Reply to Referee #3

We would like to thank the referee for thoughtful and useful comments. In the following, we describe our responses (in blue) point-by-point to each referee comment (*italic*).

The manuscript by Tsutaki et al. presents a comparison of three glaciers in the Bhutan Himalaya. Two of the three glaciers are studied to determine differences in glacier dynamics, retreat and mass wastage between land-terminating and lake-terminating glaciers, and whether the presence of a proglacial lake increases dynamics and ice wastage. To do this the authors: (a) present in situ measurements of surface elevation made using DGPS in 2004 and 2011 and compare them with remotely sensed elevation changes reported in literature; (b) derive glacier surface flow velocities using feature tracking on ASTER satellite imagery; (c) manually delineate retreat of the tongues using Landsat 7 imagery; (d) model surface mass balance of the debris covered glaciers, and (e) present a two-dimensional ice dynamics model and two model experiments. The results show that the lake-terminating glacier (Lugge) has considerable higher thinning rates than the land-terminating glacier (Thorthormi), but that this is mainly caused by differences in ice dynamics and not by differences in surface mass balance. A strong emergence is present for Thorthormi due to its longitudinally compressive flow regime that offsets its much more negative surface mass balance, and this is largely absent for Lugge. The manuscript in generally well-written besides some style issues, and the subject is of interest to the readers of the Cryosphere. There are, however, some technical issues and uncertainties with the modelling. At least moderate revisions are required before the manuscript can be published.

Major comments:

The authors present three glaciers in the manuscript: Thorthormi, Lugge and Lugge II. Lugge II was measured using the DGPS, was included in the spaceborne flow velocity measurements and was included in the SMB calculations, and its *results are presented in figures 1–3. However, it is not included in the ice dynamics model experiments, is barely discussed in the results and discussion, is not included in the abstract and therefore seems of little significance to the overall story. The authors argue in the introduction that Lugge II is at a different elevation and is therefore difficult to compare to the other two glaciers, but there are many more factors that control the dynamics and mass balance of the glaciers that can complicate the comparison, also between Thorthormi and Lugge, which should be acknowledged. In this light it is also odd that the authors state that the surface mass balance of Thorthormi is 37% more negative than Lugge because it is situated at lower elevation (L360). I would suggest that the authors decide to either remove Lugge II Glacier completely from the manuscript to focus more on a clear comparison of Thorthormi and Lugge, or to consistently include all glaciers in all analyses.*

We excluded Lugge II Glacier from the detailed discussion because lack of the bed topography hampered the flow modelling. Spatial variability in surface elevation change derived from ASTER-DEMs is greater than those of Thorthormi and Lugge Glaciers (Fig. R1). Therefore, it is unsure whether the elevation change derived from DGPS-DEMs is representative. For these reasons we excluded Lugge II Glacier from the surface velocity measurements, SMB modelling and the detailed discussion. We will remove descriptions and figures related to Lugge II Glacier from the revised manuscript but we will leave the rate of elevation change of the glacier as an observational fact.

Comparison of Thorthormi and Lugge Glaciers are not easy. We hypothesize that the emergence velocity will decrease at Thorthormi Glacier after the expansion of the supraglacial lake, resulting in an increase in ice thinning rate as observed in Lugge Glacier. To test this hypothesis, we will discuss the influence of lake expansion on the emergence velocity based on lake- (Experiment 1) and land-terminating (Experiment 2) simulations for Lugge Glacier in the revised manuscript.

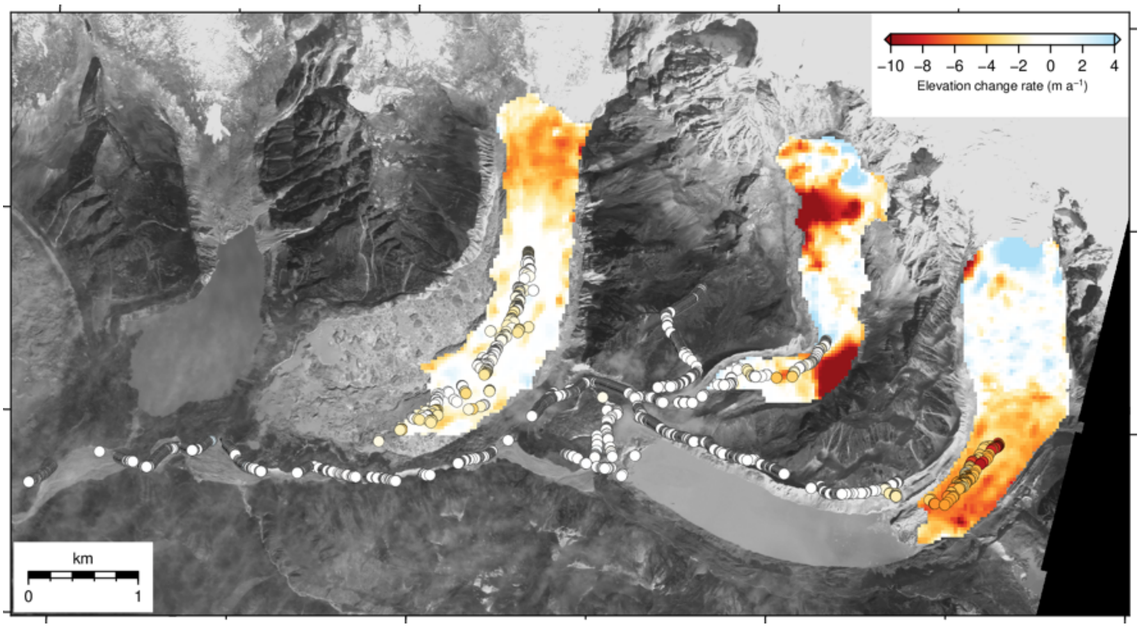

Figure R1: Rate of elevation change for the 2004–2011 period derived from ASTER-DEMs (background shadings) and DGPS-DEMs (circles filled with the same color scale). Glacier outlines are of December 2011.

I think more discussion on and comparison with other lake/land terminating glaciers reported in literature is required in the manuscript. This is touched on lightly in the manuscript but needs be more elaborate, especially because at present only two glaciers are used in draw conclusions and hypothesise on the dynamics of lake/land terminating glaciers. Can the differences in dynamics that are found for these glaciers transfer to others? Why, why not?

More rapid thinning of lake-terminating glacier than neighboring land-terminating glacier has been revealed by satellite remote sensing observations in Bhutan (Maurer et al., 2016), Nepal (Nuimura et al., 2012; King et al., 2017), Pamir-Karakoram-Himalaya (Gardelle et al., 2013) and Alaska (Trüssel et al., 2013). However, the previous studies have not quantified contributions of ice dynamics and SMB to those contrasted glacier thinning. This point is a unique approach of this study. In the revised manuscript, we will discuss the differences in ice dynamics affecting ice thinning by comparing a ratio of thinning rates between land- and lake-terminating glaciers reported by the previous studies.

Most of the methods deployed by the authors have considerable ranges of uncertainty and those should be addressed and discussed better. Especially the SMB modelling that is largely based on the rather uncertain thermal resistance obtained from ASTER data and a few (risky) assumptions seems to prone to uncertainty. The relatively very large negative SMB of Thorthormi is therefore questionable in my opinion. It has been shown in a number of articles in the last few years that using spaceborne thermal infrared imagery over debris-covered glaciers (e.g. Rounce & McKinney, Foster et al., Mihalcea et al, Gibson et al.) provides opportunities but also numerous difficulties and these should be acknowledged.

Although debris thickness was not measured during the field campaign, ice is exposed from place to place over Thorthormi and Lugge Glaciers (Figs R2a and R2b), suggesting that debris-cover is rather thin than that of Lugge II Glacier (Fig. R2c). In addition, few supraglacial ponds and ice cliff exist over Thorthormi and Lugge Glaciers. So we emphasize that spatial variability of elevation change, thermal resistance and SMB are less than those the reviewers supposed. Anyhow, following the referees suggestion, we recalculated thermal resistance with considering sensible heat, for which pressure level temperature and geopotential height of NCEP2 are taken into account (Fig. R3). Scatter plot and spatial distribution of thermal resistances derived from the original method (net radiation only) and from recalculated one (net radiation + sensible heat) are shown in Figs R4 and R5. Spatial distribution of the difference between the two results is also shown in Fig. R5c. Thermal resistance significantly increased after the consideration of sensible heat (Fig. R4). However, large difference appeared only near the western margin (Fig. R5) probably because of relatively thick debris covering the area. We will recalculate the SMB distribution with revised thermal resistance in the revised manuscript. We evaluated sensitivity of calculated meltwater against meteorological parameters (Fig. R6). We chose the meltwater instead of SMB to quantify the uncertainty in percentage. The tested parameters are surface albedo, air temperature, precipitation, relative humidity, solar radiation, thermal resistance and wind speed. Uncertainty of thermal resistance and albedo were assumed to be 100% and 40% based on Figs R3b and R3d. Uncertainties of each meteorological variable were assumed to be RMSEs of ERA-Interim reanalysis data against the observational data (Fig. R7). Variations in meltwater within a possible parameter range are estimated by quadratic sum of results from each parameter shown in Fig. R6. Estimated uncertainty of meltwater is less than 50% at a large part of Thorthormi and Lugge Glaciers (Fig. R8). We will replace figures by the recalculated results and add Figs R6, R7 and R8 to the revised supplement.

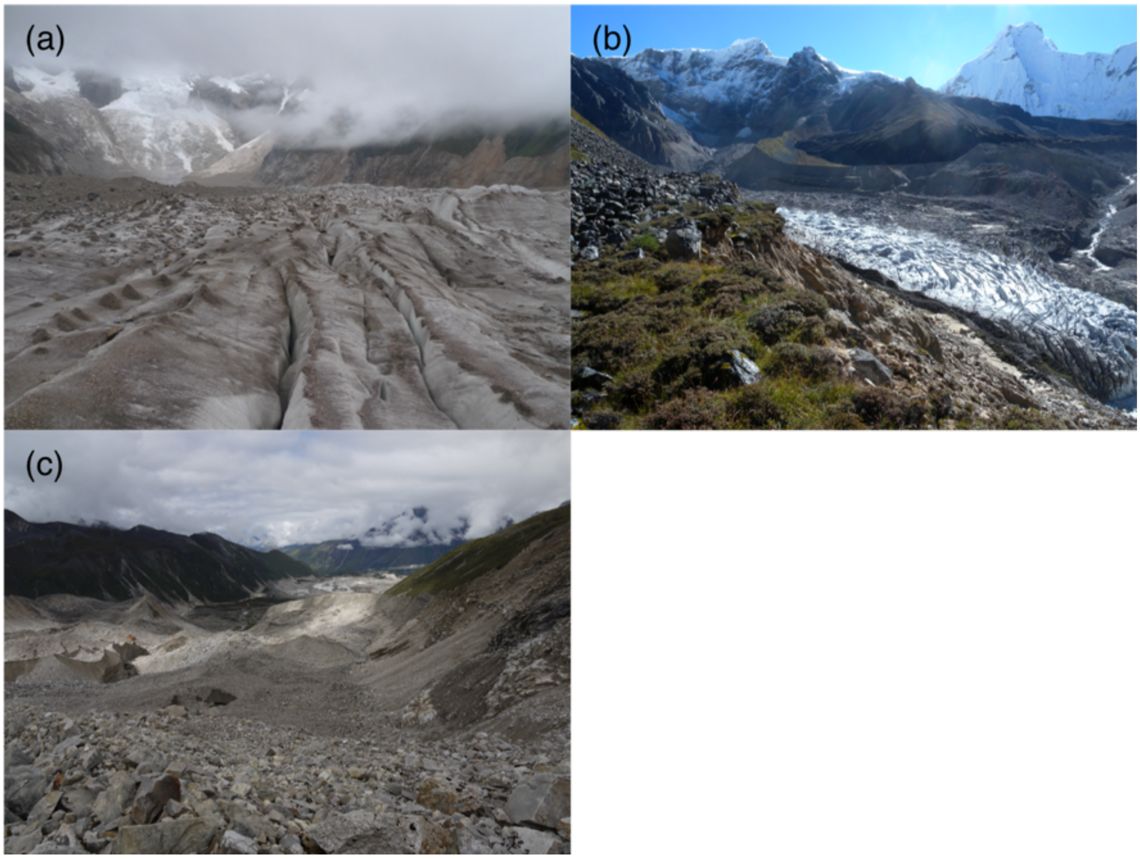

Figure R2: Photographs showing surface condition near the termini of (a) Thorthormi (18 September 2011), (b) Lugge (20 September 2011) and Lugge II Glaciers (21 September 2011).

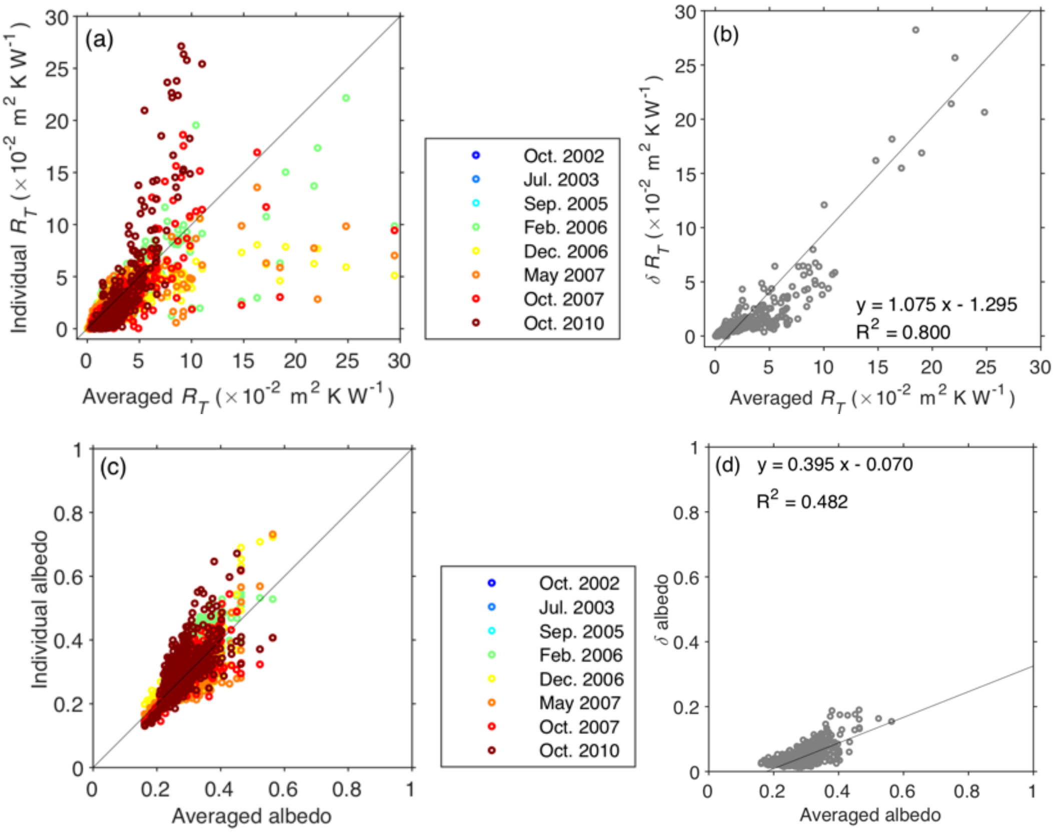

Figure R3: Scattergram of (a) thermal resistance (R_T) of the multitemporal ASTER data against their average derived from net radiation + sensible heat, which is used to calculate ice melting under the debris-covered surface of Thorthormi, Lugge and Lugge II Glaciers. (b) Standard deviations (δ) of thermal resistance. (c) Scattergram and (d) standard deviations of albedo.

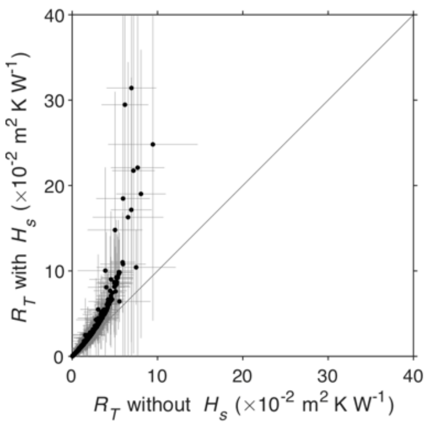

Figure R4: Scatter plot between thermal resistance calculated from only net radiation (without H_s) and from net radiation + sensible heat (with H_s).

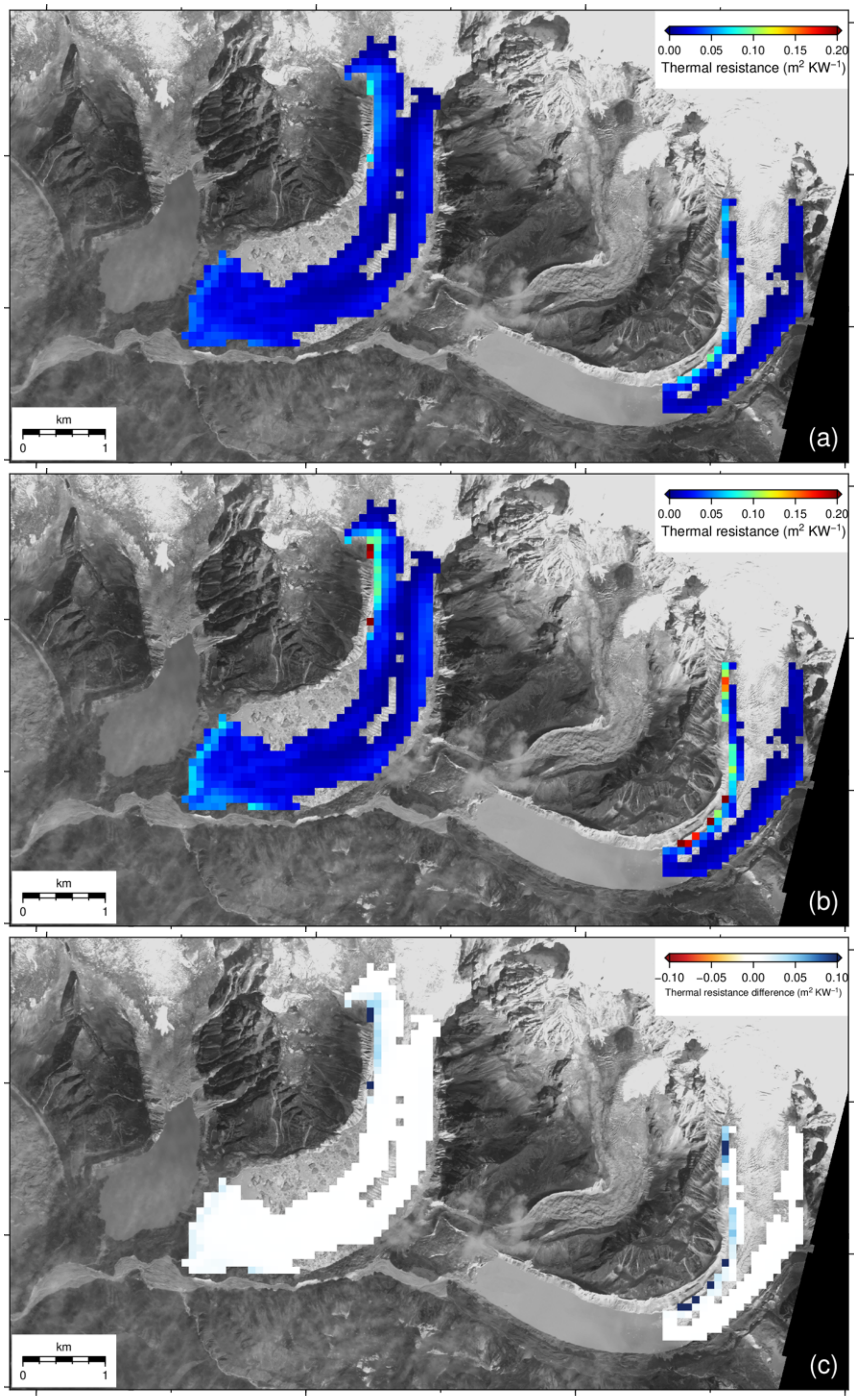

Figure R5: Spatial distribution of thermal resistance calculated (a) from only net radiation, (b) from net radiation + sensible heat and (c) difference of thermal resistance calculated by the two methods.

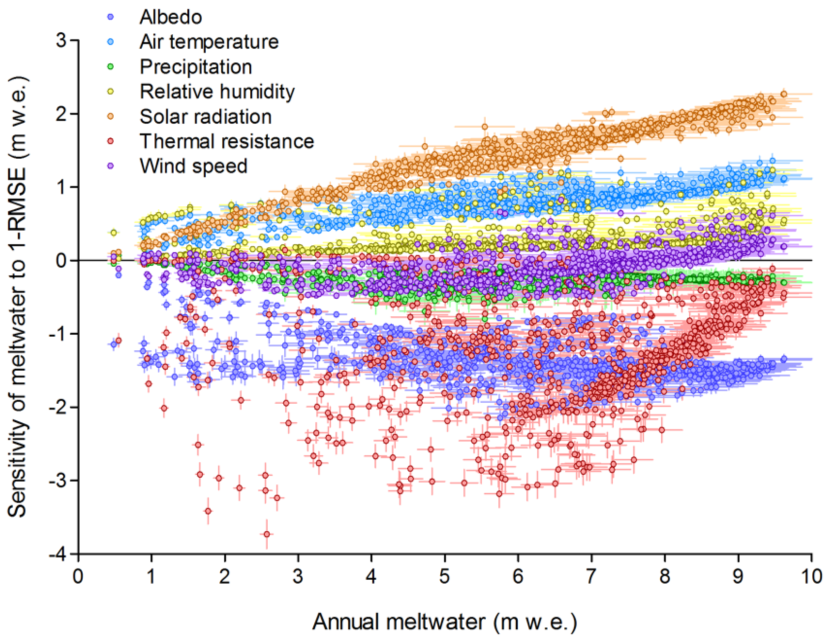

Figure R6: Sensitivity analysis of annual meltwater at debris-covered area as a function of variation of each parameter. RMSEs of ERA-Interim against the observed data were used for the meteorological variables. Uncertainty derived from 8 satellite images are used for thermal resistance and albedo.

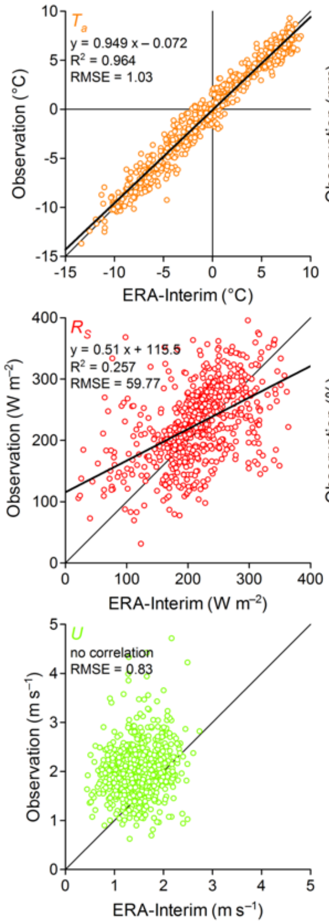

Figure R7: Scatter plot of air temperature, precipitation, solar radiation, relative humidity and wind speed between ERA-Interim reanalysis and observational data for 2002–2004.

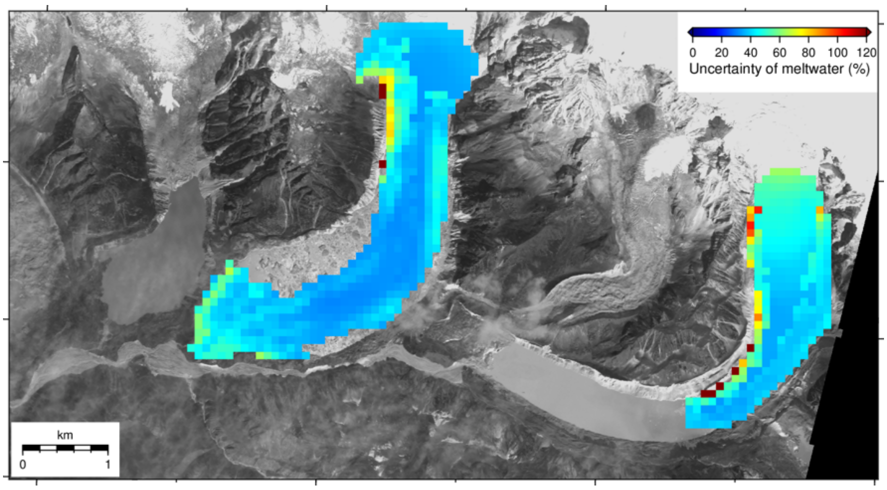

Figure R8: Spatial distribution of uncertainty of meltwater.

The accuracy of the '1 m resolution' DEM obtained by IDW interpolation of a seemingly very limited number of moderately well distributed DGPS points (Fig 1a) is also uncertain. Maybe it's spatial variability could be validated/substituted with other DEMs. What about the new High Mountain Asia DEMs available at NSIDC DAAC? I think the manuscript would greatly benefit from a more comprehensive sensitivity analysis (e.g. Monte Carlo) to show the total range of uncertainties affecting the final interpretations.

In order to evaluate spatial representativeness of glacier surface elevation change obtained from our DGPS measurements, we compared elevation changes obtained from DGPS-DEMs and from ASTER-DEMs acquired on 11 October 2004 and 6 April 2011, which cover similar period of our field campaign (2004–2011). ASTER-DEMs with 30 m resolution provided by the ASTER-VA (https://gbank.gsj.jp/madas/map/index.html) were used to compute the surface elevation change. Elevation of ASTER-DEMs was calibrated by the DGPS data on ice-free terrain in 2011. The 2004 and 2011 ASTER-DEMs showed positive biases (dZ) of 12.73 and 11.20 m, and standard deviations (σ) of 20.24 and 14.04 m, respectively (Fig. R9). Vertical coordinates of the ASTER-DEMs were then corrected for the corresponding bias. Elevation change over the glacier surface was computed as difference of the calibrated DEMs in 2004 and 2011 (see Fig. R1). Given the error range of ASTER-DEM, the rate of elevation change derived from DGPS-DEMs is similar to that from ASTER-DEMs (Fig. R10). In order to evaluate spatial representativeness of the DGPS survey, we compared the rate of elevation change of 1-m-grid DGPS-DEMs with that of 30-m-grid ASTER-DEMs along elevation (Fig. R11). Mean rates of elevation change with its standard deviation from DGPS-DEMs are -1.40 ± 0.77 and -4.67 ± 1.36 m a^{-1} for Thorthormi and Lugge Glaciers, respectively, while those from ASTER-DEMs over the elevation range where the DGPS measurements exist are -0.70 ± 1.25 and -4.87 ± 1.29 m a^{-1} for Thorthormi and Lugge Glaciers, respectively. Figure R4 shows that the rates from DGPS-DEMs fall within those of ASTER-DEMs, and thus it supports applicability of our survey results to the entire ablation zone.

In the revised manuscript, we will take into account spatial variability in the rate of elevation change from ASTER-DEMs to uncertainty of the mean rate over the entire ablation zone.

We evaluate uncertainties from each analysis (DGPS-DEM, thermal resistance, SMB model and flow model) and a total uncertainty in the revised manuscript. We believe that these new evaluations for uncertainties increase reliability of our results.

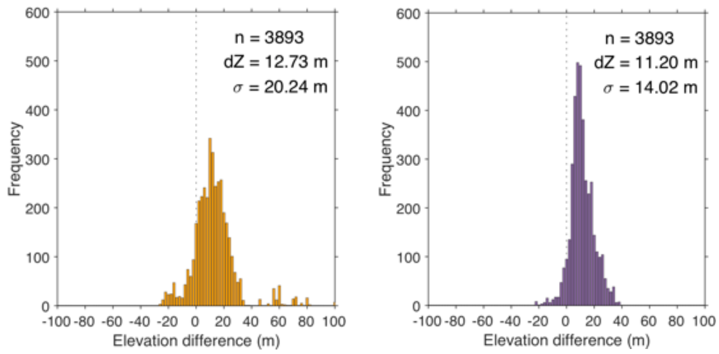

Figure R9: Elevation differences in the ice-free area (left) between 2004 ASTER-DEM and DGPS-DEM and (right) between 2011 ASTER-DEM and DGPS-DEM.

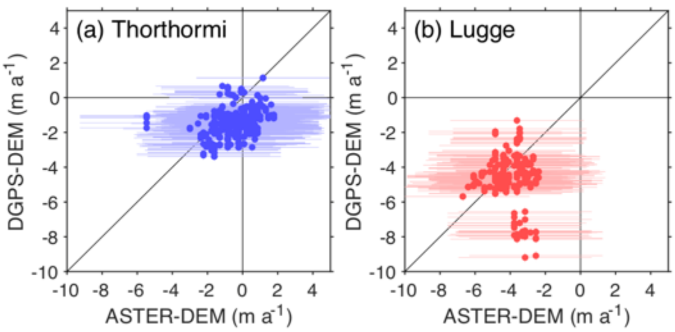

Figure R10: Scatter plot of the rate of surface elevation change between from ASTER-DEMs and DGPS-DEMs at (a) Thorthormi and (b) Lugge Glaciers. Error bars denote standard deviations of DEM differences over the ice-free terrain.

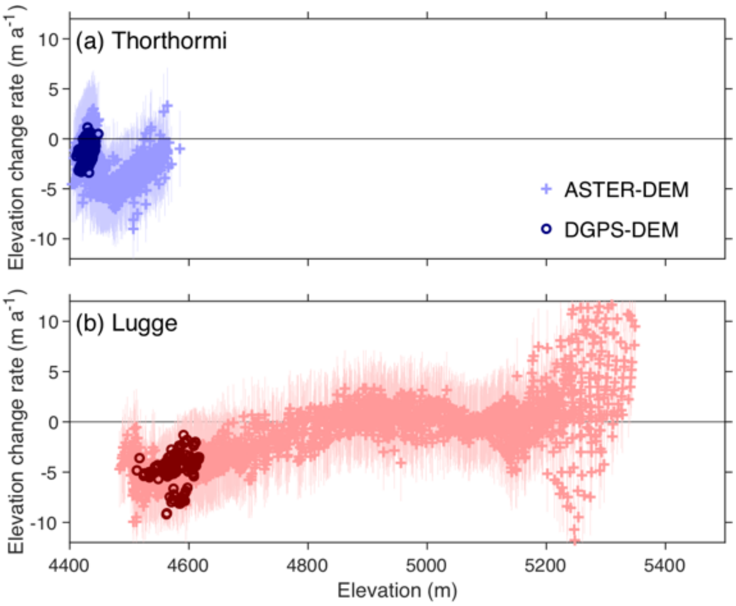

Figure R11: Rate of elevation change along elevation at (a) Thorthormi and (b) Lugge Glaciers. Dark-colored circles are from DGPS-DEM and light-colored crosses are from ASTER-DEM. Error bars denote standard deviations of DEM differences over the ice-free terrain.

Line by line comments:

12: Why 'more' than offsets? Rephrase

We will change "more than offsets" to "compensates" in the revised manuscript.

18: Maybe add Scherler 2011 (10.1038/ngeo1068)

We will add Scherler et al. (2011) in the revised manuscript.

30: There are some more recent papers on this, also by Huss and Hock themselves: 10.1038/s41558-017-0049-x, 10.1038/nature23878, 10.1038/s41558-018-0093-1.

We will change a citation to their latest study in the revised manuscript.

54: 'of most spaceborne DEMs'. DEMs of high resolution stereo satellite imagery (e.g. Pleiades), LIDAR and UAVs are remote sensing methods perfectly capable of deriving several metres (even sub-metre) elevation change

Reviewer #1 and #2 also pointed out accuracy of DEMs derived from UAV and laser/radar altimetry, and we agree. We will remove the statement "However, the accuracy of the remotely sensed DEMs is still insufficient to measure several metres of glacier elevation change." in the revised manuscript.

59-66: The aim of the paper is not entirely clear to me from the introduction. This paragraph now is more of a methods summary. Consider changing it to clearly convey the research aim and question.

We will add the aim of this study as "The aim of this study is to quantify contribution of dynamic ice thickness change and SMB to thinning of adjacent land- and lake-terminating glaciers." in the revised manuscript.

69: Is the glacier area measurement really accurate to 0.01 km2?. Same for other glaciers.

In a recently published glacier inventory of glaciers in Bhutan (Nagai et al., 2016), accuracy of glacier areas delineated using ALOS PRISM imagery (2.5 m resolution) was reported as 0.01 km^2.

75: Use separate paragraphs per glacier to improve readability.

We will separate the text into several paragraphs.

77: moraine-dammed

We will change to "A moraine-dammed" in the revised manuscript.

75: No space between '~' and the number. Throughout.

We will remove space in the revised manuscript.

86: 'were carried out on/around' -> 'were performed for'

We will change as suggested in the revised manuscript.

92: These are surface flow velocities, right, not integrated over the vertical? Rephrase into something like 'surface flow velocity of Thorthormi'.

We will change from "The ice flow velocity across" to "Surface flow velocity of" in the revised manuscript.

101: I've never seen full web URLs in a body of a paper. Use a reference entry for the website in the bibliography instead.

As replied to a comment from Referee #2, this format was used in a paper recently published in The Cryosphere (e.g., Friedl et al., 2018). Therefore, our manuscript also follows this format.

104: Are the elevation variations caused by a person carrying the pack on a debris-covered glacier really only 10 cm? How were these estimated?

Change in the height between GPS antenna and surface was measured at the beginning and the end of the observation. We neglected the influence of debris-cover on change in the height of GPS antenna is thought to be negligible because debris-cover over the observed glaciers is sparse and thin, and we therefore could walk on ice surface in the most of the surveyed area.

106: Mentioning UTM is not quite relevant.

DGPS-DEM was generated in the UTM coordinate system. Mentioning UTM is important to ensure DEM reproducibility with our method.

107: Why this 1 m resolution?

If the grid size sets larger (e.g., >5 m), it is difficult to capture detailed change in surface elevation in Himalayan glaciers where surface slope significantly varies. However, if the grid size set smaller (e.g., <1 m), the number of points of elevation change significantly decrease. As a compromise between the two, we have adopted the 1-m grid as used in previous studies in the Himalayas (Fujita et al., 2011; Tshering and Fujita, 2016).

122: remove 'the' after calculated.

We will remove it in the revised manuscript.

125-126: There is no info whatsoever on the accuracy of the orthorectification of the ASTER images? Could these maybe be retrieved? This can be quite an issue in steep mountainous regions.

Accuracy of 3D orthorectified ASTER image is reported to be <16.9 m in a flat area and <28.4 m in a mountain region (ASTER Science Project, Japan Space Systems, 2012). An error caused by orthorectification is small in the studied region because glacier surface is flat.

131: Why did you select the statistical correlation mode. I was under the impression that the mode that works on the frequency domain is better and is better suited detect subpixel displacements. Please elaborate on the choice.

We agree that the frequency domain is suitable for detecting subpixel displacements (e.g., Abe et al., 2016; Sakakibara and Sugiyama, 2018). COSI-Corr performed well with a statistical correlation mode to detect displacements of glaciers in the Nepal Himalayas (e.g., Lamsal et al., 2017; Nuimura et al., 2017). Our study also used the statistical correlation following the previous studies.

134: So no filtering was applied using the signal to noise ratio statistics that are provided by COSI-Corr?

We removed data with the signal to noise ratio < 0.9.

137: The SLC-off gaps in the ETM+ imagery did not provide an issue in the analysis? This should at least be mentioned.

We used multiple ETM+ images acquired from October to December for each year to avoid the SLC-off gaps. We will add this explanation in the revised manuscript.

139: 'that possessed the' -> 'with'

We will change as suggested in the revised manuscript.

141: Use of QGIS in particular is not relevation and, again, the weburl is unnecessary. Just state that delineates were performed in a geographical information system.

We will change as suggested in the revised manuscript.

143: So there is no user-induced accuracy error?

According to analysis using Landsat images with 30 m resolution (Paul et al., 2013), a user-induced accuracy error was estimated to be 5% of delineated area of glaciers with more than 1 km^2. Following the previous study, we estimated user-induced accuracy error by 5% in the revised manuscript.

162-163: These are quite bold assumptions and this should be acknowledged.

We explicitly mention the assumption was taken in the analysis. We evaluated uncertainty from the thermal resistance based on these assumption (see Fig. R2).

260: Preferably also show the off-glacier displacements in figure 3a.

Figure R12 shows surface displacement off the glacier derived from an image pair on 3 February 2006 and 30 January 2007. Displacements were excluded where surface slopes exceeded 25 degrees. The mean displacement is 12.1 m a^{-1}, which will be given as a measure of uncertainty in the revised manuscript. Figure R12 will be added in the revised supplement.

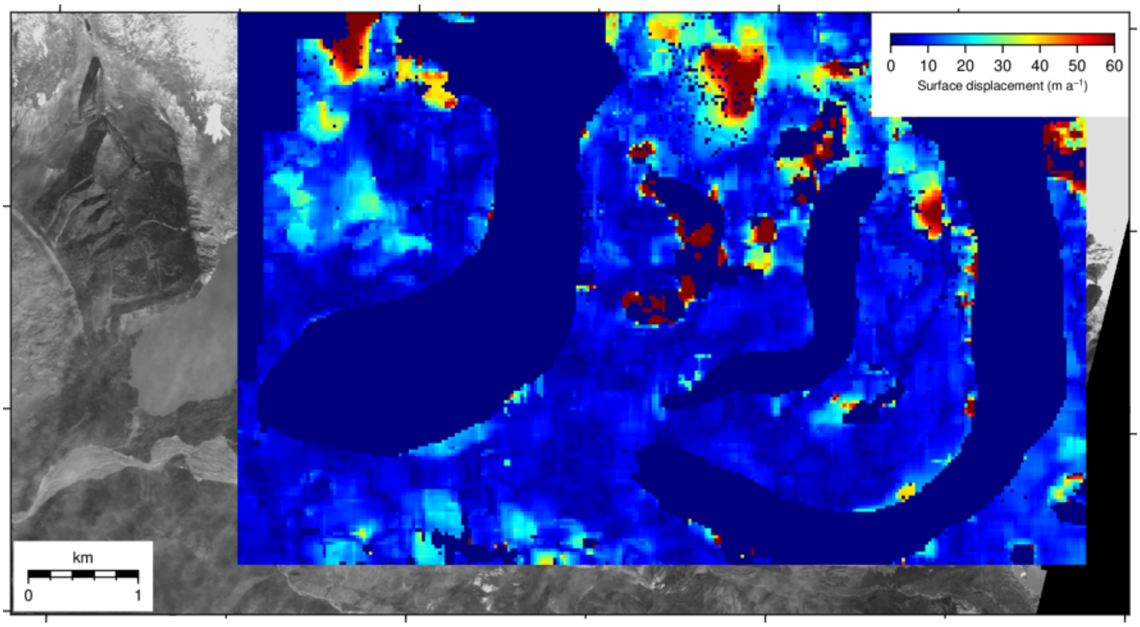

Figure R12: Surface displacements on ice-free terrain derived from image pair on 3 February 2006 and 30 January 2007.

273: Is does not appear that heterogeneous to me. Especially since the actual heterogeneity is likely much higher given the hummocky surface of most debris-covered glaciers. I understand that this is not captured by the ASTER data, and that this is the variability that is obtained, but it should be reworded.

See a reply to the major comment #3.

330-333: The authors speak of accelerating mass losses, but the numbers and accompanying year ranges do not show this per se.

The mass loss has increased since 2000 according to the studies by Gardelle, Brun, Kaab and this study with Maurer's result. But detailed and quantitative discussion is difficult. So, we will change to "Regional mass balances in northern Bhutan have accelerated from the period for 1974–2006 to after 1999. For example, the region-wide mass balance is -0.17 ± 0.05 m w.e. a^{-1} for 1974–2006 (Maurer et al., 2016), -0.22 ± 0.12 m w.e. a^{-1} for 1999–2011 (Gardelle et al., 2013), -0.42 ± 0.20 m w.e. a^{-1} for 2000–2016 (Brun et al., 2017) and -0.52 ± 0.16 m w.e. a^{-1} for 2003–2008 (Kääb et al., 2012)." in the revised manuscript.

341-342: Please elaborate.

We will add "A likely interpretation is that the expansion of Lugge Glacial Lake after the 1960s and glacier thinning decreases the effective pressure (ice overburden minus basal water pressure). A decrease in the effective pressure causes glacier acceleration by enhancing basal ice motion as seen previously near the front of a lake-terminating glacier (Sugiyama et al., 2011). It is likely that acceleration and enhanced longitudinal stretching near the terminus resulted in further ice thinning." in the revised manuscript.

344-365: I found this section rather confusing. There are methods and results presented in the discussion section. I strongly suggest relocating this to the appropriate sections.

We will relocate method to "3.6" and results to "4.6" in the revised manuscript.

360: This is not due to differences in debris cover and debris thickness?

Debris cover is thin and sparse in the ablation area of Thorthormi and Lugge Glaciers. Therefore, we consider that 37% more negative SMB of Thorthormi Glacier is not totally due to debris, but also other factors including difference of surface elevation. Details are addressed in a reply to the major comment #3.

375: A difference of 5 ma-1 is a lot. As suggested in the main comments, I think a comprehensive sensitive analysis would be a great addition to the paper and could help to support the conclusions.

Thanks to the suggestion. We evaluate uncertainties in each analysis (DGPS-DEM, thermal resistance, SMB model and flow model) in the revised manuscript.