First in situ record of decadal glacier mass balance (2003–2014) from the Bhutan Himalaya

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ABSTRACT. This study presents the first decadal mass-balance record of a small debris-free glacier in the Bhutan Himalaya, where few in situ measurements have been reported to date. Since 2003 we have measured the mass balance of Gangju La glacier, which covers an area of 0.3 km^2 and extends from 4900 to 5200 m a.s.l., using both differential GPS surveys (geodetic method) and stake measurements (direct method). The observed mass balance ranged from –1.12 to –2.04 m w.e. a^{-1} between 2003 and 2014. The glacier exhibited much greater mass loss than neighbouring glaciers in the eastern Himalaya and southeastern Tibet, which are expected to be sensitive to climate change due to the monsoon-influenced humid climate. Observed mass-balance profiles suggest that the equilibrium-line altitude has been higher than Gangju La glacier since 2003, implying that the entire glacier has experienced net ablation for at least the past decade.

KEYWORDS: glacier fluctuations, glacier mass balance, mountain glaciers

INTRODUCTION

Himalayan glaciers, like most other mountain glaciers worldwide, have been retreating in recent decades. The consequences for both the local and global climate systems are poorly understood, including changes in river runoff patterns, their contribution to global sea-level rise, and glacial lake outburst floods (e.g. Richardson and Reynolds, 2000; Kaser and others, 2010; Radić and Hock, 2011; Bolch and others, 2012). Glacier mass balance is one of the best indicators of climate change and is also a direct indicator of the state of a given glacier (Oerlemans, 2001). Recent studies have highlighted discrepancies among methodologies for calculating glacier mass balance in High Mountain Asia (Bolch and others, 2012; Kääb and others, 2012) and have reported spatially heterogeneous changes in glaciers (Fujita and Nuimura, 2011; Yao and others, 2012; Gardelle and others, 2013). In situ measurements of individual glaciers have shown greater mass loss than has been estimated from regional satellite data across the Himalaya and Tibetan Plateau (e.g. Fujita and Nuimura, 2011; Nuimura and others, 2012; Yao and others, 2012; Gardelle and others, 2013; Yang and others, 2013). Spatial distributions of changes in the terminus position, area, volume and equilibrium-line altitude (ELA) (Karma and others, 2003; Fujita and Nuimura, 2011; Gardelle and others, 2013) of glaciers suggest that Bhutanese glaciers have undergone more rapid retreat and shrinkage than other Asian glaciers, probably because of their sensitivity to changes in air temperature and precipitation of the monsoon-influenced humid climate (Ohmura and others, 1992; Fujita and Ageta, 2000; Fujita, 2008; Rupper and others, 2012). Rupper and others (2012) specifically considered Bhutanese glaciers and highlighted this strong sensitivity in determining glacier mass balance from their modelling approach, although no validation of their results was provided.

The first-ever information on Bhutanese glaciers was reported by Mool and others (2001) who compiled the first inventory of Bhutanese glaciers, revealing total number of glaciers and glacier area. Terminus retreat and glacier shrinkage were first estimated for ~15% of Bhutanese glaciers from 1963 to 1993 by comparison of topographical maps and Landsat images (Karma and others, 2003) and have recently been updated for the entire Bhutan Himalaya using multitemporal satellite imagery (Bajracharya and others, 2014). Volumetric changes in these glaciers have been estimated from satellite-derived digital elevation models (DEMs) (Kääb and others, 2012; Gardelle and others, 2013). Most field observations have primarily targeted glacial lakes because of the inherent risk of outburst floods (Yamada, 1998; Ageta and others, 2000; Fujita and others, 2008; Ohashi and others, 2012), with only a few in situ measurements of the associated glaciers (Naito and others, 2006, 2012). This study aims to fill the gap between simulations and remotely sensed analyses by providing the first field observations of decadal glacier mass balance in the Bhutan Himalaya.

LOCATION AND METHODS

Location, differential GPS surveys and stake measurements

Gangju La glacier is located at the headwater of Pho Chhu ('Chhu' means 'river' in the local language) (27.94° N, 89.95° E) in the Bhutan Himalaya and was selected for this study because of its easy accessibility. This small debris-free glacier covered an area of 0.29 km^2 in 2004, extending from 4900 to 5200 m a.s.l. (Fig. 1). It is referred to as 'Pho_gr16' in a former glacier inventory (Mool and others, 2001).

The first stake measurements of glacier mass balance were conducted between 2003 and 2004, when a theodolite with laser distance finder (Total Station SET2000, Sokkia Co., Ltd) was used to measure stake positions across the glacier. The glacier surface elevation was also measured in 2004 using a carrier-phase differential GPS (DGPS) (CMC All star, Amtecs, Inc.); the DGPS survey was repeated in 2011, 2012, 2013 and 2014 (Promark 3, Magellan and GEM-1, GNSS

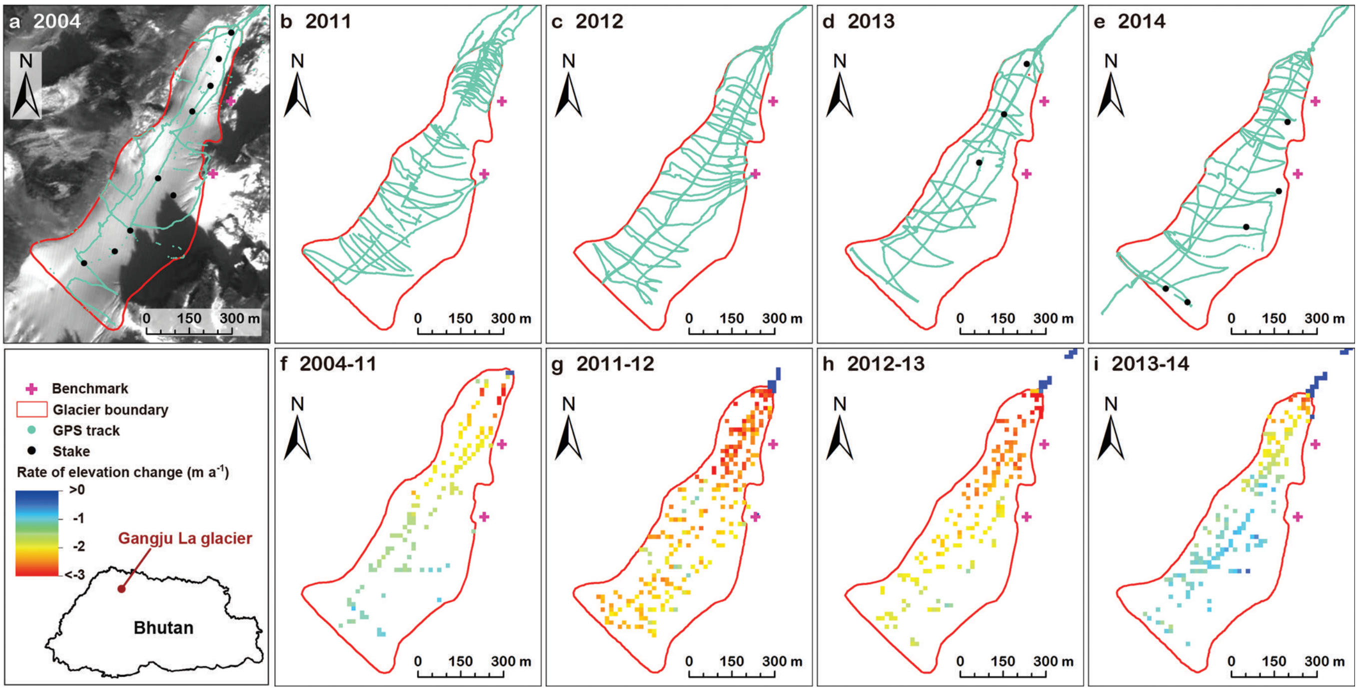

Fig. 1. Location of Gangju La glacier, Bhutan (dark red circle in legend), along with glacier boundary (red lines), GPS tracks (light blue points in a–e), stake locations (black circles in a, d and e) and rate of elevation change (coloured squares in f–i) for 2004–14. Benchmarks are denoted by pink crosses. For better visibility, the elevation changes obtained from 1 m DEMs are averaged to 15 m resolution (shown in f–i).

Technologies, Inc.). Mass-balance stakes were reinstalled on the glacier in 2012 and have been maintained since then. For the DGPS surveys, one receiver was set up as a base station near our camp site during the individual visit, and one or more receivers were used as mobile stations in kinematic mode. Two benchmarks were installed on bedrock on the right bank of the glacier and were originally used for the theodolite surveys in 2003 and 2004. Their precise locations were obtained by the Precise Point Positioning service (www2.unb.ca/gge/Resources/PPP/index.htm; last access on 25 July 2015) (see crosses in Fig. 1). Stake positions have been measured using the static mode of the DGPS since 2012. All surveys were carried out at the end of the melt season, between the end of September and early October.

Geodetic mass balance

The DGPS data were post-processed using GNSS Solutions software (Ashtec, Inc.). Exported points with analytical horizontal and vertical errors >1 m were excluded from the analysis. All data were then merged onto the same coordinate system (UTM zone 45N, World Geodetic System 1984 ellipsoidal elevation) using the benchmarks. The inverse distance weighting (IDW) interpolation tool in ArcGIS software was used to generate 1 m DEMs for each time period with a search radius of 0.7 m as this method was used successfully in earlier studies (e.g. Fujita and others, 2011; Nuimura and others, 2012). Gridcells with no DGPS point nearer than 0.7 m were excluded. Alternative methods such as IDW without fixing the search distance, arithmetic averaging and kriging with various settings, which we tested with the same survey data of 2011, do not exhibit significant difference from the IDW method (root-mean-square errors (RMSEs) 0.1–0.3 m) because of the short searching distance (0.7 m). On the other hand, the spline method with various settings showed significant discrepancy against the IDW method (RMSEs >6.7 m) probably because the spline method fills and smooths unmeasured surface by assuming smooth topography, which is unlike the Himalaya, while the interpolated points are not affected by the unmeasured points in the other methods. Changes in glacier surface elevation between two measurement dates were finally obtained at points where observations were available at both dates.

The annual mass balance at a point was calculated as

$$b_g = \frac{\Delta h_g \rho_i + (s_{t2} - s_{t1})(\rho_s - \rho_i)}{(t2 - t1)} \quad (1)$$

where b_g is the annual mass balance at a given point by the geodetic method (kg m^{-2} a^{-1} equivalent to mm w.e. a^{-1}); Δh_g is the elevation change (m), which is negative when the surface has lowered; ρ_i is the ice density (assumed to be 880 ± 30 kg m^{-3}); ρ_s is the snow density (assumed to be 400 ± 100 kg m^{-3}); and S_{t1} and S_{t2} represent the snow thickness (m) for years $t1$ and $t2$, respectively. The snow thickness at a given altitude was estimated from a linear regression line that was obtained from snow thicknesses measured at the mass-balance stakes.

The area-averaged annual mass balance ($\overline{b_g}$; mm w.e. a^{-1}) is

$$\overline{b_g} = \frac{\Sigma_z A_z b_{gz}}{A_T} \quad (2)$$

where A_z and A_T are the area within a 50 m altitude band and the total area (m^2), respectively, and b_{gz} is the average mass balance within the 50 m altitude band (mm w.e. a^{-1}). Following Fischer (2011), we use $A_z = (A_{t1} + A_{t2})/2$, where A_{t1} and A_{t2} represent the areas of the measurements taken in years $t1$ and $t2$ at a given altitude band (m^2), respectively.

Direct mass balance

The direct annual mass balance was calculated by formulating the changes in stake height and snow thickness

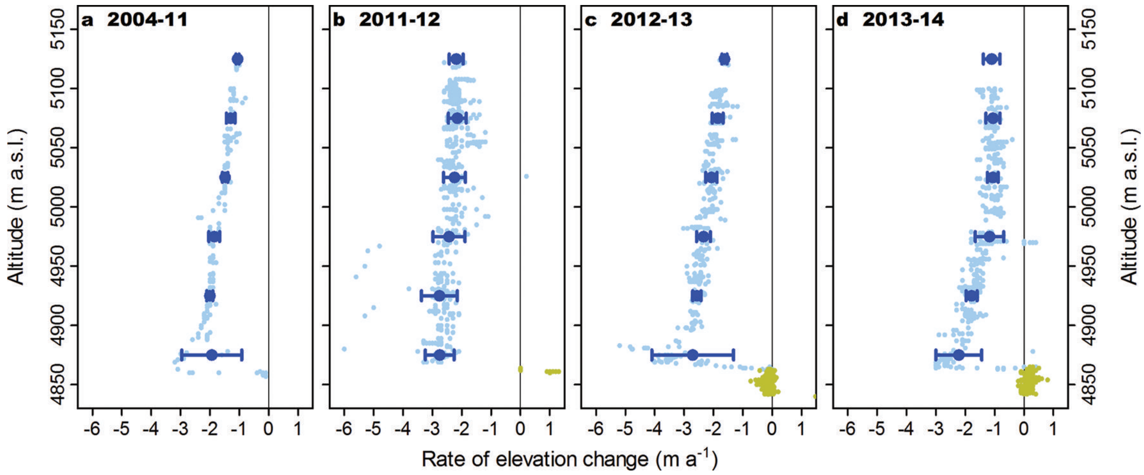

Fig. 2. Altitudinal profiles of rate of elevation change derived from DGPS surveys for Gangju La glacier over the four observed time periods. Light blue and brown dots represent the individual in situ measurements on- and off-glacier, respectively, and blue circles with error bars

with snow and ice densities:

$$b_d = \frac{\Delta h_d \rho_i + (s_{t2} - s_{t1})(\rho_s - \rho_i)}{(t2 - t1)} \quad (3)$$

where Δh_d is the difference in stake height between years $t1$ and $t2$ (m). Because the number of stakes is insufficient to calculate the average mass balance within a 50 m altitude band, we calculated a linear regression line, and thus obtained the mass balance at each 50 m altitude band (b_{dz}; mm w.e. a^{-1}). The area-averaged annual mass balance ($\overline{b_d}$; mm w.e. a^{-1}) was calculated from Eqn (2) by replacing b_{gz} with b_{dz}.

Hypsometry

An ALOS-PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping aboard the Japanese Advanced Land Observing Satellite) image with 2.5 m pixel resolution, taken in December 2010 (Fig. 1a,), was used to extract the glacier area. The boundaries at the head and both sides of the glacier were delineated from the image, with the terminus boundary determined from the DGPS measurements in each survey. Hypsometry maps were created from each DGPS survey by first generating 30 m DEMs with the IDW method, resampling them into 1 m DEMs and then extracting the area of each 50 m altitude band by counting the number of 1 m cells present.

Uncertainty estimation

The uncertainties in the area-averaged geodetic and direct annual mass balances (σ; mm w.e. a^{-1}) were evaluated by assuming that they consisted of three uncertainties: (1) uncertainty from the mass balance at each altitude band (db_z; mm w.e. a^{-1}); (2) uncertainty from the boundary delineation (dA_z; m^2); and (3) uncertainty from the density assumption (db_ρ; mm w.e. a^{-1}), as follows:

$$\sigma = \frac{\sum A_z db_z + \sum dA_z |b_z| + \sum A_z db_\rho}{A_T} \quad (4)$$

The mass-balance uncertainty is the standard deviation of the mass balance in the 50 m altitude band for the geodetic method and the RMSE of the linear regression line for the direct method. The delineation error is assumed to be half a pixel in the ALOS-PRISM image (1.25 m) multiplied by the boundary length of each altitude band. The absolute value of mass balance at the altitude band ($|b_z|$; mm w.e. a^{-1}) is multiplied by this boundary delineation uncertainty. For the density-related uncertainty, we assumed the following density uncertainties: 30 kg m^{-3} for ice and 100 kg m^{-3} for snow. We calculated two mass balances by assuming the maximum and minimum densities, which yielded the maximum difference. Uncertainties from both the mass-balance and density assumptions are multiplied by the area of the 50 m altitude band. All uncertainties are then summed and divided by the total area.

RESULTS

Figure 1a–e show the survey tracks and stake positions across Gangju La glacier since 2004 and the spatial distribution of surface elevation changes (Fig. 1f–i). Although some of the 2004 tracks are fragmented (because of poor instrument performance during bad weather), the dense measurements in 2011 provide a sufficient distribution of surface elevation changes (Fig. 1f). Figure 1 shows that the glacier has experienced overall thinning for at least the past decade (since 2004). Altitude profiles (Fig. 2) of rates of elevation change show maximum surface lowering (maximum glacier thinning) at lower altitudes and less at higher altitude. No elevation change was measured in the lowermost part of the surveyed domain where off-glacier bedrock is encountered. The altitude profiles are similar to those observed on other Asian glaciers by the same method (Fujita and Nuimura, 2011; Fujita and others, 2011). Uncertainties in the elevation changes obtained by kinematic surveys are estimated to be 0.10 ± 0.40 m a^{-1} by calculating the standard deviation of the elevation change rates over the off-glacier surface, though some surface movement might have occurred during 2011–12. The observable mass loss from this glacier thinning is supported by the continuous retreat of the glacier terminus from 2003 to 2014 (Figs 3 and 4; Table 1). Little snow was observed in 2003, 2011 and 2012 (bare ice surface was exposed); our altitude profiles of snow thickness were thus limited to 2004, 2013 and 2014 (Fig. 5a). Linear regression lines for each of the three years were used to calculate the mass balance at each altitude band using Eqn (1).

Although more than ten stakes were installed during each visit to Gangju La glacier (2003 and since 2012), many stakes

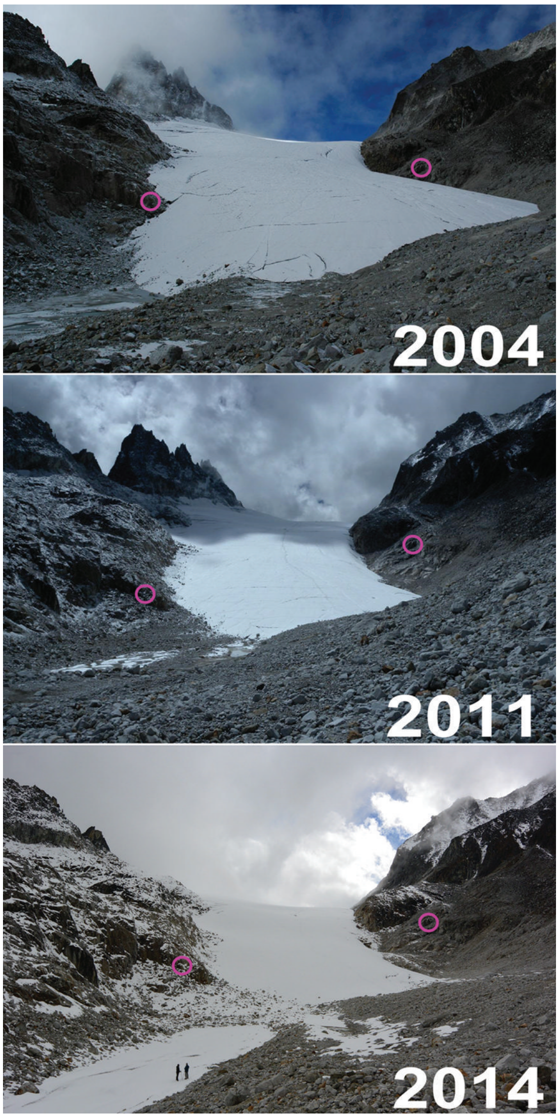

Fig. 3. Photographs of Gangju La glacier, taken in 2004, 2011 and 2014. Pink circles highlight bedrock reference points.

could not be located on the subsequent visit. Although boreholes were drilled and stakes were installed up to 4 m deep into the glacier near the terminus, the stakes along the central flowline were completely lost, with the exception of the 2004 visit (Fig. 1a–e). This glacier was chosen because of its accessibility; however, this also means that local people probably frequented the glacier and may have disturbed the

Table 1. Mass balance and rates of terminus retreat and area change of Gangju La glacier since 2003

Period	Mass balance mm w.e. a^{-1}	Terminus retreat m a^{-1}	Area change 10^{-2} km^2 a^{-1}
2003–04	–1230 ± 230*	–	–
2004–11	–1790 ± 260	10	–0.32
2011–12	–2040 ± 460	13	–0.41
2012–13	–2020 ± 290	17	–1.09
2012–13	–1810 ± 160*	–	–
2013–14	–1120 ± 310	8	–0.27
2013–14	–1110 ± 160*	–	–

*Direct method.

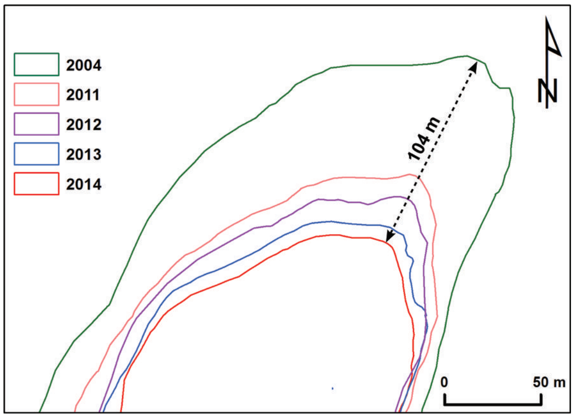

Fig. 4. Location of the terminal boundary of Gangju La glacier from 2004 to 2014. The maximum retreat is measured along the dotted arrow.

stakes. Despite the limited number of stakes, three mass-balance profiles by the direct method were reconstructed for 2003–04, 2012–13 and 2013–14 (Fig. 5b).

Hypsometry shows a less significant area change in the lowermost altitude band of the glacier, whereas the uppermost and second lowest altitude bands show significant area reductions (Fig. 5c). Despite both surface lowering and terminus retreat, the flat bedrock topography probably allowed the glacier to maintain the shape of its terminus.

Our spatial observations of elevation changes across Gangju La glacier were integrated to calculate the average mass balance of the glacier since 2003 (Table 1; Fig. 6). This is the first in situ record of glacier mass balance in the Bhutan Himalaya. Considering that the regression lines of the mass-balance profiles do not cross zero balance until they are well above the highest part of the glacier (5230 and 5240 m a.s.l., Fig. 5b) and that the area-averaged mass balances from the direct method provide smaller mass loss estimates than those from the geodetic method, the ELA of this glacier has been situated above the glacier extent for at least the past decade.

DISCUSSION

Our results reveal that Gangju La glacier has experienced continued mass loss at an alarming rate since 2003 in comparison with nearby glaciers (Table 2; Fig. 6). Glaciers in the eastern Nepal Himalaya (Yala and AX010) and in the south-eastern Tibetan Plateau (Parlung No. 94) are also sensitive to the monsoon-influenced humid climate and have exhibited significant mass loss in recent years (Fujita and Nuimura, 2011; Yang and others, 2013). In comparison with the mass-balance estimates derived from similar methods, Gangju La glacier is undergoing the greatest mass loss (Table 2). The spatial distribution of precipitation, which increases from west to east and north to south along the Himalayan arc (Bookhagen and Burbank, 2010), causes the glaciers in Bhutan to be situated at lower altitudes (Nuimura and others, 2015; Sakai and others, 2015). Ohmura and others (1992) have shown that glaciers in humid climates are more sensitive to changes in air temperature. In addition, Fujita and Ageta (2000) and Fujita (2008) reported that summer-accumulation type glaciers may be even more sensitive than winter-accumulation type glaciers that experience similar amounts of annual precipitation, because changes in air

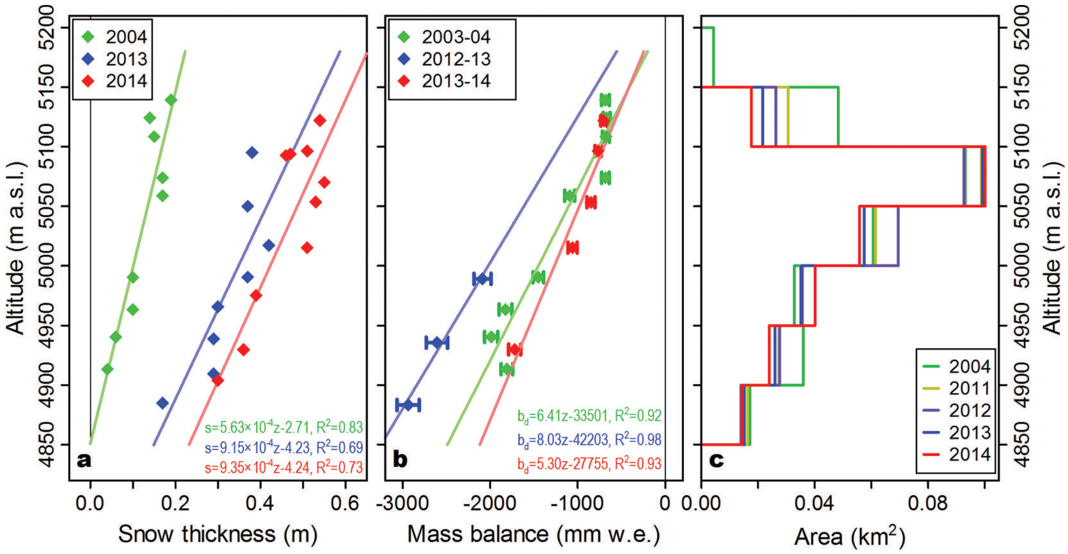

Fig. 5. Altitudinal profiles of (a) snow thickness, (b) mass balance by stake measurement and (c) hypsometry of Gangju La glacier. Little snow was observed in 2003, 2011 and 2012, so no point is plotted in (a).

temperature may alter both the surface melt rate and the surface albedo by affecting the precipitation phase (rainfall or snowfall). Yang and others (2013) showed that Parlung No. 94 glacier is a spring-accumulation type glacier; this difference in precipitation seasonality could be one of the reasons why Gangju La glacier has recently undergone greater mass loss. The small glacier size (altitudinal extent ~300 m) should also affect the highly negative mass balance. Fujita and Nuimura (2011) demonstrated that, if ELA approaches or exceeds the top of the glacier, mass balance should be highly negative. In fact, our observational results strongly suggest that the ELA was above the glacier and thus no accumulation zone has existed for the past decade. The humid climate, summer accumulation and small size probably all contributed to the greater mass loss of Gangju La glacier.

Remote-sensing approaches have estimated significantly smaller mass loss than that estimated through in situ measurements for the region (Table 2). Several possible reasons have been proposed for these discrepancies, including the smaller scale and lower altitudes of the glaciers selected for fieldwork (Cogley, 2012). However, no systematic investigation has explored the cause of these discrepancies (Cogley, 2012). Although the simulation by Rupper and others (2012) employed a mass-balance model that yielded a mass-balance estimate similar to our study results (Table 2), it should be noted that their simulations have not been validated with in situ observations. Given the small glacier size, the mass-balance estimate from our study may not represent the mass-balance value for the entire Bhutanese Himalayan region; however, our study does provide timely information regarding the behaviour of such small glaciers in the current global climate.

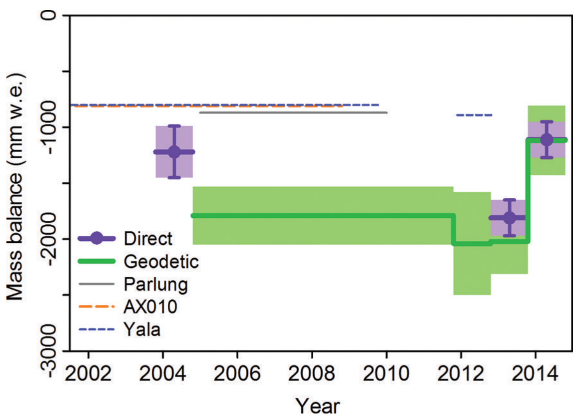

Fig. 6. Mass balance of Gangju La glacier and surrounding glaciers in Nepal and southeastern Tibet (Fujita and Nuimura, 2011; Yang and others, 2013; Baral and others, 2014). Shading and error bars denote the estimated errors from the direct and geodetic methods in this study. All values are shown in Tables 1 and 2.

CONCLUSIONS

We conducted mass-balance measurements from 2003 to 2014 on Gangju La glacier, a small debris-free glacier in the Bhutan Himalaya, using geodetic and direct methods. This paper presents the first in situ mass-balance record from the Bhutan Himalaya, a region expected to be highly sensitive

Table 2. Mass-balance estimates of individual glaciers and regions in the eastern Himalaya

Glacier or region	Period	Mass balance mm w.e. a^{-1}	Method*
Gangju La, Bhutan	2003–14	–1550 ± 290	GM, DM[1]
Parlung, southeast Tibet	2005–10	–870 ± 500	DM[2]
AX010, Nepal	1999–2008	–810 ± 85	GM[3]
Yala, Nepal	1996–2009	–800 ± 80	GM[3]
Yala, Nepal	2011–12	–890	DM[4]
Khumbu, Nepal	1970–2007	–320 ± 80	RS[5]
Khumbu, Nepal	1992–2008	–400 ± 250	RS[6]
Khumbu, Nepal	1999–2010	–510 ± 190	RS[7]
Bhutan	1999–2010	–220 ± 120	RS[7]
Bhutan	1980–2000	–1400 ± 600	MD[8]

*GM: in situ geodetic method; DM: direct method; RS: remotely sensed geodetic method; MD: mass-balance model.
[1]Present study; [2]Yang and others (2013); [3]Fujita and Nuimura (2011); [4]Baral and others (2014); [5]Bolch and others (2011); [6]Nuimura and others (2012); [7]Gardelle and others (2013); [8]Rupper and others (2012).

to climate change due to the influence of the monsoon-influenced humid climate. The glacier showed greater mass loss since 2003 than other glaciers observed in neighbouring monsoon-affected regions. Although large discrepancies exist between the observational methods (in situ and remote sensing), these results will contribute to future regional studies as a means of validating simulations and remote-sensing observations.

AUTHOR CONTRIBUTION STATEMENT

K.F. designed the study; P.T. and K.F. conducted the fieldwork, analysed the data and wrote the paper.

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