We thank both reviewers and the editor for their additional detailed comments on our resubmission to The Cryosphere. We have considered them carefully, and where necessary re-computed some of our data to ensure they are adequately addressed. We have also revised the manuscript to provide further clarification or information where requested.

Both reviewers made similar points about our treatment of surface elevation change data as an indicator of mass balance. We acknowledge that this may be flawed and consequently no longer use surface elevation change profiles to infer mass balance versus altitude relationships. We have been particularly careful to distinguish between the two different datasets throughout the updated version of the manuscript. As we are able to present mass balance estimates for each of the glaciers in our sample (following previous additional data processing and analyses) we believe that the main findings of the paper remain robust.

Here we outline our approach to amending the manuscript in response to other more general comments made by both reviewers and the editor, along with smaller changes recommended.

Reviewer 1- Joseph Shea

General comments:

1. Mass loss calculations: how are missing areas in the SRTM dealt with, particularly in accumulation areas? And why not use the slightly lower and generally more accepted density of 850 +/- 60 kg/m3 (Huss, 2013)?

We followed a similar approach to that of Ragettli et al. (2016) to fill data gaps in DEM difference data. We have added a much more thorough description of this process to the manuscript (the new section 3.3.3). In summary, median values of surface elevation change data from 100 m elevation bands were used to fill data gaps.

As we adopt the approach of Huss (2013) in assigning an additional 7% to the uncertainty estimate of mass balance loss data, we have adjusted the conversion factor used from 900 kg m^{-3} to 850 kg m^{-3} as the reviewer suggests. Updated mass balance estimates have been substituted into the manuscript and supplementary information, although the differences from this adjustment are small.

Also: a mass balance can be calculated for the entire glacier/region, but for vertical profiles (e.g. Figure 5 in the revised manuscript) it must be kept as surface elevation differences - the conversion to mass change can only be done if dynamics are taken into account (or they cancel each other out, as in the case for the whole glacier). As Gardelle et al. note in their 2013 paper: "Note, elevation changes over separate sections of a glacier cannot be treated as mass changes due to the disregard of glacier dynamics."

As a result, mass loss rates cannot be compared for different elevations (P10L15-27). This will need to be treated as elevation differences. And ablation gradients should be 'surface lowering' or 'elevation change' gradients (P11L1-10).

We acknowledge that we cannot treat surface elevation change as a measure of surface mass balance throughout the entire elevation range of each glacier and thank both reviewers for their clear explanation of this point. We have followed the above recommendation and now present surface elevation change curves; we have also been careful to make the distinction between these dh/dt curves and our separate mass balance estimates made for whole glaciers. As the contrast in mass balance estimates remains depending on glacier terminus type (lake Vs land terminating), one of the main findings of the work still stands.

2. Derivation of ELA from mass balance (Sec. 3.7). In the previous version of the mansucript, both reviewers pointed to this as a potentially weak point in the methods. The authors have not provided any additional support for the assumption that the ELA can be determined from geodetic mass balance observations (other than Nuth et al., 2007). I think the method of estimating future ELAs/AARs is useful

but the method for current ELA calculation needs to be further justified. Also, as the authors calculate mean geodetic mass balance for 100 m elevation bands to estimate ELA the submergence/emergence velocities again become an issue that needs to be considered.

Thanks for this assessment – we are happy to provide further justification both here and in the revised submission.

A similar assumption about the similarity of the zero point of dh/dt and the ELA has been made by a number of other studies (e.g. Huss et al., 2008; Farinotti et al., 2009; Huss and Farinotti, 2012). These studies show how, at the ELA, there is little difference between observed (measured in the field) surface mass balance and the change in surface elevation of the same point in the glacier system. We acknowledge that this may not hold with increasing distance from the ELA (see Huss and Farinotti, 2012 their figure 1) due to the influence of ice dynamics, as both reviewers have clearly stated. But we consider the point of zero elevation change to be a reasonable estimate of ELA because here submergence and emergence should be at a minimum. We have reinforced section 3.7 with reference to the studies mentioned above and believe that the method we follow to estimate ELA is robust.

Comparison of the ELAs we have derived using this method with those of other studies (that have used alternative techniques) also reinforces our approach. Our ELA estimate for the Khumbu glacier (6000 m) is identical to that of Rowan et al. (2015) who used a dynamic glacier model to reconstruct glacier evolution since the Little Ice Age. Our ELAs for Imja glacier, Bhote Kosi Glacier and Ngozumpa Glacier (approximately 5600, 5700 and 5600 m, respectively) are also very similar to those of Thakuri et al. (2014) who mapped snow line altitudes (SLA) over these and many other glaciers in our study area for six different time periods between 1962 and 2011. Thakuri et al. (2014) use SLA as an estimate of ELA, and suggest ELAs of 5691, 5632 and 5570 m, respectively for Imja, Bhote Kosi and Ngozumpa glaciers.

Specific comments:

Abstract: just a suggestion to shorten to the recommended 100 - 200 words

We have shortened the abstract to 263 words.

P2L23: Central Himalayan glaciers have less negative mass balances (as opposed to more stable).

Agreed. Text amended.

P3L24: clarify - do the 40 largest glaciers comprise 70% of the total glacierized area?

Yes, precisely that (Bajracharya and Mool, 2009). We have changed the text slightly to make this point clearer.

P3L29: New paragraph for Tama Koshi.

Agreed. Text amended.

P4L1: "The Tama Koshi is a poorly studied catchment..."

Agreed. Text amended.

P4L3: New paragraph for Pumqu catchment.

Agreed. Text amended.

P9L25: By definition, lapse rates are positive. I'd personally keep it negative and use 'vertical temperature gradient'.

Agreed. Text amended.

P11L28: Thakuri et al (2014) also examine smaller glaciers, which might help explain the greater rates of area change.

We have added ‘smaller’ to this sentence to make this point clearer.

P12L24: 'elevation change' instead of 'mass loss' (and elsewhere)

We have changed this incorrect wording throughout the manuscript.

P12L26: 'here' - be specific again, e.g. 'north of the divide'

Agreed. Text amended.

P13L1: Measured precipitation is actually low - suggest 'delivers a large proportion of total annual precipitation'

Agreed. Text amended.

P13L25: Shrestha et al., (1999)

Agreed. Text amended.

P14L17: (Barundun et al., 2015)

Agreed. Text amended.

P14L17: 'Our results'...re-state the regional mass loss estimates here for comparison. A table with the current results and those from previous studies would also be helpful.

We have altered the text as requested and added a table to compare the regional mass balance estimates in the literature:

Table 3. Mass balance estimates (from geodetic and altimetric studies) for the broader Everest region and comparable sub-regions/ catchments.

Time period and area	Mass balance estimate (m w.e. a^{-1})	Study
Dudh Koshi		
1970-2008	–0.32 ± 0.08	Bolch et al. (2011)
1992-2008	–0.45 ± 0.25	Nuimura et al. (2012)
2000-2015	–0.50 ± 0.28	This study
Pumqu (Tibetan Plateau)		
1974-2006	–0.40 ± 0.27	Ye et al. (2015)
2003-2009	–0.66 ± 0.32	Neckel et al. (2014)
2000-2015	–0.59 ± 0.27	This study
Tama Koshi		
2000-2015	–0.40 ± 0.21	This study
Everest region		
1999-2011	–0.26 ± 0.13	Gardelle et al. (2013)

2003-2008	–0.39 ± 0.11	Kääb et al. (2012)
2000-2015	–0.52 ± 0.22	This study

P14L27: 'surface lowering' instead of 'mass loss'

We have changed this incorrect wording throughout the manuscript.

P15L26: awkward phrasing. Perhaps: '...suggests large glacier mass losses."

Agreed. Text amended.

P16L5-120: Expand on Figure 7! E.g. at high-end temperature projections, AARs go to zero and ELAs are above the head of glaciers in the Tama Kosi. Initial response to temperature change is greater for Dudh Kosi...

We have added text to explain figure 7 in more detail:

'Should greater temperature increases occur, for example high-end RCP 6.0 warming, AARs could reduce to zero in the Tama Koshi catchment as ELAs rise above glacierised altitudes. Clean ice glacier AAR adjustment could be rapid given more than 1 ^{o}C of warming, with AARs again approaching zero should high-end RCP 8.5 warming occur in the region. The AAR of glaciers in the Dudh Koshi catchment could reduce quickly under RCP 2.6 warming, but their AAR reduction may be less rapid given greater temperature increases, presumably because of the extreme relief of the catchment. The AAR of glaciers on the Tibetan Plateau could become lower than glaciers of the Dudh Koshi catchment once warming approaches 2.5 ^{o}C.'

P18L3. "Projected warming in the Everest region will lead to increased ELAs and, depending on glacier hyspometry, substantial increases in ablation areas.'

Agreed. Text amended.

Figure 1: Glacier names still too small to read.

We have increased the font size of glacier names again.

Figure 2: Glacier names too small, and are the grey regions on the glaciers areas with no data?

We have increased the font size of glacier names again. Yes, grey areas (actually the ASTER GDEM underlay) are areas of no data. We have added to the figure caption to explain this.

Figure 7: What does each point represent?

Each point represents a projected AAR given minimum, mean or maximum temperature rise under each RCP scenario. We have added this to the figure caption.

Reviewer 2

The revised MS is improved in several aspects but unfortunately one of the major issues that I raised in my first review has NOT been corrected. Authors are still believing/pretending that they measured the pattern of mass balance (for example with altitude, see the legend and axis title in Figure 5, 6 and 8) although they only measured the rate of elevation change (dh/dt, see comment 9.17 below). I think many of their conclusions (e.g., role played by glacial lakes in controlling glacier mass loss) would still hold without this basic error but the paper cannot be published in its current form. If the paper is publish like this, there would be a risk that many glaciologists would confuse dh/dt (readily available from DEM comparison) and mass balance in the future and this would be dramatic because these are two very different quantities with profoundly different meaning/interpretation. Only the glacier-wide averages of these two quantities are equal (with a proper density assumption).

Another major issue is the error estimate that is different from the one presented in the submitted MS. Authors have followed a non standard approach (not a problem per se) but not very clearly described/justified. In my view some errors are double-counted which lead to overestimated uncertainties.

We respond to line by line comments relating to these two issues below.

My line by line comments are provided below (Page.Line).

Abstract and elsewhere in the paper. Space sometime missing between "w.e." and " a-1"

This mistake has been corrected throughout the manuscript.

3.1-5 paragraph not well linked with the rest of the introduction

We have added a sentence to try and link the description of the conceptual model of Benn et al. (2012) and the previous statement about the findings in the study by Gardelle et al. (2013).

5.4 Two versions (X and C-Band) of the SRTM DEMs are presented. Authors need to clarify which one of the two was used. See comment from my initial review on this. By the way, why presenting the SRTM X-Band DEM if it is not used at all?

We have removed any mention of the X-band SRTM data as we did not use it in this study. We have explained as clearly as possible that we use only SRTM C-band data.

6.26 Authors used EGM2008 for the WV DEM geoid correction. But SRTM C-Band uses a different geoid, i.e. EGM96. It would have been best to use the same geoid. Further, if the DEMs are both registered to the geoid I do not understand why a 30 m systematic elevation difference (see Table 2) remain between them. I would have expected a few meters of bias, no more (orbital WV errors + differences between EGM96 and EGM2008). These unexpected systematic elevation differences make the whole DEM processing suspicious.

The figures presented in the most recent version of the manuscript were incorrect and included by mistake. The correct, pre-registration DEM difference statistics have now been included in Table 2. We apologise for this oversight.

7.8 can the authors confirms (and write in the MS) that no penetration correction was applied for debris-covered areas? Was still unclear to me. Authors use an average value for the ablation/accumulation area because these are the one available from Kaab et al. However, they need to state that there is a potentially

strong spatial/altitudinal variability in the SRTM penetration depth (depending on firn temperature and water content) and thus that this is source of error when examining the spatial pattern of elevation change.

We did not apply any penetration correction to debris covered areas given the uncertainty expressed by Kääb et al. (2012) about the influence of greater than average snowpack depth at the point of ICESat acquisition and the properties of the snowpack at the point of SRTM data acquisition on their penetration estimate. We have updated section 3.3.2 to emphasise that the SRTM penetration depth is likely to be spatially variable and clearly state that we have not applied a penetration correction over debris covered glacier areas as suggested by the reviewer.

7.23 Error estimate. Equation (1): First I do not understand why authors do this calculation, taken from Wang & Kaab. They are not really interested in the error of individual DEMs but rather in the error on elevation changes which is directly provided by Sigma_i. Or did I miss something?

Further, following standard error propagation, I would have expected that $\text{Sigma\_dh}^2=\text{Error\_dem1}^2+\text{Error\_dem2}^2$ so the sign does not appear to be OK here. This error was also present in the Wang & Kaab paper unfortunately and authors should avoid propagating it in the literature. See http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf for example.

We have reverted back to a slightly modified version of our original method of calculating uncertainty associated with elevation changes. We now follow the approach originally outlined by Gardelle et al. (2013) that calculates the standard error of elevation changes over different elevation bands. This is a more standardised approach that has been recommended by the editor. In regard to the reviewer comment above, we have checked the sign on our RSS calculations (explained in more detail below) to ensure error propagation is accounted for correctly. We thank the reviewer for guidance on this issue. Our uncertainty estimates are lower than those produced by the method adopted in our resubmission – which was a concern raised by reviewer 2.

8.1. Write maybe "standard elevation differences over stable terrain (□stable)".

We have amended the text following the advice above.

8.15 in their □season, the authors include the □stable that is the std deviation of the DEM differencing on the stable terrain. But this source of error has already been accounted for earlier in Eq 2? Rather the mean bias on glaciers between two WV2 DEMs acquired a few weeks/months apart could maybe be a better estimate for the (systematic) seasonal error.

We have incorporated the mean elevation difference (+0.69 m) over glaciers (G1 and Bamolelingjia) covered in the overlapping segments of SETSM DEMs from different time periods into our uncertainty budget to try and quantify any seasonal variability in elevation, in accordance with the reviewers suggestion. This can only be considered a rough approximation of this source of error as the depth of any remnant snowpack in the later DEMs is likely to have been highly variable across the study area.

9.17-19 "We do not quantify emergence velocity". Of course, it is very difficult to infer mass balance (MB) from elevation change (velocity, ice thickness data are needed and not available, true). Then, locally, the values that the authors show are not mass balances but elevation changes. Despite this statement, in the rest of the MS, authors ignored totally that they did not observe mass balance. Maybe the authors believe that Himalayan glaciers are special and that in their case MB and dh/dt are equal? If this is so, they are wrong. It has been demonstrated for one of their study glaciers (Khumbu).

Authors can refer to Nuimura et al. 2011 to check that the magnitude of the emergence velocity (even in Himalaya) can match or be even much larger than the value of the surface mass balance. In Nuimura's Table 4, the dh/dt are 0.7 m/a and the emergence velocity needed to retrieve the surface mass balance for some portions of the ablation area of Khumbu Glacier is... 5 to 6 m/yr, i.e. one order of magnitude larger!!! Clearly it illustrates how dh/dt and MB cannot be mixed/confused.

Nuimura, T., Fujita, K., Fukui, K., Asahi, K., Aryal, R. and Ageta, Y.: Temporal changes in elevation of the debris-covered ablation area of Khumbu Glacier in the Nepal Himalaya since 1978, Arctic, Antarctic, and Alpine Research, 43(2), 246–255, 2011.

Thanks for the clear description of the issue with our confusion of elevation changes and mass balance. It is now clear that we cannot present one as the other, and we have adopted our previous approach of showing surface elevation change curves in the manuscript. As we have carried out additional data processing (SRTM correction, gap filling) and are able to generate mass balance estimates for all of the glaciers in our sample, we can still make a comparison between the mass balances of glaciers of different terminus type, thus one of the main messages of the paper remains robust.

We have also chosen to remove the section of the manuscript where we made a comparison between surface lowering curves and the conceptual mass balance curves presented in Benn et al. (2012). The reviewer has very clearly explained how these two datasets differ.

9.21 Authors did not calculate mass balance but elevation changes! See comment (9.17). Consequently, the altitude where dh/dt approaches 0 is NOT the ELA. If this was true then the ELA would be above most Alaskan glaciers for example (See dh/dt vs altitude curve in Arendt et al., 2006 approaching 0 close to the glacier head, just one example among many studies showing that thinning can indeed affect the entire accumulation zone of some glaciers) but we all know that the AAR of most of these Alaskan glaciers is not 0! They still have an accumulation area. The same would hold in the Alps and many other mountain ranges. Altitude of zero elevation change and ELA have nothing in common.

We disagree with the reviewer on this point. Huss and Farinotti (2012) have shown (following Huss et al. 2008 and Farinotti et al. 2009) that for a number of glaciers in the European Alps the altitude of zero elevation change (derived through DEM differencing) may be a useful indicator of the point of neutral measured surface mass balance. Around the ELA, ice flux divergence, or what Farinotti et al. (2009) calculate as 'apparent mass balance', should be minimal (as has been shown in field measurements – Cherkasov and Ahmetova, 1996) and have little influence on surface elevation change. Therefore, we would suggest that the identification of an area of zero elevation change at a glaciers surface (obviously disregarding the area around a debris covered glaciers terminus) is a reliable proxy for the position of the ELA. The impact of irregular avalanche input is hard to quantify and could influence surface elevation changes, but over our 15 year study period it may be considered negligible.

Comparison of the ELAs we have derived using this method with those of other studies (that have used alternative techniques) also reinforces our approach. Our ELA estimate for the Khumbu glacier (6000 m) is identical to that of Rowan et al. (2015) who used a dynamic glacier model to reconstruct glacier evolution since the Little Ice Age. Our ELAs for Imja glacier, Bhote Kosi Glacier and Ngozumpa Glacier (approximately 5600, 5700 and 5600 m, respectively) are also very similar to those of Thakuri et al. (2014) who mapped snow line altitudes (SLA) over these and many other glaciers in our study area for six different time periods between 1962 and 2011. Thakuri et al. (2014) use SLA as an estimate of ELA, and suggest ELAs of 5691, 5632 and 5570 m, respectively for Imja, Bhote Kosi and Ngozumpa glaciers.

10.4 "in the" repeated

Text deleted.

10.5 Here I want to recall my above comment (9.17) to the authors that their dh/dt can only be interpreted as (glacier-wide) mass balance after averaging over the whole glacier area. This is not true for point, individual altitude band and considering ablation/accumulation areas separately because of the divergence of the ice fluxes. See text books.

We have updated this section of the manuscript so that we now refer to the mass balance estimates (calculated for whole glaciers, not with elevation) that we have generated and the surface lowering curves in a much more distinct manner, so as to avoid the incorrect inference that the two are similar as the reviewer has pointed out.

10.29 authors did not measure the ablation gradient. They measured the gradient of dh/dt with altitude. See comment 9.17.

We have updated our measurements of elevation change gradients and again reworded this portion of text to emphasise that we show the gradient of dh/dt and not mass balance. We still include these gradients because they show clearly the contrast in the pattern of surface lowering that has occurred on land Vs lacustrine terminating glaciers.

12.26 what do the authors mean by "here"?

To the north of the orographic divide. We have altered the text slightly to make this clearer.

13.19 I would expect the rise in mean temperature to be between the minimum and the maximum. But maybe I wrong? Maybe authors can double check the reference cited?

After checking Salerno et al. (2015) we have amended the text and updated the minimum temperature increase figure taken from this study.

14.5 This is a conclusion inherited from the previous version of the paper that does not hold anymore. Or is it for a specific altitude range?

We believe that our suggestion of enhanced ice loss from glaciers on the northern slope of the Himalayas is still correct. These glaciers show elevated maximum surface lowering rates and surface lowering through a much broader elevation range when compared to glaciers flowing south. The available meteorological data from both sides of the main orographic divide also clearly shows a north-south contrast in annual precipitation amount, and Owen et al. (2009) have suggested that such a contrast may have substantially influenced fluctuations in glacier extent during the Late Quaternary. We would suggest that this contrast exerts a similar control on present day glacier behaviour.

As requested by the editor, we have added to this section of the manuscript to point out that there are other factors (debris cover extent and thickness evolution, monsoon strength) that could have influenced recent glacier mass loss and also mass loss into the near future.

14.17 omit parenthesis

Agreed. Text amended.

15.7 "m a-1" or "m/a", author need to be consistent in their notations

We have checked carefully to make sure m a^{-1} has been used throughout the manuscript.

15.27 what do the authors mean by "here" in this context?

We are referring to the Dudh Koshi catchment. We have clarified that in the manuscript.

26.5-7 This is already stated in the Method, no need to repeat I believe.

Agreed. We have removed this unnecessary portion of text from the manuscript.

16.28 again, authors did not measure mass balance curves. This whole comparison is then problematic. See comment 9.17

As we have explained in response to earlier comments, we have now removed the comparison with the conceptual model of Benn et al. (2012) so this point no longer applies.

17.33 does it mean that water is stored in the englacial hydrological network? Or in ponds? Maybe authors could clarify what is the "distributed water storage".

As we no longer compare our surface lowering data with the conceptual model of Benn et al. (2012) this portion of text has been removed and the comment no longer applies.

17.7 no "s" for glacier margin

Agreed. Text amended.

Figure2. Authors do not only show "surface lowering" as written in the legend and caption. There are some areas of thickening (!) in their map. Rather they show the "rate of elevation change". Same for Figure 3.

We have altered figure captions in accordance with this suggestion. Thanks for pointing this out.

Figure 5. How normalization was done should be described in the method section of the text (maybe with a reference to justify/explain it?). This normalization is really useful to compare the different basins and glacier type. Thanks for following my advice.

Agreed. We have updates the methods section to include a description of the normalisation process of Arendt et al. (2006). This amendment was an excellent suggestion.

Figure 5-6 and 8. Caption and axis title are wrong. These are NOT mass balance curves. But curve of dh/dt

We have updated the figure captions now that we show surface lowering curves again.

Supplementary. Figure 2. With this color scale one does not see much. Supplementary figure 1 (which by the way is very convincing) suggests that a color scale between -15 to +15 (with a step of 5 m) would be more appropriate.

We have updated the figure as requested.

Editor- Tobias Bolch

I have received the reviews and studied your revision by myself carefully. Although both reviewers differ with the overall recommendation they both point out one major shortcoming which was not addressed: Using a geodetic approach, glacier mass balance can only be calculated for an entire glacier or region. However you used the SRTM DEM which has several data voids. Hence, it needs to be clearly written how you dealt with this problem. You need also provide more information about how you tackled outliers. If these issues are not treated adequately I cannot accept this paper.

In addition, the other reviewers comments I ask you to consider the following:

- Shorten the Abstract: A good word count is 250 words.

We have shortened the abstract to 263 words.

- P2, L5: Wrong statement. What is about Alaska? Lease also consider that the % of the volume of the glaciers is much lower than the area.

We have removed the incorrect statement from the manuscript. The introduction now begins with a slightly altered version of what was the second sentence.

- L. 22 Eastern Nyainqentanglha is not considred as being part of the Himalaya

We have removed mention of Eastern Nyainqêntanglha from the manuscript.

- L. 30: Although the sample is quite limited you may think about considering Basnet et al. 2013.

We have now cited the work of Basnet et al. (2013) in the introduction of the manuscript.

- P. 3, L 17: Hambrey et al. 2008 does only study Khumbu Glacier to my knowledge. Please check.

Hambrey et al. (2008) studied the Khumbu, Imja, Lhotse and Chukhung glaciers. These glaciers are good representations of land terminating and lacustrine terminating glaciers in the region, and also of glaciers with and without decoupled margins. There are few other studies that have assessed the glacial geomorphology of the region in such detail and we believe it is the best reference to cite here.

- P. 4, L. 5: Is it really only terminus recession? Please check.

Che et al. (2014) do not describe any particular pattern or style of glacier area loss so we have changed the wording of this sentence.

- L. 13: This number is difficult to interpret without knowing the extent of "Everest region". Please also consider other publications on glacial lakes in this region, e.g. those by Franco Salerno.

We have amended the text to better describe the spatial extent of studies that have mapped glacial water body extent in the area. We have also made mention of the studies of Salerno et al. (2012) and Watson et al. (2016).

- L. 21/23: supraglacial ≠proglacial…

We have rewritten this short section as the distinction between glaciers with proglacial and supraglacial lakes was previously quite poor. Thanks for pointing this out.

- P. 8, L. 5: Should be 2011.

Text amended.

- Section 4.2: What is about the uncertainty in area and area changes?

We have now followed the approach of Ye et al. (2006) to quantify the uncertainty associated with our total area change estimates. We have added area-weighted uncertainty estimates to the manuscript where necessary and updated Table 3 in the supplementary information.

- Sections 4.2.2 and 2.3 are rather short. I suggest to combine. A very interesting addition would be to add the hypsometry of the debris-covered vs. the debris-free glaciers.

Agreed and we have combined these two sections. We have also added more detail on the hypsometry of clean ice glaciers and made direct comparison with debris covered glaciers in our sample, although we haven't changed any of the figures including hypsometric curves (figures 5 and 6). We have also updated the manuscript to include ELA and AAR estimates for these clean glaciers.

- P. 14 L. 5ff: Rather speculative. What is about the influence of the overall topography and debris-cover?

We have added text to this section to point out that there are a number of other factors that could substantially influence the amount of ice mass loss that occurs in this region in the future, including the effect of evolving debris cover extent and thickness and the strength of the summer monsoon. Similarly, we have added text to state that the influence of ice flux divergence has not been considered in this study, to avoid convincing the reader that submergence or emergence velocities could be disregarded.

- Section 5.2: What is about Gardelle et al. 2013, Ye et al. 2015, Bolch et al. 2011 (latest period in this study)?

We already provided a summary and comparison between our results and those of Bolch et al. (2011) and Gardelle et al. (2013), but we have added a comparison with the results of Ye et al. (2015) and also Nickel et al. (2014) to give a more thorough discussion of the rate of glacier ice mass loss on the part of the Tibetan Plateau that our data covers. We have also added a Table (3) to summarise geodetic mass balance estimates for our study area, as requested by reviewer 1 (Joe Shea).

- Section 5.3: You may consider Thakuri et al. 2016, Ann. Glaciol.

Thanks for pointing this recently published paper out. We have incorporated the findings of Thakuri et al. (2016) into this section.

- Section 5.4: L. 11 There are also other studies who measured the velocity. Include at least one more (not necessarily mine) which would make the statement stronger. You may also be interested to read Ragettli et al. 2016 TCD. It is now accepted for TC.

We have added citations of the work by Scherler et al. (2008, 2011) and Luckman et al. (2007) to reinforce the statement about glacier stagnation in the Everest region.

- P. 16, ~L. 20. A word about the estimated distribution of the volume possible?

The paucity of ice thickness data available for glaciers across the region (other than the Khumbu) could make any estimate of the ablation zone' volume' expansion quite inaccurate, so we haven't attempted to do so.

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Spatial variability in mass loss of glaciers in the Everest region, central Himalaya, between 2000 and 2015

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Abstract. Region wide averaging of Himalayan glacier mass change has masked any catchment or glacier scale variability in glacier recession, thus the role of a number of glaciological processes in glacier wastage remains poorly understood. In this study, we quantify mass loss rates over the period 2000–2015 for 32 glaciers across the Everest region and assess how future ice loss is likely to differ depending on glacier hypsometry. The mean mass balance of all 32 glaciers in our sample was –0.52 ± 0.22 m water equivalent (w.e.) a^{-1}. The mean mass balance of 9 lacustrine terminating glaciers (–0.70 ± 0.26 m w.e. a^{-1}) was 32 % more negative than land-terminating, debris covered glaciers (–0.53 ± 0.21 m w.e. a^{-1}). The mass balance of lacustrine-terminating glaciers is highly variable (–0.45 ± 0.13 m w.e. a^{-1} to –0.91 ± 0.22 m w.e. a^{-1}), perhaps reflecting glacial lakes at different stages of development. To assess the importance of hypsometry on glacier response to future climate warming, we calculated current (Dudh Koshi- 0.37, Tama Koshi- 0.36, Tibetan Plateau- 0.40) and prospective future glacier Accumulation Area Ratios (AARs). IPCC AR5 RCP 4.5 warming (0.9-2.3 °C by 2100) could reduce AARs to 0.25 or 0.03 in the Tama Koshi catchment, 0.26 or 0.18 in the Dudh Koshi catchment, and 0.30 or 0.17 on the Tibetan Plateau. Our results are important because they suggest glacial lake expansion across the Himalaya could expedite ice mass loss and the prediction of future contributions of glacial meltwater to river flow will be complicated by spatially-variable glacier responses to climate change.

Keywords: Himalaya, glacier mass, debris-cover, Everest region, glacial lakes

1. Introduction

~~The Himalaya holds the largest store of glacier ice outside of the polar ice sheets.~~ Estimates of Himalayan glacier ice volume range from 2,300 km^3 to 7,200 km^3 (Frey et al., 2014 and references within) distributed amongst more than 54,000 glaciers across the Hindu Kush, Himalaya ~~(HKH)~~ and the Karakoram (Bajracharya et al., 2015). The current mass balance of Himalayan glaciers is predominantly negative, with accelerating mass loss having been observed over the past few decades (Bolch et al., 2012; Thakuri et al., 2014). This mass loss is occurring because of a combination of processes. Shrestha et al. (1999) show a rise in the mean annual air temperature of 0.057 °C/yr across the Himalaya between 1971 and 1994. Bollasina et al. (2011) show a reduction in total precipitation (–0.95 mm day^{-1}) amounting to 9 to 11% of total monsoon rainfall over a broad area of northern India between 1950 and 1999. Bhutiyana et al. (2010) show both decreasing total precipitation and a changing precipitation phase, with a lower proportion of precipitation falling as snow across the northwest Himalaya between 1996 and 2005. The snow cover season has been shortening as a result (Pepin et al., 2015). Under different climate scenarios, glacier imbalance in the region may contribute 8.7–17.6 mm of sea level rise by 2100 (Huss and Hock, 2015). Prolonged mass loss from Himalayan glaciers may cause diminishing discharge of the largest river systems originating in the region (Immerzeel et al., 2010; Lutz et al., 2014), thereby impacting on Asian water resources in the long-term.

Recent studies have identified spatial heterogeneity in mass loss across the Himalaya in the first decade of the 21^{st} century (Kääb et al., 2012; Gardelle et al., 2013; Kääb et al., 2015). Glaciers in the ~~Eastern Nyainqêntanglha, in the eastern Himalaya, are losing mass most quickly (Kääb et al., 2015), followed by glaciers in the~~ Spiti Lahaul and Hindu Kush are losing mass most quickly (Kääb et al., 2015). Glaciers in the central Himalaya appear to have less negative mass balances ~~be more stable~~ (Gardelle et al., 2013). The anomalous balanced, or even slightly positive, glacier mass budget in the Karakoram is well documented (Bolch et al., 2012; Gardelle et al., 2012). Few previous studies have assessed the variability of glacier mass loss within catchments (Pellicciotti et al., 2015). Nuimura et al. (2012) examined the altitudinal distribution of glacier surface elevation change in the Khumbu region, Nepal, and found similar surface lowering rates over debris-free and debris-covered glacier surfaces. Gardelle et al. (2013) detected enhanced thinning rates on lacustrine terminating glaciers in Bhutan, West Nepal, and the Everest region, but did not make an explicit comparison with land terminating glacier recession rates. Similarly, Basnett et al. (2013) have shown that lacustrine terminating glaciers in Sikkim, Eatern Indian Himalaya experienced greater area loss between ~1990 and 2010 compared to land terminating glaciers. Benn et al. (2012) proposed a conceptual model of Himalayan glacier recession that included important thresholds between regimes of ice dynamics and mass loss at different stages of lake development. Benn et al. (2012) also suggested idealised mass balance curves and equilibrium line altitudes (ELAs) that represent each of these regimes and in turn indicate likely future ice loss given sustained climatic forcing. A direct comparison of mass loss data and the model of Benn et al. (2012) is yet to be made, however.

~~In this work, w~~We aim to quantify glacier mass loss rates in three major catchments of the central Himalaya and assess the glacier-scale variability of ice loss within and between catchments. We specifically examine the mass balance, hypsometry and total area change of each glacier and compare those terminating in a glacial lake with those terminating on land. We use these data together with climatic data from the region to define the major mechanisms that may have driven mass loss in recent decades, and to assess scenarios of likely future ice loss from our sample of glaciers.

2. Study area

We studied glaciers in three catchments of the Everest region (Figure 1), spanning both Nepal and Tibet (China). Two of the catchments, the Dudh Koshi and the Tama Koshi, are located in north-eastern Nepal and drain the southern flank of the Himalaya. The third catchment is located to the north of the divide, and the glaciers drain north into Tibet (China). Most glaciers in the studied catchments are characterised by long (10–15 km), low-slope angle, debris-covered tongues that are flanked by large (tens of metres high) moraine ridges (Hambrey et al., 2008). Some glaciers have accumulation areas several kilometres wide, accumulation zones that reach extreme altitudes (up to 8000 m in the case of the Western Cwn of the Khumbu), whereas others sit beneath mountain massifs (e.g. Lhotse and the Lhotse face), are fed almost exclusively by avalanches and are less than 1 km in width for their entire length.

The largest 40 of 278 glaciers in the Dudh Koshi catchment account for 70% of the glacierised area (482 km^2- Bajracharya and Mool, 2009). These glaciers are all partially debris-covered, with debris mantles reaching at least several decimetres in thickness (Rounce and McKinney, 2014; Rowan et al., 2015). ~~Of the 278 glaciers in the Dudh Koshi catchment, the largest 40 are partially debris-covered, with debris mantles reaching at least several decimetres in thickness (Rounce and McKinney, 2014; Rowan et al., 2015), and comprise 70 % of the total glacierised area (482 km² - Bajracharya and Mool, 2009).~~ Here, the total area of glacier surface covered by debris has increased since the 1960s (Thakuri et al., 2014) and several previous studies have published surface lowering data for the catchment indicating accelerating surface lowering rates over recent decades (e.g. Bolch et al., 2011; Nuimura et al. 2012). We select nine of the largest glaciers (Supplementary table 1) for analysis given that they provide the greatest potential volume of meltwater to downstream areas.

There are a total of 80 glaciers in the Tama Koshi catchment covering a total area of 110 km^2 (Bajracharya et al., 2015). We again selected the largest nine glaciers (Supplementary table 1) for analysis based on relative potential contributions to river flow. The Tama Koshi~~is~~ is a poorly studied catchment, perhaps best known for the existence of Tsho Rolpa glacial lake, which underwent partial remediation during the 1990s (Reynolds, 1999).

The fourteen glaciers within our sample that flow onto the Tibetan Plateau (Supplementary table 1) all contribute meltwater to the Pumqu river catchment, which covers an area of 545 km^2 (Che et al., 2014). Debris cover is less prevalent on glaciers of the Pumqu catchment, and ~~terminus~~ glacier recession has caused a 19~~21~~ % of glacier area loss since 1970 (Jin et al., 2005; Che et al., 2014). There is relatively little information on glacier ELAs other than in the Dudh Koshi catchment. In the Dudh Koshi, Asahi et al. (2001) estimated ELAs to be at around 5600 m a.s.l. in the early 2000s. Wagnon et al. (2013) measured annually variable ELAs of 5430- 5800 m a.s.l. on the Mera and Polkalde glaciers between 2007 and 2012, Shea et al. (2015) estimate the current ELA to be 5500 m a.s.l., and Gardelle et al. (2013) estimated the ELA to be around 5840 m over the period 2000-2009. On the Tibetan Plateau, those in the Rongbuk catchment were estimated between 5800 and 6200 m a.s.l. for the period 1974-2006 (Ye et al., 2015).

A number of studies have identified an abundance of glacial water bodies in the Everest region. Salerno et al. (2012) identified 170 unconnected glacial lakes (4.28 km^2), 17 proglacial lakes (1.76 km^2) and 437 supraglacial lakes (1.39 km^2) in the Dudh Koshi catchment. Gardelle et al. (2011) identified 583 supraglacial ponds and lakes in ~~the Everest regio~~an area comparable in coverage to Figure 1. Watson et al. (2016) mapped 9340 supraglacial ponds on 8 glaciers of the Dudh Koshi catchment and the Rongbuk glacier in the Pumqu catchment. Watson et al. (2016) also show a net increase in ponded area for 6 of their 9 studied glaciers~~n~~. Some of the largest glacial lakes in this region have also been expanding in recent decades (Sakai et al., 2000; Che et al., 2014; Somos-Valenzuela et al., 2014). This increased meltwater ponding at glacier termini has potential to affect ice dynamics and down-valley meltwater and sediment fluxes (Carrivick and Tweed, 2013) as well as causing a hazard to populations living downstream. Several of the lakes have burst through their moraine dams in previous decades causing rapid and extensive flooding downstream; the best studied outburst floods are those from Nare glacier in 1977 (Buchroithner et al., 1982) and from Dig Tsho in 1985 (Vuichard and Zimmerman, 1987).

We classify nine glaciers from the sample as lacustrine terminating, where the glacier termini and glacial lakes are actively linked. We do not consider either the Rongbuk Glacier or the Gyabray Glacier as lacustrine terminating. The Gyabrag Glacier is now separated from a large proglacial lake by a large outwash plain and we do not believe the lake can have an influence on the retreat of the glacier. In the case of the Rongbuk Glacier, the lake is supraglacial and far up-glacier from its terminal region and thus does not currently influence the recession of the terminus of the glacier. The expanding Spillway Lake at the terminus of Ngozumpa Glacier

(Thompson et al., 2012) is currently of limited depth, and is unlikely to affect glacier dynamics in its current state so we also exclude the Ngozumpa from the lacustrine terminating category.

~~We classify nine glaciers from the sample as lacustrine terminating, where the glacier termini and glacial lakes are actively linked. While both the Gyabrag and Rongbuk glaciers are associated with a proglacial lake we do not consider either as lacustrine terminating. In the case of the Gyabrag Glacier the ice is now separated from the lake by a large outwash plain. In the case of the Rongbuk Glacier, the lake is supraglacial and far up-glacier from its terminal region and thus does not currently influence the recession of the terminus of the glacier. The expanding Spillway Lake at the terminus of Ngozumpa Glacier (Thompson et al., 2012) is currently of limited depth, and is unlikely to affect glacier dynamics in its current state so we also exclude the Ngozumpa from the lacustrine terminating category.~~

3. **Data sources and methods**

3.1 Data sources

3.1.1 Digital elevation models

Our reference elevation dataset across all three catchments is the Shuttle Radar Topographic Mission (hereafter SRTM) version 3.0, non-void filled, 1 arc second digital elevation model (hereafter DEM). The main objective of the SRTM mission was to obtain single-pass interferometric SAR imagery to be used for DEM generation on a near global scale (56˚S to 60˚ N- 80% of the planet's surface) with targeted horizontal and vertical accuracies of 16 m and 20 m, respectively, although Farr et al. (2007) report horizontal and vertical accuracies of better than 10 m for most regions globally.. This dataset was acquired in February 2000 and was released at 30 m resolution in late 2014 (USGS, 2016). The SRTM data we used was acquired by a 5.6 cm C-band radar system.

Our 2014/2015 elevation dataset comprises a number of high resolution (8 m grid) DEMs generated by Ohio State University and distributed online by the Polar Geospatial Centre at the University of Minnesota that provide coverage of an extended area around the Everest region (Table 1). These stereo-photogrammetric DEMs have been generated using a Surface Extraction with TIN-based Search-space Minimization (hereafter SETSM) algorithm from Worldview 1, 2 and 3 imagery (Noh and Howat, 2015). The SETSM algorithm is designed to automatically extract a stereo-photogrammetric DEM from image pairs using only the Rational Polynomial Coefficients (RPCs) as geometric constraints. The geolocation accuracy of RPCs without ground control for Worldview 1 and 2 data is 5 m (Noh and Howat, 2015) which may ultimately result in matching failure. The SETSM algorithm updates RPCs to mitigate this error and produces DEMs with an accuracy of ± 4 m in X, Y and Z directions (Noh and Howat, 2015). SETSM DEMs are gap-filled using a natural neighbour interpolation; we removed these pixels before DEM differencing and the calculation of mass loss rates across the ablation areas of individual glaciers.

Over two small areas of the Dudh Koshi (over the lower reaches of the Bhote Kosi and Melung glaciers) the SETSM DEMs contained data gaps. To complete coverage of DEMs over these glaciers we generated ASTER DEMs and used the surface to cover elevation bands across these glaciers where no data were available from the SETSM grids. We used ERDAS Imagine (2013) to generate ASTER DEMs with ground control points (GCPs) matched between features in the ASTER imagery and the high resolution imagery available in Google Earth. We used a large number of GCPs (45) and tie points (> 75) to minimise the root mean squared (RMS) error of GCP positions. All SETSM and ASTER DEMs were resampled to a 30 m resolution to match that of the SRTM data before any differencing was carried out.

3.1.2 Glacier outlines

Glacier outlines were downloaded from the Global Land Ice Measurement form Space (GLIMS) Randolph Glacier Inventory (RGI) Version 5.0 (Liu and Guo, 2014; Bajracharya et al., 2014; Racoviteanu and Bajracharya, 2008) and modified for 2000 and 2014 glacier extents based on Landsat scenes closely coinciding in acquisition with the DEM data. Glacier extents from these two epochs were used to calculate area changes. The 2000 Landsat scene was acquired by the ETM+ sensor and thus has a single 15 m resolution panchromatic band and six 30 m multispectral bands. The 2014 scene was acquired by the OLI sensor and also has a single 15 m panchromatic band as well as eight 30 m multispectral bands. Both scenes were pan-sharpened to match the resolution of the multispectral bands to that of the panchromatic band before glacier outlines were adjusted. Adjustments were limited to correcting changes in glacier frontal position and changes along the lateral margins because of surface lowering.

3.2 DEM correction

3.2.1 Stereoscopic DEMs

We followed the three-step correction process of Nuth and Kääb (2011), through which biases inherent in stereoscopic DEMs can be corrected. We assessed and corrected where necessary for: (i) mismatch in the geo-location of the modern DEMs versus the reference SRTM dataset (in x, y, and z direction); (ii) the existence of an elevation dependant bias, and; (iii) biases related to the acquisition geometry of the data. Each step was taken individually, so that separate error terms could be understood, rather than bundling them together as multiple regression based adjustments as previous studies have done, such as Racoviteanu et al. (2008) and Peduzzi et al (2010), for example. Corrections applied to DEMs where any one of the three biases were present included shifting of DEM corner coordinates, simple vertical shifting through addition or subtraction, and the fitting of linear and polynomial trends depending on the spatial variability of elevation differences across DEMs and through their elevation ranges. Acquisition geometry related biases (along or cross satellite track) were detected in two SETSM strips (Table 3) and both ASTER scenes and were corrected for using linear trends fitted through difference data. DEM co-registration was carried out following the conversion of SETSM elevation data to geoid heights using the Earth Gravitational Model (EGM) 2008 grid available from the National Geospatial-Intelligence Agency.

3.2.2 SRTM DEM correction

Some studies have shown that the SRTM dataset may underestimate glacier surface elevations because of C-band radar wave penetration into snow and ice (Rignot et al., 2001). Kääb et al. (2012) assessed the magnitude of C-band penetration over various test sites in the Himalaya and over different ice facies (clean ice, snow and firn) by extrapolating ICESat Vs SRTM glacier elevation differences back to the SRTM acquisition date, showing penetration estimates of several metres. To account for this bias, we have corrected the SRTM dataset using the penetration estimates of Kääb et al. (2012), after generating a mask for clean ice, firn and snow cover using the most suitable Landsat ETM+ scenes (Table 1) available around the acquisition date of the SRTM dataset. We applied a correction to the SRTM DEM of +4.8 m over areas of firn/snow, and +1.2 m over areas of clean ice (see supplementary table S2 of Kääb et al. (2012)). We do not apply any penetration correction over debris-covered areas given the uncertainty expressed by Kääb et al. (2012) about the influence of possibly greater than average snowpack depth at the point of ICESat acquisition and the properties of the snowpack at the point of SRTM data acquisition on their penetration estimate.

Berthier et al. (2006) suggested that the extreme topography present in mountain regions is poorly replicated in coarse-resolution DEMs such as the SRTM DEM. Different studies have applied positive or negative corrections to the SRTM DEM (Berthier et al., 2007; Larsen et al., 2007), depending on the severity of the terrain at their respective study sites. Inspection of DEM differences across the study site showed no clear relationship between elevation differences and altitude (see supplementary information Figure 1), thus no elevation dependant correction was applied.

3.2.3 Gap filling and outlier filtering

Once DEMs had been co-registered and corrected for present biases, DEMs were differenced to yield surface elevation change data. To remove outlying values, we firstly excluded obviously incorrect difference values, (exceeding ± 120 m) and then followed the approach of Gardelle et al. (2013) in using the standard deviation of DEM difference data to classify probable outliers. We removed values exceeding 3 standard deviations. Such outlier definitions are justified in areas of shallow slope and high image contrast where DEM quality is generally higher (Ragettlie et al. 2016), but could be considered lenient where featureless surfaces, for example snow covered areas of accumulation zones, might lead to poor elevation data derivation and limit the accuracy of stereoscopic DEMs. Noh and Howat (2015) show how the iterative approach of the SETSM algorithm and the high spatial and radiometric resolution of WorldView imagery preclude such an issue, and we therefore consider a 3 standard deviation threshold appropriate.

To complete data coverage and allow for glacier mass balance estimates, the filling of data gaps was required. Only small gaps were present in DEM difference data over most of the glaciers in our sample, but some larger gaps could be found over areas of steep surface slope, for example high in accumulation zones, or where deep shadows might have been extensive in WorldView imagery. We filled gaps in DEM difference data using median values from the 100 m elevation band in which the data gap was situated (Ragettli et al. 2016).

3.3 **Uncertainty**

3.3.1. DEM differencing uncertainty

Our elevation change uncertainty estimates have been calculated through the derivation of the standard error ($E_{\Delta h}$) - the standard deviation of the mean elevation change- of 100 m altitudinal bands of elevation difference data (Gardelle et al., 2013; Ragettli et al., 2016):

$$E_{\Delta h} = \frac{\sigma_{stable}}{\sqrt{N}}$$

Where σ_{stable} is the standard deviation of the mean elevation change of stable, off-glacier terrain, and N is the effective number of observations (Bolch et al., 2011). N is calculated through:

$$\boldsymbol{N} = \frac{\boldsymbol{N_{tot} \cdot PS}}{\boldsymbol{2d}} \qquad (1)$$

Where N_{tot} is the total number of DEM difference data points, PS is the pixel size and d is the distance of spatial autocorrelation. We follow Bolch et al. (2011) in estimating d to equal 20 pixels (600 m). $E_{\Delta h}$ for each DEM is the sum of standard error estimates of each altitudinal band (Gardelle et al., 2013).

We have also considered whether the different acquisition dates of Worldview imagery (Table 1) has led to the sampling of seasonal glacier surface elevation variations caused by a remnant snowpack (e.g. Berthier et al. 2016). Such a bias should be partly corrected for during vertical DEM adjustment using off-glacier terrain assuming a similar snowpack thickness on and off-glacier (Wang and Kääb, 2015). Two overlapping SETSM DEMs (ending FA100 and 3C00 in Table 1) have been generated from Worldview imagery acquired before and after the summer monsoon (when glaciers receive most accumulation) of 2014, thus any spatially consistent vertical differences may show a remnant snow pack that would cause an elevation bias. The difference between these two SETSM DEMs over the Bamolelingjia and G1 glaciers is slight (mean 0.69 m, σ 3.81 m), but we cannot be sure that these differences represent a region-wide average. We have incorporated the mean elevation difference of these SETSM DEMs over glacier surfaces (dZ_{season}) into our overall uncertainty budget. We summed different sources of error quadratically to calculate our overall uncertainty ($\sigma_{dh/dt}$) associated with DEM difference data:

$$\sigma_{dh/dt} = \sqrt{E_{\Delta h}^2 + dZ_{season}^2} \qquad (2)$$

$\sigma_{dh/dt}$ is then weighted depending on the hypsometry of each glacier, giving a glacier specific measure of elevation change uncertainty that considers the spatially nonuniform distribution of uncertainty (Ragettli et al., 2016).

3.3.2 Glacier area change uncertainty

There are two principle sources of uncertainty in the measurement accuracy of the position of a glacier margin; sensor resolution and the co-registration error between the images acquired at each measurement epoch (Ye et al., 2006; Thakuri et al., 2014). We follow the approach of Ye et al. (2006) to quantify the uncertainty associated with the total area changes documented across our sample of glaciers. We incorporate geolocation accuracy estimates of 10.5 m for Landsat ETM+ imagery and 6.6 m for Landsat OLI imagery (Storey et al., 2014) into the uncertainty budget and suggest the total measurement uncertainty in glacier area between 2000 and 2015 image sets was ± 0.04 km^2 a^{-1}. Area weighted, glacier specific uncertainty estimates are given in supplementary table 3.

~~3.3~~3.4 Hypsometric analyses and elevation range normalisation

Glacier hypsometry, the distribution of glacier area over altitude, is governed by valley shape, relief and ice volume distribution (Jiskoot et al., 2009). It is important for long-term glacier response because it defines the distribution of mass with elevation and thus determines how the glacier responds to changes in elevation-dependent temperature (Furbish and Andrews, 1984). To assess glacier hypsometry, we used the aforementioned glacier outlines and the SETSM DEMs, which offer better data coverage than the non void filled SRTM dataset, to split these glacier extents into segments covering 100 m elevation ranges, and calculated the area of each segment. We followed the approach of Jiskoot et al. (2009) to categorise each glacier or the population of glaciers in each catchment according to a hypsometric index (HI), where:

$$\boldsymbol{HI} = \frac{(\boldsymbol{H_{max}} - \boldsymbol{H_{med}})}{(\boldsymbol{H_{med}} - \boldsymbol{H_{min}})} \quad (3\cancel{6})$$

and H_{max} and H_{min} are the maximum and minimum elevations of the glacier, and H_{med} the median elevation that divides the glacier area in half (Jiskoot et al., 2009). Glaciers were grouped into five HI categories: 1- HI < –1.5, very top heavy; 2- HI –1.2 to –1.5, top heavy; 3- HI –1.2 to 1.2, equidimensional; 4- HI 1.2 to 1.5, bottom heavy; and 5- HI > 1.5, very bottom heavy. Top heavy glaciers store more ice at higher elevation, for example in broad accumulation zones, whereas bottom heavy glaciers have small accumulation zones and long tongues.

To construct elevation change and glacier hypsometry curves for the 32 glaciers in our sample, we have normalised the elevation range of each glacier following the method of Arendt et al. (2006):

$$H_{norm} = \frac{(H - H_{min})}{(H_{max} - H_{min})}$$

where H_{min} and H_{max} are the elevations of the glacier terminus and the elevation maximum of each glacier. This normalisation process allows the direct comparison of elevation changes and glacier hypsometry regardless of termini elevation. Surface elevation change and glacier hypsometry curves are presented in Figures 5 and 6.

3.5 Mass loss calculations

A conversion factor of 850 kg m^{-3} was used to account for the density of glacier ice for all glaciers in the sample (Huss, 2013). ~~As in previous mass loss studies in the Himalaya (Bolch et al., 2011; Gardelle et al., 2013) a conversion factor of 900 kg m~~$\cancel{^{-3}}$ ~~was used to account for the density of glacier ice for all glaciers in the sample.~~ We assigned an additional 7 % to mass loss uncertainty estimates to account for error in the density conversion (Huss, 2013). The mass loss estimates generated for lacustrine terminating glaciers are slight underestimates because, with no information available on bed topography, we cannot account for ice that has been replaced by water during lake expansion. Mass balance estimates for these glaciers therefore only incorporate aerial mass loss from the 2000 calving front, up-glacier. We also acknowledge that our surface lowering estimates incorporate any upward or downward flow of ice resulting from, for example, compressional flow over a zone of transition from active to inactive ice. We do not quantify emergence velocity as the ice thickness and surface velocity data required to do so (Immerzeel et al. 2014) are not available for an adequate number of glaciers in our sample.

3.6 Estimation of ELAs

We follow the method of Nuth et al. (2007) to estimate the ELA of glaciers in our sample. We calculate mean ~~mass balance~~surface lowering rates over 100 m elevation bands for the entire altitudinal range of each glacier, and assume that the altitude at which ~~mass balance~~surface lowering curves approach zero is a reliable ~~indicator~~ proxy of the ELA of each glacier over the study period. The surface elevation change at a glaciers surface is not a direct measure of its surface mass balance because of ice flux divergence. However, the ELA is the point in the glacier system where submergence and emergence should be at a minimum (Cherkasov and Ahmetova, 1996; Rowan et al., 2015), thus we use the point of zero elevation change as an approximation of ELA position (see Huss and Farinotti (2012) their figure 1 and Farinotti et al. (2009) their Figure 11).

To estimate prospective future ELAs in response to climatic warming, we used ~~adiabatic lapse rates~~vertical temperature gradients of –8.5 °C/km for the Tibetan Plateau (Kattel et al., 2015) and –5.4 °C/km for the Dudh Koshi and Tama Koshi catchments (Immerzeel et al., 2014) to calculate prospective ELA shifts given different warming scenarios. We calculated ELAs for projected minimum, mean and maximum temperature increases under the 4 main RCP scenarios outlined in the IPCC AR5 working group report (Collins et al., 2013).

4 Results

4.1 Glacier mass balance

The mean mass balance of all (32) glaciers in our sample was –0.52 ± 0.22~~7~~ m w.e. a^{-1} between 2000 and 2015. There is considerable variability~~ in the~~ in the mass balance ~~rates~~ of glaciers with different terminus type (Figures 3 and 4) and in the rates of surface lowering through the altitudinal range of highlighted glaciers (Figures 5 and 6)~~,~~. The mean mass balance of glaciers in catchments either side of the orographic divide are not markedly different, however.

Mean glacier mass balance (including land and lake terminating glaciers) was –0.51 ± 0.22 m w.e. a^{-1} in the Tama Koshi catchment, –0.58 ± 0.19 m w.e. a^{-1} in the Dudh Koshi catchment, and –0.61 ± 0.24 m w.e. a^{-1} for glaciers flowing onto the Tibetan Plateau over the study period. The mean mass balance of 9 lacustrine terminating glaciers was –0.70 ± 0.26~~9~~~~44~~ m w.e. a^{-1}. This was 32% more negative than land terminating glaciers (mean mass balance of –0.53 ± 0.21 m w.e. a^{-1}) we include in our sample. The lowest mass loss rates occurred over debris-free glaciers at high altitude (5600 – 6200 m a.s.l) on the Tibetan plateau. The mean mass balance of these glaciers was –0.25 ± 0.26~~40~~ m w.e. a^{-1} ~~m a^{-1}~~ (supplementary table 2) over the study period.

4.2 Variability in surface lowering

The altitude at which maximum ~~mass loss rates~~surface lowering rates occurred differed depending only on glacier terminus type (Figures 5 and 6). Across all three catchments, substantial ~~mass loss~~surface lowering was pervasive over the middle portions of larger, land terminating glaciers (Figure 2). In the Dudh Koshi, surface lowering rates are at their highest (–1.06 ± 0.13~~40~~ m ~~w.e.~~a^{-1}) around 5200 m a.s.l., although similar surface lowering rates occurred between 5100 and 5300 m a.s.l (Figure 5). In the Tama Koshi the highest rates ~~mass loss~~of surface lowering (–1.08 ± 0.15~~44~~ m ~~w.e.~~a^{-1}) occurred at around 5~~3~~400 m a.s.l (Figure 5). On the Tibetan Plateau, the highest ~~mass loss~~mean surface lowering rates ~~were almost double those of the Tama Koshi or Dudh Koshi catchments.~~again occured ~~B~~between 5300 and 5400 m a.s.l.;~~,~~ the mean ~~mass loss~~surface lowering rate at this altitude was –1.62~~96~~ ± 0.16~~40~~ m w.e. a^{-1} over the study period. ~~Mass loss~~Surface lowering rates over glaciers on the Tibetan Plateau were higher than those in the Tama and Dudh Koshi catchments (Figure 5) up to 57~~7~~00 m a.s.l. (–1.24~~19~~ ± 0.21~~40~~ m a^{-1} ~~m a^{-1}~~ at this altitude). Of note is the ~~mass loss~~surface lowering over clean ice areas high up on glaciers such as the Ngozumpa, Rongbuk, Gyabrag and Bhote Kosi (Figure 2). Surface lowering extended into tributary branches and the cirques of these largest glaciers. Individual glaciers showed much greater ~~mass loss~~surface lowering, particularly on the Tibetan Plateau. The Gyabrag glacier lost an exceptional –3.33 ± 0.28~~35~~ m ~~w.e.~~a^{-1} between 5300 and 5400 m a.s.l (Figure 5).

The maximum surface lowering~~mass loss~~ rates (–2.79~~36~~ ± 0.39~~44~~ m ~~w.e.~~a^{-1}) occurred at the lowest elevations (between 4700 and 4900) of lacustrine terminating glaciers (Figure 6). These 9 glaciers all showed a linear ~~ablation~~ surface lowering gradient. We calculate the ~~ablation~~ lowering gradient as ~~the water equivalent of ice melt~~surface elevation change per 100 m (m ~~w.e.~~a^{-1}/100 m) vertical elevation change below the ELA. Lacustrine terminating glaciers showed an ~~ablation~~ lowering gradient of 0.57 m ~~w.e.~~a^{-1}/100 m over the study period. The ~~ablation~~ lowering gradient of land terminating glaciers was non-linear. Surface lowering was negligible around the terminus of most land terminating glaciers, with enhanced ice loss occurring further up-glacier where debris cover may have been thin or patchy. ~~Ablation~~ Lowering gradients for the area of land terminating glaciers between the ELA and the altitude of maximum ice loss were 0.49, 0.72 and 0.52 m ~~w.e.~~a^{-1}/100 m for glaciers on the Tibetan Plateau, and in the Dudh Koshi and Tama Koshi catchments, respectively. Clean ice glaciers also showed a linear ~~ablation~~ lowering gradient- 0.77 m w.e. a^{-1}/100 m. Individual glacier mass balance estimates can be found in the supplementary information.

4.3~~2~~ Glacier area changes and hypsometry

4.3~~2~~.1 Total area changes

Two different patterns of ice area loss occurred over the study area during the last 15 years. Lacustrine terminating glaciers and clean ice glaciers all lost ice around their termini/ calving fronts (Figures 3 and 4) as glacial lakes expanded and termini retreated. On average, lacustrine terminating glaciers each lost 0.54 ± 0.07 km^2 of ice (3.58% of their total area) over the 15 year study period. Drogpa Nagtsang reduced in size by 2.37 km^2 (9.12 % of its total area: Supplementary Table 3) as the associated rapidly-forming lake expanded. Clean ice glaciers lost 0.09 ± 0.03 km^2 of ice (1.31 % of their total area) on average.

Land terminating glaciers lost little area as their surfaces lowered rather than their termini retreating. In the Tama Koshi and Dudh Koshi catchments, and on the Tibetan Plateau, land terminating glaciers lost a mean of 0.14 ± 0.12 km^2 (0.50 % of their total area), 0.09 ± 0.13 km^2 (0.60 % of their total area) and 0.41± 0.12 (1.77 % of their total area) of ice, respectively. Over these glaciers, any ice area loss was concentrated up-glacier, where their lateral margins dropped down inner moraine slopes and glacier tongues narrowed slightly.

Overall, our sample of glaciers lost 0.12 ± 0.04 % of their total area per year over the study period. This figure is identical to that of Bolch et al. (2008) who assessed area change over a smaller number of the same glaciers in our sample between 1962 and 2005. The annual area change rate we calculate is lower than those estimated by Thakuri et al. (2014) and references within. Thakuri et al. (2014) calculated a median annual surface area change rate of –0.42 ± 0.06 % a^{-1} in the Dudh Koshi catchment between 1962 and 2011. However, Thakuri et al. (2014) document area change over a number of smaller glaciers that are free of debris cover, and therefore readily advance or retreat in response to climatic change, thus our estimates are not directly comparable.

4.4~~2~~.2 Glacier hypsometry and approximate ELAs

The distribution of ice with elevation varies widely among the three studied catchments (Figures 5 and 6). Debris covered ~~G~~glaciers of the Dudh Koshi catchment and on the Tibetan Plateau are typically very bottom heavy, with average HI scores of 2.63 and 2.34, respectively (Supplementary Table 1). Glacier hypsometry is concentrated between 4800 and 5500 m (Figure 5) for the Dudh Koshi catchment, and between 5600 and 6500 m on the Tibetan Plateau. Notable exceptions are the Khumbu and Ngozumpa Glaciers which store ice in broad accumulations zones above 7000 m (Supplementary Tables 1 and 2). The majority of glaciers in the Tama Koshi have an equi-dimensional hypsometry (mean HI of 1.14), with most ice stored between 5300 and 5800 m. Glaciers in the Tama Koshi have broader accumulation basins than in the Dudh Koshi catchment, and main glacier tongues are formed of multiple, smaller tributaries flowing from higher altitude in a number of cases (Figure 1). The mean hypsometry (Figure 6) of lacustrine terminating glaciers shows no distinctive morphology as the sample is composed of glaciers from all three catchments in the study area. Clean ice glaciers have a mean HI score of 1.18 and could therefore be summarised as equidimensional, but the morphology of the 5 glaciers we assess is highly variable (see supplementary Table 3). In complete contrast to debris-covered glaciers, their ice is stored at much higher altitudes on average- primarily between 6000 and 6500 m (Figure 6).

~~4.2.3 Approximate equilibrium line altitudes~~

We estimate the mean ELA of debris covered glaciers glaciers in the Dudh Koshi and Tama Koshi catchments, and of our selection of glaciers on the Tibetan Plateau to be 5742~~57~~, 5633~~77~~, and 6155~~066~~ m a.s.l., respectively, although, as Figures 5 and 6 show, the altitude of zero surface lowering~~ELA~~ can differ by hundreds of metres on individual glaciers within each catchment. We estimate the mean ELA of the 5 clean ice glaciers in our sample to be 6180 m. Using those ELAs the accumulation area ratio (AAR) (Dyurgerov et al., 2009) can be estimated for each glacier and this is a parameter strongly related to long-term mass balance (König et al., 2014). We have calculated mean AARs of 0.37, 0.36 and 0.40 for debris covered glaciers in the Dudh Koshi and Tama Koshi catchments, and on the Tibetan Plateau, respectively. The mean AAR of clean ice glaciers in our sample is 0.29.

5 Discussion

5.1 Variability in rates of ice loss across the orographic divide

The mean mass balance estimates we have derived for glaciers situated in catchments North and South of the orographic divide are not markedly different. However, the contrast in maximum of ~~mass loss~~surface lowering (Figure 5) from glaciers flowing north of the divide and the sustained mass loss through a broader portion of their elevation range (Figure 5) suggests an additional or amplified process has driven glacier change north of the divide~~here~~ over recent decades. In this section we discuss possible topographic and climatic drivers of the difference in the rates of mass loss across the range divide.

The Indian summer monsoon delivers ~~extremely large amounts of~~a large proportion of total annual precipitation (up to 80% of the total annual amount) to the Everest region of Nepal, resulting in high glacier sensitivity to temperature (Fujita, 2008; Sakai et al., 2015). The extreme topography in this region and the location of the orographic divide perpendicular to the prevailing monsoon result in rainfall peaks that are offset from the maximum elevations, with greatest rainfall occurring to the south of the divide and decreasing to the north across the Everest region (Bookhagen and Burbank, 2010; Wagnon et al. 2013). Around 449 mm a^{-1} of rainfall falls at the Pyramid research station (5000 m a.s.l.) at Khumbu Glacier (Salerno et al., 2015), whereas to the north at Dingri on the Tibetan Plateau (4300 m a.s.l.), 263 ± 84.3 mm a^{-1} of rainfall occurs annually (Yang et al., 2011). Snowfall may follow a similar across-range gradient to rainfall, although falling snow may be carried further into the range by prevailing winds from the south. However, no reliable measurements of snowfall exist in this region with which to compare these trends. The north-south precipitation gradient across the orographic divide promotes differences in the response of these glaciers to climate change, such that those to the north are relatively starved of snow accumulation (Owen et al., 2009) and exposed to greater incoming radiative fluxes under generally clearer skies. Owen et al. (2009) suggest that this precipitation gradient resulted in greater glacier sensitivity to climate change on the northern slopes of the Himalaya during the Late Quaternary, with asymmetric patterns of ELA rise occurring since the Last Glacial Maximum (LGM).

During the period of this study (2000–2015), mean annual air temperatures have increased and rainfall amounts appear to have decreased in the Everest region (Salerno et al., 2015). At the Pyramid Observatory at Khumbu Glacier in the Dudh Koshi catchment, increases in minimum (+0.07 °C/a), maximum (+0.009 °C/a) and mean (+0.044 °C/a) annual air temperatures above 5000 m a.s.l. were observed between 1994 and 2013 (Salerno et al., 2015). At Dingri on the Tibetan Plateau 60 km northeast of Mt. Everest, increases in minimum (+0.034~~7~~ °C/a), maximum (+0.041 °C/a) and mean (+0.037 °C/a) annual air temperatures occurred over the same period (Salerno et al., 2015). Yang et al. (2011) found a clear relationship between increasing temperatures over time at Tingri and at temporary (operational between May 2007 and August 2008) weather stations on the Rongbuk and East Rongbuk glaciers, and suggest that the increases in temperature at Tingri have been replicated at glacierised altitudes. Yang et al. (2011) also show a longer-term increase in the mean annual air temperature at Dingri, as do Shrestha et al. (1999) across the southern flank of the greater Himlaya. Between 1959 and 2007, the mean annual air temperature increased by 0.06 °C/a at Dingri (Yang et al., 2011). Shestha et al. (1999~~0~~) calculated an increase in the mean annual air temperature of 0.057 °C/a between 1971 and 1994 across a number of sites in the greater Himalaya.

The snowline altitude also appears to have increased recently on the southern flank of the Himalaya; Thakuri et al. (2014) showed a rapid ascent of the snow-line altitude in the Dudh Koshi between 1962 and 2011 (albeit through documenting transient snowlines from single scenes acquired at each epoch), and Khadka et al. (2014) suggest declining snow cover over the winter and spring months in the glacierised altitudinal ranges of the Tama

Koshi catchment, between 2000 and 2009; a factor that may influence accumulation rates. Kaspari et al. (2008) showed decreasing accumulation in the East Rongbuk Glacier Col (6518 m a.s.l.) on the northern side of Mount Everest between the 1970s and 2001.

We suggest that the north–south orographic precipitation gradient across the main divide may have caused greater surface lowering rates on glaciers on the Tibetan Plateau than those glaciers to the south over the study period. We also suggest that measured, contemporary increases in air temperature, observations of increasing snowline altitude and declining accumulation are likely to enhance glacier mass loss across the range in future, but considerable unknowns remain in the temporal evolution of debris cover extent and thickness (Thakuri et al., 2014), the strength of the summer monsoon in coming decades (e.g. Boos et al., 2016), and the expansion or shrinkage of glacial lakes (see section 5.3), all of which could additionally influence future glacier mass balance.

5.2 Comparison of mass balance estimates with other studies

Several other studies have generated geodetic mass balance estimates for glaciers of the Everest region over several different time periods. Bolch et al. (2011) measured a mass balance of –0.32 ± 0.08 m w.e. a^{-1} for ten glaciers to the south and west of Mt Everest over the period 1970-2007. Nuimura et al. (2012) calculated a regional mass balance of –0.45 ± 0.25 m w.e. a^{-1} for 97 glaciers across the region over the period 1992-2008. Kaab et al. (2012) estimated a mass balance of –0.39 ± 0.11 m w.e. a^{-1} for a 3° x 3° cell centred on the Everest region between 2003 and 2008. Gardelle et al. (2013) calculated a slightly less negative mass balance of –0.26 ± 0.13 m w.e. a^{-1} between 1999 and 2011, although the SRTM penetration correction applied by Gardelle et al. ~~(2013)~~ may have caused bias towards less negative mass balance (Kääb et al. 2012; Barundun et al., ~~(~~2015). ~~Our results~~The regional mass balance of –0.54 ± 0.27 m w.e. a^{-1} that we have calculated suggests that the mass loss rates measured by Bolch et al. (2012), Nuimura et al. (2012) and Kääb~~Kaab~~ et al. (2012) have been sustained and possibly increased in recent years.

On the Tibetan Plateau, Neckel et al. (2014) estimated the mass balance of glaciers on the northern side of the orographic divide in the central and eastern Himalaya (their sub-region G) to be –0.66 ± 0.36 m w.e. a^{-1} between 2003 and 2009. The mass balance of glaciers in our sample within the same region was –0.59 ± 0.27 m w.e. a^{-1} between 2000 and 2015. Ye et al. (2015) estimated glacier mass balance to be –0.40 ± 0.27 m w.e. a^{-1} in the Rongbuk catchment between 1974 and 2006, suggesting that glacier ice mass loss rates may have increased over the last decade in this area of the Tibetan Plateau.

5.3 The influence of glacial lakes on glacier mass balance

Only Nuimura et al. (2012) have directly compared mass loss rates of lacustrine and land terminating glaciers in the study area, showing faster surface lowering rates over Imja and Lumding glaciers in the Dudh Koshi catchment. Our data confirm that lacustrine terminating glaciers can indeed lose ice at a much faster rate than land terminating glaciers. The variability in the mass balance of the 9 lacustrine terminating glaciers (Figure 6) we highlight suggests the fastest mass loss rates occur in the later stages of lake development. Glaciers such as the Yanong and Yanong North, in the Tama Koshi catchment, sit behind large proglacial lakes and ~~have shown extremely high mass loss rates~~are in a state of heavily negative mass balance (–0.76 ± 0.19 and –0.62 ± 0.19 ~~3~~ m w.e. a^{-1}, respectively). Their surfaces lowered by 3 m a^{-1} or more over their lower reaches~~ (~~(Figure 6) over the study period. These glaciers are now relatively small and steep and no longer possess a debris-covered tongue, and so may represent the end-product of debris-covered glacier wastage described by Benn et al. (2012). In contrast, glaciers such as Duiya~~ or Longmojian~~, on the Tibetan Plateau, currently has~~ve~~ only a small lake~~s~~ at its~~their~~ termini, showed moderate area losses (~~0.44 and~~ 0.5 km^2, or 4.28~~ and 2.07~~ % of its total area~~, respectively~~) and ~~mass loss rates~~moderately negative mass balance (~~–1 to 2~~–0.45 ± 0.16 m w.e. a^{-1}) over the study period. Continued thinning of the terminal regions of these glaciers would lead to a reduction in effective pressure, an increase in longitudinal strain and therefore flow acceleration (Benn et al., 2007). The retreat of the calving front up-valley into deeper bed topography may also increase calving rates (Benn et al., 2007), and a combination of both of these processes would lead to enhanced ice loss. Very little surface velocity data exist for lacustrine terminating debris-covered glaciers. Only Quincey et al. (2009) measured high surface velocities (25 m a^{-1}~~/a^{-1}~~ or more) over the Yanong glacier (their Figure 4, panel D), suggesting it is possible for lacustrine terminating glaciers to become more dynamic in the later stages of lake development in the Himalaya. Conversely, Thakuri et al. (2016) have shown flow deceleration of glaciers that coalesce to terminate in Imja Tsho over the period 1992-2014, and suggest that reduced accumulation caused by decreasing precipitation is responsible for diminishing surface flow on this glacier. Clearly, more expansive investigation into the evolving dynamics of lacustrine terminating glaciers in the Himalaya is required if we are to better understand their potential future mass loss.

5.4 Glacier stagnation

A number of studies (Luckman et al. 2007; Scherler et al. 2008, 2011; Quincey et al. 2009) have shown how many glaciers in the Everest region appear to be predominantly stagnant, with large parts of the long, debris covered glacier tongues in the area showing little to no flow.~~Quincey et al. (2009) identified a number of glaciers in the Everest region that appear to be predominantly stagnant, with large parts of the long, debris~~

~~covered glacier tongues in the area showing little to no flow.~~ Watson et al. (2016) have documented an increasing number and total area of supraglacial melt ponds over a number of the same glaciers studied by Quincey et al. (2009) in the Dudh Koshi catchment (Khumbu, Ngozumpa, Lhotse, Imja and Ama Dablam), since the early 2000's. Over these glaciers, our data show a very distinctive surface lowering pattern (Figure 2), with localised, heterogenous surface lowering appearing to mirror the distribution of large supraglacial ponds and ponds networks. This ice loss pattern is prevalent on the Erbu, Gyachung, Jiuda, Shalong, and G1 glaciers (Figure 2), and high resolution imagery available on Google Earth shows that these glaciers also have well developed networks of supraglacial ponds. We would therefore suggest that large parts of the biggest glaciers in the Tama Koshi catchment and on the Tibetan Plateau are also stagnant, and may see increasing supraglacial meltwater storage in the future, similar to that documented by Watson et al. (2016).

5.5 Susceptibility of glaciers to future mass loss

5.5.1 ELA ascent in response to warming

The coincidence of maximum surface lowering rates with the altitude of maximum hypsometry in the Dudh Koshi catchment (Figure 5) ~~means a large amount of ice is readily available to sustain mass loss rates~~suggests large glacier mass losses ~~here~~in this catchment. Sustained and prolonged mass loss may lead to a bi-modal hypsometry here, with the separation of debris covered glacier tongues and their high-elevation accumulation zones a possibility (Rowan et al., 2015; Shea et al., 2015). Surface lowering maxima in the Tama Koshi catchment presently occur at a slightly lower elevation range than the main hypsometric concentration, and across lower reaches of glacier tongues on the Tibetan Plateau.

Our ELAs are above those estimated by Asahi (2001) for an earlier epoch (see section 2) and similar to those estimated by Gardelle et al. (2013) over a similar study period to ours, suggesting that ELAs have indeed risen over recent decades. ~~We have calculated prospective, future AARs for glaciers in our sample based on ELA rise driven by temperature increases under the four main Representative Concentration Pathways (RCPs) used by the IPCC in its fifth Assessment Report (AR5).~~ Figure 7 shows ~~these~~ projected AARs, averaged across each catchment, in response to different levels of temperature rise. These predictions are based on published lapse rates (Immerzeel et al., 2014; Kattel et al., 2015) that may be spatially variable and assume no changes in precipitation type or amount, or any variability in the contribution of avalanches to accumulation.

To allow the comparison of our results with similar estimates of other studies (Shea et al., 2015; Rowan et al., 2015), we focus specifically on ELA rise resulting from RCP 4.5 warming (+0.9 ^{o}C to +2.3 ^{o}C by 2100). Such temperature increases would cause a rise in ELA of between 165 and 425 m in the Dudh and Tama Koshi catchments, and between 107 and 270 m of ELA ascent over glaciers on the Tibetan Plateau. A rise in ELAs would most significantly affect the Tama Koshi catchment glaciers, with AARs potentially decreasing to 0.25 and 0.03, respectively. The greater altitudinal range and higher accumulation zones of glaciers in the Dudh Koshi catchment and on the Tibetan Plateau would dampen the effects of a rise in ELA on glacier mass balance. AARs could decrease to 0.26 or 0.18 in the Dudh Koshi and to 0.30 or 0.17 on the Tibetan Plateau. ELA rise in response to this particular warming scenario would mean a 17-51% increase in the total glacierised area below the ELA on the Tibetan Plateau, a 17-30 % increase in the Tama Koshi catchment, and a 14-37% increase in the Dudh Koshi catchment.

Should greater temperature increases occur, for example high-end RCP 6.0 warming, AARs could reduce to zero in the Tama Koshi catchment as ELAs rise above glacierised altitudes. Clean ice glacier AAR adjustment could be rapid given more than 1 ^{o}C of warming, with AARs again approaching zero should high-end RCP 8.5 warming occur in the region. The AAR of glaciers in the Dudh Koshi catchment could reduce quickly under RCP 2.6 warming, but their AAR reduction may be less rapid given greater temperature increases, presumably because of the extreme relief of the catchment. The AAR of glaciers on the Tibetan Plateau could become lower than glaciers of the Dudh Koshi catchment once warming approaches 2.5 ^{o}C.

~~5.5.2 Comparison with a conceptual model of glacier wastage~~

~~Benn et al. (2012) presented a conceptual model of Himalayan glacier wastage composed of three distinct process regimes each operating given certain climatic states. They suggested that transitions between these three process regimes marked major thresholds in glacier response to climatic forcing. By comparing the results from this study with the conceptual model of Benn et al. (2012), it is possible to identify at which stage of recession our highlighted glaciers, and which processes will drive glacier melt in the near future.~~

~~Figure 8 shows a comparison of the mass balance curves we derive for the three major catchments in the study area, along with the 9 lacustrine terminating glaciers, and the conceptual mass balance curves proposed by Benn et al. (2012). There is a clear resemblance of the mass balance curves generated for land-terminating glaciers in the three catchments of our study area and the mass balance curve of regime 2 outlined by Benn et al. (2012). The ablation gradients shown by lacustrine terminating glaciers are also very similar to regime 3 of Benn et al. (2012). Regime 2 is typified by accelerating ice loss and distributed water storage, and regime 3 is dominated by calving retreat and high amounts of water storage, according to Benn et al. (2012).~~

~~The transition of glaciers from regime 2 to regime 3 depends on the margins of a glacier being ‘decoupled’, specifically when the supply of supraglacial or englacial sediment at a glaciers margin is greater than the sediment transport capacity of meltstreams (Benn et al., 2003), and a large moraine dam is free to develop. The presence of such a moraine dam allows the formation of base level lakes and large scale calving events to occur, which is the main mechanism of ice loss in regime 3 of the Benn et al. (2012) model. Many of the glaciers we highlight possess a large terminal moraine and long, low surface gradient tongues, and thus seem primed for the transition from regime 2 to regime 3. We would expect an increase in mass loss rates of the lacustrine terminating glaciers that we highlight following the transition of glaciers from regime 2 to regime 3.~~

6 Conclusions

DEM differencing has revealed substantial mass loss from many large, debris-covered glaciers in the central Himalaya over the last 15 years. Geodetic mass balance estimates have been calculated for 32 glaciers across three different catchments around the Everest region. We found similarly negative mass budgets for glaciers flowing onto the southern flank of the Himalaya, in the Tama Koshi (–0.51 ± 0.22~~4~~ m w.e. a^{-1}) and Dudh Koshi ~~–~~(–0.58~~60~~ ± 0.19~~31~~ m w.e. a^{-1}) catchments, and onto the Tibetan Plateau (–0.61~~3~~ ± 0.24~~7~~ m w.e. a^{-1}).

The subdivision of our sample of glaciers depending on their terminus type shows contrasting mass loss rates between land and lacustrine terminating glaciers. The mean mass balance of 9 lacustrine terminating glaciers we assessed was –0.70 ± 0.26~~9~~ m w.e. a^{-1}, 32% more negative than land terminating glaciers (mean mass balance of –0.53~~2~~ ± 0.21~~7~~ m w.e. a^{-1}). The mass balance of 9 lake terminating glaciers ranged from –0.91 ± 0.22~~9~~ m w.e. a^{-1} to –0.45 ± 0.13~~6~~ m w.e. a^{-1} and we would suggest that glacial lakes in the region are at different stages of expansion. Accelerating mass loss is likely from several of these lake terminating glaciers whose termini will retreat into deeper lake water.

Surface lowering curves show that the maximum lowering rate rate (–1.62 ± 0.14~~0~~ m a^{-1} between 5300 and 5400 m.a.s.l.) of glaciers flowing onto the Tibetan Plateau was well above the maximum mass loss rate of glaciers flowing south of the orographic divide (–1.06 ± 0.140 m w.e. a^{-1} between 5200 and 5300 m a.s.l. in the Dudh Koshi catchment, –1.08 ± 0.12~~44~~ m w.e. a^{-1} between 5200 and 5300 m a.s.l. in the Tama Koshi catchment), and that glaciers flowing onto the Tibetan Plateau are losing ice over a much broader altitudinal range than their south-flowing counterparts. We suggest that the across-range contrast in annual precipitation total, combined with rising temperatures over recent decades may have caused greater ice loss rates on the north flowing glaciers that we observe.

Predicted warming in the Everest region will lead to increased ELAs and, depending on glacier hypsometry, substantial increases in ablation areas. We show that glaciers of the Tama Koshi catchment will see the greatest reduction in glacier AAR due to their more equidimensional hypsometry and limited more limited elevation range in comparison to glaciers of the Dudh Koshi or Tibetan Plateau. Warming of +0.9 °C to +2.3 °C by 2100 (IPCC AR5 working group report RCP 4.5) would decrease glacier AAR to 0.25 or 0.03 in the Tama Koshi catchment, 0.26 or 0.18 in the Dudh Koshi catchment, and 0.30 or 0.17 on the Tibetan Plateau, respectively.

Our findings are important for two reasons. First, they suggest that glacial lake growth and current glacial lake expansion that has been documented across the Himalaya could be accompanied by amplified glacier mass loss in the near future. Second, they show that glacier AAR adjustment in response to predicted warming across the HKKH could be spatially very variable, complicating the prediction of future glacier meltwater runoff contribution from river catchments across the region.

Author contribution

OK, DQ and JC designed the study. OK carried out all data processing and analysis. OK, DQ, JC and AR wrote the paper.

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SETSM DEMs are available for download from http://www.pgc.umn.edu/elevation. The SRTM dataset is available from https://lta.cr.usgs.gov/SRTM1Arc. EGM2008 gridded data is available from http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_gis.html. OK is a recipient of a NERC DTP PhD studentship. We are grateful for the comments of Benjamin Robson for his comments on an early version of the paper, and for guidance on the use of SETSM data from Ian Howat. We finally thank Tobias Bolch, Joseph Shea and an anonymous reviewer for their thorough and constructive assessments of the manuscript.

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Table 1. Scenes used in glacier outline delineation, ASTER DEM generation, SRTM ice facies mask generation and by the Polar Geospatial Centre in the generation of SETSM DEMs.

Sensor	Scene ID	Date of acquisition	Purpose
Landsat OLI	LC81400412014334LGN00	30/11/2014	Glacier outlines
Landsat ETM+	LE71390412000302SGS00	29/10/2000	Glacier outlines
Landsat ETM+	LE71400402002005SGS00	05/01/2002	Ice facies mask
Landsat ETM+	LE71400412002005SGS00	05/01/2002	Ice facies mask
ASTER	L1A.003:2014050545	29/11/2014	ASTER DEM
ASTER	L1A.003:2014045939	12/04/2014	ASTER DEM
Worldview 3	WV03_20150121_10400100076C0700	21/01/2015	SETSM DEM
Worldview 1	WV01_20150504_102001003C5FB900	04/05/2015	SETSM DEM
Worldview 1	WV01_20140115_102001002A289F00	15/01/2014	SETSM DEM
Worldview 2	WV02_20140311_103001002E546F00	11/03/2014	SETSM DEM
Worldview 1	WV01_20140324_102001002D263400	24/03/2014	SETSM DEM
Worldview 1	WV01_20150204_102001003A5B7900	04/02/2015	SETSM DEM
Worldview 2	WV02_20150202_103001003D4C7900	02/02/2015	SETSM DEM
Worldview 1	WV01_20140218_102001002C5FA100	18/02/2014	SETSM DEM
Worldview 1	WV01_20141022_102001003525D400	22/10/2014	SETSM DEM
Worldview 1	WV01_20150131_1020010038618500	31/01/2015	SETSM DEM
Worldview 2	WV02_20141226_103001001D66C000	26/12/2014	SETSM DEM
Worldview 2	WV02_20141110_1030010039013C00	10/11/2014	SETSM DEM
Worldview 1	WV01_20141129_102001002776B500	29/11/2014	SETSM DEM
Worldview 1	WV01_20140514_102001003001E400	14/05/2014	SETSM DEM

Table 2. Mean differences and the standard deviation associated with off-glacier elevation difference data between ASTER, SETSM and SRTM DEMs before and after the DEM correction process. The uncertainty associated with DEM difference data is also listed for each SETSM and ASTER DEM.

Sensor	ASTER scene ID	Pre correction mean & StDev stable ground differences Vs SRTM (m)		Post correction mean & StDev stable ground differences Vs SRTM (m)		dh/dt uncertainty (± m a^{-1})
ASTER	L1A.003:2014050545	–64.12	25.99	0.43	11.30	0.47~~0.87~~
	SETSM tile					
WV 3	WV03_20150121_10400100076C0700	–6.07	11.54	0.53	6.43	0.25~~0.25~~
WV 1	WV01_20150504_102001003C5FB900	–5.68	15.76	–0.43	5.89	0.40~~0.40~~
WV 1	WV01_20140115_102001002A289F00	–3.56	9.50	0.50	6.64	0.27~~0.27~~
WV 1	WV01_20140324_102001002D263400	–2.21	8.92	0.07	5.90	0.33~~0.33~~
WV 1	WV01_20150204_102001003A5B7900	–1.26	17.50	–0.36	5.65	0.31~~0.31~~
WV 2	WV02_20150202_103001003D4C7900	–3.80	12.34	–0.03	6.56	0.29~~0.29~~
WV 1	WV01_20140218_102001002C5FA100	–2.00	9.80	–0.23	6.71	0.28~~0.28~~
WV 1	WV01_20141022_102001003525D400	–9.54	16.50	0.36	6.89	0.35~~0.35~~
WV 2	WV02_20141110_1030010039013C00	–2.89	9.83	0.07,	5.87	0.15~~0.15~~
WV 1	WV01_20141129_102001002776B500	–5.72	8.31	0.16	4.76	0.18~~0.18~~
WV 1	WV01_20140514_102001003001E400	–3.51	10.12	–0.26	5.91	0.26~~0.26~~

Table 3. Mass balance estimates (from geodetic and altimetric studies) for the broader Everest region and comparable sub-regions/ catchments.

Time period and area	Mass balance estimate (m w.e. a^{-1})	Study
Dudh Koshi		
1970-2008	–0.32 ± 0.08 ~~-0.32 ± 0.08~~	Bolch et al. (2011)
1992-2008	–0.45 ± 0.25 ~~-0.45 ± 0.25~~	Nuimura et al. (2012)
2000-2015	–0.58 ± 0.19 ~~-0.50 ± 0.28~~	This study
Pumqu (Tibetan Plateau)		
1974-2006	–0.40 ± 0.27 ~~-0.40 ± 0.27~~	Ye et al. (2015)
2003-2009	–0.66 ± 0.32 ~~-0.66 ± 0.32~~	Neckel et al. (2014)
2000-2015	–0.61 ± 0.24 ~~-0.59 ± 0.27~~	This study
Tama Koshi		
2000-2015	–0.51 ± 0.22 ~~-0.40 ± 0.21~~	This study
Everest region		
1999-2011	–0.26 ± 0.13 ~~-0.26 ± 0.13~~	Gardelle et al. (2013)
2003-2008	–0.39 ± 0.11 ~~-0.39 ± 0.11~~	Kääb et al. (2012)
2000-2015	–0.52 ± 0.22 ~~-0.54 ± 0.27~~	This study

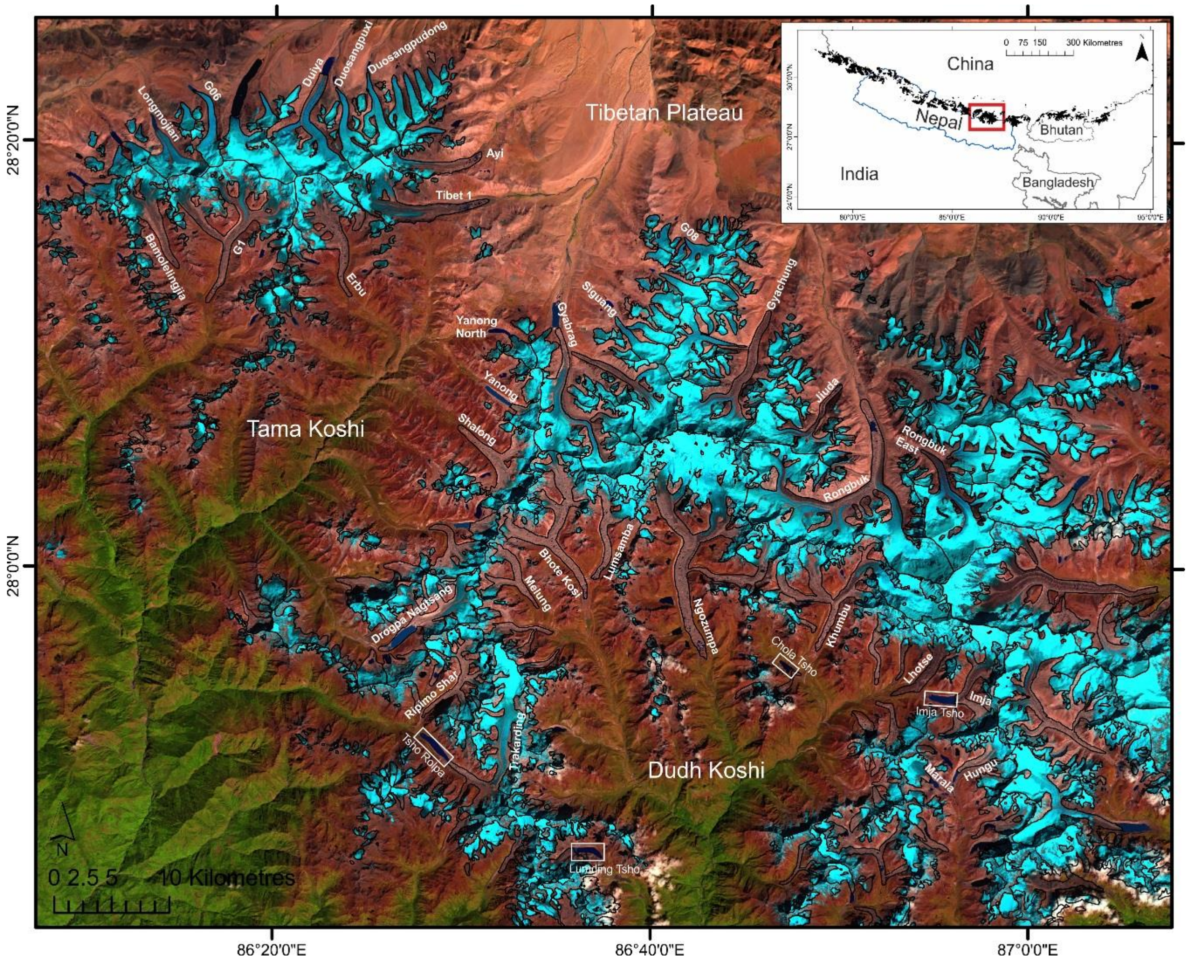

Figure 1. The glaciers of the Everest region. Named glaciers are the glaciers we highlight in this study. Major catchments include the Tama Koshi and Dudh Koshi on the southern flank of the Himalaya and the Pumqu river catchment on the northern side of the divide, with glaciers flowing onto the Tibetan Plateau (China). Named glacial lakes are highlighted, although many remain unnamed. Background imagery is a Landsat OLI image from 2014 available from http://earthexplorer.usgs.gov/.

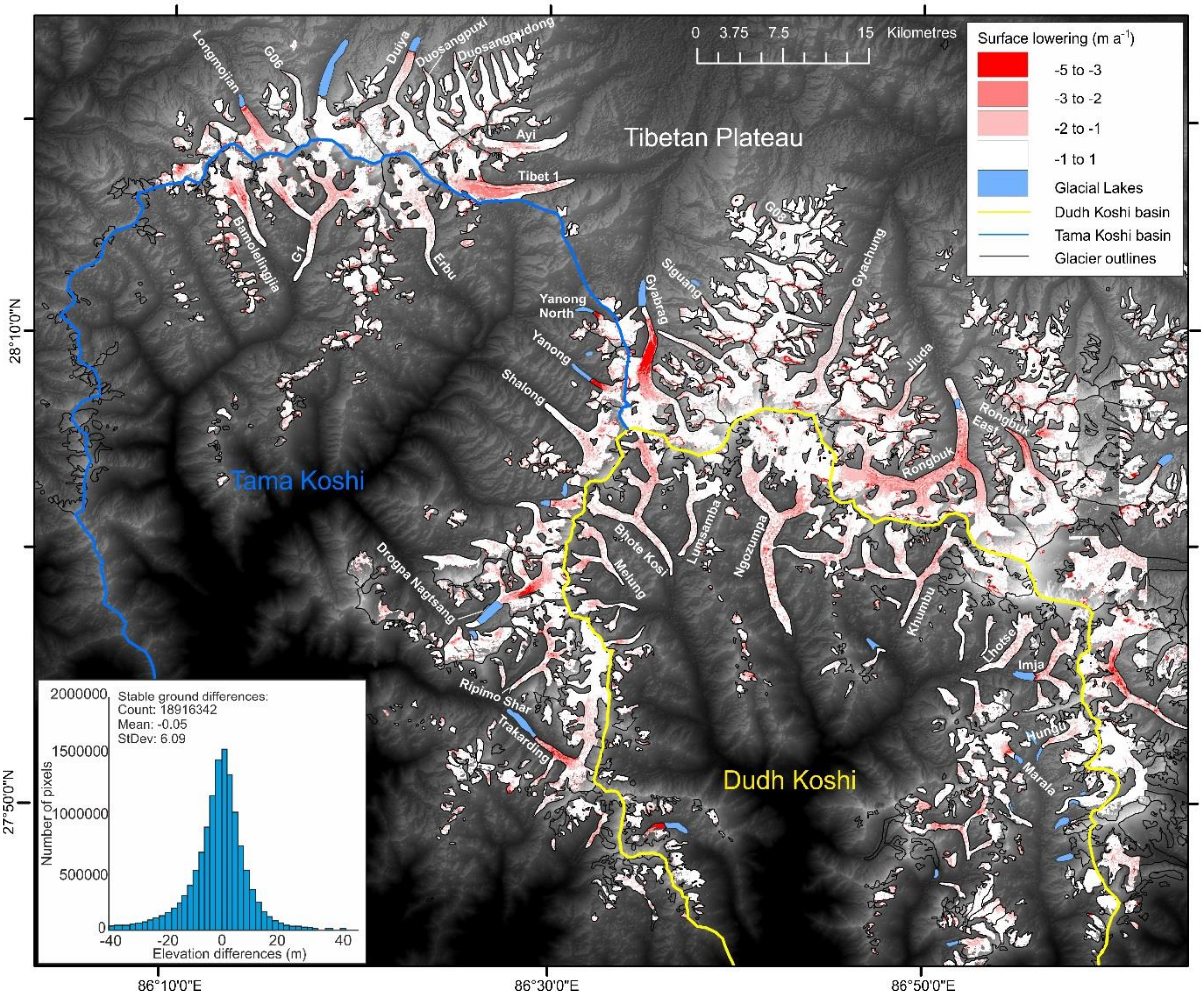

Figure 2. Glacier surface elevation change over the study area between 2000 and 2014/15. Also shown is a summary of off-glacier terrain differences. Areas of no data show the ASTER GDEM underlay.

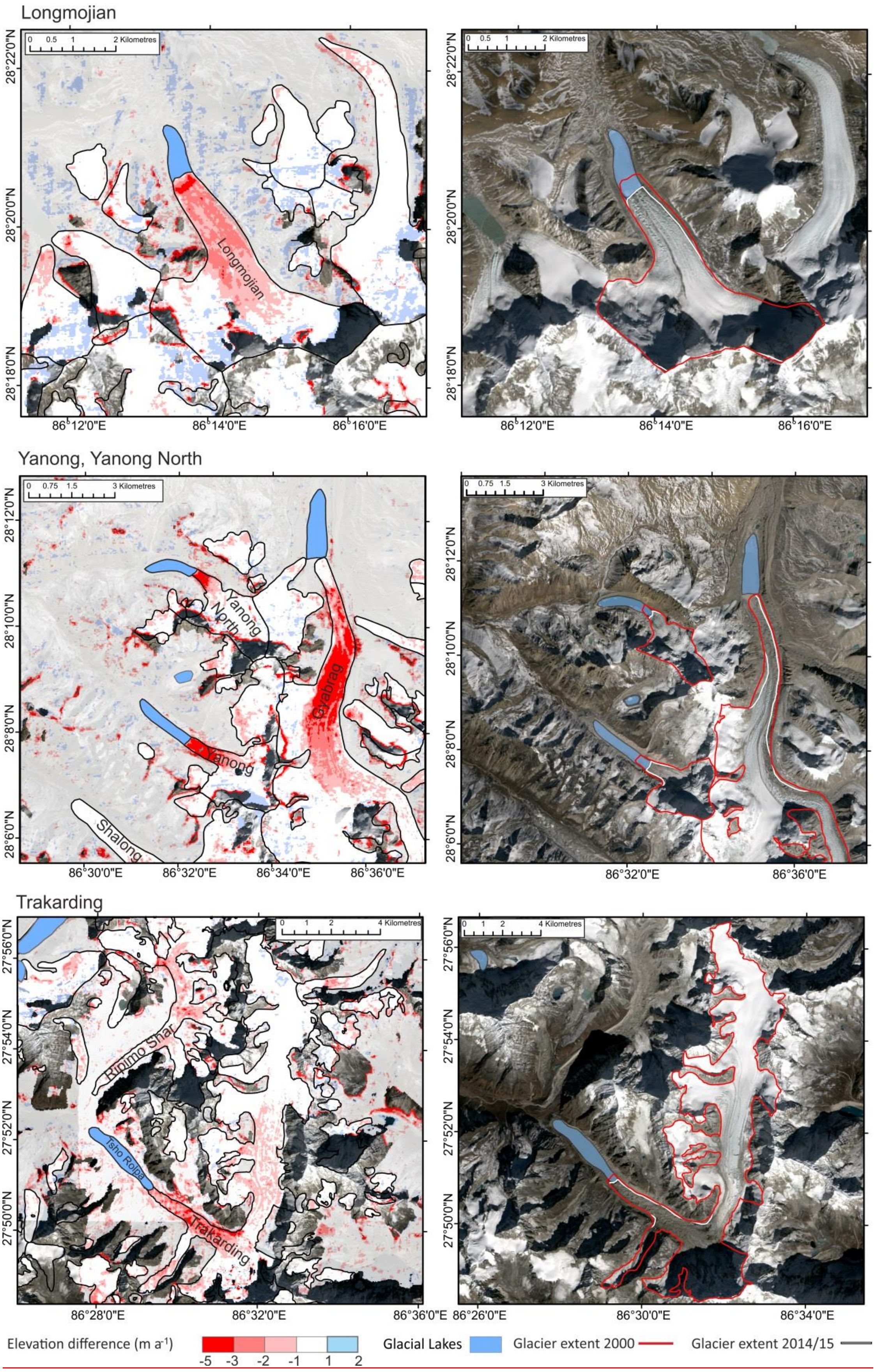

Figure 3. Examples of surface elevation change and total area change over the study period on lacustrine terminating glaciers. Semi-transparent, off-glacier differences are also shown.

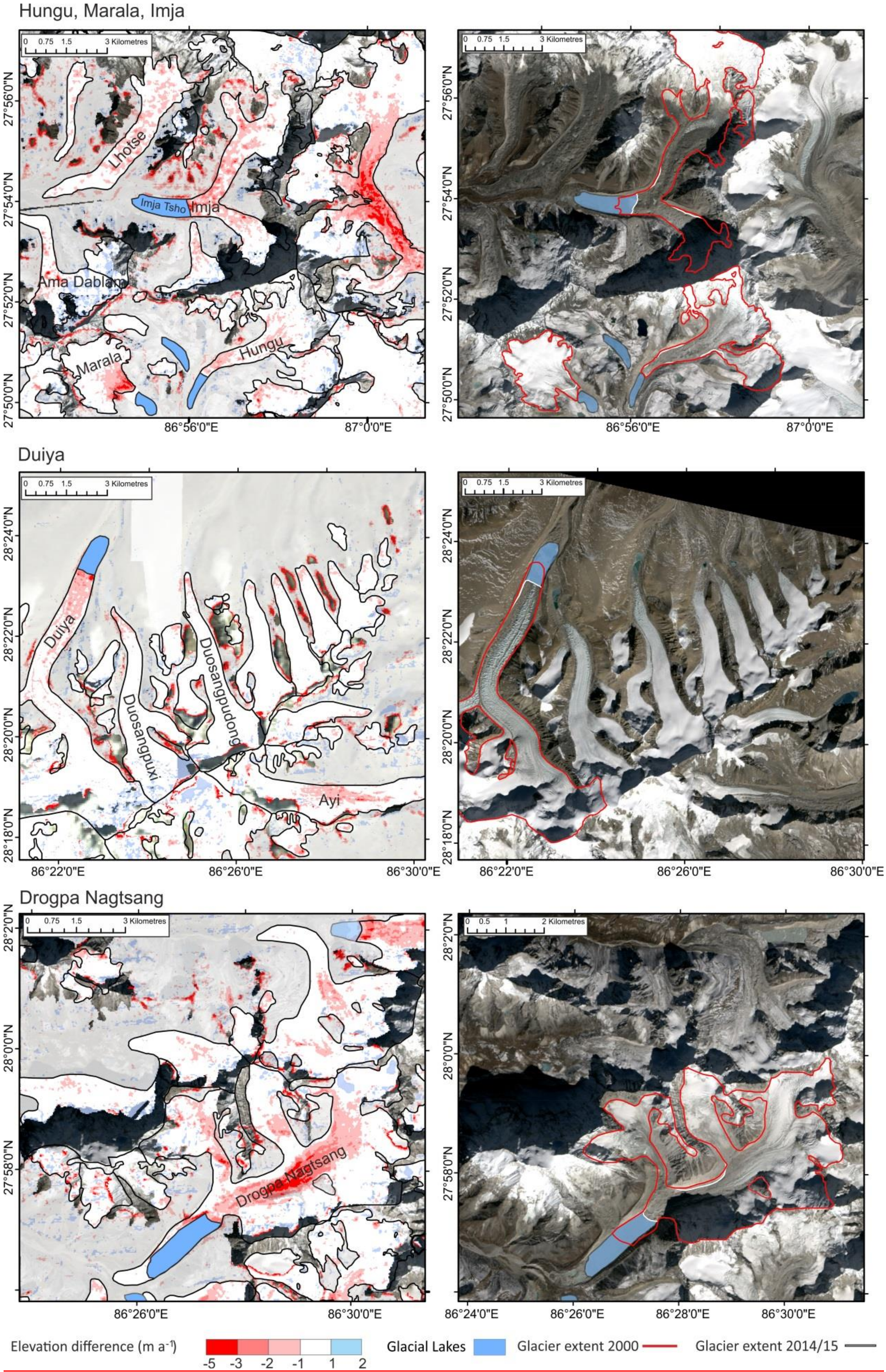

Figure 4. Further examples of glacier surface elevation change and total area change over the study period on lacustrine terminating glaciers. Semi-transparent, off-glacier differences are also shown.

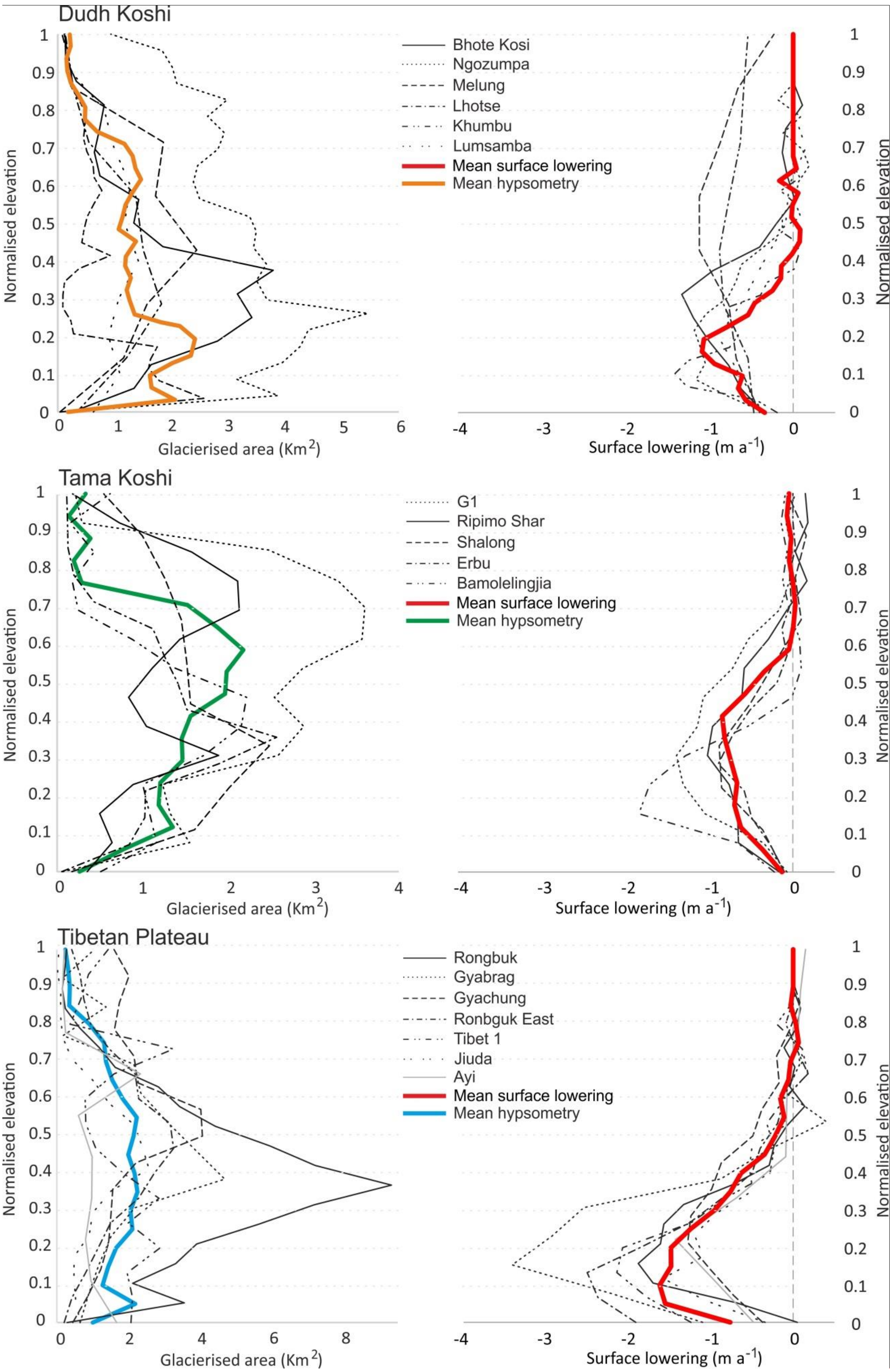

Figure 5. Surface elevation change and glacier hypsometry curves for all land terminating glaciers in the three different catchments of the study area.

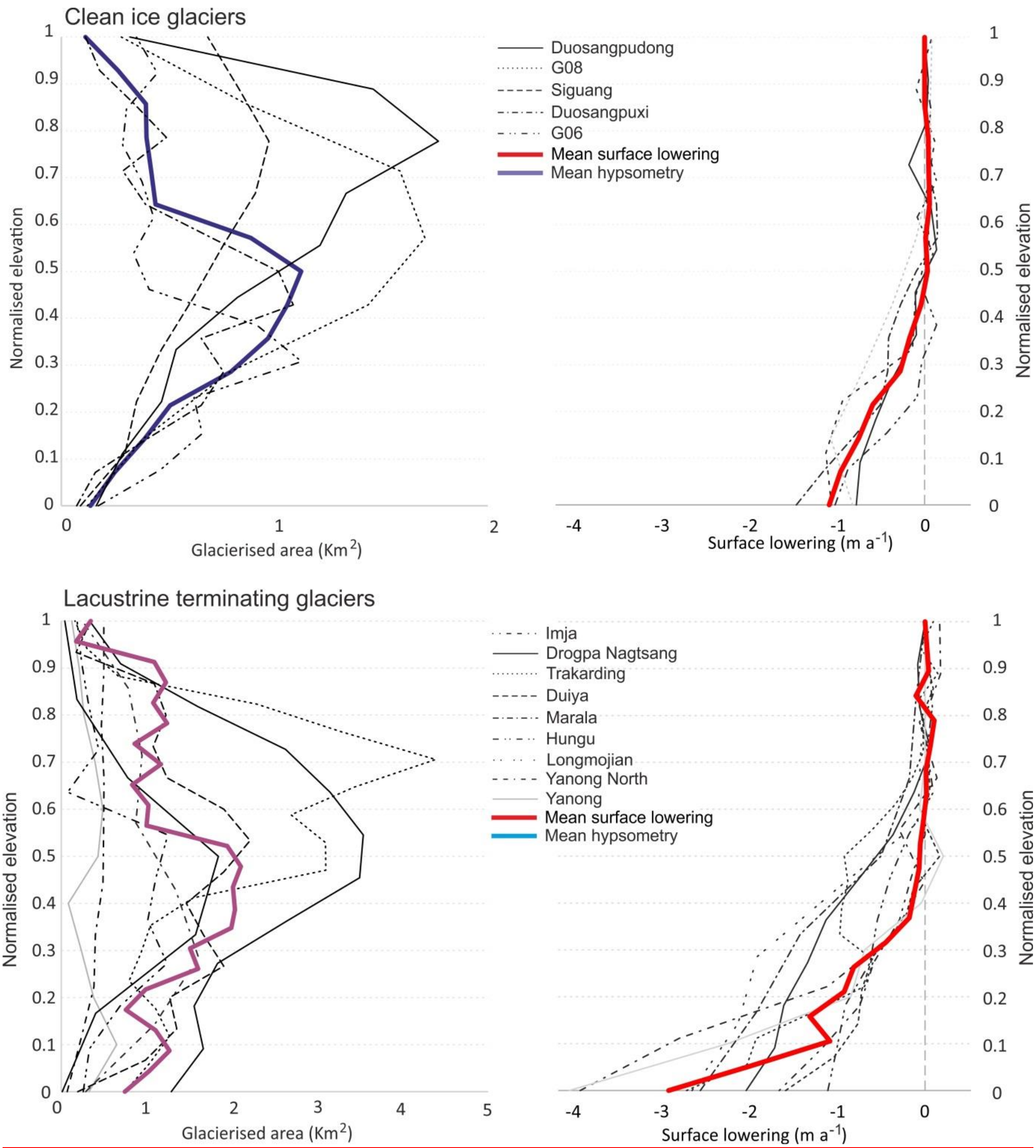

Figure 6. Surface lowering and glacier hypsometry curves for clean ice and lacustrine terminating glaciers in the study area.

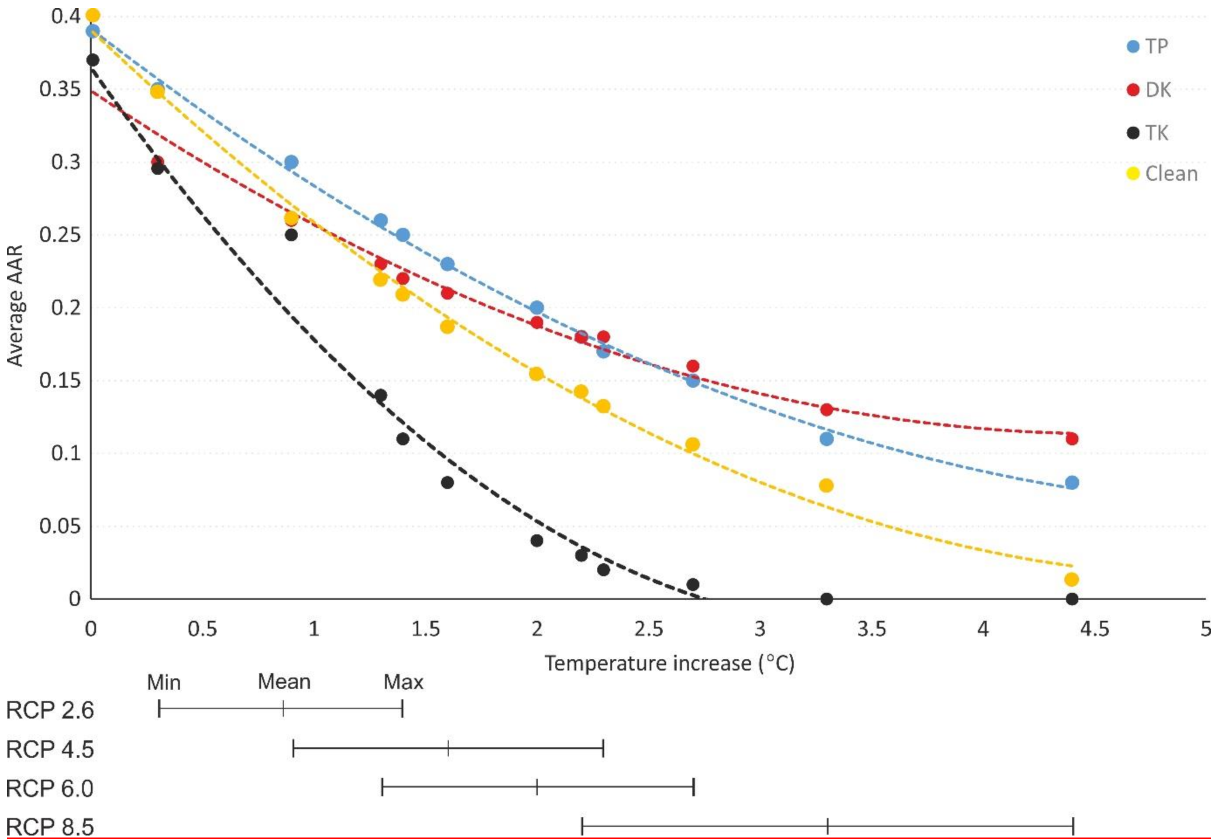

Figure 7. Projected AARs (averaged across each catchment) based on different scenarios of temperature increase relative to the present day and accompanying ELA rise. Temperature rise scenarios have been used from the IPCC AR5 Working Group report. TP- Tibetan Plateau; DK- Dudh Koshi; TK- Tama Koshi; Clean-Clean ice glaciers. Each point represents a projected AAR given minimum, mean or maximum temperature rise under each RCP scenario.