monitoring. Observations on Gangju La glacier started as early as 2003 by group of Japanese researchers, later continued by NCHM from 2011 while research activities on Thana glacier was initiated in 2012 through a collaborative work by erstwhile Department of Hydro-Met Services.

2. Objectives

The main objectives of setting up the benchmark glacier and monitoring are:

- To observe glacier mass balance of clean type glaciers in the Bhutan Himalayas
- To understand the impact of climate change on the glaciers in Bhutan
- To monitor status of terminus retreat of the glaciers through dGPS survey
- To estimate glacier wide-discharge and contribution to surface runoff in future in the context of water resources

3. Study area

Thana glacier is located in the headwater of Chamkhar Chhu at 28.016°N, 90.613°E and is centrally located in terms of glacier distribution in Bhutan Himalayas. It takes seven days trek from the motorable road end at Khaktang, Bumthang. Gangju La is located in the headwater of Pho Chhu, sub basin of Punatsangchu at 27.940°N, 89.950°E and is towards western part of the Bhutan Himalayas. It is en route to Lunana Gewog of Gasa Dzongkhag. Location of the glaciers are shown in figure 1.

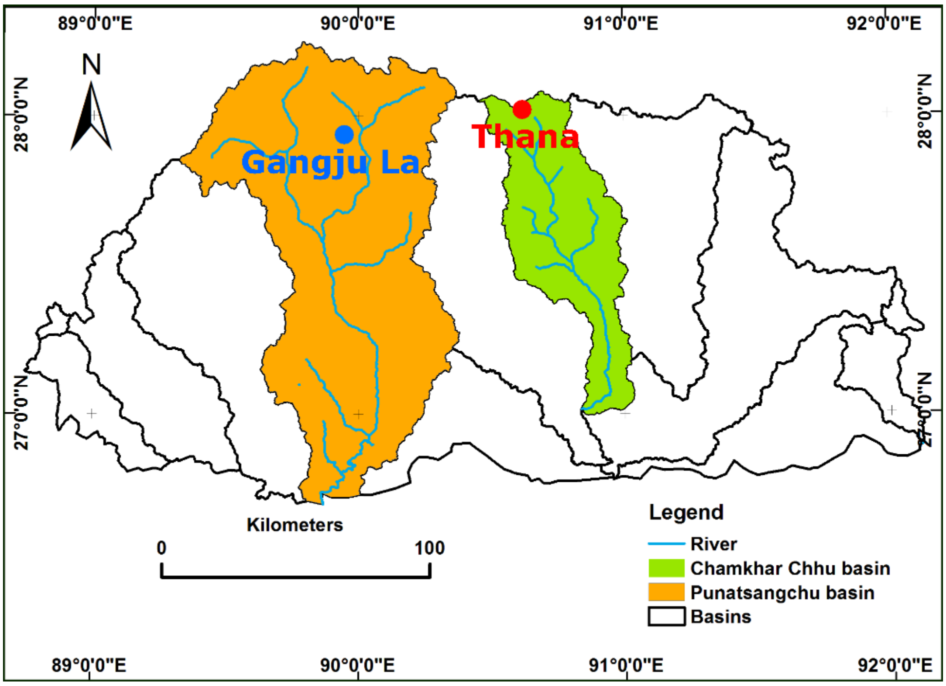

Figure 1: Location map of Gangju La and Thana Glaciers, located in the headwater of Pho Chhu sub-basin of Punatsangchu and Chamkhar Chhu respectively

4. Methodology

4.1. Data acquisition

The direct/glaciological method and *in-situ* geodetic method involving installation of bamboo stakes and dGPS survey respectively were used for data acquisition over the glacier surface. For Thana glacier, both the methods were deployed whereas only *in-situ* geodetic method was used for Gangju La glacier since 2013 as direct method was found to be not feasible. Certain number of bamboo stakes representing spatial surface area (e.g., Fig. 2a) with unique stake label were installed over Thana glacier during the field survey periods and the readings (data retrieval) were carried out in the consecutive survey year. Simultaneously, the *in-situ* geodetic survey (dGPS) were conducted using Promark 3 and Trimble R10-2 GNSS receiver on the glacier surface (Fig. 2b). It requires two or more GPS sets, one as a base and others as rovers. The base was set up on a known point near the advance camp in static mode and the rovers were set in kinematic mode, tied on backpack and walked randomly over the glacier surface (Thana) and zig-zag way (Gangju La). The point recording interval of 1 m was set and surveyed. On Gangju La glacier, similar *in-situ* geodetic method was deployed to map the glacier surface elevation (fig. 2c). The direct/glaciological method was found not feasible on Gangju La glacier due to human interference as the local people travel over the glacier surface. Such failures were reported by Tshering and Fujita (2016), while they made an attempt to install stakes during their field visit in September 2012.

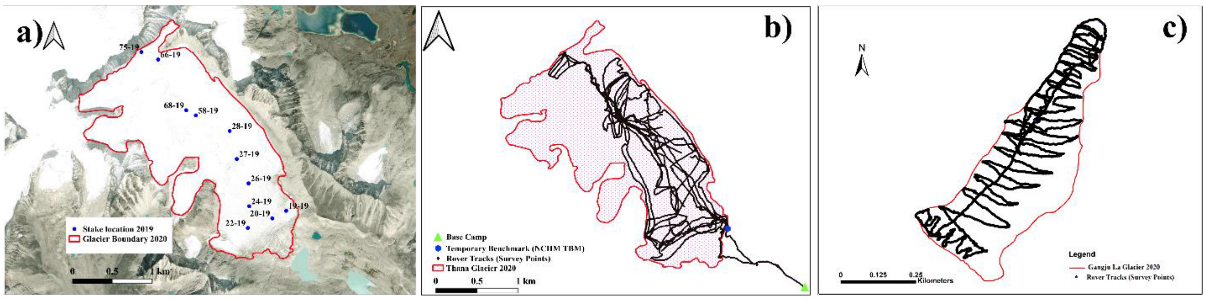

Figure 2: Survey map of Thana and Gangju La glacier (Survey year 2019 – 2020). (a) Thana glacier with background on ESRI showing the stake locations of 2019, retrieved in 2020 field survey. (b) in-situ geodetic point tracks shown in closely spaced black dots and (c) in-situ geodetic point tracks of Gangju La glacier. The red polygons of a, b and c are the glacier boundary delineated using sentinel 2 (GRD).

4.2. Data post-processing

The data acquired through direct method and in-situ geodetic methods were post-processed separately for mass balance calculations using the following methods.

4.2.1. Direct method

Throughout the survey periods, ice thickness changes were computed by retrieving stake height changes between two consecutive years incorporating the snow height (thickness) at the stake locations. The stakes were installed spatially on the glacier surface, representing the whole glacier area. Following (Tshering & Fujita, 2016), the annual mass balance (specific) at the stake locations were calculated using equation 1.

$$b_d = \frac{\Delta h_d \rho_i + (s_{t2} - s_{t1})(\rho_s - \rho_i)}{t2 - t1} \quad \text{.............................. (1)}$$

Where;

b_d is the annual mass balance at a particular 50 m elevation band (kgm^{-2} a^{-1}),

Δh_d is the ice thickness change (m) obtained from linear regression line within every 50 m elevation band between time $t1$ and $t2$,

s_{t1} and s_{t2} are the snow thickness at 50 m elevation band for survey years $t1$ and $t2$ respectively,

ρ_s and ρ_i are the density of snow and ice respectively.

The ice density value used for the mass balance calculation was 880±30kgm^{-3} throughout the glacier surface whereas the snow density of 400±100 kgm^{-3} in the lower elevation and 488.8 kgm^{-3} towards upper elevation obtained from snow pit measurement were used. In case of Gangju La glacier, the density of snow was assumed to be 400±100 kgm^{-3} throughout (Tshering & Fujita, 2016). Though stakes were spatially installed on the glacier surface, in some 50 m elevation bands, no stakes were installed due to inaccessibility. In order to calculate mass balance within each 50 m elevation band, linear regression line was drawn and the mass balance within each 50 m elevation band was picked from the linear regression line.

The area-averaged annual mass balance ($\overline{b_d}$, kgm^{-2}, equivalent to mm w.e. a^{-1}) is calculated using the equation 2.

$$\overline{b_d} = \frac{\Sigma_z A_z b_{dz}}{A_T} \quad \text{... (2)}$$

Where;

A_z and A_T are the glacier surface are within the 50 m elevation band and the total area (m^2) respectively,

b_{dz} is the mass balance within the 50 m elevation band. Usually, the total area is computed as the average of two years surface area (Tshering & Fujita, 2016).

4.2.2. Geodetic method

The surface elevation point data acquired using Promark 3 receiver were post processed in GNSS solution software and exported to comma separated values (.csv) whereas data obtained using Trimble R10-2 GNSS receiver were exported directly to .csv format using the inbuilt Trimble access software in TSC7 controller. The dataset obtained were then quality checked and erroneous data were excluded from further analysis. In order to obtain the elevation change over the glacier surface, Digital Elevation Model (DEM) were generated for different consecutive survey years using Inverse Distance Weighting (IDW) interpolation tool with a search radius of 0.7 m in ArcGIS (UTM WGS 1984 coordinate system). Such DEMs were then compared to obtain the surface elevation change (Fig. 3(h) – (i); Fig. 4(a) – (c)). The elevation change point data were exported to excel format and processed for mass balance calculation using equation 3.

$$b_g = \frac{\Delta h_g \rho_i + (s_{t2} - s_{t1})(\rho_s - \rho_i)}{t2 - t1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, b_g is the specific balance within the 50 m elevation band, Δh_g corresponds to the average elevation change (m) within the 50 m elevation band obtained through geodetic method, and rest of the annotations remain same as that of direct method (equation 1).

In a similar manner, the area-averaged mass balance through geodetic method ($\overline{b_g}$, kgm^{-2}, equivalent to mm w.e.a^{-1}) was then calculated as:

$$\overline{b_g} = \frac{\Sigma_z A_z b_{gz}}{A_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, b_{gz} is the average mass balance within the 50 m elevation band.

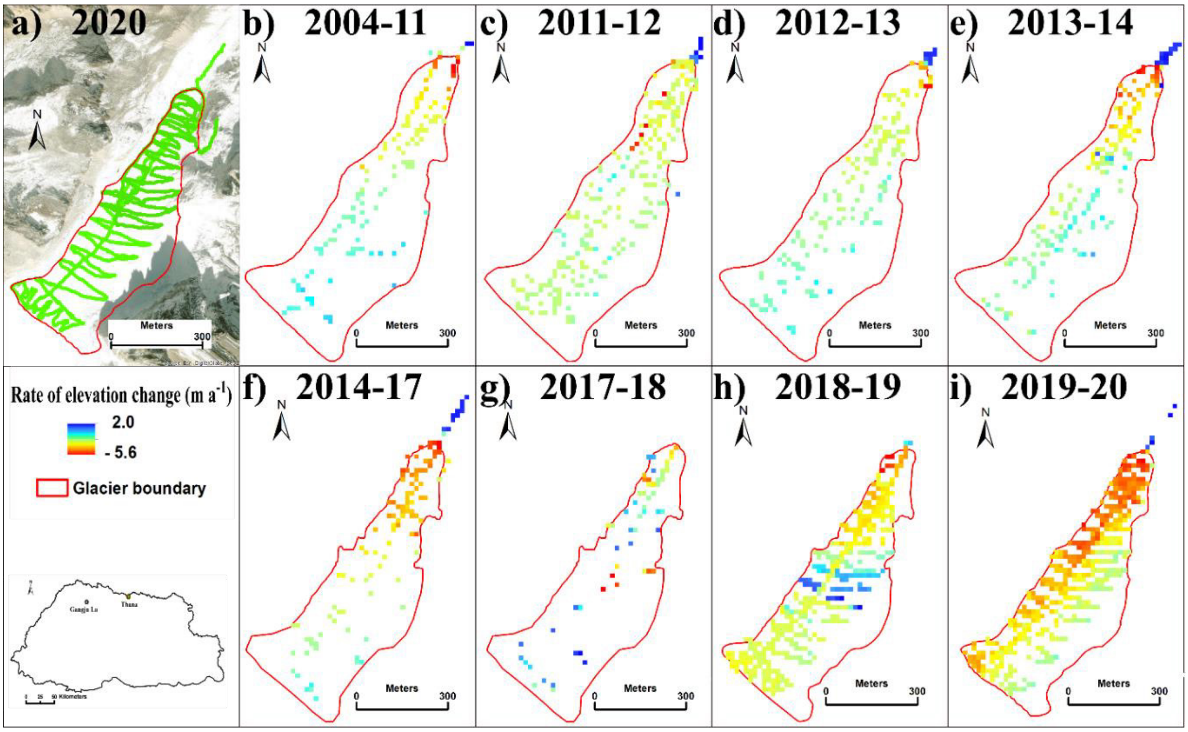

Figure 3: (a) Closely spaced green dots are the GPS tracks of 2020 survey on ESRI base map. Red polygons are the yearly mapped glacier boundary and (b) – (e) are the glacier elevation changes (per year) from 2004 – 2014, reproduced from Tshering and Fujita (2016) and (f) –

(i) are the elevation changes (per year) from 2014 – 2020. For better visibility, the elevation changes (points) in all the cases were averaged to 15 m resolution.

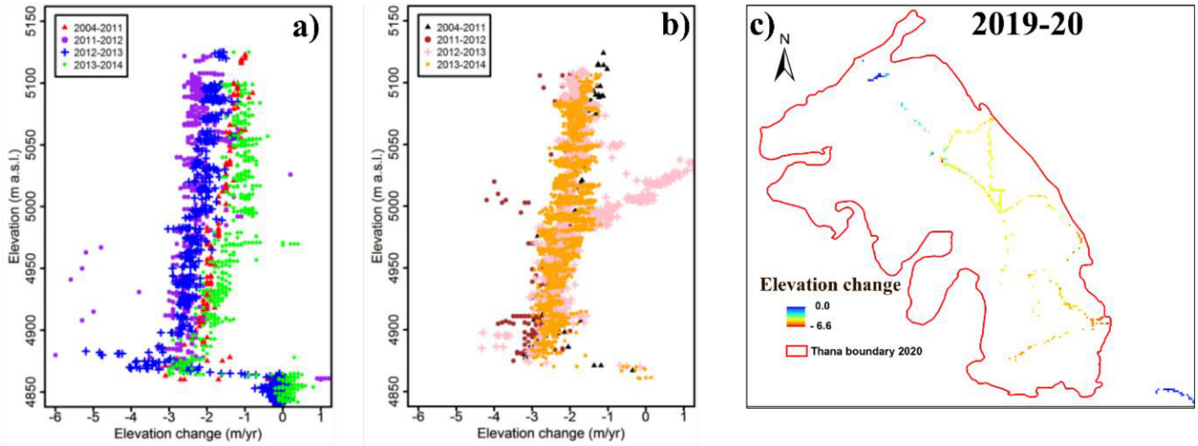

Figure 4: The rate of surface elevation changes of Gangju La glacier plotted against glacier surface elevation (a) and (b) and the surface elevation change (2019 – 2020) of Thana glacier plotted over the glacier surface (c). For better visibility, the points were averaged to 15 m resolution.

5. Hypsometry

ALOS-PRISM image with 2.5 m pixel resolution was used for extracting the surface area of Gangju La glacier till 2013 survey year (Tshering & Fujita, 2016). The glacier boundaries of the glacier terminus were delineated using dGPS survey edges (Fig. 7) as reference points and sides including top most part of the glaciers were delineated using the image. Since then, glacier surface area were extracted using the 1m DEM resolution produced from the dGPS survey of 2014. In each 50 m elevation band the pixels were counted to get the final area.

In case of Thana, the glacier surface area for survey year 2017 and 2018 was extracted using the SRTM DEM (Fig. 5a) having a pixel resolution of 30 m. For the survey year 2019 and 2020, HMA DEM having a pixel resolution of 10 m was used. Since 2017, the glacier boundaries for both the glaciers were delineated using the latest high-resolution Sentinel 2 imageries.

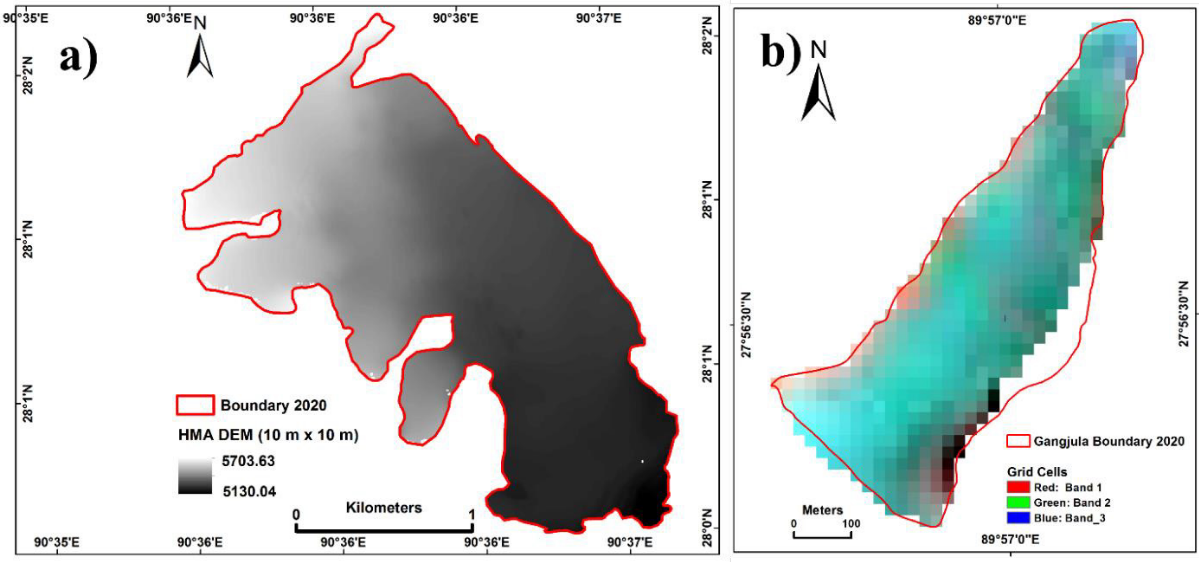

Figure 5: (a), Thana glacier surface area, SRTM DEM extracted using the glacier polygon and (b), Gangju La glacier surface area extracted from DEM produced using the GPS points and glacier boundary polygon.

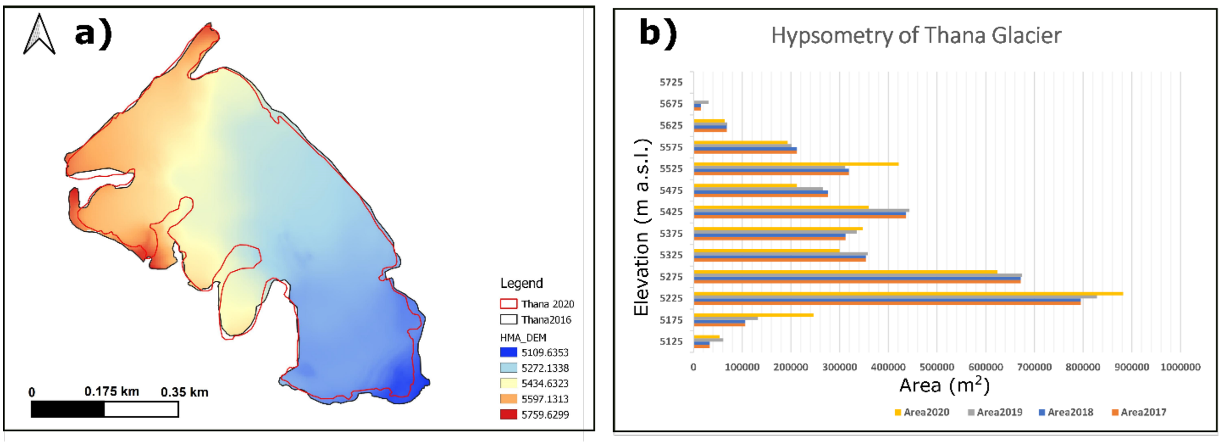

Figure 6: Thana glacier boundary of 2016 and 2020 (a) and (b) 50 m elevation band-wise hypsometry from 2017 to 2020.

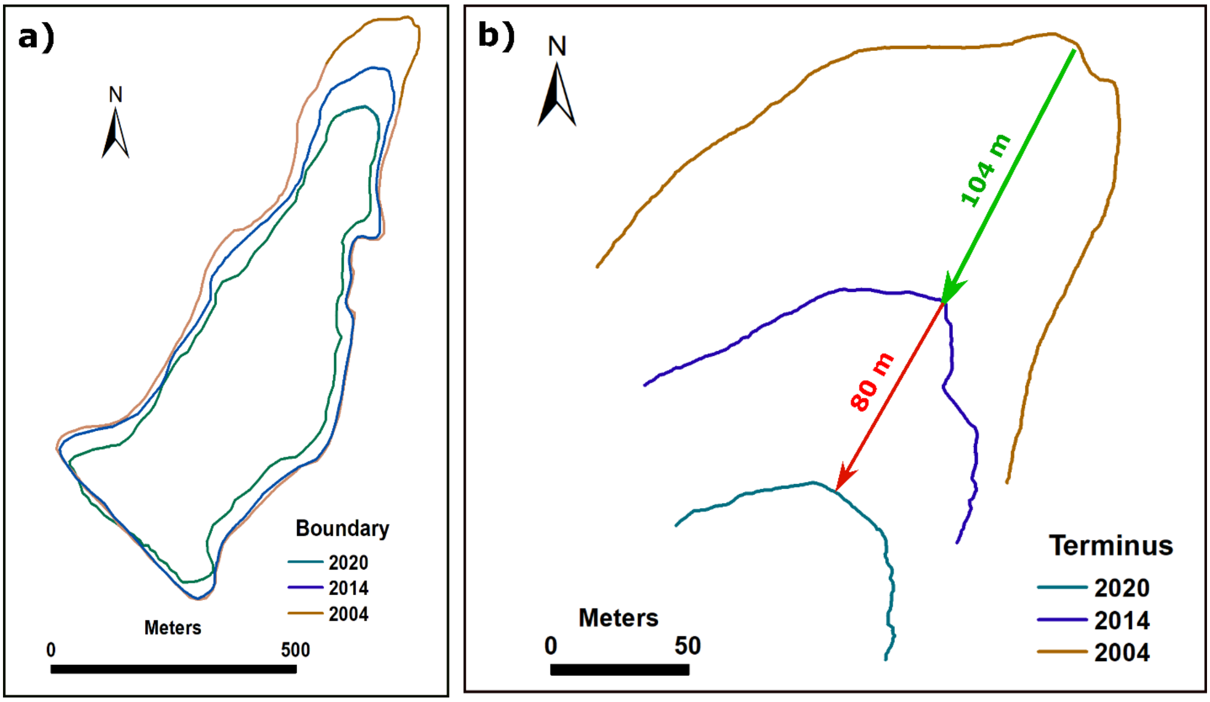

Figure 7: (a) Gangju La glacier boundary and (b) terminus map (2004, 2014 and 2020)

6. Uncertainty estimation

Throughout the survey periods, uncertainties were assumed to occur from three main factors; 1) uncertainties associated with mass balance estimation within each 50 m elevation band 2) uncertainties associated with glacier boundary polygons and pixel resolution of DEM and 3) uncertainties related to the assumption of densities of snow and ice.

6.1. Uncertainties related to mass balance calculation

Uncertainties related to mass balance calculation was evaluated using equation 4.

$$\sigma_b = \Sigma A_z db_z \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In every elevation band, the mass balance uncertainty was evaluated separately for direct and geodetic method. For direct method, the Root Mean Square Error (RMSE) of the linear regression line was multiplied with the glacier surface area of the particular 50 m elevation band whereas in case of geodetic method, the standard deviation of the surface elevation change within the particular elevation band was multiplied with the surface area within the particular 50 m elevation band.

6.2. Uncertainties related to glacier boundary delineation

Uncertainties related to glacier boundary delineation was evaluated using equation 6.

$$\sigma_l = \Sigma dA_z |b_z| \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

In order to extract the glacier surface area, different pixel resolution DEMs were used along with glacier boundary obtained through different methods. The boundary delineation uncertainty is obtained by multiplying the boundary length (m) with half the pixel of DEM used and absolute mass balance at the elevation band.

6.3. Uncertainties related to density assumptions

Uncertainties related to density assumptions for snow and ice was evaluated using equation 7.

$$\sigma_{\rho} = \Sigma A_z db_{\rho} \text{.......................... (7)}$$

The densities of snow and ice are not same throughout the glacier surface. Since the densities for ice and snow used were 880 and 400kg^{-3} respectively, we used density uncertainties of 30 kgm^{-3} (Tshering & Fujita, 2016) for ice and 100 kgm^{-3} for snow and then multiplied with the surface area.

Final uncertainty (σ) was then evaluated using equation 8.

$$\sigma = \frac{\sigma_b + \sigma_l + \sigma_{\rho}}{A_T} \text{................................ (8)}$$

7. Result

7.1. Gangju La

In all the survey years, we have followed Tshering & Fujita, 2016 for the estimation of mass balance for both direct method as well as *in-situ* geodetic method. Figures 3 (a) – (e) show the GPS survey track of Gangju La glacier and the reproduced 15 m averaged spatial distribution of surface elevation change from 2004 – 2014. Figures 3 (f) – (i) shows the 15 m averaged surface elevation change from 2014 – 2020 of Gangju La. Since survey year 2019, we used the Trimble R10-2 GNSS receiver having TSC7 monitor. Unlike Promark 3 receiver, it has the function to upload the GPS tracks of previous survey year and use as the reference track for the subsequent survey. Therefore, we acquired more intercepting points for 2018 and 2019 (fig. 3(h), (i)) leading to more concentrated and spatially distributed surface elevation changes. Overall, almost over the past two decades, Gangju La glacier has suffered mass loss over the entire glacier surface leading to negative mass balance ranging from -1110±160 mm w.e. a^{-1} to -2390 mm w.e. a^{-1} (Fig. 8a; Table 1). Gangju La glacier lies below the equilibrium line altitude (ELA) which is also the reason why the glaciers is losing mass drastically every year.

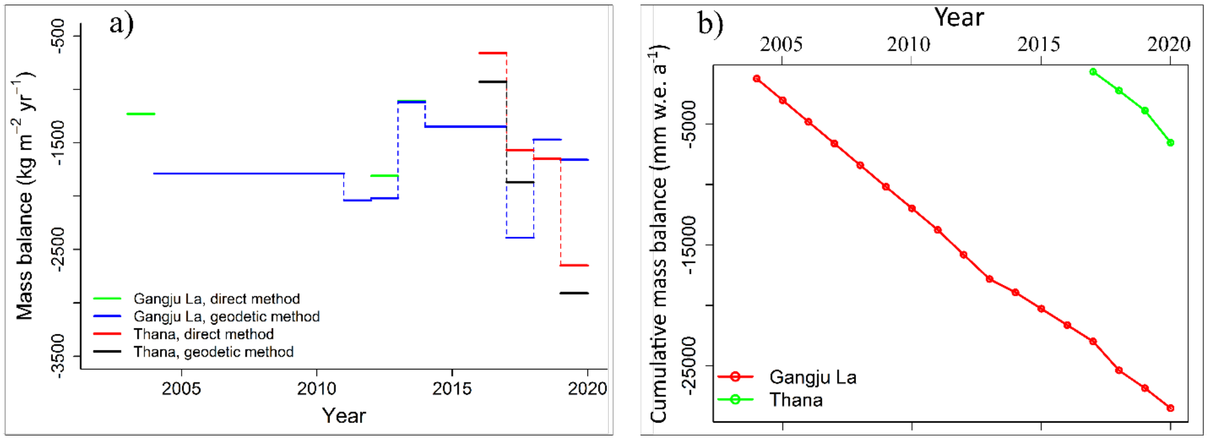

Figure 8: Mass balance of Gangju La and Thana glacier (a) and the cumulative glacier mass balance of Gangju La glacier (b) from 2004 – 2020, through in-situ geodetic method.

Such overall thinning of the glacier surface and losing more mass over the years can be seen from the increased terminus retreat rate (10.4 m a^{-1} from 2004 – 2014, 13.3 m a^{-1} from 2014 – 2020) as shown in figure 7b. Since 2004 till 2020 (Fig. 7a), the total surface area has decreased by 89,054 m^2 which accounts to 30% decrease. The cumulative mass balance of Gangju La glacier from 2004 till 2020 is about -28500 mm w.e. (Fig. 8b) translating to an overall loss of approximately 1.7 million tons of glacier ice. If we assume such mass loses over the entire Bhutanese glaciers covering approximately 630 km^2 and holistically apply for rest of the glaciers, Bhutan has lost about 17 gigatons of ice from 2004 – 2020. The cumulative results presented are based on *in-situ* geodetic survey as we have only few years data for direct method.

Year	**Gangju La (mm w.e. a^{-1})**		**Thana (mm w.e. a^{-1})**	
	Direct	**Geodetic**	**Direct**	**Geodetic**
2003 – 04	-1230±230	–	–	–
2004 – 11	–	-1790±260	–	–
2011 – 12	–	-2040±460	–	–
2012 – 13	-1810±160	-2020±290	–	–
2013 – 14	-1110±160	-1120±310	–	–
2014 – 17	–	-1350	–	–
2016 – 17	–	–	-660	-930
2017 – 18	–	-2390	-1570	-1870
2018 – 19	–	1470	-1650	–
2019 – 20	–	1660	-2645	-2910

Table 1: Annual glacier mass balance values of Thana and Gangju La glacier.

7.2. Thana

Survey on Thana was initiated way back in 2012 and continuous surveys were conducted till date. Prior to 2015 survey year, no measurement stakes were installed in the accumulation area due to inaccessibility. The results presented in this report are only from 2015 to 2020. Unlike Gangju La glacier, Thana glacier shows bit of accumulation towards the upper reach. However, similar to that of Gangju La, Thana glacier also exhibits net negative mass balance. The revealed net balance from Thana ranges from -660 to -2645 mm w.e. a^{-1} through direct method and -930 to -2910 mm w.e. a^{-1} through geodetic method (Fig. 8a; Table 1). Such annual mass loss is supported by the surface area loss of approximately 2,76,790 m^2 which accounts to 7% decrease in area from 2016 to 2020. Thana glacier exhibited cumulative net balance of -6530 mm.w.e. (Fig. 8b) from 2016 to 2020 revealing a total loss of approximately 24 million tons of ice. Unlike Gangju La glacier, the ELA lies within the glacier surface but near to topmost part (5523 m a.s.l.). The cumulative glacier mass loss presented are based on direct method as we have continuous data since 2016.

8. Discussion

Our studies based on both direct and *in-situ* geodetic method so far reveal that both Gangju La and Thana glaciers are losing mass continuously (Fig 8a; Table 1). The glaciers in the eastern Nepal and southern Tibetan Plateau which lies in the monsoon-influenced humid climate were reported to have exhibited significant mass loss (Fujita & Nuimura, 2011; Yang et al., 2013) in the recent times. In a similar manner Tshering & Fujita, 2016 reported that Gangju La glacier from 2004 – 2014 has lost more mass than others in the region. Our results reveal that still Gangju La and Thana glaciers are losing more mass than others in the region. In terms of glacier area loss for both glaciers (Gangju La, Thana), it well agrees with a result from Bajracharya et al., 2014. Based on repeated decadal glacier inventories they have found out that Bhutan glaciers have lost about 13.3±0.1% of area between 1990 and 2010. In the recent study by NCHM (BGI, 2018), similar glacier area shrinkage was reported. In particular, Thana glacier exhibited higher negative mass balance in the recent survey periods and Gangju La glacier exhibited more or less the similar trends. Such negative net mass loss are supported by the location of ELA which lies above the glacier for Gangju La and near to topmost part for Thana.

9. Conclusion

The findings presented in this report are the mass balance results of two glaciers within the Bhutan Himalaya. Both the glaciers are found to shrink and lose mass annually since initial observation which started since 2004 and 2012 respectively. Such findings are in consistency with glaciers of other parts of the Himalaya with exceptions in the Karakoram region (Brun et al., 2018). Overall, based on the studies and observations following conclusion can be drawn:

1. Gangju La glacier has lost mass with annual net balance of -1110 to -2390 mm w.e. with area shrinkage of about 30% leading to 1.7 million tons of ice loss from 2004 to 2020.
2. The cumulative net mass balance of Gangju La glacier from 2004 to 2020 is -28500 mm w.e.
3. The annual frontal (terminus) retreat rate has increased from 10.4 m a^{-1} from 2004 – 2014, 13.3 m a^{-1} from 2014 – 2020.
4. The ELA on Gangju La glacier lies much above the glacier area leading to net annual mass loss.
5. The annual net balance of Thana ranges from -660 to -2910 mm w.e. with area shrinkage of about 7% leading to 24 million tons of ice loss from 2016 to 2020.
6. The cumulative net mass balance of Thana glacier is about -6530 mm w.e.
7. The ELA lies within the glacier surface but towards the upper reach leading to annual negative balance.
8. Holistically applying the cumulative net balance of Gangju La glacier from 2004 – 2020 to other glaciers covering an area of 630 km^2, Bhutan has lost 17 gigatons of glacier ice.

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United Nations Secretary-General

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