# REVISION STATEMENT

## “Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal”

**by S. Ragettli, T. Bolch and F. Pellicciotti**

### IN RESPONSE TO THE EDITOR

We thank the editor for his comments and suggestions. All comments by the two reviewers have been carefully considered and the entire manuscript has been deeply revised. We implemented the corrections as outlined in our response to the reviewers in the interactive discussion. In our statements below we specify clearly what we have changed in the revised manuscript and where. Some of the detailed comments have been addressed differently than announced in the interactive discussion and we have updated the revision statement accordingly:

- Rev. 1, Page 8, line 4; Rev. 2, page 25, line 13-page 26, line 9: a new figure in the Supplement (Figure S5) compares the hypsometry of Yala and Kimoshung Glacier, which depicts why the two glaciers have such different AARs.
- Rev. 1, Page 9, lines 2-5: we have added a new figure to the Supplement (Figure S2) which compares the glacier outlines for Langshisha Glacier used by the present study and by Pellicciotti et al. (2015).
- Rev. 1, Page 11, line 18; Rev. 2, Data and Method section: to shorten the manuscript we have removed all content on triangulation residuals.
- Rev. 1, Page 43, Table 7: we have added uncertainty estimates to the revised Table 7 (glacier area changes).
- Rev. 2, 3. Influence of the earthquake: We now assess more carefully in Section 4.1 (“Impacts of the April 2015 earthquake”) which of the post-earthquake DEMs can be considered to discuss recent glacier changes.
- Rev. 2, page 26, line 11-page 27, line 11: We merged the previous section 7.1.2. with the new Section 5.1. We have removed all statements that cannot be firmly supported by our data.

Together with this document we submit also a marked-up manuscript version showing the changes made. From this, it is evident that all sections have been deeply revised. We hope that the effort in the revision of the original material will be recognized and that the manuscript is now acceptable for publication in TC.

### GENERAL REVISIONS

We would like to thank very much the two reviewers for their thorough and detailed comments. We have addressed all the reviewers concerns in our detailed point by point answers below. Both referees raised important methodological issues, mostly regarding outlier exclusion and uncertainty quantification. We agree that a revision of our methods was necessary. We have thus substantially modified some of our procedures and we have recalculated all thinning rates and mass balances. Nearly all figures have been modified as a result of these changes.

The major issues in the revision were: 1) to revise the outlier removal procedure to make it simpler and based on logical criteria (reviewer 1 and 2), 2) to increase the reliability of the data by addressing the unusually large thickening and thinning patterns in the accumulation areas (reviewers 1 and 2), 3) to redo the uncertainty analysis based on approaches that are established in the literature (reviewer 1), 4) to improve the manuscript by reducing its length, make it more focused and by drawing only conclusions based on reliable data (reviewers 1 and 2), 5) to separate the elevation changes after the earthquake from the rest of the study period (reviewer 2).

As a result of changes in response to the reviewers' comments, these are the main changes in our study:

1. We now use a simpler and more straightforward procedure for the selection of data for our ensemble approach.
2. We have revised our approach for outlier removal at the grid scale. The approach does not fail anymore to identify erroneous patterns in the accumulation areas of glaciers.
3. We use a new approach for uncertainty estimation based on Gardelle et al. (2013).

4a. We use a new dataset of supraglacial cliff and lake inventories to explain the observed thinning patterns instead of the proxies previously used in the submitted manuscript; these new data sets allow to directly relate spatial thickness change patterns to observations of glacier surface characteristics.

4b. We increased the readability and sharpened the focus of the manuscript: the 'Methods' section has been shortened and the separate section on outliers and uncertainty has been removed.

4c. Generally, figures and text now better emphasize the added value of using an ensemble approach, which we are convinced is a novelty of this paper but has not been recognized (or only partly) by the reviewers. The availability of multiple independent DEM differencing results for overlapping periods allows identifying a sound signal and narrowing down the uncertainty of recent volume changes.

5. We show that over longer periods ($\Delta t > 4$ years) the effect of the post-earthquake avalanches six months after the earthquake (in April 2015) is negligible compared to the uncertainties in calculated elevation changes (Section 4.1, Figure 8). The October 2015 DEM is thus still used to assess long term elevation changes, whereas the May 2015 DEM is not.

We are convinced that the changes in methodology and structure of the paper have benefited the papers' quality. They have also strengthened the novelty and relevance of the results. We are now able to unambiguously identify for which glaciers overall thinning has accelerated in recent periods, or where thinning has remained approximately constant. The new dataset on cliff and lake area that reviewer 2 suggested to include provides valuable insights regarding the mechanisms that lead to spatially heterogeneous thinning patterns on debris-covered glaciers. The more reliable results for the accumulation areas allow now for more convincing conclusions regarding the differences in glacier response to climate. None of our main results or conclusions however changed significantly, thus supporting the methodological choices made originally. Overall, we strongly believe that our study now indeed represents one of the most rigorous documentations to date of glacier response to climate change over the last 40 years in the Himalaya.

Since some of the comments were common to both reviewers, we describe below the major changes made and refer to those in our detailed responses to the reviewers.

**NEW METHODS**

**1. Data selection** (Section 3.2.5, previously 'Outlier detection at the catchment and glacier scale', Sections 3.4.2 and 3.4.3): Instead of selecting the data based on four different data quality proxies (% data available after outlier correction at the grid scale, sensitivity to outlier correction, triangulation residuals, and mean off-glacier elevation differences) we now simply select all $\Delta h/\Delta t$ maps from the period 2006-2015 that cover periods of four years or longer. Shorter periods are discarded and not discussed in the paper, except for assessing the short-term effect of post-earthquake avalanches. This change responds to the reviewers comments about simplifying our methods, which we agree with.

There are two main reasons to discard short periods and focus only on multi-annual periods within 2006-2015 instead:

- Uncertainties substantially decrease for longer periods (see new Figure 5).
- Data from overlapping periods within 2006-2015 provide a range of plausible values for this period, especially as the elevation changes between the different selected periods show very similar characteristics (Figures 8 and 11). This data ensemble allows narrowing down the uncertainty: the uncertainty in a sample mean is lower than the uncertainty in individual estimates (according to standard principles of error propagation). We thus obtain an ensemble of results for the relatively short period 2006-2015 that can be used to assess changes in thinning rates with respect to the longer period 1974-2006 in which much larger absolute elevation changes occurred.

The ALOS 2010 scene is excluded from the ensemble since we can show that the uncertainties of the corresponding $\Delta h/\Delta t$ maps are 20-80% higher than the uncertainties calculated for other maps (see revised Table 3; we are referring here to the new uncertainties calculated with the approach based on Gardelle et al. 2013, see point 3. below). The post-earthquake scene from May 2015 is also excluded from the 2006-2015 ensemble since elevation changes are essentially different due to the post-earthquake avalanches. The October 2015 DEM is still considered for the ensemble, since a larger part of the avalanche deposits melted already and, hence, the avalanche effect on multi-annual glacier volume changes is minor in comparison to the ensemble uncertainty (see our detailed answer to the third major comment by reviewer 2).

**2. Outlier correction** (Section 3.2.3, previously ‘Outlier detection at the grid scale’, Section 3.4.1): We revised our outlier correction by narrowing the range of acceptable values for the *accumulation* areas and now use a 1σ threshold to identify outliers. Pixels are thus defined as outliers when the absolute elevation differences differ by more than one standard deviation (considering all elevation differences within glacier area located above the ELA). Below the ELA we now use a 3σ level (instead of a 2σ level for debris-free terrain as in the original manuscript), following Gardelle et al. (2013). We are aware that ELA estimates are uncertain (see our response to the comment on Page 8, line 4, by reviewer 1), and thus we assess the sensitivity of our results to an ELA uncertainty of ±100 m (Section 4.2.1, Table 6).

The application of more restrictive criteria for plausible elevation change values in the accumulation areas required also a revised procedure for gap filling, because gaps tend to be quite large when using 1-sigma thresholds. We now first calculate the mean elevation change rates per 100-m elevation band of each glacier and then calculate the median of the ensemble (see revised Figure 11). This value is then used to replace outliers from a given elevation band in the accumulation area. For the ablation areas we still use inverse distance weighting (IDW) for gap filling, since gaps are very small and the variability in plausible values is high. This procedure led to more realistic values especially in the accumulation areas of the period 1974-2006. Previous geodetic studies have used glaciological expert knowledge for outlier removal and gap filling in the accumulation areas (e.g. Pieczonka et al., 2013; Pieczonka and Bolch, 2015), considering that elevation changes in the accumulation areas are minor over periods of several years (e.g. Schwitter and Raymond, 1993; Huss et al., 2010). Since we now only consider time intervals between DEMs that are longer than 4 years we think it is justified to use empirical values from the same glacier to fill data gaps in the accumulation areas, even if data from very different periods are used to calculate ensemble-median values.

The revised outlier correction now detects obviously erroneous data in the accumulation areas of the 1974-2006 map (see revised Figure 4a).

**3. Uncertainty quantification** (Section 3.2.4): Our new uncertainty estimates are based on the standard error calculated per elevation band as in Gardelle et al. (2013). Accordingly, we now take into account the number of independent pixels per elevation band. The distance of spatial autocorrelation for each Δh/Δt map is calculated considering the range of the semivariogramm of all off-glacier elevation differences (e.g Magnússon et al., 2016). We identified distances between 260 and 730 m (average of all Δh/Δt maps: 495 m). Weighted mean uncertainty values per glacier are then calculated as in the original manuscript by taking into account the altitudinal distribution of uncertainty and glacier hypsometry.

Our previous approach took into account both the mean elevation differences (MED) and the standard error (SE). The large uncertainties obtained for the 1974-2006 map were related to the erroneous elevation change patterns that were due to errors in the Hexagon 1974 DEM. However, both reviewers suggested discarding all unrealistic elevation changes in the accumulation areas. To account for the MED is therefore not necessary anymore, since deviations from zero are prevented by the more restrictive outlier definitions. Accordingly, the uncertainty estimates for the 1974-2006 map are now much lower (revised figures 9 and 10). This facilitates the interpretation of results shown by figures 9 and 10 and allows for stronger conclusions regarding the differences between 1974-2006 and 2006-2015.

Ensemble-mean and ensemble-uncertainty values are now provided in Table 5 for the period 2006-2015. 'Ensemble uncertainty' is defined as the standard deviation in ensemble values for 2006-2015 multiplied by 1.96 (p.11, lines 15-21). Standard deviation is commonly interpreted as 68% confidence level assuming normal error distribution. By multiplication with 1.96 we obtain 95% confidence levels.

**4. Supraglacial cliffs/lakes** (Section 3.3): We now use six quality checked maps of cliffs and lakes from each available satellite image for the period 2006-2015 (2006, 2009, 2010, 2014, May and October 2015). These inventories are used to calculate cliff and lake area per elevation band, and replace the statistical proxies (σ Δh/Δt, Δh/Δt Q50-Q10). Since both reviewers criticized that only limited conclusions are possible from the original Figure 10, we have replaced this figure by elevation profiles showing ensemble-mean thinning rate changes (Δ Δh/Δt), surface velocities and lake/cliff area (Figure 12).

The new dataset allows for interesting and convincing conclusions regarding the mechanisms that lead to spatially heterogeneous thinning patterns on debris-covered glaciers. Correlations between the presence of cliffs and accelerations in local thinning are evident from the revised Figure 12.

**RESPONSE TO REVIEWER 1**

**General comments: In the paper Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal an interesting set of geodetic data from various sources is presented and used to infer the geodetic mass balance of the Langtang catchment in the Nepal part of the Himalayas focusing mostly on two periods (1974-2006 and 2006-2015). The authors undergo complex automatic classification of their data archive to sort out what they consider as reliable data for geodetic mass balance calculation as well as applying partly new approach to estimate the uncertainty. Unfortunately this work is not completed and is still some way from being scientifically sound.**

We would like to thank E. Magnusson for his very useful review. His suggestions for improvement of our outlier removal and uncertainty estimation procedures helped us to considerably increase the robustness of our conclusions. We believe that our results are now scientifically sound, in the sense that now only reliable data are used and that we can show that identified variations in glacier thinning are significant. The revision of the methods led to a more robust statistical assessment of our main results.

However, we also would like to note that the changes in outlier removal and uncertainty estimation procedures did not lead to different conclusions compared to the original manuscript. As in the original manuscript, our results depict a heterogeneous response of glaciers to climate, with a strong spatio-temporal variability of thinning trends at debris-covered tongues and clear evidence about the crucial role of glacier hypsometry for mean thinning trends. We also would like to note that the reviewer ignored some key novel aspects of our work, such as using an ensemble of independent observations to narrow down the uncertainty of our results. We were puzzled by his proposition in one of his detailed comments below on Section 4 to use less data (only three DEMs). To us it is obvious that several independent measurements (differential DEMs for the period 2006-2015) lead to higher confidence in detected signals. To make this clearer we now provide ensemble-mean and ensemble-uncertainty values (Table 5), as described at the beginning of this revision statement under 'New Methods'. Overall, we are however thankful for all the reviewers' detailed comments since they helped us to understand where the methods needed to be improved and where the advantages of a given approach needed to be clarified.

**1) The logic behind the complex outlier removal is often difficult to understand, and various steps in it are poorly justified. Despite this complex automatic outlier removal it seems to fail at many locations when looked at the difference maps of the 1974-2006 (Figure 6a). If the authors belief that the accumulation areas of glaciers thinned or thickened by 60-100 m at many locations as the this figure indicates they need to come up with some logical and justified explanation why (surges, enormous avalanches?) and they also need to explain the absence of this pattern of extreme thickening and thinning in the accumulation area of the glaciers for the period 2006-2015 (Figure 6b).**

We agree with the reviewer that the outlier removal procedure used in the original paper was complex and the presentation of the method takes substantial manuscript space. We also agree that the threshold criteria are sometimes difficult to justify, but this is because perfectly objective criteria are not available.

Regarding the 1974-2006 elevation difference map it is true that outliers in the accumulation areas remained and therefore the outlier removal procedure failed for these areas. We do not believe that thinning or thickening values of 60-100 m are plausible in the accumulation areas. This was stated clearly in the manuscript (p. 17, lines 10-12: "*The Nov 1974 - Oct 2006 Δh/Δt map (Figure 6a) reveals* *an irregular and unrealistic distribution of Δh/Δt values at high altitudes, which can be likely associated to errors in the Hexagon 1974 DEM*", p. 25, lines 25-26: "*Presumably, unrealistically high thinning rates at high altitudes due to errors in the Hexagon 1974 DEM led to this result*"). It is therefore not necessary to explain the absence of these patterns in other maps, since we clearly say that those unrealistic values are due to errors in the Hexagon map and thus the absence of errors in the other maps is due to better data quality.

However, we have carefully revised our outlier removal procedure to address the reviewers' concern and following his suggestions. The revised outlier detection algorithm now identifies unrealistic patterns in the accumulation areas. Missing data in the accumulation areas are replaced by plausible values. All new methods are described above under 'New Methods' and 'Outlier correction'.

The procedure for the selection of an ensemble of maps from the 28 available elevation change maps has been substantially simplified (see 'New Methods' and 'Data selection' above), even though we retain the ensemble as we think this approach provides a valuable estimate of uncertainty and sounder signal. The main focus of the paper now is, as suggested by this reviewer, on the comparison of the periods 1974-2006 and 2006-2015, and for the second period we consider a number of overlapping periods that allow narrowing down the uncertainty of volume change during this period.

**2) The explanation on how the uncertainty is calculated is not very clear and the procedure seems vague from statistical point of view. It is therefore hard to obtain any sense for its actual meaning. The authors do not even attempt to guess what confidence level it may represent. If more simple approaches such as using the e.g. standard deviation of off glacier DEM difference as proxy for the volume change uncertainty, it is at least known that such proxy is likely to result in very conservative uncertainty estimate compared to more advanced methods as shown by several studies.**

Our uncertainty calculations were based on the approach used in Bolch et al. (2011), a published and established approach (used e.g. also in Thompson et al., 2016, JG). We summed quadratically the mean off-glacier elevation differences (MED) and the standard error (SE) (eq. 5). We noticed that the uncertainties increase with altitude (which is common for geodetic elevation changes in the Himalaya, e.g. Nuimura et al., 2011). This is partly due to the fact that higher elevations tend to have steeper slopes and it is well know that the accuracy of DEMs derived from stereo data decreases with increasing slope. Therefore, we first calculated the uncertainty for each elevation band independently and then calculated a weighted average per glacier by taking into account glacier hypsometry. This resulted in conservative uncertainty estimates (i.e. large uncertainties) since both the mean error and the standard deviation were taken into account and we assumed no error compensation across elevation bands. However, when revising our approach we identified the following issues:

- The spatial autocorrelation of the error was insufficiently accounted for by considering *n* in eq. 4 equal to the number of pixels per elevation band (as explained on p. 14, lines 6-13) and not the number of independent pixels per elevation band (such as in Gardelle et al. 2013).
- Summing quadratically MED and SE led to very high uncertainty estimates at high altitudes, especially where the Hexagon 1974 DEM was used (because of errors in this DEM over snow-covered surfaces). This led to uncertainty ranges which suggested that even positive glacier mass balances are possible for debris-covered glaciers such as Langtang or Langshisha, although at the glacier tongues we unambiguously identified strong surface lowering (figures 8 and 11 of the manuscript).

Following the reviewer's remark, we therefore used a different approach for uncertainty estimation. The new uncertainty estimates are based on the standard error calculated per elevation band as in Gardelle et al. (2013).

To use just a crude proxy such as the standard deviation of the off-glacier elevation differences, however, seems not appropriate. This would imply assuming that the DEM errors at all locations are totally correlated, which we know is not the case. The standard error (thus the standard deviation of the sample-mean's estimate of the error) can be interpreted as 68% confidence level assuming normal distribution. Since we are assuming no error compensation across elevation bands the confidence level in our uncertainty estimates per glacier is higher than 68%. This is now stated in the revised manuscript (p.11, lines 11-14).

**3) The most critical weakness of this work is however that the authors seems neglect almost completely the uncertainty they actually obtain when discussing their results. A large proportion of the paper is spent on discussion on the temporal and spatial variation of the geodetic mass balance, while in most cases the variation they are discussing are not at all or barely significant if one believes the uncertainties obtained for the discussed values.**

We kindly disagree with the reviewer here. There are two main reasons for this. First, uncertainties and outliers were discussed in detail in the manuscript. Indeed, we devoted a whole section to this (previous Section 4). In the Results section the uncertainties were always provided when presenting mass balance values or mean thinning rates. If necessary, uncertainties were addressed explicitly when discussing results (e.g. original manuscript p. 18, lines 3-5; p. 18, lines 23-25; p. 20, lines 5-12; p. 21, lines 21-23; p. 25, lines 23-27).

Second, the reviewer does not take into account that we use an ensemble of independent measurements, which allows constraining the uncertainty of individual $\Delta h/\Delta t$ maps. This was stated in the original manuscript (e.g. at page 18, lines 1-3, "*The ensemble of values helps to distinguish between trends that should be classified as uncertain… from trends that are consistent within the ensemble"*). To us it was clear that the ensemble of values, available for overlapping periods, is an asset of this study. Now we understand that the advantages of the ensemble approach might not have been clear and needed to be stressed more. We do this in the revised figures 9 and 10 and we emphasize this point in the text of the revised manuscript (e.g. in the Introduction on p. 4, lines 1-6, or in Section 3.2.5).

We also point here to the fact that our results regarding the spatial and temporal variations in elevation change rates in the ablation areas are affected by very low uncertainties. Consequently, a large part of the Results and Discussion sections are devoted to discuss the spatio-temporal patterns in the ablation areas. We are surprised that the reviewer does not mention this here and instead suggests that most our results are affected by high uncertainty, although he agrees that "the data on the debris covered glaciers is the most convincing part of this manuscript." (see his comment below about Page 44, Figure 2).

**My main advices for the authors are the following:**

**a) Revise how you do your outlier removal, ideally make it more simple and if not make it such that the logic behind is understandable. It is also OK to use common sense when doing the outlier removal, instead of counting entirely on automatic outlier removal (this is presumably the difference between this work and the study of Pellicciotti et al. (2015) where part of the 1974 DEM of the accumulation area of Langshisha glacier was considered as erroneous data and therefore rejected).**

We have simplified the outlier removal, especially regarding the selection of maps for the ensemble which was based on four different data quality proxies. In the revised paper, we simply select only $\Delta h/\Delta t$ maps from the period 2006-2015 that cover periods of four years or longer (Section 3.2.5).

Regarding the grid scale outlier correction it is necessary to define clear criteria to prevent arbitrary or subjective choices. Note that also in Pellicciotti et al. (2015) outlier detection was based on an automatic algorithm, but in the case of Langshisha Glacier the threshold of acceptable elevation changes was lower (see our response below to the reviewers' comment on Page 29, lines 6-10). Accordingly, we revised our outlier correction by narrowing the range of acceptable values for the accumulation areas. Detailed explanations are provided in Section 3.2.3.

**b) Redo your uncertainty analysis. I would use approaches suggested by others unless you can better justify your approach and at least give the reader any evidence that the assumption you make when carrying out your uncertainty analysis is likely to result in an overestimate of your uncertainty rather than underestimate. You also need to be able to clarify what you mean by your uncertainty in terms of confidence level do give your uncertainty any meaning.**

We have followed the reviewer's advice and now use an approach that is more established in the literature (see detailed explanations above under 'New Methods' and 'Outlier correction'). We now state in the revised manuscript that the estimated confidence level of our uncertainty values is higher than 68% (see our answer to the reviewers' second main point above).

Finally, we now also provide the ensemble uncertainties (procedure summarized above and described in Section 3.2.4.). The variability in the ensemble of values extracted for overlapping periods is a better indicator for the actual uncertainty in the values identified for the period 2006-2015.

**c) When the above has been done, carefully revise what your data actually tells you with any confidence. This could lead to a good concise paper if carried out in the above suggested manner.**

We have done all of the above in terms of methodology, and have revised the paper accordingly. With the improvements in our procedures for outlier correction and uncertainty analysis it is possible to clearly identify changes in mean thinning rates over time (see revised figures 9 and 10). The $\Delta h/\Delta t$ glacier profiles (Figures 8 and 11) allow identifying unambiguously where in the ablation areas thinning has accelerated.

While it is true that the paper is more concise now as a result of the simplifications suggested by the reviewer, our main results however have not changed.

In addition, with a new dataset of cliff and lake areas (see our answers to the second reviewer) it is possible to directly relate spatial patterns of change to glacier surface characteristics (see the revised Figure 12).

Indeed, we think the suggestions by the two reviewers have helped us to present more concise and interesting results.

**Specific comments:**

**The list of the specific comments on the paper content here below should not be considered as complete, particularly regarding language, spelling, references etc., since in my opinion this manuscript and the work it describes needs almost a complete revision. The specific comments are mostly of two kind. Firstly, where I find reasoning of the methodology hard to understand or poorly justified. Secondly, where the authors are concluding much more from the data than they actually can, given the derived uncertainties (this is not a complete list, the remaining text free of such comments should also be critically revised, with this kept in mind).**

We thank E. Magnusson for his detailed comments. As stated above, we have revised the methodology. Regarding the uncertainties, the advantage of using an ensemble DEMs to constrain uncertainty is now better emphasized in the text. We do not agree that we concluded more than allowed from the data, for the reasons summarized in the general response.

The remaining text free of comments has also been revised. We tried to make shorter sentences and made sure that the methods are well explained. In our answers below we provide detailed indications how we streamlined the text, which we hope increased the readability of the paper.

**Page 1, line 12: This first line does not tell the reader anything since glaciers are losing mass at very variable rate (even glaciers short distance apart).**

The reviewer is right that the mass loss rates of individual glaciers are variable. However, we are referring to regional trends here. It is true that most Himalayan glaciers are losing mass at rates similar to glaciers elsewhere (Bolch et al. 2012). We modified the sentence slightly ("Himalayan glaciers are *on average* losing mass at rates similar to glaciers elsewhere").

**Page 1, lines 18-19: The uncertainties here have large overlap. Assuming that the uncertainties where e.g. 95% confidence level (let alone lower confidence), you cannot state with great confidence that you show that the volume loss rate is higher now (even though it is more likely that it is, rather than the opposite).**

We agree that the sentence needed clarification. In the revised manuscript we emphasize the ensemble of independent values available for the period 2006-2015, which allows constraining uncertainty. The new uncertainty estimates based on the standard error (Gardelle et al., 2013) yield lower uncertainties for the period 1974-2006. It is therefore possible to state now with great confidence that volume loss rates are higher. We have replaced the sentence with the following text:

*"The availability of multiple independent DEM differences allows identifying a robust signal and narrowing down the uncertainty about recent volume changes. The volume changes calculated over several multi-year periods between 2006 and 2015 consistently indicate that glacier thinning has accelerated with respect to the period 1974-2006. We calculate an ensemble-mean thinning rate of -0.45 ± 0.18 m $a^{-1}$ for 2006-2015, while for the period 1974-2006 we identify a thinning rate of 0.24 ± 0.08 m $a^{-1}$."*

Note that the uncertainty bounds provided above are still overlapping at the ends. In the revised manuscript we thus quantify the confidence level in our statement that thinning rates have accelerated (p. 16, lines 1-6). The estimated confidence level in accelerated thinning rates that is higher than 99%.

**Page 2, lines 8-10. Strange sentence, since you talk about examples of regional differences but only mention the upper limit values.**

The reviewer is right that the sentence was incomplete. We have changed the sentence as follows: "Prominent examples of current-day regional differences in glacier evolution across the Hindu Kush–Karakoram–Himalaya (HKH) are the reported positive glacier mass balances in the Pamir and Karakoram). *Glaciers in the rest of the HKH are thinning and receding (e.g. Bolch et al., 2012; Kääb et al., 2012; Gardelle et al., 2013)"* (p. 2, lines 13-16).

**Page 2, line 15. Is "scientific debate" a good phrase to describe this, isn't the common goal of everyone studying this just to obtain answer to the same scientific questions?**

We agree with the reviewer. We have replaced "scientific debate" by "research" and changed the sentence as follows: "However, also within the same climatic region the rate of glacier changes can be highly heterogeneous (Scherler et al., 2011b). A main focus of current *research is on the effect of supraglacial debris-cover on glacier response to climate*." (p. 2, lines 20-22).

**Page 3, lines 7-17. Here the authors seem to give observations and models the same weight. When you have models on one hand and on the other hand conclusive observations, which don't fit the models, the reason for this is usually the incompleteness of the models, which in this case is probably the melting mechanism of the debris covered glacier.**

We kindly disagree with the reviewer. In our opinion the results of the two cited detailed modeling studies (Juen et al., 2014; Ragettli et al., 2015) are also relevant when discussing the effect of debris cover on melt. Note that these two modeling studies are based on a large number of field data that were used to inform, develop and validate the model. The two modeling studies include point scale glacier mass balance observations while geodetic studies usually do not. Moreover, the glacier thinning rates derived by geodetic studies are not equivalent to melt rates, because glacier uplift affects the derived thinning rates (see our answer to the reviewers' next comment below), while models can provide actual melt rates. Both modeling studies and geodetic studies have therefore limitations when assessing the role of supraglacial debris on glacier response. We have however slightly changed the sentence on model results:

"Several detailed modelling studies on the other hand have *provided evidence for a* melt reducing effect of debris at the glacier scale (e.g. Juen et al., 2014; Ragettli et al., 2015), and have concluded that supraglacial debris prolongs the response of the glacier to warming (*Banerjee and Shankar, 2013*; Rowan et al., 2015)" (p. 3, lines 2-6).

**Page 3, lines 15-17. I don't understand this sentence. What melt is caused by the glacier emergence velocity? Are you maybe referring to emergence of debris to the surface but not the classical glaciological term emergence velocity?**

The sentence was not clear and we apologize for this. What we meant by the "discrepancy between thinning and melt due to glacier emergence velocity" was that melt and thinning is not the same thing, since glacier emergence has to be accounted for when comparing thinning rates to melt rates (see e.g. Immerzeel et al., 2014). We have stated this more clearly in the revised manuscript (p. 3, lines 9-10).

**Page 5, lines 11-17. The author don't discuss at all the effects of seasonal changes on their geodetic results despite the fact that the DEMs (including the ones with most emphasizes, November 1974, October 2006 and February 2015) are from different time of the year. Can the seasonal effect be neglected? If so, based on what?**

According to detailed simulations by Ragettli et al. (2015) for the Upper Langtang catchment and the hydrological year 2012/2013, icemelt during post-monsoon and winter only represents about 2% of annual icemelt from debris-free glacier area and about 3% of icemelt from debris-covered glacier area.

The model that had been used for these simulations was informed by a large number of field data to guarantee internal consistency of simulated processes (data from glacier ablation stakes, temperature sensor network, automatic weather stations, glacier surface elevation change derived from UAV observations, glacier runoff data, debris thickness observations) and was thoroughly calibrated and validated. Moreover, also precipitation (and thus snow accumulation in the accumulation areas) is highest during the monsoon season. Post-monsoon and winter precipitation represents less than 20% of annual precipitation (Immerzeel et al., 2014b). Elevation changes during the winter half-year are thus minor in comparison to the changes during pre-monsoon and monsoon (March to September). To convert elevation changes into units of *meters per year* we therefore divide by the number of ablation seasons (p. 8, line 22). All our DEMs are either from late winter/early pre-monsoon (February – April) or from post-monsoon (October-November). Effects of seasonal changes on the geodetic results can therefore be neglected, especially since we mainly discuss time intervals between DEMs of 4 years or longer. We state this now clearly in the revised manuscript (p. 8, lines 23-26).

**Page 6, lines 31-32. What about glacier motion, does your velocity data give any upper limit on what the motion of the GCPs could be within the time frame (if so state it)?**

According to our velocity data, glacier motion during a period of 9-18 days leads to a horizontal shift of 10-20 cm. This is less than the grid size of the Pléiades image (0.5 m) and is therefore negligible.

**Page 8, line 1. Systematic errors in the glacier change map?**

We have changed the sentence as follows: "Systematic errors *in the elevation change maps* due to tectonic uplift which could be relevant after the April 2015 Nepal earthquake are also corrected with the co-registration."

**Page 8, line 4. Did Ragettli et al., (2015) do independent estimate on this or did they get the value from Sugiyama et al., 2013. If the latter Sugiyama et al., 2013 should be referenced for this. This ELA estimate, which presumably is just some average value for this catchment, is used in this paper to estimate accumulation area ratio (AAR) for each glacier. It is then repeatedly referred to in the paper like some actual observation of the AAR for the glaciers. It is not and given the unrealistically high variability of AAR in table 1 (15-86%) it is probably not even a good estimate for individual glaciers.**

ELA estimates: these are two independent observations. The ELA estimate of Sugiyama et al. (2013) is based on thinning profiles of Yala Glacier determined from surface elevation measurements. The ELA estimate of Ragettli et al. (2015) is based on observations from glacier ablation stakes. We agree there is uncertainty in our ELA estimate but it is the best assessment possible for the Langtang catchment. In the revised manuscript we have assessed the effect of ±100 m ELA uncertainty (Section 4.2.1 and Table 6).

AAR estimates: we agree that the AARs in our paper should not be regarded as derived from observations but as estimates. This is clear now in the revised manuscript (e.g. in Section 5.2 where we now explicitly state that our AARs are estimates). However, the variability of AARs is not unrealistic, given the large heterogeneity of glaciers in our study catchment. Similar ranges of values can be found in literature (e.g. Khan et al., 2015, find AARs ranging from 7% to 80% in the Upper Indus Catchment based on end-of-summer snow line elevation observations). Extreme values, such as the AAR estimate of 86% for Kimoshung Glacier, are discussed in the paper (Section 5.2) and can be explained by topographic characteristics. A new figure in the Supplement (Figure S5) compares the hypsometry of Yala and Kimoshung Glacier, which depicts why the two glaciers have such different AARs.

**Page 9, line 1. I am not really following you here, when you mention the term automated flow accumulation process. Are you delineating ice divides between neighbouring ice catchments? Is the big difference for Langshisha glacier between Pellicciotti et al.,(2015) and this study caused by some part of Langshisha glacier as defined in the former study, being considered as separated ice catchment in this study? If so state this clearly. I would also recommend that you revise Figure 1 to better reveal the coverage of each glacier with improved background image behind it. By doing so you can (hopefully) convince the reader that your delineation of the glaciers is the more appropriate one.**

Yes, some parts of Langshisha glacier as defined in the former study by Pellicciotti et al. (2015) belong to a different catchment. This is very clear if a high resolution DEM is used to delineate the upper boundaries of glacier but is not evident from optical images, since the ice divides are often entirely snow covered. We have clarified the sentence in the manuscript ("We also re-delineated the catchment boundaries using the SRTM 30 m DEM and an automated flow accumulation process to accurately *delineate the ice divides between neighboring catchments*", p. 12, lines 27-29).

We now use the Cartosat-1 2006 ortho-image as a background image in Figure 1. The shading on north-aspect slopes slightly facilitates the visual identification of ice divides.

**Page 9, lines 2-5. This is a huge difference and is bound to have great effect on the result. You compere these two studies later on for this glacier, without even mentioning this important difference.**

We agree the differences in area are large and that this should be mentioned in the comparison. We have added a sentence on p. 27, lines 21-23. See also the new Figure S2 which compares the glacier outlines for Langshisha Glacier used by the present study and by Pellicciotti et al. (2015). p.

**Page 9, line 12. Standard deviation of deltah/deltat at given point calculated for the up 28 difference maps or is this calculated over a given window?**

The standard deviations of $\Delta h/\Delta t$ ($\sigma$ $\Delta h/\Delta t$) values were calculated for each difference map and each 50 m elevation band of each debris-covered glacier tongue. However, in the revised manuscript $\sigma$ $\Delta h/\Delta t$ is not be used anymore but we directly use the information of the cliff and lake inventories to identify cliff/lake areas (Section 3.3).

**Page 9, line 16. Well here is the answer to the question above. Personally I don't find this a good way writing, when something is only partly explained in a sentence and the same sentence and the following sentence does not indicate that further explanations will be given, but then later on the missing puzzle suddenly pups up. When I read such text, I am always asking myself "did I miss something?"**

We agree that the two sentences (one starting on line 13 and one on line 16) should have been presented in reverse order. Both sentences have been removed from the manuscript due to the change of methods (see comment above).

**Page 10, lines 12-15. Here a justification why this should be errors but not actual elevation changes are completely missing. The span of elevation change rate over an entire glacier can easily be greater than the DEM errors but this depends on the time span, DEM quality, glacier type, etc.**

We agree that a justification was missing. We have corrected this in the revised manuscript (paragraph on 'outlier removal' in Section 3.2.3). 3$\sigma$ levels are selected for outlier definitions outside the accumulation areas following e.g. Gardelle et al. (2013). 3σ error levels are less strict that the 2σ levels that were used in the original manuscript and therefore the risk of misclassifying actual elevation changes as errors decreases. On the other hand, stricter 1σ error levels are applied in the accumulation areas since here outliers are more likely to occur and since in the accumulation areas only narrow ranges of values are plausible over periods of several years.

**Page 11, line 4. Outlier correction uncertainty? Do you maybe rather mean sensitivity to outlier removal?**

In the revised manuscript the term is renamed 'sensitivity to outlier correction' (Section 4.2.1). We think the two terms are mostly equivalent, since sensitivity to outlier removal leads to uncertainty in the geodetic estimates, given that perfectly objective and unambiguous threshold criteria for outlier detection do not exist.

**Page 11, lines 5-17. This is very confusing text. I don't really understand what you are doing including why the thinning rate 2006-2015 is appropriate proxy for the outlier removal (of all data sets or just the 2006-2015 difference map?).**

Here we assess if the mean $\Delta h/\Delta t$ values are sensitive to outlier definitions. Note that 'Outlier correction uncertainties' (i.e. uncertainties associated with the correction of outliers) are not used anymore for the detection of $\Delta h/\Delta t$ map outliers to simplify our procedures. The paragraph to which the reviewer is pointing here has therefore been removed from the manuscript.

The thinning rate 2006-2015 was the value used as threshold to identify outliers, in order to keep the level of noise below the level of signal (where the thinning rate 2006-2015 is the signal and the outlier correction uncertainty is the noise). However, we agree that we could as well have chosen a different thinning rate from the ensemble as threshold. In this respect the 2006-2015 thinning rate was not a good choice, because our decision lacked objectivity.

**Page 11, line 18. DEM adjustment uncertainty? Is the term uncertainty appropriate here? I do not see that the parameter explained in this section is really used in your uncertainty assessment.**

We agree that the term 'DEM adjustment uncertainty' was not a good choice since in the literature it is known as 'triangulation residual' (e.g. Paul et al., 2015). We agree that the determined triangulation residuals were not abundantly discussed in the original manuscript (we only referred to Figure S2 once).

'Triangulation residuals' are not used anymore as outlier criteria in the revised manuscript. We considered discussing triangulation residuals in the new Section 4.2.1 and provide the values in the new Table 6. However, we noticed that none of the triangulation residuals exceeds the elevation change uncertainties as provided by Table 5. To shorten the manuscript we have therefore removed all content on triangulation residuals.

**Page 11, line 29. I have problem obtaining the same results as the authors from this equation. If n=8 making Ndeltat=28 and k=3, I get C_2= (8 over 3)/(2*28)=(8!/(3!*5!))/(2*28)=56/56=1, not 6 as authors say one should get.**

The equation as shown in the paper was wrong but our calculations were correct. The denominator should return the number of permutations for a given k-element subset that can be selected from a number of n objects. The correct expression is 'n!/(n-k)!)' instead of 'n over k'.

The equation has been removed from the main manuscript and in general all content on triangulation residuals (see comment above)..

**Page 12, line 7-14. It took me quite a bit of time to actually understand what you are doing. I think I do now. Again I can't see what is logical about using the thinning rate from October 2006 to October 2015 as a threshold value. Can you explain that?**

The thinning rate 2006-2015 was used as a threshold to guarantee that the signal to noise ratio is higher than 1:1, which indicates more signal than noise (same explanation as above regarding the comment on p. 11, lines 5-17). However, the outlier criterion discussed here is not used anymore in the revised manuscript and the selection of $\Delta h/\Delta t$ maps for the ensemble is based on simple and straightforward criteria, following the reviewers comments.

**Page 12. Do I understand you right that the last outlier detection you do is the catchment scale outlier detection? Wouldn't be more appropriate to do that before you the do glacier scale outlier detection?**

The order of steps is not significant, since the results of the glacier scale outlier detection do not depend on the catchment scale outlier correction. Note that the outlier criteria discussed here is not used anymore in the revised manuscript.

**Page 12, lines 23-24. Here we are left with the question "how?" until half a page later. Again, this is not a good way of writing, it makes the paper hard to read.**

We apologize for the writing style here. The outlier criteria discussed is not used anymore in the revised manuscript and therefore the sentences "half a page later" has been removed.

**Section 3.4.3. Here you come up with three outlier criterion. Why this complexity? It is not really justified in the paper.**

The three criteria look at mean off-glacier elevation differences (MED) and the role of slope and snow cover for MED. These criteria are not used anymore for outlier detection in the revised manuscript. We have moved the revised Figure 3 of the original manuscript to the Supplement (Figure S1).

**Sections 3.4.2-3. It seems to me that the glacier catchment scale outlier removals are not likely to function appropriately when the time interval between DEMs is so variable and you do the outlier detection on deltah/deltat. deltat is ranging from < 1 year up to 32 year. This means e.g. for the last criteria that the DEM error for the 1974 DEM causing the 1974-2006 delath/deltat to be considered as an outlier would need to be 32 times larger than the error in 2009 DEM causing the 2009-2010 deltah/deltat to be considered an outlier. DEMs over short interval off course need to be very accurate to have informative value for volume change estimates, hence this is logical from that perspective. If my understanding of the outlier removal procedure is correct it does however result in very weak outlier criterion for the 1974-2006 interval. If the authors rely entirely on this automatic outlier removal, it may result in erroneous result for this period, which to me, seems to be the case when looking at Figure 6 a. This is very unfortunate given that the main focus of your results and discussion is on the difference between the periods 1974-2006 and 2006-2015.**

At the catchment scale we used the distributions of the mean off-glacier elevation differences (MED) to identify outliers. We agree that the DEM errors are more likely to be classified as outliers if the intervals between DEMs are short. This is certainly one of the reasons why the DEM differencing maps involving the Hexagon 1974 DEM were not identified as outliers. However, we think it was justified not to compare absolute values (due to DEM errors, units in m) for outlier detection, since throughout the manuscript we are using units of m/a to discuss elevation changes.

To prevent erroneous results for the period 1974-2006 we now apply stricter outlier definitions for the accumulation areas, since only narrow ranges of $\Delta h/\Delta t$ values are realistic in the accumulation areas. Note that also before the revisions of our methods; it would not have been justified to reject the entire 1974-2006 $\Delta h/\Delta t$ map, since the quality at debris-covered areas is very good. Figure 4a confirms that the off-glacier elevation differences at lower elevations (where the image contrast is high and the terrain is less steep) are very small.

**Page 14, line 5. I find the problem with your bias or trend correction approach manifest in this equation (I guess you are not the only one doing this). If this study had been only on one of these glaciers the data used for trend or bias correction would (presumably) only have been from the neighbouring area of this glacier resulting in MED~=0. But since you do the trend correction for the catchment as a whole (which I think is fine if you are studying the catchment but not individual glacier), MED~=0 is often not true for individual glacier, hence you will get different value for a given glacier than if you had focused the study only on that glacier. You are trying to compensate for this by adding this effect here into the uncertainty, but you are still left with the fact that the probabilistic mean of the actual average elevation change is likely not well represented by the centre of the given error bars. This becomes particularly awkward since your discussion of the results almost neglect the derived uncertainty limits and focuses on the centre of the error bars.**

We agree with the reviewer that the center of the error bars does not well represent the probabilistic mean of the actual elevation change if MED~=0, and we agree that our discussions should have better reflected this. However, MED can only be different from zero at the very high elevations, where the presence of snow does not allow using off-glacier terrain for bias correction. In the revised paper we now use a new approach to deal with $\Delta h/\Delta t$ errors in the accumulation areas of glaciers and consider only a narrow range of plausible values close to zero (Section 3.2.3). As a consequence of this new approach the center of the error bars now agrees with the probabilistic mean of the actual elevation change, and it is also not necessary anymore to consider MED for the uncertainty calculations (hence we use only the standard error following Gardelle et al. 2013).

**Page 14, lines 8-10. Are you saying that you use n=1? If so state it clearly, you could add to the sentence (i.e. n=1). Your usage of i.e. is not appropriate here (if I understand the sentence correctly). The fact that you use n=1 implies only that all pixels within the elevation band are fully dependent on one another (which truly is a conservative estimate). It does not however implies that there is no dependence between elevation bands. Since no attempts has really made to quantify the effect of the spatial correlation of your data (see e.g. Rolstad et al., 2009 or Magnússon et al., 2016, for further info) we don't really know if your assumption of no error compensation across elevation band is likely to lead to a conservative estimate of the uncertainty.**

We now use the standard error for uncertainty estimations, where n is equal to the number of *independent* measurements per altitude band, which means that the spatial correlation of the data is now taken into account. However, we would like to clarify that in the original manuscript n was not equal to 1, but n was the number of pixels per elevation band. We apologize if our usage of i.e. was not clear ("*i.e. assuming no error compensation across elevation bands*") and we have rewritten the sentence (p. 10, lines 26-28). It really meant that we weight the uncertainties identified per elevation band according to elevation distributions to calculate weighted averages per glacier. This implies that we are assuming no error compensation across elevation bands (and thus 100% dependency between elevation bands). This is indeed a conservative estimate.

**Section 3.6. It seems to me that your surface velocity could do with some more masking of errors and outliers e.g. with correlation threshold. The masking that you are carrying leaves almost the entire velocity field intact as revealed by Figure 11 even though it is clear that much of it is just errors. The level of errors seen outside the glaciers is such that it is not clear if the signals on the glaciers are real or just errors as well. The figure itself is very hard view.**

We agree that Figure 11 (now Figure 13) needed to be improved, so that signal from glaciers can be better distinguished from errors outside the glacier area. Note that on the relatively flat debris covered areas errors are much less likely to occur. Errors occur where the terrain is steep or where image contrasts are low.

In the revised Figure 13 we masked out areas with slopes that are not representative for glacier area. We used a threshold of 45°, which corresponds to the 95th percentile of the slope of all glacier grid cells. Off-glacier velocity data are shown in transparent color so that signal from glaciers can be better distinguished.

The velocity profiles of debris-covered tongues (and error bars) are now shown in the revised Figure 12. The error bars represent the standard deviation in pixel values per elevation band and do not suggest that additional outlier correction is necessary

**Page 15, line 9. Outlier and uncertainty assessment? Confusing. Wasn't this already done?**

Here we presented results and not methods. As such, this section could have been part of the result section, but we decided to discuss uncertainties and outliers in a separate section given their importance. This section has been removed to shorten the paper, since most of its content became redundant after the simplifications in the data selection procedure.

**Section 4. This is all rather confusing. You calculate a lot of quality proxies used for outlier detection, mostly to convince yourself that the data that you derive your results from is of good quality. This is all good if one also reviews critically the outcome, which seem to be lacking in this study. A lot of these proxies are referred to as uncertainties apparently without being used to estimate uncertainty of the presented geodetic results. It is also not clear if all the DEM available during the period 2006-2015, apart from the initial and the final DEM, were really used to narrow down the uncertainty of volume change during this period. If not it seems to me that this paper would be much clearer if the focus of this paper were only on three DEMs, the ones from 1974, October 2006 and February 2015.**

We are not convincing ourselves of a good data quality. This section simply presented an honest assessment of uncertainties and outliers. The quality proxies that were chosen have all been already applied in previous studies (although mostly for quality assessments and not for outlier removal). We agree however that outlier removal algorithm obviously failed in the accumulation areas. In this respect we should have reviewed the outcome more critically. In the revised manuscript we correct this by improving the outlier removal at the grid scale (Section 3.2.3). Those instances of failure are no longer there.

It is true that the proxies were not used to estimate uncertainty of the presented geodetic results but only for quality assessments and for outlier removal. This made the paper lengthy and difficult to read. In the revised manuscript the quality proxies outlier correction uncertainty (or 'sensitivity to outlier correction') and mean elevation differences (MED) are now only be presented for quality assessment.

Contents regarding DEM adjustment uncertainty (or ‘triangulation residual’) have been removed from the manuscript to shorten the paper since we noticed that triangulation residuals are within the uncertainty bounds as provided by the revised Table 5. Our main criteria to select Δh/Δt maps for the ensemble is now the time interval between DEMs, since we can show that the uncertainties decrease with period length (see new Figure 5). In this respect the uncertainty estimates are now used directly for outlier detection. Section 4 has been entirely removed to shorten the paper.

We are sorry if it is not clear that we used all DEMs available for 2006-2015 to narrow down the uncertainty. We thought it was (e.g. p. 18, lines 1-3; p. 18, lines 10-12; p. 18, lines 25-26, p. 24, lines 30-33, p. 30, lines 9-13). We did use all the DEMs and are convinced that there are clear advantages in doing so, since several independent measurements (differential DEMs for the period 2006-2015) lead to higher confidence in detected signals, even if the uncertainty of each measurement is high. For this reason, we do not see the point of using only three DEMs (the alternative suggestion of the reviewer). However, we have made an effort to more clearly explain the advantages of the ensemble approach throughout the revised paper.

**Page 18, line 18. Well if you think this is due to remaining systematic error, did you consider that your outlier removal is maybe not functioning so well?**

The outlier removal functioned excellently for ablation areas, considering for instance Figure 8, which clearly shows which thinning patterns are consistent across different dataset. If we considered all 28 differential DEMs for Figure 8 it would not have been possible to clearly identify patterns which are consistent across datasets, because the ability to identify these patterns requires a level of accuracy which is not granted per se. However, in the accumulation areas we agree that the outlier removal did not help to clarify thinning/thickening changes. This is why we decided to choose a different approach for grid scale outlier correction here (Section 3.2.3). The outlier removal the  catchment scale has also been completely revised (Section 3.2.5).

**Page 18, line 23-24. This is very true. Unfortunately you seem to forget it repeatedly in your discussion. Given that your uncertainties will be the same after revision of this work, much of the discussion on the results can be omitted because it is meaningless due to the large uncertainties.**

After revision of the methods the uncertainty estimates are different, especially for the periods 1974-2006 and 1974-2009. Regarding the particular example of Kimoshung Glacier, to which the reviewer is pointing here, the uncertainty could be constrained by only accepting realistic Δh/Δt values in the accumulation areas (Figure 9g). We are puzzled by the dismissive tone of the reviewer.

**Page 19, line 6. This is a good example of what I am talking about regarding the author neglecting the uncertainty in their discussion of the results. You cannot state here that the thinning rate increased by more than 100 %. If we know that John owns between 0 and 4 cars and Mike owns between 2 and 6 cars can you state that Mike owns at least twice as many cars as John? No and the probability of such statement being true is only 14/25=0.56 (given even probability distributions for the car ownership in both cases).**

The reviewer’s schoolmasterly example is not appropriate here. We are not comparing only two estimates, but thinning rates of two periods (1974-2006, and 2006-2015), where for the second period we use several independent datasets. This changes the situation as a whole. To take up the reviewers’ example, John belongs to an automobile club and we are estimating the average number of cars owned by the members of the club. If each member owns between 2 and 6 cars, then the standard deviation of the sample mean is

$$\mathrm{SD}_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$ (https://en.wikipedia.org/wiki/Standard_error).

whereas σ is the standard deviation of each single estimate and *n* the sample size (number of club members). Therefore the standard deviation converges towards zero for a large ensemble. Already with only four ensemble members the standard deviation of the sample mean decreases by 50%. In other words, the error might be too large when comparing only two periods, but when comparing two groups of values for the two periods the differences between the values become significant. We show this clearly in the revised manuscript (see figures 9 and 10).

Throughout the revised manuscript we now emphasize better the value of the ensemble approach by reporting ensemble mean and ensemble uncertainty values for the period 2006-2015.

We would also like to strongly rebut the reviewer's statement that we are neglecting the uncertainties in the discussion of our results. In the particular sentence to which the reviewer is pointing here the uncertainties were provided in brackets. We think this was an honest way of presenting the results. Uncertainties were discussed abundantly throughout the manuscript (with Section 4 we dedicated a whole section to the discussion of outliers and uncertainties). We have however revised the manuscript to discuss uncertainties now together with the results (e.g. by stating the confidence level in detected thinning accelerations, Section 4.2). Accordingly, we have removed Section 4 of the original manuscript).

**Section 5.2.1. This comparison between debris covered and debris free glacier looking at "Explanatory variables" is rather primitive. For one thing it is rather inappropriate to refer to some of them as variables. I would rather refer to outcome of processes, which in some cases probably show correlation since they are dependent on the same physical variables. It is also strange that only Yala is included as candidate for the debris free glacier. The behaviour of Yala is then compared with 5 other debris covered glaciers. Even though the difference between Yala and each of the other 5 glacier is sometimes visually clear it is misleading to calculate the r-value for all the 5 debris covered glacier at ones and compare with a value calculated for a single glacier. When using data from several glaciers, various variables which effect the glaciers in different manner is bound to reduce the studied correlation compared to having data from just a single glacier.**

This section has been thoroughly revised, also based on comments by reviewer 2. We now use a new dataset of cliff and lake areas, which substitutes the cliff/lake proxies (detailed explanations above under 'New Methods' and 'Explanatory variables'). The section has been renamed to "Section 4.5: Surface velocities and supraglacial cliff/lake areas". The old Figure 10 has been removed and replaced with the new Figure 12. With the scatterplots and r values (old Figure 10) we attempted to explain the variance in thinning rate changes of all debris-covered glaciers at the same time. However, single variables cannot possibly explain all the spatial variation in thinning rates, and therefore the r values were generally low (max. 0.55 for debris-covered glaciers). We agree that the sample size affects the correlation coefficients, and therefore the r values calculated separately for debris-covered terrain and Yala Glacier were not comparable.

In the revised Section 4.5 we discuss the spatial variability in thinning rates at each debris-covered glacier separately (see revised Figure 12). The differences between debris-free and debris-covered glaciers are not presented anymore in this section, but are addressed briefly in Section 4.3 ("Altitudinal distributions of elevation changes"). It is sufficient to state that at debris-free glaciers thinning rate changes are elevation dependent while this is not the case at debris-covered glaciers (p. 18, lines 23-29).

Note that we think it is justified to consider Yala Glacier as the main reference for debris-free glacier characteristics. Kimoshung Glacier has an unusually high accumulation area ratio , is very dynamic and is affected by higher DEM uncertainties due to the steepness of the tongue. Yala Glacier has an AAR of approximately 40% (Table 1) which is identical to the mean AAR indicated by Kääb et al. (2012) for the entire HKH region and is therefore suitable as a reference. In the revised paper this is now mentioned (p. 25, lines 9-11).

It is not clear to us which of the variables discussed in the original Section 5.2.1 we cannot refer as "variables". In Section 5.2.1 we considered elevation, slope, surface velocity and the variability of local thinning rates (as cliff/lake proxies). The reviewer is right that e.g. the variability of thinning rates (σ dt/dh) is an outcome of processes. All the others are variables. Still, in our opinion it was correct to refer to them as explanatory variables (σ dt/dh explains the role of heterogeneous surface properties for local changes in thinning rates).

**Page 22, line 1. You mean April 2015.**

Yes, thank you for noticing. We have corrected this.

**Section 5.3. It is probably of interest for some to know the volume of these enormous avalanches. It however seems clear that avalanche falling on debris covered glacier (particularly the low insulated part of the glacier) is only going have minor and short last effect on the mass balance since it is going to melt much faster than the debris covered ice beneath it.**

It is not clear per se that the avalanche cones disappear quickly. It is documented and described in our manuscript that a new debris layer appears on top of the avalanche material (as snow/ice melts out from the debris; p. 15, lines 4-7). Avalanche accumulation is one of the most important processes for debris-covered glacier formation (Scherler et al., 2011a). Likely the tongue of Lirung Glacier would not exist without accumulation through avalanches (Ragettli et al. 2015). We therefore do not agree that the long term effect on mass balance of the enormous post-earthquake avalanches is clear. In the revised manuscript we provide more background information about debris-covered glacier formation (Section 5.1.1).

**Page 24, line 25. What is numerical evidence?**

We have removed "numerical" and just left the "evidence".

**Page 25, line 14. Is there no uncertainty in the area change?**

We have added uncertainty estimates to the revised Table 7 and to area changes reported in the text (assuming a 0.5 pixel buffer around the tongues; p.12, lines 22-23). We now dedicate a separate results section on glacier area changes (Section 4.4), following a suggestion by reviewer 2. **Page 25, lines 16-17. I don't understand what you specifically mean by correlation between areal changes and surface elevation height.**

What we meant here is that one can expect glacier mass balances near steady state if the glacier area remains nearly constant, as it is the case for Kimoshung Glacier. We have removed the corresponding sentence to shorten the paper.

**Page 25, lines 23-26. Again not promising for your outlier removal, even though it is better to admit it does not work to well. It would however be even better to justify why you think this is an error, e.g. by pointing out that local lowering of 60-100 m over 32 years (as indicated by figure 6a) on such small glacier at such high altitude is very unlikely to say the least.**

We agree with the reviewer that the values were unrealistic. We correct this with a new outlier removal approach for accumulation areas (see response in our general statement above).

**Page 25, line 28-29. Even though it is likely that hypsometry plays a crucial role here this statement is far too bold given that it is based on very limited and apparently erroneous data (according to Figure 6a).**

After replacing the erroneous data we now get results which are trustworthy. The data now unambiguously reveal the differences in elevation change rates between Kimoshung and Yala Glacier (revised Figure 8f and g). Those differences can only be explained by the very different altitudinal distributions of the two glaciers (see new Figure S5). The results now clearly suggest that the hypsometry plays a crucial role.

**Page 25, line 31. See my previous comment regarding the AAR.**

We think the AARs in our study are realistic estimates. Especially at Kimoshung Glacier an uncertainty in the ELA by ±100 m would not lead to very different AARs because the glacier is very steep near the ELA (AARs given an ELA uncertainty of ±100 m: 80%-88%, see new Table 6). The uncertainty about the ELA does not change the fact that the AAR of Kimoshung Glacier is high, and this is what really counts for the discussion here.

**Page 26, line 26. Here and at other places in this paper, some temperature data (if available) would support your discussion.**

It is not the purpose of this study to document warming trends in the Nepalese Himalaya. It is difficult to relate spatial changes in elevation over different glaciers to remote point observations of temperature trends and the meaning of this would be very limited. In fact, no study of geodetic mass balance has used this coarse information to explain some of the observed thinning patterns. We therefore refrain from doing this here. References on warming rates in this part of the Himalaya are provided on page 23, line 23.

**Page 27, lines 16-18. You have far too little data with far too great uncertainty to make such statement.**

We agree with the reviewer that the wording needed to be improved here. However, we stated that our observations do not support the findings of previous studies and that is true. We find this an important result especially because it is the first time that this is proven with detailed, multi-ensemble data for a specific catchment using high resolution DEMs (in contrast to large scale regional studies). We agree that we cannot extrapolate this finding to larger glacier samples and we reworded the sentence to make this clear ("Our observations do not support the *findings* of previous studies about *similar present-day lowering rates of debris-covered and debris-free glacier areas* at the same elevation (Kääb et al., 2012; Nuimura et al., 2012; Gardelle et al., 2013)", p. 25, line 31).

**Page 27, lines 20-23. You can say that Kimoshung glacier has higher hypsometry than Yala. The staggering difference between AAR values (which here are treated as some kind of truth but not as estimates based on the assumption of fixed ELA=5400 m a.s.l. for the whole catchment) is however misleading.**

We do not agree with the reviewer, as explained above. Previous studies have found similar ranges of AARs in the HKH (e.g. Khan et al. 2015) and the AAR differences between individual glaciers (e.g. Yala and Kimoshung Glacier) can be explained by topographic differences (new Figure S5). We have added the reference to Khan et al. (2015) to the paper (p. 24, line 6).

**Page 28, lines 16-17. I am confused, is this in accordance with previous statement in this section (page 27, lines 16-18).**

We apologize if the wording was not clear here. Our observations tell us that the thinning rates at debris-covered tongues are lower than at debris-free Yala Glacier AT THE SAME ELEVATION (this relates to the discussion on page 27, lines 16-18, in the original manuscript). However, there are examples for both types of glaciers where AVERAGE thinning has increased significantly or where thinning remained approximately constant (p. 26, lines 7-10). Differences in thinning rates at the same elevation do not allow concluding about differences in average thinning. When it comes to glacier mass balances or glacier-wide average thinning rates, the elevation distribution of glaciers plays a crucial role. We have almost entirely rewritten section 5.3 ("Differences between debris-free and debris-covered glaciers") to be more clear and to base the discussion also on observations from debris-free Kimoshung Glacier (the new Figure S5).

**Page 28, lines 27-28. There is completely insignificant difference between these values. There is no point in trying to explain the "difference" between them.**

We agree that the differences are not significant, but we think it is justified to point to a possible overestimation of thinning rates identified by Pellicciotti et al. (2015) due to an underestimation of the SRTM radar penetration depth.

**Page 29, lines 6-10. I am very puzzled here. You need to justify here why this data is now suddenly considered as usable data, when the one processing the data rejected it in recently published paper. Why has he/she as the third author of this paper changed his/her mind?**

The two studies (Pellicciotti et al. 2015 and the present study) use different outlier correction approaches, but both studies tried to avoid arbitrary or subjective criteria. Pellicciotti et al. 2015 used 2σ thresholds to define outliers at the grid scale, but those thresholds are calculated only once for all altitude ranges together. In the original manuscript we used a slightly less restrictive outlier definition (thresholds calculated separately for accumulation and ablation areas), with the consequence that at some places (e.g at Langshisha Glacier) erroneous data remained in the dataset, while at other places (e.g. at the tongues of debris-free glaciers) the application of a less strict criteria lowered the risk of classifying correct data as outliers. This choice was justified by the fact that the quality of the new DEMs (2006-2015) is generally much higher than the quality of the Hexagon 1974 and the SRTM DEMs used in Pellicciotti et al. (2015). The third author therefore did not change her mind. The choice of the method depended on data quality. We also notice that there is progress in scientific research, and that improvements of revision of methods are common in papers by the same authors when data of better quality are available or new approaches are deemed more suitable. We do not see anything wrong here.

However, the 1974 DEM is the same for both studies, and therefore the less restrictive outlier definition failed to identify erroneous data in the 1974 difference maps. We have corrected this with the revised outlier correction procedure (see 'New Methods' above).

**Page 29, line 13. How can you state this? Does including apparently erroneous data make the uncertainty estimate more realistic?**

Yes, we think that the uncertainty estimates should reflect the quality of the data. On the other hand it is also justifiable to exclude erroneous data from the start and use uncertainty estimates that reflect the quality of the data without considering those outliers. We think this is what the reviewer suggests and this is what we have done in the revised manuscript. In general, please see our response on the new outlier removal and uncertainty estimates.

**Page 29, lines 15-16. What other data did they use? They were hardly using GPS in 1982.**

The reviewer is right, they did not use GPS in 1982. To cite Sugiyama et al. (2013): "The surface elevation in 1982 was surveyed by ground photogrammetry (Yokoyama, 1984) and later digitized into a 10m resolution digital elevation model (DEM) (Fujita and Nuimura, 2011)." This is now stated correctly in the revised manuscript (p. 28, lines 8-9).

**Page 30, lines 21-23. Sorry, I don't think many will agree on this statement.**

We think that many will agree on this statement – especially after the revision of this paper. However, we have omitted this sentence and leave it to others to judge if our study is one of the most solid ones.

**Page 32, lines 5-9. This text does not fit into conclusion. If the authors think this text should be in the paper, it would be more appropriate to include it in the introduction.**

We agree that the text does not fit here. We have removed those lines and added the reference to Kargel et al. (2015) to the introduction (p. 4, line 17).

**Page 40, Table 1. See previous comments regarding the AAR.**

The reviewer's comments regarding AAR are addressed above.

**Page 42, Table 5. It is not clear how the uncertainty of the average elevation change over the entire Langtang glacier catchment is calculated. Given its value it seems close to being basically (-)/(A*2), which basically corresponds to assuming that errors between glacier are completely dependent. Such assumption gives really conservative estimate, even too conservative causing the results to be downgraded. I also recommend that you stick to the same order of glaciers in the table as given in Table 7 with the glacier id.**

We calculate uncertainties of the entire glacierized terrain identically as for any other given area: we consider the standard error per elevation band (eq. 2) and the altitudinal distribution to calculate weighted averages. We explain this more clearly in the revised manuscript (page 10, lines 26-28).

It is not clear to us what the reviewer means by (-)/(A*2). It is true that errors between glaciers are dependent, since always the same off-glacier data are used. Only the altitudinal distributions are different (and therefore the uncertainty estimates). We have stated this clearly in the revised manuscript (p. 11, line 1).

We have changed the order of glaciers in Table 5 as suggested.

**Page 43, Table 7. Why no uncertainties? Are they within the digit of the given value, or did you simple not think about it? You are discussing these area changes in the paper without giving the reader any confirmation that these changes are significant.**

We have added uncertainty estimates to the revised Table 7 (assuming a 0.5 pixel buffer around the tongues; p.12, lines 22-23). The uncertainties are small given that we used high resolution (1.5 m to 4 m) optical satellite imagery to delineate the glaciers. Detected area changes are significant.

**Page 43, Figure 1. See my previous comments regarding this figure.**

The reviewer's comments regarding this figure are addressed above.

**Page 44, Figure 2. The data on the debris covered glaciers is the most convincing part of this manuscript.**

We thank the reviewer for this assessment and we agree with his evaluation. Indeed, the uncertainties are low over debris because of good image contrast and shallow slopes. We agree that here the data are least ambiguous, and allow to unambiguously infer some very interesting results on thinning patterns.

**Page 45, Figure 3. It seems to me that using all the 6 proxies result in the same outlier removal as when you just use med2 and sigma2.**

The reviewer is right. As explained above, none of these criteria are used anymore for outlier removal in the revised manuscript. This figure has been moved to the Supplement (Figure S1) and now only shows the stable terrain uncertainties of the $\Delta h/\Delta t$ maps in the final selected ensemble.

**Page 46, Figure 4. 50% confidence level? What would the error bars be for a reasonably strict confidence level like 95%?**

In the revised manuscript we provide the error bars with a confidence level of 95% but only considering the $\Delta h/\Delta t$ maps of the final selected ensemble (Figure 3 in the revised manuscript).

**Page 47, Figure 5. Do you mean: a) A whiskers plot showing the distribution of uncertainties for the (up to?) 28 deltah/deltat maps. What do the red crosses indicate?**

The boxplots show the distribution of uncertainties for non-rejected $\Delta h/\Delta t$ maps. This is now specified in the caption text of the revised manuscript (now Figure 2). The red crosses indicated outliers according to the standard Matlab boxplot function. In the revised figure we removed the red crosses and whiskers extend to the most extreme data points. Please note that we have replaced the old Figure 5b by the previous Figure S1 (and removed the latter from the Supplement). We think that the stereo matching scores are more directly linked to calculated uncertainties (new Figure 2a) than the fraction of pixels remaining after removing low stereo matching scores and outliers. If the reviewer prefers, we can still add the old Figure 5b to the Supplement. **Page 47, Figure 6. See various previous comments on this figure. Should also be enlarged for better readability.**

The reviewer's comments on this figure (now Figure 4) are addressed above. We will decide later (in the proof stage) if this figure will be sufficiently large if printed as a two-column paper figure. Please note that we have added a new figure to the Supplement (Figure S3) showing the elevation change rates of all $\Delta h/\Delta t$ maps in the 2006-2015 ensemble.

**Page 48, Figure 7. The order of panels for the glaciers should be kept the same as the numbering of the glaciers in Table 7.**

Ok, we have reordered the panels as suggested (see revised Figure 9).

**Page 50, Figure 9. Something went wrong with the altitudinal distribution for Yala.**

The altitudinal distribution for Yala Glacier is shown correctly. The altitudinal distributions of all glaciers are shown for 50 m elevation bands. The reviewer might not have noticed that the x-axis ranges are different for each sub-figure. We now point to this in the revised caption text (see revised Figure 11).

**Page 51, Figure 10. See previous comment regarding this figure.**

This figure has been removed from the paper and replaced by a new figure (now Figure 12) that better shows the relationship between glacier thinning and glacier characteristics and supraglacial features (see previous comment on this).

**Page 52, Figure 11. Very hard to read. The arrows are e.g. very hard to detect. Results do not appear very reliable (see previous comment).**

The reviewer's comments on the reliability of the velocity data are addressed above. We have improved the quality of this figure (larger arrows, focus on debris-covered areas, see revised Figure 13).

**IN RESPONSE TO REVIEWER 2**

**General comments:**

**This paper presents glacier surface elevation change in Langtan Himal from 1974 to 2015 based on DEMs generated from satellite images. The authors analyzed temporal and spatial patterns of glacier thinning over the studied seven glaciers. Focuses of the discussion are spatial heterogeneity in the thinning rate, comparison of debris-covered and debris-free glaciers, changes in the thinning rate after 2006. The data are also used to quantify the impact of the earthquake in 2015.**

**Despite the increasing importance and interests on the Himalayan glaciers, long-term data on glacier changes are few in the region. Considering intensive research activities in the Langtang region in the past and recent periods, the presented data set is valuable. Nevertheless, uncertainty is rather large particularly in higher elevation areas.**

**This is very common in photogrammetric elevation analysis because snow covered surface loses surface features required for this method. Judging from the unrealistic thickening and thinning patterns in Figure 6a, it is questionable whether the DEM analysis is applicable in the accumulation areas. Moreover, estimated uncertainties are based on very complex outlier rejection criteria, which sometimes appear to be subjective and unconvincing. These problems result in limited reliability in the conclusions. Overall impression on the manuscript is that conclusions are too conclusive as compared to what are shown by the data.**

**I encourage the authors to thoroughly revise the manuscript (1) by using only reliable data, (2) with well focused objectives, (3) to draw only convincing conclusions. For example, omitting data from the accumulation reduces total uncertainties in Figure 7, which leads to more reliable discussion on recent increase in the thinning rate. Among others, elevation change over the debris-covered regions and impact of the earthquake are promising subjects.**

We thank the reviewer for his/her very useful comments and appreciating that the data set is valuable. We agree with his/her comment on the accumulation area values and have changed for this our outlier removal procedure (following also suggestions from Reviewer 1). As a result, erroneous data from the accumulation areas are now corrected. In this way, all conclusions presented can be solidly justified.

We also agree that the paper should have well focused objectives. We have simplified the procedure for selecting maps for the 2006-2015 ensemble (see explanations above under ‘New Methods’ and ‘Data Selection’ and the new Section 3.2.5), which allow to focus better on the three paper objectives as defined in the Introduction (p.4, lines 9-14).

We agree with the reviewer that the results on the debris covered sections and impact of the earthquake are relevant and interesting results of our work, and thank him/her for noticing this.

We kindly disagree that overall “the conclusions are too conclusive as compared to what are shown by the data”; since also with our original methods and data we were able to present unambiguous evidence for heterogeneous thinning patterns (e.g. spatially variable thinning trends at debris-covered tongues). We think this result alone deserves publication in TC, but we agree that the manuscript required revision. After following both reviewers’ suggestions for improvement, we are now able to draw more convincing conclusions regarding all addressed main points.

To demonstrate that with the revised methods we are able to draw relevant conclusions that are supported by data we shortly summarize the main quantitative outputs of our study regarding the three main goals:

1.) Assess if overall thinning of glaciers in the region has accelerated in recent years.

Thinning rates have increased, from -0.24 ± 0.08 m $a^{-1}$ (1974-2006) to -0.45 ± 0.18 m $a^{-1}$ (2006-2015, ensemble mean). The uncertainty bounds are overlapping at the ends. However, the probability that thinning rates have not increased is less than 1% (estimated confidence levels are now reported in the revised manuscript on p. 16, lines 1-5).

2.) Determine if spatial thinning patterns have changed over time.

We can now conclude that spatial thinning patterns have changed over time, since thinning accelerations at the debris-covered tongues are highly non-uniform in space. Local changes in thinning rates (comparing the periods 1974-2006 and 2006-2015, Figure 8) range from -80% (at Ghanna Glacier, 4800 -4850 m a.s.l.) to +150% (at Shalbachum Glacier, 4650-4700 m a.s.l.). The uncertainty in identified thinning accelerations is only about ±10% (p. 29, line 15).

3.) Assess if there are major differences between the response of debris-covered and debris-free glaciers in the sample.

Here we partly agree that we were too conclusive in the original manuscript regarding this point. In the revised manuscript we state clearly that our observations need to be confirmed by studies using larger glacier samples (p. 27, lines 1-2). However, considering that the elevation distribution of Yala Glacier is common for the HKH (an AAR of 40% is common in the HKH, see Kääb et al. 2012), this glacier can be used as a reference. There are indeed ***major differences*** between debris-covered glaciers and Yala Glacier: Within the same altitudinal range, thinning rates of debris-covered glaciers do not exceed 35% - 75% of the thinning rates at Yala Glacier (p. 26, line 6-8). Considering the changes in mean thinning rates, we identified a strong thinning acceleration at Yala Glacier from -0.33 ± 0.06 m $a^{-1}$ (1974-2006) to -0.89 ± 0.23 m $a^{-1}$ (2006-2015, ensemble mean) (p. 16, lines 25-26). Debris-free Yala Glacier is currently downwasting at 60%-100% higher rates than the large debris-covered glaciers in the valley (p. 26, lines 29-31). Our work is one of the first to assess differences between debris covered and debris-free glaciers at this level of details and high spatial resolution.

**Major concerns:**

**1. Reliability of the DEM in the accumulation area Figure 6a shows unusually large thickening and thinning patterns in the accumulation areas. The regions of the suspicious elevation change agree with the frequently snow covered regions shown in Figure 1. Most likely, photogrammetric analysis is hampered by featureless snow surfaces. Because such data from the accumulation areas are used for the mean thinning rate over each glacier, conclusions on the recent thinning acceleration and comparison between debris-covered and debris-free glaciers are unreliable.**

We have carefully revised our outlier removal procedure to address the reviewers' concern. It is true that outliers in the accumulation areas remained in the 1974-2006 map and therefore the outlier removal procedure failed for these areas. Our new approach for outlier correction is described at the beginning of this document under 'General Revisions' (and in Section 3.2.3). The revised outlier detection algorithm now identifies unrealistic patterns in the accumulation areas and removes them. Missing data in the accumulation areas are replaced by plausible values (see Figure 4a which corresponds to old Figure 6a).

Although erroneous data over featureless snow surfaces in the Hexagon 1974 DEM are evident, we are convinced that with the revised outlier correction and gap filling procedure now allows for convincing conclusions regarding recent thinning accelerations. As the reviewer states above it is common in photogrammetric elevation analysis that uncertainties are high over featureless snow surfaces. Many previous studies addressed the same problem. Errors in the accumulation areas do not require rejecting the whole dataset, since it known that over long time periods only narrow ranges of Δh/Δt values close to zero are realistic in the accumulation areas (e.g. Schwitter and Raymond, 1993; Huss et al., 2010). Previous geodetic studies have thus assumed no elevation changes in the accumulation areas (Pieczonka et al.,2013) or have used glaciological expert knowledge to define acceptable Δh/Δt ranges in the accumulation areas (Pieczonka and Bolch, 2015). In our study we benefit of a large dataset of several independent Δh/Δt maps. We now use the available information to narrow down the uncertainty and replace missing data in the accumulation area with data from the same glaciers (Section 3.2.3).

We now also use a more established method for uncertainty quantification (Gardelle et al. 2013). The new approach results in substantially lower uncertainty estimates for the 1974-2006 scene (see revised Figure 9). Our previous approach clearly overestimated the uncertainties (see our response to the second main comment by reviewer 1). We are therefore convinced that the revision of the outlier correction and uncertainty estimation procedures allows now for substantially more convincing conclusions regarding recent thinning accelerations and differences between debris-covered and debris-free glaciers.

**2. Data and Method section. The authors spend more than 1/3 of the manuscript for Data and Method section. This section is suffered from too much detailed explanations on how to reject outliers and estimate uncertainty. All details are given, but hard to understand the reasoning of each process. First, I suggest the author to move these details to the supplement, and describe in the main text only essence of the techniques in an understandable way. Second, the structure of the section should be reconsidered. It can be something like, 3.1. Satellite data, 3.2. DEM (generation, differencing, processing, uncertainty), 3.3. delineation, 3.4. velocity.**

We agree with the reviewer that the outlier removal procedure was complex and the presentation of the method took substantial manuscript space. The selection of maps for the ensemble was based on four different data quality proxies (% data available after outlier correction at the grid scale, sensitivity to outlier correction, triangulation residuals, and mean off-glacier elevation differences). Although all these proxies have already been applied in previous studies for quality assessments, perfectly objective criteria were not available to decide whether a map should be included in the ensemble or not. We assume this is the reason why the reviewer states that it is “hard to understand the reasoning of each process”.

We have therefore decided to considerably simplify the procedure for the selection of maps. We now simply select all Δh/Δt maps from the period 2006-2015 that cover periods of four years or longer (Section 3.2.5). Short periods are discarded from the beginning, since uncertainties increase with shorter time intervals (due to lower signal to noise ratios, see also new Figure 5). We have restructured the Methods section (Section 3) as suggested by the reviewer.

Since the quality proxies are now not used anymore as criteria for outlier detection we have proceeded as follows: Sensitivity to outlier correction is now assessed in a short separate sensitivity section (Section 4.2.1, new Table 6). The figure about mean off-glacier elevation differences has been transferred to the Supplement (Figures S1). The fraction of glacier pixels remaining after removing outliers and low stereo matching scores (old Figure 5b) and triangulation residuals (old Figure S2) is not presented anymore in the paper to shorten the manuscript. If the reviewer finds this important we can add the old Figure 5b to the Supplement and/or discuss triangulation residuals in Section 4.2.1, but would prefer not for reasons of shortness. None of the triangulation residuals exceeds the elevation change uncertainties as provided in Table 5. This means that the potential co-registration errors are within our uncertainty estimates.

**3. Influence of the earthquake It is interesting and important to evaluate the impact of the earthquake on the glacier surface elevation. However, the elevation change due to the earthquake in 2015 is essentially different from those occurred from 1974 to 2014. Accordingly, elevation change from 1974 to 2015 (e.g. Table 5 and Figure 6b) is not suitable to discuss recent glacier changes in general. Therefore, I suggest the author to separate the elevation change after the earthquake from the rest of the study period.**

We agree that elevation changes after the earthquake are locally very different from those during the period before the earthquake. For this reason, the May 2015 SPOT7 DEM has not been used to assess long-term glacier changes. However, we also concluded from our analysis that "Over periods of several years, the effect of the post-earthquake avalanches on the altitudinal thinning profiles such as presented in Figure 8 is only minor." (p. 23, lines 6-8, original manuscript). We now assess more carefully in Section 4.1 ("Impacts of the April 2015 earthquake") which of the post-earthquake DEMs can be considered to discuss recent glacier changes. We do this by comparing the avalanche impact to long term glacier changes and to uncertainties associated to elevation changes.

Almost 90% of the avalanche debris remaining in October 2015 accumulated on Lirung and Langtang glacier tongues. However, neither at Lirung tongue nor at Langtang tongue post-earthquake elevation changes represent outliers with respect to other 2006-2015 multi-annual periods (p. 17, lines 7-10).

The short-term effects of the post-earthquake avalanches (April 2014 – Oct 2015 elevation changes) are now shown in the revised Figure 8 and can be compared to the elevation changes 2006 - Oct 2015 and 2009 - Oct 2015. It becomes clear that in contrary to Apr 2014 – Oct 2015, the elevation change profiles 2006 - Oct 2015 and 2009 - Oct 2015 show very similar characteristics in comparison to other recent periods.

For the reasons stated above we therefore still use the October 2015 SPOT7 scene to discuss glacier changes in general (e.g. Figures 9-11). However, we replaced the differential DEM on Figure 6b (now Figure 4b) by a map showing only pre-earthquake elevation changes (but all other $\Delta h/\Delta t$ maps of the 2006-2015 ensemble are now presented in the new Figure S3).

**4. Text. I understand that the author tried to be careful and accurate in the text. However, the manuscript is lengthy, redundant and diffuse at many places. This hinders reader's understanding of the methodology, important results and conclusions. Please consider to shorten and simplifies sentences throughout the manuscript.**

We agree that the text needed to be improved by shortening and simplifying sentences throughout the manuscript. We have revised the text as requested by the reviewer.

**Specific comments:**

**page 1, line 15: we present volume and mass changes of . . . (omit "glacier")**

Ok.

**page 1, line 22: "mass balance trends" sounds to me "surface mass balance trends". What about "mass loss trends" or "thinning trends"?**

We indeed refer to "surface mass balance trends" (p.1, line 26).

**page 1, line 22: "highly non-linear" to what? elevation? time?**

We will add "spatially non-linear thinning profiles" (p.1, line 27).

**page 3, line 4: What do you mean by "downslope condition"?**

We have removed the corresponding sentence to shorten the manuscript. What we meant is that the surface mass balance at the debris-covered tongues may be influenced more quickly by changes in high-altitude precipitation due to avalanche nourishing. **page 3, line 8: . . . present-day "surface" lowering rates. . .**

We have changed the sentence as suggested (p. 2, line 31) .

**page 3, line 16: What is "melt due to glacier emergence velocity"?**

The sentence was not clear and we apologize for this. What we meant is that glacier emergence velocity has to be accounted for when comparing thinning rates to melt rates. We have rewritten the sentence ("*Models can also provide actual melt rates while geodetic studies only provide glacier thinning rates, which are affected by glacier emergence velocity*", p. 3, lines 9-10).

**page 4, line 26: . . ., Kimoshung Glaciers. . .**

We have corrected this.

**page 4, line 31-32: Please consider to shorten this kind of sentences. It should be OK to write ". . . are exceeded most part of the debris-covered area (Ragettle et al., 2015). Relatively thin debris layer appears only near the equilibrium line."**

We have revised the sentences as suggested (p. 4, lines 30-32).

**page 5, line 6: a.s.l.**

Ok. We now consistently use a.s.l. instead of asl

**page 7, line 9: ALOS PRISM**

Ok.

**page 8, line 5: What is "correlation score"?**

During the automatic DEM extraction, image correlation is used to extract matching pixels in two overlapping images. The correlation score indicates if pixels have been matched successfully. We have changed the sentence as follows: "The correlation score maps, *indicating which pixels have been matched successfully during the DEM extraction process*, are used to exclude all DEM grid cells with a correlation score below 0.5." (p. 8, lines 9-11).

**page 8, line 9: Either of "older" or "earlier acquisition date" is fine.**

Ok. We now simply state 'the older DEM' (p. 8, line 20).

**page 9, line 12-13: I understand that these parameters are useful to measure spatialnon-uniformity in the melt rate. However, I do not understand why you use both of them. Particularly, the second one needs a reason why you take 50% and 10%. Moreover, why not using the information on cliffs and lakes delineated from the satellite image (Figure 2b)?**

This was a good comment and we have revised our approach accordingly. Quality-checked cliff and lake inventories have been set up based on the available satellite imagery for the period 2006-2015 (Section 3.3). Those inventories are now used in the revised manuscript to directly relate cliff/lake area to local thinning rates. The two cliff proxies are not used anymore.

**page 10, line 16: I wonder why "higher accuracy" can be the reason to apply the higher threshold.**

We show that the standard deviations (σ) are lower over flat and non-snow covered terrain (Figure 3 of the original manuscript and Figure S1 in the Supplement of the revised manuscript). In the accumulation areas, on the other hand, the presence of many outliers leads to higher standard deviations in the elevation differences. Accordingly, with a 3σ-threshold we identify outliers at debris-covered terrain, whereas over featureless and steep terrain a lower threshold is necessary for efficient outlier detection. This is now better explained in the revised manuscript (“*Above the ELA, steep terrain or featureless snow surfaces lead to low DEM accuracy and therefore the outlier criteria should be more restrictive (e.g. Pieczonka et al., 2013; Pieczonka and Bolch, 2015).*” (p. 9, lines 20-22).

**page 11, line 11: Why do you use the thinning rate from 2006 to 2015 as a threshold?**

The thinning rate 2006-2015 was used as a threshold to guarantee that the signal to noise ratio is higher than 1:1, which indicates more signal than noise (whereas the thinning rate 2006-2015 is the signal and the DEM adjustment uncertainty is the noise). However, the outlier criterion discussed here is not used anymore in the revised manuscript and the selection of $\Delta h/\Delta t$ maps for the ensemble is now based on simple and straightforward criteria (see ‘General Revisions’ above).

**page 11, line 18-page 12, line 18: It is hard to understand the concept and the procedure to obtain U_cadj. If this is a commonly used parameter, please provide a good reference. I recommend the author to describe this kind of details in supplement.**

To compute triangulation residuals is a quite common approach for DEM co-registration quality assessment (e.g. Paul et al. 2015). However, we agree that the presentation of the method is lengthy and the results are not much discussed in the paper. Since we are not using this quality proxy anymore for outlier detection and potential errors due to co-registration are covered by our uncertainty estimates (see our response above to the reviewers $2^{nd}$ main comment) we removed all figures and text regarding triangulation residuals from the manuscript.

**page 13, line 12-13: I wonder how these thresholds were chosen and why they "effectively minimize the uncertainty".**

These thresholds minimized uncertainty because they allowed detecting outliers regarding mean elevation differences (MED). However, these thresholds and MED are not used anymore for outlier detection in the revised manuscript.

**page 14, line 5: Using three characters as a symbol is not common. By the way, do you need to define this symbol "unc"?**

We now use $E_{\Delta h}$ following Gardelle et al. (2013)

**page 14, line 14: Do you use the same density in the accumulation area?**

Yes. This is a common assumption in geodetic mass balance studies (e.g. Bolch et al., 2011, Gardelle et al. 2013).

**page 15, line 12: Should be "92 maps were removed because they FULFIL outlier criteria"?**

Ok. This text is now redundant and has been removed from the manuscript since we do not perform an outlier correction at the glacier scale anymore.

**page 15, line 22: Define the acronym "RPC".**

The acronym indicates Rational Polynomial Coefficients. However, we have removed the corresponding sentence to shorten the manuscript.

**page 17, line 5: Please be consistent with the unit, m/a or m a-1.**

Agree. We now consisently use m $a^{-1}$.

**page 17, line 29-30: "but a majority of values suggest that . . .." » This is not very sure from the data. It appears to me that the thinning rate is decreasing recently**

After applying the new outlier correction and uncertainty estimation procedures the data is now less ambiguous about mean thinning rates at Shalbachum Glacier (where indeed the thinning rates seem to have increased, see new Figure 8c and p. 16, lines 8-10). At Ghanna Glacier the data are still unclear. We now state that the ensemble uncertainty is too high to draw any conclusions regarding thinning trends at Ghanna Glacier (p. 16, lines 15-20).

**page 18, line 1: What do you mean by "ensemble of values"?**

This is an important point and we explain this clearly in the revised manuscript (Section 3.2.5). By ‘ensemble of values’ we mean the ensemble of observations available for overlapping periods. In the revised manuscript we use the data ensemble available for the period 2006-2015 more systematically to identify a sound signal and narrow down uncertainty. See our general response at the beginning of this document.

**page 18, line 30: What about simplifies the sentence to "The most negative elevation change for 1974-2006 was observed at Shalbachum . . ...".**

We have revised the sentence as suggested (p. 16, line 21).

**page 19: line 2-3: It makes more sense to compare 1974-2006 and 2006-2014 to eliminate the influence of the earthquake.**

Here we referenced to the values reported in Table 5 where the pre-earthquake February 2015 DEM was considered. There was a mistake in the manuscript text (it should have been “Comparing the two periods 1974-2006 and 2006-*Feb* 2015”). However, we think the October 2015 DEM is valuable to discuss multi-annual ($\Delta h$ > 4 years) elevation changes and should not be excluded from the ensemble. See our comment to the reviewers’ main comment 3 above.

**page 19, line 1: m a-1 » You need a space between m and a-1.**

Agree.

**page 19, line 9: "The most important differences in mean Δh/Δt values. . ." » "The greatest increase in thinning rate . . ."?**

We have removed this sentence and entirely rewritten the corresponding paragraph (from p. 16, line 28, until the end of Section 4.2) .

**page 19, line 15-21: I find this paragraph is not necessary here. Because Figure 8 clearly shows the thinning patters, you do not need to give questionable comment on Figure 6.**

Ok. We agree and we have removed the paragraph as suggested.

**page 19, line 32-page 20, line 3: This sentence is very hard to read. Please consider to rewrite it.**

We agree that the sentence was too long. We have rewriten the paragraph as follows:

*"On Langshisha Glacier (Figure 8b) near the terminus, the comparability of 1974-2006 thinning rates with the 2006-2015 ensemble is limited. Here, the glacier tongue became very narrow in the last decade and ultimately a small part below 4500 m a.s.l. disconnected from the main tongue (Figure 1) between 2010 and 2014. The fragmentation of the tongue leads to mean thinning rates close to zero at elevation bands where a substantial part of the glacier area disappears during a given time interval.*" (p. 18, lines 12-17).**page 21, line 30: "Δh/Δt_1974-06-Δh/Δt_2006-15<-0.2 m/a" » Is this correct? Isn't the left side positive if the thinning is accelerated?**

The reviewer is right here. It should have been "Δh/Δt_2006-15 - Δh/Δt_1974-06". We have rewritten the paragraph (p. 21, lines 22-27). In the caption text of new Figure 12 we now state "Negative Δ(Δh/Δt) values represent thinning accelerations".

**page 22, 5.3. Impacts of the April 2014 earthquake: This is an interesting analysis. I suggest the author to use the DEM after the earthquake only for this purpose. In other words, elevation change from 1974 to 2014 should be used for the rest part of the discussion.**

We agree that the May 2015 DEM should be used only for this purpose. However, the long-term impacts of the post-earthquake avalanches (Δh > 4 years) are already negligible in October 2015 and we thus use the October 2015 DEM also for the long-term comparison. See our statements above.

**page 22, line 2-8: This should be explained in the introduction section.**

We have removed those lines from the results section. We have added the reference to Kargel et al. (2015) to the introduction (p. 4, line 17).

**page 22, line8-21: This should be explained in the method section.**

Ok. We have followed the reviewers' advice (see new Section 3.5).

**page 23, line 5: "compensated by about 50%" » What density do you assume for the avalanche debris deposition?**

Here we only discussed volume changes and no mass changes. We therefore did not make any assumption about density. However, we have added to the paper an estimation of mass change due to the post-earthquake avalanches. According to Scally and Gardner (1989) avalanche deposit density increases until the end of the ablation season to about 720 kg/m$^3$. Considering this value and a density of ice of 900 kg/m$^3$, the mass deposits compensate by about 40% for glacier mass loss during an average year (p. 25, lines 1-4).

**page 23, line 12: "Elevation changes in the debris-covered area are primarily independent of elevation (Figures 8 and 10c) as previously identified in Langtang catchment (Pellicciotti et al., 2015) and elsewhere . . ..."**

Thank you. We have revise the sentence as suggested (p. 22, lines 3-6).

**page 23, line 16: "downward-" » downglacier?**

Ok. We have replaced ‘downward’ by ‘downglacier’ (p. 22, line 7).

**page 24, line 1-2: Not clear where and how water pressure is elevated.**

The delivery of surface-generated meltwater to the en- and subglacial environment is the driver of raising water pressure. Likely, lake formation itself can be attributed to enhanced englacial water pressure. It is therefore sufficient to state: “Such stresses are usually not large enough to initiate open surface crevasses, but in combination with elevated water pressure *due to local water inputs* lead to hydrologically driven fracture propagation (hydrofracturing) and englacial conduit formation (Benn et al., 2009)” (p. 22, lines 22-27).**page 24, line 5-6: Do you mean that thinning accelerated where ice motion is active because cliffs and lakes develops? It contradicts to my experience to observe cliffs and lakes formation on debris-covered stagnant ice.**

Yes, with the revised Figure 12 we can show clearly that especially cliffs appear more frequently where the glacier is not stagnant. This is not contradictory to previous studies. Several studies have shown that ice cliffs on depris-covered glaciers in the Himalaya appear most frequently in the transition zone between the active and inactive glacier parts (Sakai et al., 2002; Bolch et al., 2008; Thompson et al., 2016). The appearance of supraglacial lakes, on the other hand, is strongly related to the surface gradient. Large supraglacial lakes can only form where the slope is less than 2° (Reynolds, 2000), and the largest supraglacial lakes in the Himalaya form near the terminus of glaciers where a terminal moraine prevents free drainage of meltwater (Benn et al., 2012). The large debris-covered glaciers in the Upper Langtang catchment, however, have not reached this regime yet. We have added a paragraph to discuss the conditions that lead to supraglacial lake appearance (starting from p. 22, line 28).

**page 24, line 20: "glacier uplift" » do you mean "ice thickening due to compressive flow regime"?**

Yes. Uplift of ice occurs by convergence of the ice flux. However, we now state that “it can be assumed that *a slowdown of the compressive flow regime* is not the primary factor that *causes* the observed thinning accelerations” (p. 23, lines 20-21), which is more precise.

**page 23, line 27-page 25, line 11: The goal of this section is not clear. It appears that this section discusses the mechanism of surface elevation change on debris-covered ice. However, the thinning rate is highly variable in space and time, and there is no general trend in the observed glaciers. What kind of results does the author try to explain here? Many processes related to surface elevation change of debris-covered glaciers are described, but none of them are connected to reliable interpretation of the data. Describe first an observational fact that you want to discuss, and interpret the observation in a logical manner.**

This is a good comment, and we have substantially revised this section on the basis of the reviewers' comment. This entire section was based on the results presented in the old Figure 10. With the scatterplots and correlation coefficients we attempted to explain the variance in thinning rate changes of all debris-covered glaciers at the same time. However, single variables cannot explain all the spatial variation in thinning rates, and therefore the r values were generally low (max. 0.55 for debris-covered glaciers). We therefore removed the old Figure 10 and now show the most important variables (cliff area, lake area, surface velocity and changes in thinning) separately for each glacier (new Figure 12).

We now use a *new dataset of cliff and lake areas*, which substitutes the cliff/lake proxies. The new Figure 12 and the new Table 8 allow for a more reliable interpretation of the data. The main 'observational facts' that are presented are i) the relation between thinning acceleration and active glacier dynamics (given by the glacier velocity) at all debris-covered glaciers except Lirung, and ii) the relation between supraglacial cliff area and thinning acceleration (see new Section 4.5).

**page 25, line 16-17: What do you mean by "correlate with"? Which data show this?**

What we meant here is that one can expect glacier mass balances near steady state if the glacier area remains nearly constant, as it is the case for Kimoshung Glacier. We have removed the sentence to shorten the manuscript. Area changes are now presented in the new section 4.4.

**page 25, line 13-page 26, line 9: The first part of this section 7.1.1. explains that thinning accelerated at Yala Glacier, whereas it appears to be at a similar level at Kimoshung Glacier. This kind of explanation should be completed in Result section. Interpretation on the difference begins at page 25, line 28, but not convincing because there is no qualitative discussion. For example, hypsometry is not shown for Kimoshung Glacier, and no information about the 0 degree C isotherm altitude.**

The first part of section 7.1.1 (now section 5.2) has been completely removed from the discussion section. Glacier area changes are now presented in a separate results section (Section 4.4).

We guess the reviewer wanted to say that a quantitative discussion was missing (since the discussion was essentially qualitative). In the revised manuscript we thus show that variations in the estimated equilibrium line altitude (5400 m a.s.l.) of ± 100 m lead to an AAR variation of 13%-70% at Yala Glacier, but at Kimoshung Glacier only to a variation of 80%-88% (Table 6). This explains why Yala Glacier is much more sensitive to warming than Kimoshung Glacier. Consequently, thinning at Yala Glacier accelerated from -0.33 ± 0.06 m $a^{-1}$ (1974-2006) to -0.89 ± 0.23 m $a^{-1}$ (ensemble mean 2006-2015), while it accelerated only insignificantly at Kimoshung Glacier from +0.07 ± 0.13 m $a^{-1}$ to -0.02 ± 0.17 m $a^{-1}$ (Table 5). Hypsometry of Kimoshung Glacier is now shown by the new Figure S5 in the Supplement. We think that the large differences between Yala and Kimoshung Glaciers are now presented clearly and that the interpretation of the differences is now convincing.

**page 26, line 11-page 27, line 11: This section has the same problem as section 7.1.1. The first paragraph describes several different observations. These details should be explained in Result section, and here the focus of the discussion should be stated briefly. In the second paragraph, speculative conclusions are given without detailed/quantitative comparison with the modeling work.**

We have removed this section (section 7.1.2. in the original manuscript) and merged some of its content with section 5.1 ('Elevation changes of debris-covered glaciers'). We partly agree that some of our previous conclusions were speculative, since the differences in retreat rates between Ghanna Glacier and other debris-covered glaciers are not significant. We therefore removed this comparison from the manuscript. The remaining text (moved to section 5.1; p. 23, line 26, until p. 24, line 9) summarizes the current theoretical knowledge about the dynamical response of debris-covered glaciers to rising air-temperatures. Our conclusions are firmly supported by our data (thinning rates near the fronts of the large debris-covered glaciers in the valley indeed have not yet started to significantly decrease, Figure 12a-c, and the glacier tongues are indeed still dynamically active, Figure 13).

**page 27, line 18-20: Not clear what are compared in Figure 6b.**

We referred to Figure 6b because the figure shows also the thinning rates of Kimoshung Glacier. We have removed those lines and now base our discussion on the new Figure S5 (p. 26, lines 9-17). The figure directly compares thinning profiles at Kimoshung and Yala Glaciers.

**page 27, line 24-25: Not clear why you compare the elevation of Yala terminus and that of maximum thinning on Langtang.**

We apologize if this was not clear. The main point here was to compare lowering rates of debris-free and debris-covered glacier area at the same altitudinal range. Since debris-covered glaciers reach much lower elevations, a comparison is only possible from 5150 m a.s.l. upwards. The elevation of maximum thinning on Langtang Glacier coincides with Yala terminus elevation, but this is likely just a coincidence and should not be our main point here. We have thoroughly revised this paragraph to be clear (p. 26, lines 19-29).

**page 27, line 26-28: It is not clear which part of the elevation range is compared here. If you discuss elevation change of debris-covered and debris-free glaciers at same elevation range, why not preparing a plot for this purpose?**

Here we compared the thinning rates near the terminus of Yala Glacier (5150-5200 m a.s.l.) to the thinning rates at Langtang Glacier at the same elevation. As stated in our comment above, we have thoroughly revised this paragraph to better explain the differences between debris-covered and debris-free glaciers (p. 25, line 19, until p. 26, line 8). If the reviewer asks for it we can also add Figure R2 below to the Supplement (comparing thinning profiles of Yala Glacier to thinning profiles of Langtang Glacier tongue). However, the same information is provided by Figure 8. We therefore do not think an additional figure is required here.

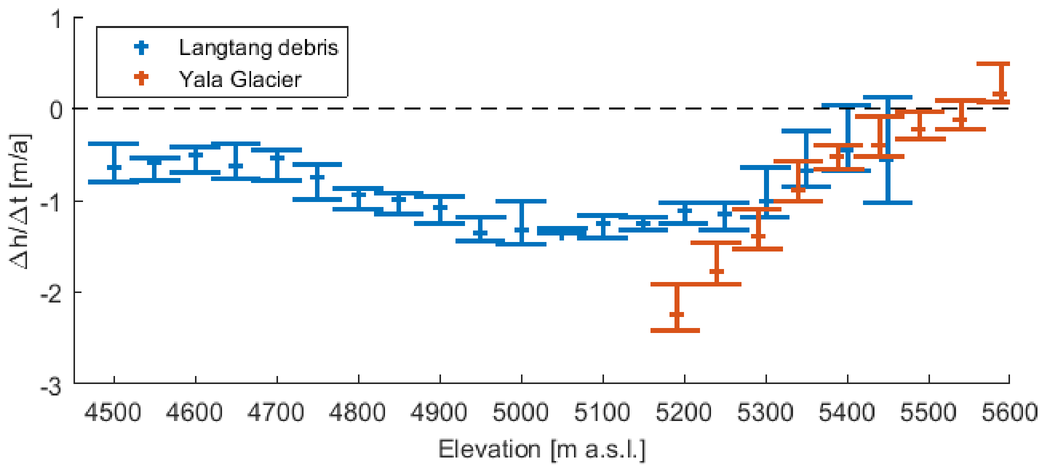


**Figure R1. Elevation change profiles of Langtang Glacier tongue (debris-covered) and Yala Glacier (debris-free). The figure shows the ensemble-median results for the period 2006-2015, and error bars represent the ensemble-uncertainty.**

**page 28, line 3-15: The point of the discussion is unclear.**

We apologize for the lack of clarity. We have improved the clarity of this paragraph by rewriting some of the sentences. The first important point here is that the magnitude of this thinning increase is very different from glacier to glacier ("*there are examples … of glaciers where thinning has increased significantly or where thinning remains approximately constant*", p. 26, lines 20-21). Then we state that "*A significant difference in thinning trends between debris-free and debris-covered glaciers in our sample cannot be identified*". This is why we conclude that "*our observations reveal a heterogeneous response to climate of both the debris-free and the debris-covered glaciers*" (p. 26, lines 18-19). Finally, we suggest that the altitude distribution of glaciers likely plays a more important role for average thinning rates than debris-cover alone (p. 26, lines 23-29). In the second part of the paragraph we have added quantitative details about the differences in glacier characteristics to make sure our conclusions are firmly supported by our data.

**page 28, line 16-17: Not clear what you mean. Do you mean that your result support the studies by Kaab, Nuimura and Gardelle?**

No, our results do **not** support the observations by Kääb, Nuimura and Gardelle, since our observations do not show that the lowering rates of debris-covered glacier area are similar to those of debris-free areas at the same elevation. We have stated this clearly on Page 25, line 31, until p. 26, line 8. On the other hand, we do not observe a significant difference in the overall mass balance trends of debris-free and debris-covered glaciers in our sample (see our previous comment above). Here we wanted to say that these two observations are not contradicting. A comparison of thinning rates at the same elevation is not representative of average thinning rates due to the differences in altitude distribution. However, since this is rather obvious we have removed those lines to shorten the manuscript.

**page 30, line 17-page 32, line 14: Only a few data appear in Conclusion section, which results in very qualitative descriptions. This represents the weakness of the paper. Please draw your conclusions which are supported by data.**

The reviewer is right that some more quantitative measures should be provided in the conclusion section. We have done this in the revised manuscript (p. 29, lines 11-12; p. 29, lines 29-31). A summary of quantitative outputs with respect to the three main goals is provided at the beginning of the revision statements to this reviewer. The summary and the revised conclusion section show that we are able to draw relevant conclusions firmly supported by our data.

**page 52, Figure 11: This velocity map is not much used for the study. Judging from the vectors on the plot, it is not sure how much this analysis is reliable.**

Velocity is a key variable to discuss thinning patterns on debris-covered glaciers (see revised Figure 12). We think the data are reliable, especially since the vectors consistently point in down-glacier direction. It is not clear to us how the reviewer came to a different conclusion regarding the vectors. The revised Figure 13 shows larger vectors, so we hope this is now clearer.

## REFERENCES


Banerjee, A. and Shankar, R.: On the response of Himalayan glaciers to climate change, J. Glaciol., 59(215), 480–490, doi:10.3189/2013JoG12J130, 2013.

Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. I., Quincey, D., Thompson, S., Toumi, R. and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Science Rev., 114, 156–174, doi:10.1016/j.earscirev.2012.03.008, 2012.

Bolch, T., Buchroithner, M. and Pieczonka, T.: Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data, J. Glaciol., 54(187), 592–600, doi:10.3189/002214308786570782, 2008.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M.: The state and fate of Himalayan glaciers., Science, 336(6079), 310–314, doi:10.1126/science.1215828, 2012.

Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, a.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, Cryosph., 7(4), 1263–1286, doi:10.5194/tc-7-1263-2013, 2013.

Huss, M., Jouvet, G., Farinotti, D. and Bauder, A.: Future high-mountain hydrology: a new parameterization of glacier retreat, Hydrol. Earth Syst. Sci., 14(5), 815–829, doi:10.5194/hess-14-815-2010, 2010.

Immerzeel, W. W., Kraaijenbrink, p. D. a., Shea, J. M., Shrestha, A. B., Pellicciotti, F., Bierkens, M. F. p. and de Jong, S. M.: High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles, Remote Sens. Environ., 150, 93–103, doi:10.1016/j.rse.2014.04.025, 2014a.

Immerzeel, W. W., Petersen, L., Ragettli, S. and Pellicciotti, F.: The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas, Water Resour. Res., 50(3), 2212–2226, doi:10.1002/2013WR014506, 2014b.

Juen, M., Mayer, C., Lambrecht, a., Han, H. and Liu, S.: Impact of varying debris cover thickness on ablation: a case study for Koxkar Glacier in the Tien Shan, Cryosph., 8(2), 377–386, doi:10.5194/tc-8-377-2014, 2014.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488(7412), 495–498, doi:10.1038/nature11324, 2012.

Khan, A., Naz, B. S. and Bowling, L. C.: Separating snow, clean and debris covered ice in the Upper Indus Basin, Hindukush-Karakoram-Himalayas, using Landsat images between 1998 and 2002, J. Hydrol., 521, 46–64, doi:10.1016/j.jhydrol.2014.11.048, 2015.

Magnússon, E., Muñoz-Cobo Belart, J., Pálsson, F., Ágústsson, H. and Crochet, p.: Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data – Case study from Drangajökull ice cap, NW Iceland, Cryosph., 10(1), 159–177, doi:10.5194/tc-10-159-2016, 2016.

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, Antarct. Alp. Res., 43(2), 246–255, doi:10.1657/1938-4246-43.2.246, 2011.

Paul, F., Bolch, T., Kääb, A., Nagler, T., Nuth, C., Scharrer, K., Shepherd, A., Strozzi, T., Ticconi, F., Bhambri, R., Berthier, E., Bevan, S., Gourmelen, N., Heid, T., Jeong, S., Kunz, M., Lauknes, T. R., Luckman, A., Merryman Boncori, J. p., Moholdt, G., Muir, A., Neelmeijer, J., Rankl, M., VanLooy, J. and Van Niel, T.: The glaciers climate change initiative: Methods for creating glacier area, elevation change and velocity products, Remote Sens. Environ., 162, 408–426, doi:10.1016/j.rse.2013.07.043, 2015.

Pieczonka, T. and Bolch, T.: Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~1975 and 1999 using Hexagon KH-9 imagery, Glob. Planet. Change, 128, 1–13, doi:10.1016/j.gloplacha.2014.11.014, 2015.

Pieczonka, T., Bolch, T. and Buchroithner, M.: Generation and evaluation of multitemporal digital terrain models of the Mt. Everest area from different optical sensors, ISPRS J. Photogramm. Remote Sens., 66(6), 927–940, doi:10.1016/j.isprsjprs.2011.07.003, 2011.

Pieczonka, T., Bolch, T., Junfeng, W. and Shiyin, L.: Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery, Remote Sens. Environ., 130, 233–244, doi:10.1016/j.rse.2012.11.020, 2013.

Ragettli, S., Pellicciotti, F., Immerzeel, W. W., Miles, E. S., Petersen, L., Heynen, M., Shea, J. M., Stumm, D., Joshi, S. and Shrestha, A.: Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model, Adv. Water Resour., 78, 94–111, doi:10.1016/j.advwatres.2015.01.013, 2015.

Reynolds, J.: On the formation of supraglacial lakes on debris-covered glaciers, IAHS Publ., (264), 153–161, 2000.

Rowan, A. V., Egholm, D. L., Quincey, D. J. and Glasser, N. F.: Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya, Earth Planet. Sci. Lett., 430, 427–438, doi:10.1016/j.epsl.2015.09.004, 2015.

Sakai, A., Nakawo, M. and Fujita, K.: Distribution characteristics and energy balance of ice cliffs on debris-covered glaciers, Nepal Himalaya, Arctic, Antarct. Alp. Res., 34(1), 12–19, doi:10.2307/1552503, 2002.

Scally, F. De and Gardner, J.: Evaluation of avalanche mass determination approaches: an example from the Himalaya, Pakistan, J. Glaciol., 35(120), 248–252, 1989.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Hillslope-glacier coupling: The interplay of topography and glacial dynamics in High Asia, J. Geophys. Res., 116(F02019), 1–21, doi:10.1029/2010JF001751, 2011a.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nat. Geosci., 4(3), 156–159, doi:10.1038/ngeo1068, 2011b.

Schwitter, M. and Raymond, C.: Changes in the longitudinal profiles of glaciers during advance and retreat, J. Glaciol., 39(133), 582–590, 1993.

Sugiyama, S., Fukui, K., Fujita, K., Tone, K. and Yamaguchi, S.: Changes in ice thickness and flow velocity of Yala Glacier, Langtang Himal, Nepal, from 1982 to 2009, Ann. Glaciol., 54(64), 157–162, doi:10.3189/2013AoG64A111, 2013.

Thompson, S., Benn, D. I., Mertes, J. and Luckman, A.: Stagnation and mass loss on a Himalayan debris-covered glacier: processes, patterns and rates, J. Glaciol., 1–19, doi:10.1017/jog.2016.37, 2016.

# Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal

**S. Ragettli[1,2], T. Bolch[2,3] and F. Pellicciotti[1,4]**

[1]{Institute of Environmental Engineering, ETH Zürich, Switzerland}

[2]{University of Zurich, Department of Geography, Zurich, Switzerland}

[3]{Institute for Cartography ,Technische Universität Dresden, Dresden, Germany}

[4]{Northumbria University, Department of Geography, Newcastle upon Tyne, UK}

Correspondence to: S. Ragettli (ragettli@ifu.baug.ethz.ch)

## Abstract

Himalayan glaciers are on average losing mass at rates similar to glaciers elsewhere, but heavily debris-covered glaciers are receding less than debris-free glaciers or ~~even~~ have stable fronts. ~~There~~Hence, there is a need for multi-temporal elevation change and mass balance data to determine ~~if~~whether glacier wastage of debris-covered glaciers is accelerating. Here, we present ~~glacier~~ volume and mass changes of seven glaciers (~~5~~five partially debris-covered, ~~2~~two debris-free) in the upper Langtang catchment in Nepal ~~of 28 different periods between 1974 and 2015 based on 8~~using a digital elevation ~~models (~~model (DEM) from 1974 stereo Hexagon satellite data and seven DEMs~~)~~ derived from ~~high-resolution~~ 2006-2015 stereo or tri-stereo satellite imagery (e.g. SPOT6/7). ~~We show that glacier~~ The availability of multiple independent DEM differences allows identifying a robust signal and narrowing down the uncertainty about recent volume ~~decreased during all~~changes. The volume changes calculated over several multi-year periods between 2006 and 2015 ~~(2006 – 2015: -0.60 ± 0.34 m a$^{-1}$) and at higher rates than between~~consistently indicate that glacier thinning has accelerated with respect to the period 1974~~ and -~~2006~~ (-0.28 ± 0.42~~. We calculate an ensemble-mean elevation change rate of -0.45 ± 0.18 m a$^{-1}$~~)~~. for 2006-2015, while for the period 1974-2006 we identify a rate of -0.24 ± 0.08 m a$^{-1}$. However, the behavior of glaciers in the study area ~~was~~ is ~~highly~~ heterogeneous, and the presence of debris ~~itself~~ does not seem to be a good predictor ~~for~~of surface mass balance trends. Debris-covered tongues have ~~highly~~ non-linear thinning profiles,

and we show that ~~local~~recent accelerations in thinning correlate with ~~complex thinning patterns characteristic of areas with a high concentration~~the presence of supraglacial cliffs and lakes. At stagnating glacier ~~area~~areas near the glacier front, on the other hand, thinning rates ~~may even decrease over~~ decreased with time~~. We conclude that trends of glacier mass loss rates~~ or remained constant. ~~in this part of the Himalaya cannot be generalized, neither for debris-covered nor for debris-free glaciers.~~ The April 2015 Nepal earthquake triggered large avalanches in the study catchment. Two post-earthquake DEMs from May and October 2015 allow quantifying the associated impact on glaciers. The remaining avalanche deposit volumes six months after the earthquake are negligible in comparison to 2006-2015 elevation changes. However, the deposits compensate about 40% the mass loss of debris-covered tongues of one average year.

## 1 Introduction

Global warming has caused widespread recent glacier thinning and retreat in the Himalayan region (Bolch et al., 2012). The impact of current and future glacier changes on Himalayan hydrology and downstream water supply strongly depends on the rate of such changes. However, planimetric and volumetric glacier ~~response rates~~changes are ~~not easy~~ difficult to characterize due to limited data availability, and many recent studies have highlighted the spatially heterogeneous distribution of glacier wastage in the Himalayas (Fujita and Nuimura, 2011; Bolch et al., 2012; Kääb et al., 2012). Prominent examples of current-day regional differences in glacier evolution across the Hindu Kush–Karakoram–Himalaya (HKH) are the reported positive glacier mass balances in the Pamir and Karakoram. Glaciers in the rest of the HKH are thinning and receding ~~(Kääb et al., 2012; Gardelle et al., 2013). Across regional scales systematic~~(Bolch et al., 2012; Kääb et al., 2012; Gardelle et al., 2013). Across regions, differences in recent glacier evolution can often be associated to differences in climatic regimes (Fujita, 2008), particularly to the varying influence of the south Asian monsoon and westerly disturbances (Yao et al., 2012). However, also within the same climatic region the rate of glacier changes can be ~~highly~~ heterogeneous (Scherler et al., 2011b). ~~As such, the~~A main focus of current ~~scientific debate concerns the differences in~~research is on the effect of supraglacial debris-cover on glacier response to climate~~ in function of varying surface characteristics caused by supraglacial debris~~. Thick debris cover is a common feature in the HKH (Scherler et al., 2011b; Racoviteanu et al., 2015) and a homogenous layer of thick debris effectively reduces melt rates of underlying ice (e.g. Östrem, 1959; Mattson et al., 1993). ~~Debris layers usually thicken in downstream direction due to the emergence of englacial debris through melting out of ice and rockfalls on the valley sides (Zhang et al., 2011; Banerjee and Shankar, 2013). Decreasing melt rates with increasing debris thickness counteract the effect on melt of air temperature increase at lower elevations. Consequently, debris-covered glaciers often form low reaching tongues with low surface velocities and low melt rates near the terminus (Benn et al., 2012). It is known that such quasi-stagnating tongues often have nearly stationary fronts also if the overall glacier mass balance is negative (Banerjee and Shankar, 2013). Glacier area loss is therefore not a good indicator to characterize the response of debris-covered glaciers to a warming climate (Scherler et al., 2011b). The characterization of debris-covered glacier response to climate is further~~However, the characterization of debris-covered glacier response to climate is complicated by the frequent occurrence of ice cliffs and supraglacial lakes. At exposed cliffs, melt rates are much higher compared to the ice covered by a thick debris mantle (Sakai et al., 1998, 2002; Immerzeel et al., 2014a; Steiner et al., 2015; Buri et al., 2016), and also at supraglacial ponds energy absorption is several times larger than that at the surrounding debris-covered surface ~~(Sakai et al., 2000; Miles et al., 2016a). The water in the ponds warms and may cause large englacial voids created by the drainage of warm water from the ponds, which may collapse and generate new depressions or ice cliffs (Benn et al., 2012). Debris-covered glaciers are also often avalanche nourished (Scherler et al., 2011a), which means that downslope conditions may be influenced more quickly by changes in high-altitude precipitation (Hewitt, 2005). To document the response of debris-covered glaciers to a warming climate, estimations of glacier-scale mass changes are therefore required (Cogley, 2012). Recent large scale geodetic studies based on remote sensing have provided evidence that the present-day lowering rates of~~(Sakai et al., 2000; Miles et al., 2016). Recent large-scale geodetic studies based on remote sensing have provided evidence that the present-day surface lowering rates of some debris-covered areas in the HKH might be similar to those of debris-free areas even within the same altitudinal range (Kääb et al., 2012; Nuimura et al., 2012; Gardelle et al., 2013), and surmise this could be due to enhanced melt from exposed ice cliffs and ~~near~~ supraglacial lakes. Several detailed modelling studies on the other hand have ~~demonstrated the~~provided evidence for a melt reducing effect of debris ~~on~~ at the glacier scale (e.g. Juen et al., 2014; Ragettli et al., 2015), and have shown how supraglacial debris prolongs the response of the glacier to warming ~~(Rowan et al., 2015).~~(Banerjee and Shankar, 2013; Rowan et al., 2015). Discrepancies between the different conclusions may be associated to glacier samples that are not comparable~~, to the discrepancy between thinning and melt due to glacier uplift and~~ or to model uncertainties (particularly regarding the representation of the effect ~~on melt caused by~~ of supraglacial cliffs and lakes on total melt). Models can also provide actual melt rates while geodetic studies only provide glacier thinning rates, which are affected by glacier emergence velocity.

Programs to monitor debris-covered glaciers ~~by direct observations~~ have been~~ recently~~ initiated in the Karakorum (e.g. Mayer et al., 2006; Mihalcea et al., 2006, 2008) ~~or~~and in the Central Himalaya (e.g. Pratap et al., 2015; Ragettli et al., 2015)~~ which will increase the knowledge on debris-covered glacier processes and enhance their representations in models.~~. However, due to the logistical and financial constraints, long~~-~~-term mass balance measurements ~~programs~~ are basically inexistent in the HKH. To document changes in debris-covered glacier thinning ~~rates~~ over time, declassified high~~-~~-resolution reconnaissance satellite data available from the 1960s and 1970s are an important source of information.~~ However, only few studies used these data and employed multi-temporal digital elevation models (DEMs) extracted from stereo satellite imagery to study changes in thinning rates of Himalayan glaciers over time.~~ In the Khumbu region in the Nepalese Himalaya, Bolch et al. (2008, 2011) have calculated multi-decadal mass loss of glaciers since 1962. They found that volume loss has possibly increased in recent years (e.g. volume loss rates of Khumbu glacier 1970-2007: -0.30 ± 0.09 m $a^{-1}$, 2002-2007: -0.50 ± 0.52 m $a^{-1}$). Similar conclusions were drawn~~ from a study~~ by Nuimura et al. (2012) who calculated accelerated thinning rates in the same study region comparing the two periods 1992-2008 (e.g. Khumbu glacier: -0.35 ± 0.20 m $a^{-1}$) and 2000-2008 (-0.76 ± 0.52 m $a^{-1}$).

~~The aim of this study is to calculate multi-decadal surface elevation changes of selected glaciers in the upper Langtang catchment in Nepal, for different periods between November 1974 and October 2015. Eight different high resolution DEMs, all extracted from stereo or tri-stereo satellite imagery, allow gaining more detailed insights in spatial and temporal changes in glacier thinning patterns than any geodetic study before in this part of the Himalaya. For each of the seven glaciers in the sample (five debris-covered and two debris-free glaciers), the analysis is constrained to those DEM combinations which are least affected by uncertainties stemming from errors in the DEM, ambiguous outlier definitions, the filling of missing data or DEM adjustment errors. The resulting 30 m resolution dataset of thinning rates~~A common problem of previous multi-temporal geodetic studies is the relatively low statistical significance of detected changes: the uncertainties in the mass loss estimates by Bolch et al. (2011) and Nuimura et al. (2012) are higher than the identified acceleration in glacier thinning. The uncertainties are especially high over short periods of $21^{st}$ century thinning rates. For long periods with much larger absolute elevation changes, the effect of DEM errors weighs less and uncertainties in glacier volume changes are lower. The aim of this study is to determine changes in glacier thinning with high confidence by considering multiple independent DEM differences for the $21^{st}$ century. For this we use seven DEMs derived from 2006-2015 stereo or tri-stereo satellite imagery and one DEM obtained from 1974 stereo Hexagon satellite data. We obtain an ensemble of multi-annual elevation changes that provides a range of plausible values for the period between October 2006 and October 2015. We then assess if the elevation changes between different overlapping periods between 2006 and 2015 show similar characteristics. If this is the case, the ensemble of results can be used to identify statistically significant changes in volume loss rates with respect to the longer period 1974-2006.

This study presents volume and mass changes of seven glaciers (five partially debris-covered, two debris-free) in the upper Langtang catchment in Nepal. The 30 m resolution dataset of multi-temporal glacier volume changes allows addressing three main research questions. First, we assess if overall thinning of glaciers in the region has accelerated~~ in recent years.~~. Second, we determine if spatial thinning patterns have changed over time. To explain changes in thinning rates we derive a number of glacier surface properties and glacier surface velocities. Third, we ~~assess~~evaluate if there are major differences between the response of debris-covered and debris-free glaciers in the sample. Finally, we also look at the ~~immediate cryospheric impact of the April 2015 earthquake that devastated large parts of the Langtang catchment by triggering large avalanches. By comparing pre-earthquake DEMs from April 2014 and February 2015 with post-earthquake DEMs from May and October 2015 we can quantify the impact of singular avalanche events on the mass balance of debris-covered glacier tongues.~~cryospheric impact of the April 2015 Nepal earthquake (7.8 magnitude, epicenter approximately 80 km west of the Langtang Valley). The earthquake devastated large parts of the Langtang catchment by triggering large avalanches (Kargel et al., 2016). Two post-earthquake DEMs from May and October 2015 are used to quantify the impact of the avalanche events on the mass balance of the debris-covered glacier tongues and assess its significance in comparison to multi-annual volume changes.

## 2 Study Site

We analyze the seven largest glaciers in the Langtang valley (Langtang, Langshisha, Shalbachum, Lirung, Ghanna, Yala, Kimoshung), located in the monsoon-dominated Central Himalaya in Nepal, approximately 50 km north of Kathmandu and 100 km west of the Everest region. While Yala and Kimoshung ~~glaciers~~Glaciers are debris-free glaciers, all other studied glaciers have tongues that are almost entirely covered by supraglacial debris (Figure 1). Langtang Glacier is the largest glacier in the valley with an area of 46.5 km$^2$ in 2006 (Table 1) and a total length of approximately 18 km. The smallest glacier~~ in our sample~~ is Ghanna Glacier with an area of 1.4 km$^2$.

Critical debris thicknesses leading to a reduction of melt rates are exceeded ~~often throughout~~ over most parts of the ~~entire ablation areas of~~ debris-covered ~~glaciers the upper Langtang catchment~~glacier area (Ragettli et al., 2015). Relatively ~~shallow layers of~~thin debris ~~appear~~appears only at the transition zone between accumulation and ablation area. However, at Lirung, Shalbachum, Ghanna and Langshisha Glaciers the upper margins of debris-covered sections are located at the foot of steep cirques ~~or icefalls, and transition zones are therefore very short. Only at Langtang Glacier englacial debris emerges gradually just below the equilibrium line altitude, which in this part of the Himalaya is located between 5400 and 5500 m asl (Sugiyama et al., 2013; Ragettli et al., 2015). In addition to spatially variable debris thicknesses due to gradual emergence of debris and rockfalls on the valley sides, ice~~and icefalls, and transition zones are therefore very short. Ice cliffs and supraglacial ponds ~~further~~ increase the heterogeneity of glacier surface characteristics in the Langtang valley (Pellicciotti et al., 2015).

The ablation season of glaciers in the Langtang valley lasts from ~~pre-monsoon (April – mid June) to post-monsoon (October – November), whereas the ablation season generally lasts longer at the low-lying debris-covered tongues.~~April to September. The monsoon season (mid June – September) is at the same time the warmest and the wettest period of the year. Snow cover at the lower elevation ~~ranges~~ of debris-covered glaciers is common only in winter (December – March). However, outside the monsoon period precipitation is limited and winters are rather dry (Collier and Immerzeel, 2015).

# 3 Data and methods

## 3.1 Satellite imagery ~~and DEM generation~~

Multitemporal high-resolution data from different sensors are applied to assess glacier change in the upper Langtang catchment. Each type of remote sensing data employed to calculate glacier elevation changes is listed below. Spatial and radiometric resolutions and base to height (b/h) ratios are provided in Table 2.

- The oldest data originate from Hexagon KH-9 stereo satellite images from November 1974 (Surazakov and Aizen, 2010; Pieczonka et al., 2013; Maurer and Rupper, 2015). ~~These are declassified images from an U.S. reconnaissance satellite program. The Hexagon DEM used here was generated for the study by Pellicciotti et al. (2015). We therefore refer to this study for further technical details regarding the Hexagon DEM.~~These are declassified images from a US reconnaissance satellite program (Burnett, 2012).
- Cartosat-1 is a remote sensing satellite built by the Indian Space Research Organisation (Tiwari et al., 2008). We purchased radiometrically corrected along-track stereo imagery (processed at level 'ortho-kit') of the upper Langtang catchment from October 2006 and November 2009. Cartosat-1 data have been previously used for DEM generation e.g. in the Khumbu region in the Nepal Himalaya by Bolch et al. (2011) and Pieczonka et al. (2011).
- ALOS-PRISM (Advanced Land Observing Satellite - Panchromatic Remote-Sensing Instrument for Stereo Mapping) was an optical sensor mounted on a Japanese satellite system which operated from January 2006 to April 2011 (Bignone and Umakawa, 2008; Tadono and Shimada, 2009; Lamsal et al., 2011; Holzer et al., 2015). We purchased a radiometrically calibrated along-track triplet mode scene from December 2010.
- SPOT6/7 (Système pour l'Oberservation de la Terre) along-track tri-stereo images ~~are available for~~were acquired upon request in April 2014, May 2015 and October 2015. SPOT6 and 7 are the newest satellites of the SPOT series which have been frequently used for geodetic glacier mass balance studies (e.g. Berthier et al., 2007, 2014; Pieczonka et al., 2013). We acquired stereoscopic images in panchromatic mode

corrected for radiometric and sensor distortions. Two of the three SPOT6/7 scenes used in this study were acquired in April/May which means that limited amounts of winter snow is still ~~is~~ present on the images. However, the imagery has a high spation resolution (1.5 m) and high radiometric depth of 12bit ~~(Table 2)~~ which leads to good correlation results also over snowy parts.

- ~~The WorldView DEMs used in this study are 8m posting Digital Elevation Models (DEMs) produced using the Surface Extraction with TIN-based Search-space Minimization (SETSM) by Noh and Howat (2015) and were downloaded from http://www.pgc.umn.edu/elevation. The DEMs are constructed from overlapping pairs of high-resolution images acquired by the WorldView-2 and 3 satellites in February 2014.~~ Overlapping pairs of high-resolution images acquired by the WorldView-2 and 3 satellites in February 2014 provide the basis of 8m DEMs downloaded from http://www.pgc.umn.edu/elevation (Noh and Howat, 2015).

~~The WorldView DEMs rely on the satellite positioning model to locate the surface in space, while all other DEMs used in this study have been extracted with ground control. The basis for the georectification were six differential GPS points collected on Lirung Glacier 23 October 2014 (Brun et al., 2016). Since no off-glacier dGPS points were available, we first generated a DEM from an across-track Pléiades stereo image pair from 1 and 9 November 2014 using the dGPS points as ground control points (GCPs). Glacier changes between 23 October and beginning of November are negligible due to the low temperatures during this period.~~

## 3.2 DEMs and elevation changes

### 3.2.1 DEM generation

The Hexagon DEM used here was generated for the study by Pellicciotti et al. (2015). We therefore refer to this study for further technical details regarding the Hexagon DEM. The SPOT6/7, Cartosat-1 and ALOS PRISM DEMs were generated for this study using the OrthoEngine module of PCI Geomatica 2015. We used~~Subsequently, we determined 17 GCPs on the basis of the Pléiades scene which were then used to derive a DEM from the SPOT6 April 2014 tri-stereo scene. The Pléiades DEM itself in the following is not used to calculate glacier elevation changes since only low correlation scores could be achieved for the upper parts of glaciers because of snowfall onset between 1 and 9 November 2014. To guarantee~~

~~high quality GCPs, only pixels with correlation scores higher than 0.7 were considered for GCPs. Since the Pléiades scene covers only about one fourth of the upper Langtang catchment, an additional 60 GCPs were determined on the basis of the April 2014 SPOT6 scene for the DEM extraction from the Cartosat-1, ALOS Prism and SPOT7 scenes. All SPOT6/7, Cartosat-1 and ALOS Prism DEMs used for this study were generated using the OrthoEngine module of PCI Geomatica 2015 and approximately 100 tie points for each scene. We were using~~ the same parameters for DEM generation as proposed by Berthier et al. (2014) except setting the parameter 'DEM detail' to 'very high' instead of 'low', which provided better results for the rugged debris-covered glacier surfaces. The basis for the georectification were six differential GPS (dGPS) points collected on Lirung Glacier on 23 October 2014 (Brun et al., 2016). Because glacier motion and ablation have to be accounted for when using on-glacier dGPS points, we first generated a DEM from an across-track Pléiades stereo image pair from 1 and 9 November 2014 using the available dGPS points as ground-control points (GCPs). Glacier melt between 23 October and the acquisition dates of the Pléiades scenes is negligible due to the low temperatures during this period. The horizontal shift due to glacier motion during this period is less than the grid size of the Pléiades image (0.5 m) and is therefore also negligible. Subsequently, we determined 17 GCPs on the basis of the Pléiades scene which were then used to derive a DEM from the SPOT6 April 2014 tri-stereo scene. The Pléiades DEM itself is not used in the following to calculate glacier elevation changes since it covers only a small part of the catchment and since only low stereo matching scores were achieved at elevations higher than 4300 m a.s.l. due to snowfall onset between 1 and 9 November 2014. To guarantee high quality GCPs, only pixels with correlation scores higher than 0.7 were considered for GCPs. Since the Pléiades scene covers only about one fourth of the upper Langtang catchment, an additional 60 GCPs were determined on the basis of the April 2014 SPOT6 scene for the DEM extraction from the Cartosat-1, ALOS Prism and SPOT7 scenes. In addition to the GCPs, approximately 100 tie points for each scene were used to match stereo pairs before DEM extraction.

The WorldView DEMs are 8m posting Digital Elevation Models (DEMs) produced using the Surface Extraction with TIN-based Search-space Minimization (SETSM) by Noh and Howat (2015). The WorldView DEMs rely on the satellite positioning model to locate the surface in space. The scenes from February 2015 which provide the basis of the two WorldView DEMs used in this study were acquired only 20 days apart (Table 2) and are adjacent to each other. The Worldview-2 DEM covers the western part of the study catchment and the WorldView-3

DEM the eastern part. Those DEMs were merged for this study and in the following are referred to as one single DEM representative of February 2015.

In addition to the DEMs ~~listed~~discussed above, the 2000 SRTM (Shuttle Radar Topography Mission) 1 Arc-Second Global DEM (~~30m~~30 m spatial resolution) was used to calculate slopes and accumulation area ratios (AARs) of glaciers (Table 1) and to define 50 m altitude bands. However, ~~for DEM differencing~~ the SRTM DEM was not used for DEM differencing because of the uncertainty regarding the penetration depth of the radar signal into snow and ice (Gardelle et al., 2013; Kääb et al., 2015; Pellicciotti et al., 2015). Only DEMs extracted from optical stereo imagery are therefore employed to calculate elevation changes in this study.

### ~~3.1.1~~3.2.2 Co-registration and DEM differencing

~~To~~ We considered all possible DEM pairs to measure the glacier elevation changes ~~we use all possible DEM pairs.~~. The number of possible two-fold combinations of *n* DEMs ~~($N_{\Delta t}$)~~ is

$$N_{\Delta t} = \sum_{k=1}^{n-1} k, \qquad (1)$$

~~Since the two available WorldView scenes were acquired only 20 days apart and are adjacent to each other (the Worldview-2 DEM covers the western part of the study catchment and the WorldView-3 DEM the eastern part), for each part of the catchment eight DEMs are available and elevation~~ Elevation differences over $N_{\Delta t}$ = 28 different time periods can therefore be calculated from the eight available DEMs extracted from optical stereo imagery. Co-registration of each DEM-pair is applied in order to minimize the errors associated with shifts. Systematic errors in the elevation change maps due to tectonic uplift which could be relevant after the April 2015 Nepal earthquake are also corrected with the co-registration. For this purpose we exclude from each DEM the non-stable terrain such as glaciers and in general all off-glacier area at elevations higher than 5400 m ~~asl~~a.s.l. (which is the estimated ~~height of the~~ equilibrium line altitude (ELA) in the Upper Langtang catchment (Ragettli et al., 2015)). The correlation score maps ~~from~~, indicating which pixels have been matched successfully during the DEM extraction process, are used to exclude all DEM grid cells with a correlation score below 0.5. Then, horizontal shifts are determined by minimizing the aspect-dependent bias of elevation differences ~~(cf. Nuth and Kääb, 2011) between each DEM pair. All terrain below a slope of 10° is excluded to allow for the slope dependency of the method. The slave DEM~~

~~(always the 'older' DEM with earlier acquisition date)~~(Nuth and Kääb, 2011) between each DEM pair. Because of the slope dependency of the method all terrain below a slope of 10° is excluded. The 'older' DEM is then resampled (bilinear interpolation) according to the determined horizontal shift. In a second step the vertical DEM shifts and possible tilts are corrected using second order trend surfaces fitted to all gently inclined (≤15°) stable terrain (Bolch et al., 2008; Pieczonka et al., 2011; Pieczonka and Bolch, 2015).

We resample all DEMs bilinearly to the grid size of the coarsest DEM (30 m) ~~in order to reduce the effect of different resolutions. Elevation differences are calculated by subtracting the older from the younger DEM (such that glacier thickening values are positive) and are converted to elevation change rates by dividing by the number of ablation seasons between the acquisition dates.~~to reduce the effect of different resolutions. Elevation differences are calculated by subtracting the older from the younger DEM (such that glacier thickening values are positive) and are converted to elevation change rates by dividing by the number of ablation seasons between the acquisition dates. Seasonal effects on elevation change rates are neglected when discussing time intervals between DEMs of 4 years or longer, since elevation changes during the winter half-year are usually minor (less than 20% of annual precipitation during post-monsoon and winter; Immerzeel et al., 2014b; and less than 3% of annual glacier ice-melt; Ragettli et al., 2015). Area-average glacier elevation change rates are calculated using always the maximum glacier extent between two acquisition dates.

### 3.2.3 ~~Delineation of glaciers~~Processing of elevation change maps

Processing of the elevation change ($\Delta h/\Delta t$) maps involves two main steps: i) removal of pixel values identified as outliers and ii) filling of gaps.

Outlier removal

The stereo matching score maps provided by PCI Geomatica are used to identify elevation data that can be considered for elevation change calculations. If the correlation score of a given DEM pixel is below 0.5, this indicates a poor matching score (Pieczonka et al. 2011) and therefore the corresponding $\Delta h/\Delta t$ values are treated as 'no data'. Very unrealistic elevation change data (exceeding ±150 m) are also excluded from the analysis.

We use the standard deviation ($\sigma$) of observed elevation changes to identify $\Delta h/\Delta t$ outliers. Outliers are defined separately for debris-covered glacier areas and debris-free glacier areas. For the latter we additionally distinguish between glacier area below and above the ELA (estimated at 5400 m a.s.l., see above). σ-levels are thus calculated for each of the three area types in every Δh/Δt map. Below the ELA (both debris-free and debris-covered area), pixels are defined as outliers if Δh/Δt values differ from the average by >3σ (e.g. Gardelle et al., 2013). This means that only very few data are classified as outliers, since three standard deviations account for 99.7% of the sample (assuming the distribution is normal). The conservative outlier definitions are justified by the shallow slopes and high contrast, which also explains why stereo matching scores are generally higher below the ELA (Figure 2c). Above the ELA, steep terrain or featureless snow surfaces lead to low DEM accuracy and therefore the outlier criteria should be more restrictive (e.g. Pieczonka et al., 2013; Pieczonka and Bolch, 2015). On debris-free glacier area above the ELA, pixels are therefore defined as outliers if Δh/Δt values differ from the average by >1σ (which applies to approximately 32% of the values if the distribution is normal). A stricter criterion for the accumulation area is also justified by the fact that it can be assumed that elevation changes in the accumulation areas over periods of several years are small (Schwitter and Raymond, 1993; Huss et al., 2010). Because we use different σ thresholds above and below the ELA we test the sensitivity of calculated glacier volume changes to a ±100 m ELA uncertainty. Furthermore, we test the sensitivity to different outlier definitions by comparing our results to the results obtained with a 2σ-level applied to all area types.

Gap filling

On the glacier areas below the ELA, with only very few data gaps, missing data are replaced using inverse distance weighting (IDW). In the accumulation areas, on the other hand, data gaps can extend over a wide elevation range if the terrain is steep or if the gaps are very large. Because of the elevation dependency of Δh/Δt values (e.g. Huss et al., 2010) only values from the same altitudinal range should be used to fill data gaps. We thus replace missing data in the accumulation areas by median Δh/Δt values per 50-m elevation band considering all available data for a given glacier (also from Δh/Δt maps representative of different periods). For this, we first calculate the mean elevation change rates per 50-m elevation band of each glacier and every Δh/Δt map and then determine the median of the ensemble. Δh/Δt maps that are rejected from the ensemble (see Section 3.2.5 below) and in general all values representative of short periods (Δt < 4 years) are not considered to calculate the ensemble-median values.

### 3.2.4 Uncertainty

Elevation change uncertainty estimates are based on the standard error $E_{\Delta h}$ calculated per elevation band (Gardelle et al., 2013). The standard error quantifies the effect of random errors on uncertainty according to the standard principles of error propagation:

$$E_{\Delta h} = \frac{\sigma_{\Delta h,noglac}}{\sqrt{N_{eff}}} \quad (2)$$

$$N_{eff} = \frac{N_{tot} \times PS}{2d} \quad (3)$$

$\sigma_{\Delta h,\ noglac}$ is the standard deviation of the mean elevation change of non-glacierized terrain per elevation band, $N_{eff}$ is the effective and $N_{tot}$ the total number of observations. *PS* is the pixel size (30 m) and *d* is the distance of spatial autocorrelation. *d* is equal to the range of the spherical semivariogram obtained by least squares fit to the experimental, isotropic variogram of all off-glacier elevation differences (Wang and Kääb, 2015; Magnússon et al., 2016). The distance of spatial autocorrelation of the 28 elevation change maps varies between 260 m and 730 m with an average of 495 m.

To quantify the elevation change uncertainty of glacier area spanning several elevation bands, weighted averages of $E_{\Delta h}$ are calculated. $E_{\Delta h}$ of each individual elevation band is weighted by the glacier hypsometry. Elevation change uncertainties therefore vary for each individual glacier because of the different glacier area-elevation distributions. $E_{\Delta h}$ tends to increase with altitude (Figure 3, Figure 4) due to steeper slopes, snow and deep shadows, which are factors that decrease the accuracy of DEMs derived from stereo data (e.g. Nuimura et al., 2011). Uncertainty estimates for each individual glacier therefore account for the spatially non-uniform distribution of uncertainty. Elevation change uncertainties of glaciers with a high accumulation area such as Kimoshung and Lirung Glaciers (Table 1) are 50%-100% higher than those of other glaciers, in accordance with lower DEM matching scores (Figure 2). The low uncertainty associated to debris-covered areas agrees with the 30%-100% lower off-glacier errors on shallow slopes (s<18°, 95th percentile of debris-covered glacier slopes) than on steeper slopes (s<45°, 95th percentile of glacier slopes; Figure S1).

The standard error can be interpreted as the 68% confidence interval of the sample mean if the distribution is normal. Since we are conservatively assuming no error compensation across elevation bands the approximate confidence level in our uncertainty estimates per glacier is higher than 68%.

This study aims at obtaining an ensemble of results about elevation change rates from the set of seven DEMs available for the period 2006-2015 and we thus calculate an ensemble uncertainty. The uncertainty in a sample mean is different from the uncertainty in individual observations about recent volume change rates. To identify the range of ensemble values (hereafter 'ensemble uncertainty') we use the standard deviation of the ensemble values multiplied by 1.96. By multiplication with 1.96 we obtain 95% confidence levels, assuming normal distribution.

For overall mass budget uncertainties we assume an ice density of 850 kg/m$^3$ to convert the volume change into mass balance (Sapiano et al., 1998; Huss, 2013) and consider the elevation change rate uncertainties and an ice density uncertainty of 60 kg/m$^3$.

### 3.2.5 Ensemble selection

The 28 available Δh/Δt maps are classified in two groups: maps that involve the Hexagon 1974 DEM and maps that represent only 21st century elevation changes (2006-2015). From the first group we only use the 1974-2006 Δh/Δt map, to strictly separate our two main study periods 1974-2006 and 2006-2015. From the second group we consider only those maps that are least affected by uncertainties. Since Δh/Δt uncertainties increase with shorter time intervals between DEMs (Figure 5, Table 3) and since similar elevation change patterns are more likely for overlapping periods, we discard all Δh/Δt maps with Δt < 4 years. In addition, we discard all Δh/Δt maps involving the ALOS PRISM DEM, since uncertainties associated to Δh/Δt maps involving this DEM are 30-100% higher than if other DEMs are involved (Table 3). The ALOS-PRISM sensor has a radiometric resolution of 8-bit, which means that in comparison to a 12-bit image (SPOT6/7, Table 2), $2^4$=16 times less information is provided per panchromatic image pixel. The image contrast is therefore lower, which decreases the accuracy of this DEM.

Due to the incomplete representation of Langtang Glacier on the SPOT6 Apr 2014 scene (the scene does not cover the area north of 28°19'N), Δh/Δt maps involving this DEM are excluded when discussing ensemble results for Langtang Glacier.

We assess separately if the Δh/Δt maps involving the post-earthquake DEMs (SPOT7 May 2015 and Oct 2015) can be considered for the 2006-2015 ensemble (section 4.1). Elevation changes after the earthquake in April 2014 might be substantially different from those before the earthquake because of large post-earthquake avalanches.

### ~~3.2~~3.3 Delineation of glaciers, debris-covered areas, and supraglacial cliffs/lakes

The glacier outlines were manually delineated. We used the orthorectified satellite images with the least snow cover (the Cartosat-1 2006 and 2009 scenes) to delineate the accumulation areas, and assumed no changes in the accumulation area over time. The tongues of the seven studied glaciers and debris extents were re-delineated for every year for which satellite images are available (1974, 2006, 2009, 2010, 2014 and 2015), using the corresponding orthorectified satellite images. A first operator delineated the outlines and a second operator provided feedback in order to improve delineation accuracy. To quantify the uncertainty in derived glacier area changes we consider a 0.5 pixel size delineation uncertainty (Paul et al., 2013).

The four largest glaciers in the valley were already delineated manually by Pellicciotti et al. (2015) for the years 1974 and 2000. However, we decided not to use those outlines because of the considerably higher resolution of the images that are available for this study and for consistency in the procedure applied for different outlines. We also re-delineated the catchment boundaries using the SRTM 30 m DEM and an automated flow accumulation process to accurately ~~define~~delineate the ~~upper limit of the glacier accumulation areas.~~ice divides between neighboring catchments. As a result, the calculated glacier areas (Table 1) changed considerably with respect to Pellicciotti et al. (2015). The 1974 glacier area of Langshisha Glacier changed by -40.4~~%,~~% (Figure S2), mostly due to clipping with the catchment mask which reduced the extent of the accumulation areas. The 1974 areas of Langtang, Shalbachum and Lirung changed by -8.7%, -9.5% and +8.0%, respectively.

~~For~~To identify glacier area associated to small glaciers in the ~~co-registration of~~catchment that are not discussed in this study we used the ~~DEMs and for stable terrain accuracy assessments we furthermore use~~glacier outlies provided by the GAMDAM glacier inventory (Nuimura et al., 2015)~~ to mask~~. Those areas were masked out ~~also the smaller glaciers~~ from off-glacier ~~data~~terrain for the co-registration of the DEMs and stable terrain accuracy assessments.

~~Since supraglacial cliffs are difficult to identify on the orthorectified satellite images, we use two statistical proxies to characterize debris-covered glacier sections. The first proxy is the standard deviation of Δh/Δt values (σ Δh/Δt). Second, we consider the difference between the 50% and 10% quantile of Δh/Δt values per elevation band (Δh/Δt $_{Q50-Q10}$). Both proxies~~

identify rugged, heterogeneous surfaces with a strong spatial variability in melt rates, characteristic of unstable debris layers where supraglacial cliffs and lakes appear (e.g. Sakai et al., 2000, 2002; Immerzeel et al., 2014; Buri et al., 2016). The proxies are calculated per 50 m elevation band of each debris-covered tongue (excluding tributary branches and large avalanche cones). The two uppermost elevation bands of each glacier are not considered due to intermittent, irregular debris cover at the transition between debris-free and debris-covered ice. Because glacier movement and changes in surface topography over time smooth out heterogeneous thinning patterns, short time intervals are required to identify cliff and lake areas on surface elevation change maps. $\Delta h/\Delta t_{2006-09}$ (Six quality checked maps of supraglacial cliffs and lakes are used to characterize debris-covered glacier surfaces (Steiner et al., 2016). The cliff and lake inventories were generated based on the available satellite imagery for the period 2006-2015 (Oct 2006, Nov 2009, Dec 2010, Apr 2014, May 2015 and Oct 2015). As for the glacier outlines, cliff and lake outlines have been delineated by two independent operators. To further improve the accuracy of the inventories, a third operator used slope and elevation change maps to identify potential cliff and lake locations. The first two operators then used these indications to review the inventories. All outlines have been obtained by manual delineation on the basis of the orthorectified satellite images.

We calculated the fraction of pixels including lakes and cliffs per 50 m elevation band of each debris-covered tongue (excluding tributary branches, Figure 6a) is thus used to calculate ). In the following, we only discuss median 2006-2015 cliff and lake proxies, because this map represents elevation changes over a relatively short time intervalarea fractions to minimize seasonal effects. Large avalanche cones, such as those present on Lirung and Langtang Glacier after the April 2015 earthquake, are masked out from the inventories before calculating median values. is not particularly affected by outliers (Table S1).

### 3.3 Outlier definitions

The relatively large dataset of 28 elevation change rate ($\Delta h/\Delta t$) maps allows for a rigorous definition of outliers in order to restrain the subsequent analysis only to those $\Delta h/\Delta t$ signals which are least affected by various sources of uncertainty. For this purpose we defined several criteria to filter out outliers at different scales (Table 3).

### 3.3.1 Outlier detection at the grid scale

Pixel values identified as outliers according to the criteria defined below are removed from Δh/Δt maps and filled using inverse distance weighting (IDW), considering the remaining glacier grid cells.

Correlation scores

PCI Geomatica provides the stereo matching score for each extracted DEM pixel. A threshold of 0.5 is applied to exclude elevations of poor accuracy. The correlation score of 0.5 is the lower bound of matching scores denominated as 'fair' in Pieczonka et al. (2011). Note that this criterion cannot be applied to the Hexagon and WorldView DEMs, since the correlation scores for these DEMs are not available.

Δh outliers

Pixels of debris-free glacier area are defined as outliers when the elevation differences differ by more than two standard deviations (2σ) from the mean elevation difference of all debris-free glacier area. The same criterion is applied to debris-covered glacier area but with a threshold of three standard deviations (3σ). The higher threshold applied to debris-covered terrain is justified by two reasons. First, the DEM accuracy is generally higher for debris-covered terrain (Figure S1b) due to more shallow slopes and high contrast. Second, the spatial variability in thinning rates can be very high over debris, due to heterogeneous surface characteristics such as variable debris thickness or supraglacial cliffs (Immerzeel et al., 2014). By applying a higher Δh outlier threshold for supraglacial debris we reduce the risk of misclassifying areas of high local thinning as outliers. The most extreme outliers (exceeding ±150 m) are not considered to calculate the standard deviations, in order to guarantee a better comparability with Δh maps where such artefacts occur more often (especially the Δh maps involving Hexagon or WorldView DEMs, where outlier correction based on matching scores is not possible).

### 3.3.2 Outlier detection at the glacier scale

Outliers at the glacier scale concern systematic errors which affect area-averaged Δh/Δt values per glacier. The glacier scale outliers are removed from the dataset, which means that from Δh/Δt maps all pixel values of concerned glaciers are removed, while the data from other glaciers can still be used.

Data availability

If for individual glaciers and Δh/Δt maps less than 50% of all pixel values remain after outlier removal at the grid scale, these are not considered for subsequent analysis.

Outlier correction uncertainty

Since no unambiguous criterion exists to identify outliers, but results might be sensitive to their definition, we apply different σ thresholds to the Δh/Δt maps (±1σ). Each time all data gaps are filled using IDW and mean Δh/Δt values per glacier are calculated. Then we compare the resulting mean Δh/Δt values per glacier corresponding to a more strict outlier definition (-1σ) with the mean Δh/Δt values corresponding to a more tolerant outlier definition (+1σ). If the absolute difference between the two values exceeds the mean thinning rates of the total glacier area calculated between October 2006 and October 2015, it is assumed that the signal to noise ratio is below a critical level. Therefore all Δh/Δt pixel values corresponding to a glacier where this criterion is exceeded are not considered subsequently, since the uncertainty which is due to outlier correction cannot be constrained sufficiently. This outlier criterion generally causes the exclusion of glaciers from the analysis which are affected by many outliers, because of factors that increase the DEM uncertainty such as steep slopes or low image contrast due to snow or shadows.

DEM adjustment uncertainty

Co-registration of DEMs is important because a small horizontal offset between two DEMs can produce a large elevation error where the topographic slope is steep (Berthier et al., 2004). However, co-registration procedures rely on curve and surface fitting functions which may be sensitive to outliers or which themselves might not describe vertical or horizontal shifts accurately due to tilts or distortions in the DEM. Assuming three acquisition dates $t_1$, $t_2$ and $t_3$, the elevation differences calculated between $t_1$ and $t_3$ ($\Delta h_{t1,t3}$) should be equal to $\Delta h_{t1,t2} + \Delta h_{t2,t3}$ if the DEMs are adjusted perfectly. However, this is rarely the case, and therefore the difference between $\Delta h_{t1,t3}$ and $\Delta h_{t1,t2} + \Delta h_{t2,t3}$ provides an estimate of the co-registration uncertainty. Having *n* DEMs available, area-average elevation differences can be calculated $C_{k-1}$ times by employing *k* DEMs (and therefore *k-1* DEM differencing steps):

$$C_{k-1} = \frac{\binom{n}{k}}{2} N_{\Delta t}^{-1} \qquad (2)$$

$N_{\Delta t}$ is the number of possible two-fold combinations of *n* DEMs (equation 1). According to equation (2), having *n=8* DEMs available, the difference between two DEMs can be determined six times by adding or subtracting the Δh values using a third DEM (*k=3*). Using *k* equal to 2, $C_1$ is equal to 1 according to equation (2). The DEM adjustment uncertainty ($U_{adj}$) is then calculated as follows:

$$U_{adj} = (abs(\Delta h_{C1} - median(\Delta h_{C2}))) / \Delta t, \qquad (3)$$

where $\Delta h_{C1}$ and $\Delta h_{C2}$ are the elevation differences calculated $C_{k-1}$ times for a given period Δt. To quantify the DEM adjustment uncertainty of area-average Δh values per glacier, we therefore first calculate mean glacier elevation differences corresponding to each of the 28 Δh maps, considering only the common minimum glacier extent. Then we combine each of the values six times as described above and calculate the DEM adjustment uncertainty according to equation (3). As a threshold for the acceptable DEM adjustment uncertainty we use again the mean thinning rates calculated between October 2006 and October 2015 of the total glacier area.

Note that gap filled Δh maps are required for the calculation of the DEM adjustment uncertainty. The gap filling itself causes uncertainty which increases $U_{adj}$. Therefore, the DEM adjustment uncertainty as defined here is used to estimate the uncertainty which stems both from the co-registration procedure and from the gap filling procedure.

### 3.3.3 Outlier detection at the catchment scale

Catchment scale outliers are Δh/Δt maps which are affected by systematic errors that lead to significant off-glacier elevation differences. Those Δh/Δt maps are removed entirely from the dataset, which means that the final analysis may be conducted using less than 28 Δh/Δt maps.

At the catchment scale we define outliers by the off-glacier mean elevation difference ($MED_{noglac}$) and standard deviation ($\sigma_{noglac}$). $MED_{noglac}$ and $\sigma_{noglac}$ are calculated excluding the steepest slopes where glaciers are unlikely to occur. This threshold slope is defined as the 95th percentile of the slope of all glacier grid cells ($Q95\ s_g$) and is equal to 45°.

To identify off-glacier elevation difference outliers we also use a map of monsoon snow-cover frequency (Figure 1) which is based on Landsat 1999 to 2013 land cover classifications (Miles et al., 2016b). Since the monsoon period is the warmest period of the year we assume that a monsoon snow-cover frequency higher than 20% represents terrain which is frequently snow covered. For a second estimate of the off-glacier mean elevation difference ($MED2_{noglac}$) and standard deviation ($\sigma2_{noglac}$) we therefore mask out also those areas since the surface elevation of snow covered terrain might change over time.

Finally a third estimate is provided by masking out also intermediate slopes which can occur on glaciers but which do not appear on debris-covered glacier area. The threshold slope is defined as the 95$^{th}$ percentile of the slope of all debris-covered glacier grid cells ($Q95\ s_d$) and is equal to 18°. Since the DEM uncertainties generally increase with steeper slopes (Nuimura et al., 2012) and lower image contrast such as over snow, it can be assumed that this third estimate leads to the lowest mean elevation difference ($MED3_{noglac}$) and standard deviation ($\sigma3_{noglac}$).

In order to effectively minimize the uncertainty in the ensemble, outliers are defined if they are larger than $q_3 + 1.5*(q_3 - q_1)$ or smaller than $q_1 - 1.5*(q_3 - q_1)$, where $q_1$ and $q_3$ are the 25th and 75th percentiles, respectively, of all $MED_{noglac}$ and $\sigma_{noglac}$ values in the ensemble.

Note that off-glacier outliers at the pixel scale are removed prior to the calculation of mean elevation differences and standard deviations analogous to the outlier correction for glacierized areas (Section 3.4.1). For off-glacier area with a monsoon snow frequency > 20% we use the same 2σ threshold as for debris-free glacier area and for off-glacier area with a monsoon snow frequency ≤ 20% we use a 3σ threshold as for debris-covered glacier area.

## 3.4 Uncertainty quantification

The uncertainty of the elevation change rates of the glacierised areas is quantified based on the individual stable terrain elevation differences. Since it is known that the distribution of uncertainty strongly depends on terrain characteristics such as slope, deep shadows, and snowfields with low contrast or the non-uniform distribution of the GCPs in altitudes (Berthier et al., 2004), we first quantify the uncertainties separately for each 50 m elevation band. It can be expected that the mentioned sources of uncertainty to become more abundant at higher altitudes (Nuimura et al., 2012). The SRTM 30 m DEM is used as a basis to delineate 50 m elevation bands. Both the standard error of the mean (SE) and the mean elevation difference (MED) are considered for the uncertainty estimates. The standard error quantifies the effect of random errors on uncertainty according to the standard principles of error propagation:

$$SE = \frac{\sigma_{\Delta h,noglac}}{\sqrt{n}}, \qquad (4)$$

where $\sigma_{\Delta h,\ noglac}$ is the standard deviation of the mean elevation change of non-glacierized terrain per elevation band, and n is the number of pixels per elevation band. To calculate the uncertainty (*unc*) per elevation band SE and MED are summed quadratically:

$$unc = \sqrt{SE^2 + MED^2}, \qquad (5)$$

To account for spatially non-uniform distribution of uncertainty we then conservatively assume 100% dependence of the uncertainty estimates for each elevation band (i.e. assuming no error compensation across elevation bands). To quantify uncertainty of area-average Δh/Δt values, uncertainties per elevation band are weighted by the altitudinal distribution of a given area. For each individual glacier uncertainty estimates therefore differ depending on glacier hypsometry, and therefore take into account the non-random spatial distribution of uncertainty.

For overall mass budget uncertainties we assume an ice density of 850 kg/m$^3$ to convert the volume change into mass balance (Huss, 2013) and consider at once the elevation change rate uncertainties and an ice density uncertainty of 60 kg/m$^3$.

### 3.53.4 Surface velocities

To assist with the interpretation of the derived volumetric changes, we use glacier velocities determined with the COSI-Corr cross-correlation feature-tracking algorithm (Leprince et al., 2007) and the available satellite imagery. Since the cross-correlations can be best determined if the period between the acquisition dates of images is short, we use theThe orthorectified Cartosat-1 Nov 2009 and ALOS-PRISM Dec 2010 images were used for this purpose. Other image pairs were not considered due to longer periods between acquisitions (leading to image decorrelation) or the presence of snow patches at lower elevations (SPOT6 April 2014, SPOT7 May 2015). The selected orthorectified images (5 m resolution) arewere adjusted according to the shifts determined by co-registration (Section 3.2).3.2.2). Since the window size must be large enough to avoid correlating only noise but small enough to not to degrade the output resolution (Dehecq et al., 2015), we tested several configurations. The best results for the COSI-Corr multiscale correlation analysis were achieved using a window size of 128 down to 32 pixels, as also proposed by Scherler et al. (2008). To post-process the velocity data we removed pixels with x- or y-velocity values greater than 40 m/a, since these were identified as errors by manually measuring the surface displacement on the basis of the orthorectified images and prominent features. We then ran a median filter on the data to remove areas which show a local reversal in x or y directions. ~~Missing values are then filled with the mean of the adjacent 8 values. Finally, the velocity map is resampled to 30 m resolution with a bicubic algorithm. To discriminate moving ice from quasi-stagnant ice we use a threshold of 2.5 m $a^{-1}$ following Scherler et al. (2011b).~~ Missing values were then filled with the mean of the adjacent 8 values. Finally, the velocity map was resampled to 30 m resolution with a bicubic algorithm.

## ~~4 Outliers and uncertainty assessment~~

~~The rigorous definition of outliers lead to a considerable reduction of the whole dataset from 196 glacier Δh/Δt maps (7 glaciers x 28 DEM difference maps) to 104 maps. 92 maps (46.9%, Table 4) were therefore removed from the dataset because they did not fulfil one or more outlier criteria at the glacier or catchment scale (Table S1).~~

~~Glacier Δh/Δt maps which involve the ALOS-PRISM Dec 2010 DEM for the DEM differencing were most often rejected (85.7% rejected, Table 4), followed by maps involving the WorldView Feb 2015 DEM (63.3%) and the SPOT6 April 2014 DEMs (59.2%). The ALOS-PRISM sensor has a radiometric resolution of 8-bit, which means that in comparison to a 12-bit image (SPOT6/7, Table 2), $2^4$=16 times less information is provided per panchromatic image pixel. The image contrast over snow and also over debris-free glacier area is therefore lower which leads to the more frequent occurrence of outliers. The high rejection rate for the WorldView DEM can be explained by the fact that this composite DEM was generated with an automatic algorithm using only the sensor RPCs and no ground control (Noh and Howat, 2015), but also due to an abundance of snow at lower elevations and low contrasts in February 2015. The presence of continuous snow surfaces down to ~5000 m asl in April 2014 also lowered the matching scores of the SPOT6 April DEM. However, the relatively high number of rejected maps involving the SPOT6 April DEM is mostly due to the incomplete representation of Langtang Glacier on the SPOT6 scene, which does not cover the area north of 28°19'N (Figure 1).~~

~~The glacier-wise outlier evaluation led to an uneven distribution of rejection rates per glacier. 37 of the rejected maps (40.2% of all rejected maps) concern Kimoshung and Lirung Glaciers. Lirung Glacier is the steepest of all glaciers (Table 1) which leads to low matching scores~~

(Figure S1a) and missing data (Figure 5b) due to deep shading and to higher DEM adjustment uncertainties (Figure S2a). Kimoshung Glacier has a very steep tongue and the accumulation area is located on a high plateau above 5400 m asl, representing 86% of its area (Table 1), which is frequently covered by a continuous snow layer. These topographic characteristics lead to significantly lower matching scores than for other glaciers (Figure S1a), more outliers and therefore higher outlier correction uncertainties (Figure S3a).

We also applied all outlier criteria (Table 3) separately to the Δh/Δt maps of debris-covered tongues. Considering only shallow slopes below 18°, representative of the slopes of debris-covered tongues, the off glacier standard deviation decreases ($\sigma3_{noglac}$, Figure 3b) and we identify significantly less outliers in mean off-glacier elevation differences than if also steeper slopes are considered ($MED3_{noglac}$, Figure 3a). The matching scores for debris-covered area are high (Figure S1b) which leads to only few data gaps (Figure 5b) and very low outlier correction uncertainties (Figure S3a). Overall, only 17.1% of all Δh/Δt maps of debris-covered tongues are removed from the dataset after outlier cleaning (Table 4).

It is important to note that most of the rejected Δh/Δt maps of glaciers and of debris-covered tongues correspond to short time intervals between DEM pairs. The median period length of all rejected Δh/Δt maps is three years for glacier Δh/Δt maps and one year for debris-covered tongue Δh/Δt maps (Table 4). Outliers are more likely to occur when the intervals are short, since errors in the DEMs in this case lead to lower signal to noise ratio. This also explains why only very few outliers concern DEM pairs involving the Hexagon 1974 DEM (Table 4), in spite of the lower spatial and radiometric resolution of the Hexagon KH-9 imagery (Table 2).

The removal of Δh/Δt maps identified as outliers on the basis of the off-glacier mean elevation difference and standard deviation led to a reduction of the ensemble uncertainty range throughout all elevation bands (Figure 4). At the lower elevations below 5300 m asl, where the debris-covered areas are located, the remaining uncertainties are very low with magnitudes of a few centimeters per year However, considerable uncertainties at high altitudes remain. We therefore calculate higher uncertainties for glaciers with large areas at high altitudes after weighting the uncertainties associated to each elevation band with the hypsometry of each glacier. This explains the overall higher uncertainty estimates for Lirung and Kimoshung Glacier, and the lower uncertainty estimates for debris-covered areas (Figure

5a). The individual uncertainty estimates for each glacier reflect their topographical characteristics and correlate well with the number of identified outliers per glacier (Table S1).

Although the uncertainties discussed above are representative of calculated elevation changes and not of DEM accuracy, we can characterize relative DEM accuracies by comparing the average uncertainty of all Δh/Δt maps generated with a given DEM (Table 4). Of all Δh/Δt maps which were not rejected, the mean off-glacier uncertainty weighted by the hypsometry of the total glacier area is 0.27 m/a. The highest uncertainties are attributed to DEM pairs involving the ALOS-PRISM DEM (0.4 m/a) and the lowest to those involving the SPOT7 Oct 2015 DEM (0.21 m/a). The mean uncertainty estimates correlate with the glacier Δh/Δt map rejection rates (also provided by Table 4). An exception represents the Hexagon 1974 DEM with low rejection rates but a relatively high average uncertainty of 0.34 m/a. The Nov 1974 - Oct 2006 Δh/Δt map (Figure 6a) reveals an irregular and unrealistic distribution of Δh/Δt values at high altitudes, which can be likely associated to errors in the Hexagon 1974 DEM. Outlier correction can attenuate the effect of such errors, but cannot completely eliminate them. The higher uncertainties calculated for Δh/Δt maps involving the Hexagon 1974 DEM seem therefore justified. However, the uncertainties at lower elevations are not higher for Δh/Δt maps involving the Hexagon 1974 DEM than for other maps (see the average uncertainties representative of the debris-covered tongues, Table 4). The average uncertainty of all Δh/Δt maps representative of the debris-covered areas (0.06 m/a) is substantially lower than the corresponding value representative of all glacierized areas (0.27 m/a). This difference reflects the extreme altitudinal range of glaciers in the study region and topographical characteristics at high altitudes that reduce DEM accuracy.

### 3.5 Assessment of the April 2015 earthquake impact

We quantify the impact of the avalanche events after the April 2015 earthquake on volume changes of debris-covered tongues. For this purpose we use the April 2014 - May 2015 Δh map to quantify the accumulated volumes less than two weeks after the earthquake, and the April 2014 - Oct 2015 Δh map to quantify the remaining volumes after one ablation season. To identify glacier area where avalanche material accumulated we consider all glacier grid cells with significant positive elevation changes (Δh > 5 m). Approximately 7.9% (1.9 $km^2$) of all debris-covered areas were affected by avalanches according to this definition. To calculate the deposited volumes we first estimate the volume loss between April 2014 and April 2015 (pre-earthquake), considering the mean annual thinning rates of the identified avalanche affected areas between Oct 2006 and Feb 2015. We then sum these volumes with the volume change measured by DEM differencing between 21 April 2014 and 7 May 2015 to obtain accumulated avalanche material volumes. Note that we do not use the Feb 2015 - May 2015 and the Feb 2015 - Oct 2015 Δh maps to quantify avalanche debris volumes because the calculated uncertainties associated to these maps are up to 300% higher than the uncertainties associated to the Apr 2014 differential DEMs (Table S1).

# ~~5~~4 Results

## 4.1 Impacts of the April 2015 earthquake

We calculate a total volume of post-earthquake avalanche debris in May 2015 of $2.49*10^7$ $m^3$, which is equivalent to a cube length of 292 m. 40% of the avalanche material remained until 6 Oct 2015 (Table 4). The two glaciers which were most affected by avalanches were Langtang Glacier (receiving 58% of the total volume) and Lirung Glacier (29%). The avalanche cone at Lirung Glacier piled up to a height of nearly 60 m, while the avalanche material at Langtang Glacier was more spread (Figure 7). Consequently, more material remained until 6 Oct 2015 at Lirung Glacier (57%), while at Langtang Glacier 31% remained (Table 4). Field visits at the end of October 2015 revealed that a smooth debris layer melted out of the avalanche material and covered the surface uniformly with a thickness of a few centimeters (P. Buri an P. Egli, personal communication).

The avalanche deposits in May 2015 and those remaining in Oct 2015 are equivalent to an average positive surface elevation change over all debris-covered glacier area of 1.31 ± 0.35 m and 0.52 ± 0.19 m (Table 4), respectively. A positive surface elevation change of 1.31 m corresponds to an average elevation change rate of approximately 0.16 - 0.26 m $a^{-1}$ if divided over five to eight years. This exceeds the uncertainty in Δh/Δt values attributed to debris-covered glacier area (±0.12 m $a^{-1}$, Table 3). The May 2015 DEM will therefore not be considered for the 2006-2015 ensemble. A positive elevation change of 0.52 m distributed over multi-annual periods within the 2006-2015 ensemble, however, corresponds to a change rate of only 0.06 - 0.09 m $a^{-1}$. This impact is within the uncertainty range associated to multi-annual Δh/Δt values. 2006-Oct 2015 and 2009-Oct 2015 elevation change rates are thus not substantially different from those before the earthquake and will be considered for the 2006-2015 ensemble (Figure S3).

The effect of avalanche debris on Apr 2014-Oct 2015 glacier thinning profiles (Figure 8) can be identified at Langtang Glacier (4500-4900 m a.s.l.), at Langshisha Glacier (4800 m a.s.l.), at Shalbachum Glacier (4750 m a.s.l.) and most prominently at Lirung Glacier (4350-4400 m a.s.l.). However, 2006-Oct 2015 and 2009-Oct 2015 thinning profiles are mostly within the error bounds associated to other multi-annual periods shown in Figure 8.

### ~~5.1~~4.2 Mean glacier surface elevation changes

The 2006-2015 ensemble ~~of mean elevation changes~~ consistently indicates an increase in mean glacier thinning rates ~~between 2006 and 2015~~ in comparison to the ~~periods starting in 1974, both at the total glacier area and at debris-covered glacier area~~ (period 1974-2006 (Figure 9~~a and b).~~ h). For 2006-2015 we calculate an ensemble-mean thinning rate of -0.45 ± 0.18 m a$^{-1}$, while for the period 1974-2006 we identify a thinning rate of -0.24 ± 0.08 m a$^{-1}$ (Table 5). This corresponds to an increase in determined mean thinning rates by 0.21 m a$^{-1}$ or 87.5%. The error bounds associated to the two periods are overlapping at the extremes. However, error bounds are not overlapping at 80% confidence levels: multiplication of the ensemble standard deviation by 1.28 (80% confidence level assuming normal distribution) instead of 1.96 (95% confidence level) results in an uncertainty of ± 0.11 m a$^{-1}$ instead of ± 0.18 m a$^{-1}$. The probability that 2006-2015 elevation changes are higher than -0.45 + 0.11 m a$^{-1}$ = -0.34 m a$^{-1}$ is thus 10%. Assuming a probability of less than 10% that 1974-2006 elevation changes are below this value, the estimated confidence level of accelerated thinning rates is higher than 99%.

From the ~~debris-covered~~ seven studied glaciers~~,~~ in the valley, the thinning rates of Langtang ~~and~~, Langshisha and Yala Glaciers ~~seem to undergo stronger thinning during the recent decade than before the turn of the century (~~have accelerated at 99% confidence levels (Figure 9~~e and g). For~~ , Table 5). At Shalbachum ~~and~~ Glacier the error bounds are overlapping but the estimated probability that 1974-2006 thinning rates are higher than 2006-2015 volume loss rates is less than 10%. At Lirung and Kimoshung Glaciers the mean thinning rates have likely remained approximately constant: the 2006-2015 ensemble mean and the value for 1974-2006 differ by 0.05 m a$^{-1}$ and 0.08 m a$^{-1}$, respectively (Table 5). The estimated probability that at one of these glaciers mean thinning rates changed by less than ± 0.15 m a$^{-1}$ between the two periods is higher than 90%. Also at Ghanna ~~Glaciers (Figure 7i and m),~~ Glacier the 1974-2006 value and the 2006-2015 ensemble mean differ by only 0.05 m a$^{-1}$ (Table 5). However, the scatter in the 2006-2015 values is such that no ~~clear trends in mean thinning rates~~ trend can be identified, but a majority of values. The ensemble uncertainty is ± 0.43 m $a^{-1}$, which is higher than at any other glacier (Table 5). Ghanna Glacier is also the only glacier where the ensemble of values available for the period 2006-2015 did not narrow down the uncertainty associated to individual periods (Figure 9).

The most negative elevation change for 1974-2006 was observed at Shalbachum (-0.43 ± 0.08 m $a^{-1}$, Table 5) and Ghanna Glacier (-0.51 ± 0.05 m $a^{-1}$). The least negative values were calculated for Langshisha (-0.12 ± 0.09 m $a^{-1}$) and Kimoshung Glaciers (0.06 ± 0.13 m $a^{-1}$). Comparing the period 1974-2006 and the 2006-2015 ensemble mean values, the strongest thinning acceleration took place at Yala Glacier (from -0.33 ± 0.06 m $a^{-1}$ to -0.89 ± 0.23 m $a^{-1}$, Table 5). Yala Glacier was also the glacier with the highest 2006-2015 ensemble mean thinning rate.

Volume change rates are also calculated separately for the five debris-covered tongues (Figure 10, Table 5). An increase in identified mean volume loss rates is evident on the Langtang, Langshisha, Shalbachum and Lirung tongues. Thinning rates increased between 15% (Langtang tongue) and 68% (Langshisha and Shalbachum tongues). For Ghanna tongue the identified changes in thinning rates are not significant given the uncertainties, but five out of six members of the 2006-2015 ensemble suggest that thinning rates remained approximately constant after 2006 in comparison to 1974-2006have more likely decreased rather than accelerated.

The ensemble of values helps to distinguish between trends that should be classified as uncertain (Shalbachum and Ghanna Glaciers) from trends that are consistent within the ensemble (Langtang and Langshisha Glaciers). Differences in values between largely overlapping periods should be attributed to uncertainty, as suggested by the uncertainty bounds (Figure 7). For Lirung Glacier an ensemble representation of values for the recent periods is not possible, since a majority of values did not fulfil the outlier criteria. The remaining values suggest slightly higher thinning rates in recent years with respect to the period 1974-2009 (Figure 7k).

The scatter in mean $\Delta h/\Delta t$ values of overlapping recent periods is much lower for the debris-covered tongues (Figure 7b) than at the whole glacier scale (Figure 7a). The temporal trends in thinning rates indicated for the debris-covered parts of glaciers are consistent within the ensemble. This result corresponds well to the low uncertainty estimates for debris-covered tongues (Figure 5a). A gradual acceleration of thinning within the last decade is suggested by the ensemble results for Langtang, Langshisha and Shalbachum tongues (Figure 7f, h and j). At Lirung tongue, the ensemble of values indicates significantly higher thinning rates in recent periods than before the turn of the century, but recent trends are less clear. We assume that the very high thinning rates calculated for the period Nov 2009 to April 2014 at Lirung tongue (-2.2 m/a, orange line Figure 7l) are due to local uncertainty. At Ghanna tongue, the values suggest a slight deceleration of thinning or constant thinning rates prior/after 2006 (Figure 7n). The mean thinning rates calculated for Ghanna tongue therefore clearly follow a different trend than mean thinning rates of other debris-covered glacier areas.

Regarding the thinning trends of debris-free glaciers (Figure 7c and d) the interpretation is again complicated by the apparent uncertainties. This is especially true for Kimoshung Glacier, where the uncertainties in mean Δh/Δt values are highest (Figure 5a). For this glacier the ensemble consistently indicates close to zero elevation changes after 2006, while the 1974-2006 and 1974-2009 mean Δh/Δt values are much more negative (-0.55 and -0.47 m/a, respectively). The opposite behaviour is suggested by the results for Yala Glacier, where thinning rates seem to gradually increase over time (Figure 7d).

The glaciers for which the most negative average elevation differences are calculated for the period 1974-2006 are Shalbachum Glacier (-0.63 ± 0.38 $ma^{-1}$, Table 5), Kimoshung Glacier (-0.55 ± 0.73 $ma^{-1}$) and Ghanna Glacier (-0.51 ± 0.13 $ma^{-1}$). The least negative values were calculated for Langshisha Glacier (-0.63 ± 0.28 $ma^{-1}$), Lirung Glacier (values only available for 1974-2009: -0.14 ± 0.45 $ma^{-1}$) and Langtang Glacier (-0.27 ± 0.30 $ma^{-1}$). Comparing the two periods 1974-2006 and 2006-Oct 2015, the strongest acceleration of thinning took place at Yala Glacier (from -0.40 ± 0.25 $ma^{-1}$ to -1.00 ± 0.26 $ma^{-1}$, Table 5), which for the period 2006-Oct 2015 was the glacier with the highest thinning rates. On average, glacier thinning rates increased by more than 100% between the periods 1974-2006 (-0.28 ± 0.42 $ma^{-1}$) and 2006-Oct 2015 (-0.62 ± 0.34 $ma^{-1}$). Only Kimoshung thinning rates decreased by 0.5 $ma^{-1}$ to -0.05 ± 0.53 $ma^{-1}$. Thinning of debris-covered areas also increased on average (from -0.77 ± 0.04 $ma^{-1}$ to -1.01 ± 0.06 $ma^{-1}$, Table 5). The most important differences in mean Δh/Δt values are determined for Lirung tongue (difference between $\Delta h/\Delta t_{1974-2006}$ and $\Delta h/\Delta t_{2006-Feb2015}$: -0.55 $ma^{-1}$), Shalbachum tongue (-0.49 $ma^{-1}$) and Langshisha tongue (-0.36 $ma^{-1}$), while thinning of Langtang tongue between the same two periods only increased moderately (-0.10 $ma^{-1}$) and decelerated at Ghanna tongue (+0.05 $ma^{-1}$).

## 5.2 Temporal and spatial patterns

A visual inspection of Δh/Δt values of debris-covered areas in Figure 6 suggests that areas of very strong thinning (< -2 ma$^{-1}$) seem to have become more common in the past nine years (Oct 2006-Oct 2015, Figure 6b) in comparison to the 32-year period between Nov 1974 and Oct 2006 (Figure 6a). However, glacier movement and changes in surface topography smooth out heterogeneous elevation change patterns over time. To assess if area-average thinning rates have changed over time we compare Δh/Δt values averaged over 50 m elevation bands of individual glaciers.

Of all debris-covered areas, the downwasting rates on Lirung tongue are the highest. This applies to both the period 1974-2006 (-1.03 ± 0.05 m a$^{-1}$, Table 5) and to the 2006-2015 ensemble mean (-1.67 ± 0.59 m a$^{-1}$, Table 5). The 2006-2015 ensemble uncertainty is very large on Lirung tongue (± 0.59 m a$^{-1}$), which we believe is due to systematic errors in the 2009-2014 differential DEM that represents an outlier in the ensemble (Figure 10). However, neither on Lirung nor on Langtang tongue (the two glaciers most affected by post-earthquake avalanches, see Section 4.1) post-earthquake elevation changes (2006-Oct 2015 or 2009-Oct 2015) represent outliers with respect to other 2006-2015 multi-annual periods. The lowest volume loss rates are identified for Ghanna tongue (Figure 10, Table 5). Here, the 2006-2015 ensemble mean value (-0.50 ± 0.20 m a$^{-1}$) indicates more than three times lower thinning rates than at Lirung tongue.

### 4.2.1 Sensitivity to outlier correction and ELA definitions

Mean elevation change values are most sensitive to outlier definitions for Langshisha Glacier 1974-2006 (Table 6). If a 2σ-level is used to define outliers for all area types (instead of a 3σ-level above and a 1σ-level below the ELA, Section 3.2.3), $\Delta h/\Delta t_{1974\text{-}2006}$ for Langshisha Glacier changes by -0.09 m a$^{-1}$ from -0.12 ± 0.09 m a$^{-1}$ to -0.21 ± 0.09 m a$^{-1}$. If we compare the results obtained with an estimated ELA at 5300 m a.s.l. to the results obtained with an ELA at 5500 m a.s.l., mean elevation changes of individual glaciers differ by up to -0.23 m a$^{-1}$ (Shalbachum Glacier 1974-2006). However, only for two glaciers the sensitivity values exceed the uncertainty values estimated from off-glacier elevation change errors (at Shalbachum and Yala Glacier 1974-2006, Table 6). In both cases the differences can be explained by unrealistic patterns (strongly negative elevation changes above 5400 m a.s.l.), that are not identified as outliers with a 3σ threshold applied to areas below 5500 m a.s.l. Our analysis thus shows that elevation change estimates are in most cases not significantly different if we assume different thresholds for outlier definition or if we consider the uncertainty in our ELA estimate. Significant sensitivity values can be explained by erroneous patterns in the accumulation areas that are properly defined as outliers with a 1σ threshold applied to areas above 5400 m a.s.l.

## 4.3 Altitudinal distribution of elevation changes

The altitudinal distribution~~s~~ of mean elevation changes clearly show that the thinning patterns of all debris-covered tongues have changed over time (Figure 8~~).~~, Figure 11). Areas with ~~a~~ clear ~~increase~~increases in thinning rates ~~in recent years with respect to the earlier periods~~ can be identified ~~at~~for Langtang Glacier ~~4950-5200~~5000-5150 m ~~asl, at~~a.s.l. (25%-100% thinning rate increase), for Langshisha Glacier ~~4600~~4650-5100 m ~~asl, at~~a.s.l. (25%-260%), for Shalbachum Glacier ~~4400~~4500-4800 m ~~asl~~a.s.l. (25%-180%) and ~~at~~for Lirung Glacier ~~above 4250~~4300-4350 m~~ asl.~~ a.s.l. (80%-170%). Thinning rates ~~mostly~~ have remained mostly ~~approximately~~ constant ~~over time near the terminus,~~ in the lower third of the elevation ranges of the tongues (Langtang, Shalbachum and Lirung Glaciers). At Ghanna Glacier, ~~unambiguously~~ thinning rates have recently declined near the glacier terminus ~~(~~at 4800-4850 m a.s.l. (60-90% thinning rate decrease, Figure 8e). ~~At~~This pattern of decreasing thinning rates contrasts with all other temporal patterns for debris-covered glacier areas.

On Langshisha Glacier (Figure 8b) near the ~~patterns near~~terminus, the ~~glacier terminus are more ambiguous~~comparability of 1974-2006 thinning rates with the 2006-2015 ensemble is limited. Here, the glacier tongue became very narrow in the last decade and ultimately a small part below 4500 m ~~asl~~a.s.l. disconnected from the main tongue (Figure 1) ~~after~~between 2010~~. The narrowing~~ and ~~eventual~~2014. The fragmentation of the tongue leads to mean thinning rates close to zero ~~if the relative weight~~at elevation bands where a substantial part of ~~disappearing~~the glacier area ~~is high, since always the maximal (initial) glacier area is considered to calculate mean thinning rates per elevation band. This seems to have been the case at Langshisha Glacier for periods starting in 2006 near 4500 m asl.~~disappears during a given time interval.

~~Small differences between~~ Overall, the thinning profiles of ~~overlapping periods from the last decade can be attributed to uncertainty (uncertainty bounds in~~ 2006-2015 ensemble members show very similar characteristics (Figure 8~~). At~~, Figure 11). The profiles diverge for the uppermost elevation bands of the ~~profiles of overlapping periods diverge because the uncertainty increases. This is nicely refelected by the uncertainty bounds for Langtang Glacier (Figure 8a), while at Lirung or Ghanna Glacier (Figure 8d and e) the local~~tongues and in the accumulation areas. This agrees with the larger error ~~is likely underestimated by the uncertainty bounds. At altitudes~~ that is attributed to higher ~~than the debris-covered tongues, the altitudinal Δh/Δt profiles diverge further (Figure 9).~~elevations (Figure 3). Above 5500 m ~~asl~~a.s.l. it is impossible to separate uncertainty from actual differences in thinning rates.

To compare the thinning patterns of debris-covered glaciers to the thinning patterns of debris-free glaciers, the altitudinal distribution of elevation changes at Yala Glacier are presented in Figure 11. Yala Glacier experiences more rapid thinning over almost its entire elevation range in recent periods (Figure 11d). This is in clear contrast to the ~~altitudinal thinning profiles of debris-covered glaciers, which present~~ much less uniform patterns ~~(~~at debris-covered glaciers (Figure 11a-c). ~~At~~Below 5400 m a.s.l there has been a three-fold increase in thinning rates at Yala Glacier, comparing 1974-2006 to the 2006-2015 ensemble results.

On Yala Glacier maximal thinning takes place at the terminus and then decreases nearly linearly with altitude until it reaches values close to zero (Figure 11d). ~~At~~For debris-covered glaciers, the elevation corresponding to the maximum thinning rates is different from glacier to glacier. ~~At~~On Shalbachum and Lirung Glaciers the maximum is reached somewhere close to the upper end of the tongue (4650~~ – ~~-4750 m ~~asl~~a.s.l. and 4300~~ – ~~-4400 m ~~asl,~~a.s.l., respectively, Figure 8c and d), ~~at~~on Langtang and Ghanna Glaciers more in the middle part (4950 – 5150 m ~~asl~~a.s.l. and 4900~~ – ~~-5000 m ~~asl,~~a.s.l., respectively, Figure 8a and e) and ~~at~~on Langshisha Glacier closer to the terminus (4450~~ – ~~-4700 m ~~asl,~~a.s.l., Figure 8b). ~~At~~On the large debris-covered glaciers, areas of maximum thinning seem to have shifted and extended to higher elevations only at Langtang Glacier, where during the period 1974-2006 maximum thinning occurred between 4850 and 4950 m ~~asl~~a.s.l. (Figure 8a). ~~At~~On Langtang and Shalbachum Glaciers the difference between thinning near the terminus and maximum thinning became much more pronounced in recent periods, but ~~at~~on Shalbachum Glacier maximum thinning during the period 1974-2006 occurred slightly higher up at 4750 – 4800 m ~~asl~~a.s.l. (Figure 8c).

Note that the altitudinal Δh/Δt profiles (Figure 8, Figure 11) always refer to the same position in space, since 50 m elevation bands were delimited only once on the basis of the SRTM 1 Arc-Second Global DEM. To account for the up-valley movement of on-glacier elevation bands over time due to surface lowering, profiles would have to be slightly shifted relative to each other. However, given the maximum thinning rates of 1-1.5 ma$^{-1}$ in ~~early periods~~1974-2006, the maximum relative adjustment of values in Figure 8 and Figure 11 would never exceed one 50~~-~~ m elevation band. Accounting for the shifting of elevation bands over time would therefore not lead to different conclusions regarding changes in spatial Δh/Δt patterns.

#### ~~5.2.1 Explanatory variables~~

~~We determine overall negative correlations between changes in Δh/Δt values over time and σ Δh/Δt (r=-0.52, Figure 10a) and between changes in Δh/Δt values and Δh/Δt Q50-Q10 (r=-0.55, Figure 10b), respectively. This indicates a link between accelerated thinning and the presence of supraglacial lakes and cliffs, but also between reduced thinning (e.g. Ghanna tongue, Figure 8e) and homogeneous layers of debris. At debris-free glacier area, for comparison, we calculate high positive correlations between spatial variability in elevation change values and changes in mean thinning rates (r=0.91, Figure 10a; r=0.97, Figure 10b). This result can be explained by increasing variability due to increasing uncertainty with altitude and at steeper slopes (Figure 4, Figure 10c and d). Indeed, changes in thinning rates at debris-free glacier area are essentially altitude dependent (Figure 9d,~~

### 4.4 Glacier area changes

Debris-free Yala Glacier experienced the strongest increase in relative annual area loss of all studied glaciers (1974-2006: -0.43 ± 0.05% a$^{-1}$, 2006-2015: -1.77 ± 0.16% a$^{-1}$, Table 7). During the same two time intervals Kimoshung Glacier shrank only at rates of 0.08 ± 0.01% a$^{-1}$ and 0.05 ± 0.02% a$^{-1}$, respectively. This represents significantly lower retreat rates for the second period than at Yala Glacier. The differences in area change rates are consistent with the identified differences in mean glacier surface elevation changes, where the two glaciers also represent opposite extremes (Section 4.2).

In comparison to the current retreat rates of Yala Glacier, all debris-covered glaciers are shrinking at a much slower pace, with retreat rates between -0.04 ± 0.04 % a$^{-1}$ and -0.40 ± 0.12% a$^{-1}$ (Table 7). Also debris-covered glaciers for which we observe high annual volume losses have nearly stationary fronts (e.g. Shalbachum Glacier: 2006-2015 thinning rate -0.53 ± 0.19 m a$^{-1}$, 2006-2015 area loss -0.04 ± 0.04 % a$^{-1}$). Ghanna Glacier in contrast shows a slighlty more significant retreat (-0.40 ± 0.12% a$^{-1}$, Table 7), although the mean thinning rates are the least negative of all debris-covered areas (Figure 10).

## 4.5 Surface velocities and supraglacial cliff/lake areas

Approximately 10% of all grid cells for the three largest debris-covered tongues (Langtang, Langshisha, Shalbachum) contain supraglacial cliff features ('Cliff Area' in Table 8). At Lirung and Ghanna tongues this value decreases to 8% and 3%, respectively. For Ghanna tongue practically no supraglacial lakes could be identified, while at the other debris-covered tongues 'Lake Area' is between 2.3% and 3.3%.

The mean surface velocities of the tongues range between 1.6 m a$^{-1}$ (Ghanna tongue) and 7 m a$^{-1}$ (Langhsisha tongue). The mean and the standard deviation of off-glacier surface velocities are 1.3 m a$^{-1}$ and 1.9 m a$^{-1}$, respectively. At Ghanna and Lirung tongue, which both have a mean surface velocity below 3 m a$^{-1}$, it is therefore practically impossible to discriminate moving ice from quasi-stagnant ice. Following Scherler et al. (2011b), all glacier grid cells with a surface velocity of less than 2.5 m a$^{-1}$ are therefore termed 'stagnant' for simplicity. According to this definition, the tongue area classified as 'stagnant' (Table 8) ranges from 20% (Langshisha tongue) to 85% (Ghanna tongue).

In our sample of five debris-covered glaciers, cliffs and lakes seem to appear more frequently on glaciers which are dynamically active. We identify a highly significant negative correlation (Pearson's linear correlation coefficient $r$=-0.99) between cliff area fraction per tongue and the percentage of stagnant tongue area. 'Lake Area' and '% stagnant area' are also negatively correlated (r=-0.87). At the scale of individual tongues, a correlation between surface velocities and cliff appearance is evident at Shalbachum Glacier (Figure 12c~~), whereas at debris-covered glacier area the~~ ). Here we identify a correlation ~~with altitude is close to zero (Figure 10c).~~

~~The correlation~~ of 0.85 (respectively 0.68) between ~~median surface~~the altitudinal velocity ~~per~~ profile and cliff (respectively lake) areas per 50 m elevation band~~ and changes in Δh/Δt values over time is rather low (r=0.31, Figure 10e). However,~~. Also on the ~~comparability of surface velocity fields across several glaciers is limited, since flow dynamics of debris-covered tongues in the catchment are differing due to the diversity in glacier lengths. The uncertainty in velocity estimates is also rather high, especially at narrow glacier tongues of smaller glaciers where cross-correlation windows are likely to overlap with glacier borders. However, at~~ two other large debris-covered tongues ~~the general patterns in the velocity fields indicate a clear interdependence of ice velocities~~in the valley, on Langtang and ~~thinning rates. We consistently find low velocities below 2.5 m/a near~~Langshisha tongues, cliff appearance clearly decreases towards the termini of debris-covered glaciers and higher velocities up to 25 m/a in the upper reaches of large debris-covered tongues (Figure 11). The pattern of down-glacier velocity decay agrees with the tendency of lower thinning rates and more homogeneous thinning patterns near the glacier termini (Figure 6, Figure 2). Indeed, 77% of all elevation bands where thinning accelerated ($\Delta h/\Delta t_{1974\text{-}06} - \Delta h/\Delta t_{2006\text{-}15} < -0.2$ m/a) are not stagnating (Figure 10e), and in 72% of all elevation bands where thinning rates remained constant or declined we observe stagnant conditions with velocities below 2.5 m/a (where the glaciers are quasi-stagnant (but the highest cliff area densities are identified 200-300 m below the altitude ranges corresponding to maximum surface velocity and therefore the two variables are not linearly correlated).

To investigate a possible link between accelerated thinning and the presence of supraglacial lakes and cliffs we compare 'Cliff Area' and 'Lake Area' (as provided in Table 8) to changes in mean thinning rates per tongue ($\Delta\ \Delta h/\Delta t$, difference between '1974-2006' and 'ensemble mean 2006-2015' as provided in Table 5). Overall, the correlation coefficient between fractional cliff area per tongue and $\Delta\ \Delta h/\Delta t$ is -0.62 (and -0.50 between lake area and $\Delta\ \Delta h/\Delta t$). The likely reduced thinning rates on Ghanna tongue (Figure 10e) indeed correspond to low cliff and lake area fractions (3.2% and 0.4%, respectively). On Lirung, Shalbachum and Langshisha tongues thinning accelerated by 0.47-0.64 m $a^{-1}$, whereas fractional cliff and lake areas are similar (cliff area: 8.0-10.5%, lake area: 2.3-2.6%). Also Langtang tongue is characterized by relatively high cliff and lake area fractions (10% and 3.3%, respectively, Table 8) but the identified changes in thinning rates are only minor. The acceleration of mean thinning rates at Langtang tongue is significant at the 95% confidence level (Figure 10a), but the difference in mean thinning rates 1974-2006 and 2006-2015 is only -0.12 m $a^{-1}$ (Table 5).

At locations where thinning rates did not increase significantly we mostly identify low cliff area fractions below 10% (e.g. on Langtang tongue below 4750 m a.s.l. and above 5150 m a.s.l., at Shalbachum below 5500 m a.s.l. and at Ghanna tongue). Conversely, cliff area fractions are generally higher than 10% where the 2006-2015 ensemble consistently indicates thinning acceleration (Figure 12e).

### 5.3 Impacts of the April 2014 earthquake

On 25 April 2015 the study area was struck by a 7.8 magnitude earthquake with an epicentre approximately 80 km west of the Langtang Valley. The earthquake triggered a large number

~~of geohazards in Nepal and China such as landslides and avalanches (Kargel et al., 2016). Also in the upper Langtang catchment earthquake-induced avalanches occurred on Lirung, Langtang, Shalbachum and Langshisha Glaciers. The availability of two post-earthquake DEMs, one acquired less than two weeks after the earthquake on 7 May 2015 (Table 2), allows quantifying the impact of this singular event on debris-covered tongues. For this purpose we use the April 2014 - May 2015 $\Delta h$ map (which is less affected by outliers than the Feb 2015 - May 2015 $\Delta h$ map, Table S1) to quantify the accumulated volumes immediately after the earthquake, and the April 2014 – Oct 2015 $\Delta h$ map to quantify the remaining volumes after one ablation season. To identify glacier area where avalanche material accumulated we consider all glacier grid cells with positive elevation changes by >5 m, which is approximately two times the standard deviation of off-glacier elevation differences calculated for the April 2014 - May 2015 $\Delta h$ map.~~). Exception to this observation are the high cliff area fractions at Langtang Glacier 4750-4900 m a.s.l., where thinning rates did not change significantly (Figure 12a), and low cliff area fractions at Shalbachum Glacier 4750-4800 m a.s.l., where thinning rates increased (Figure 12c). Lirung tongue also shows an opposite behavior, except for the lowest elevation band. However, maximum thinning acceleration at 4300 m a.s.l. corresponds to a relatively high lake area fraction of 6% (Figure 12d).

Altitude bands with no significant increases in thinning rates on Langtang Glacier consistently coincides with relatively low surface velocities below 5 m a$^{-1}$. At Langhisha and Shalbachum tongues this is also the case (Figure 12). Across all debris-covered glacier tongues, 77% of all elevation bands where thinning accelerated ($\Delta(\Delta h/\Delta t) < -0.2$ m a$^{-1}$) are not stagnating, and in 72% of all elevation bands where thinning rates remained constant or declined ($\Delta(\Delta h/\Delta t) \geq -0.2$ m a$^{-1}$) we observe stagnant conditions with velocities below 2.5 m a$^{-1}$.

~~Approximately 7.9% (1.9 km$^2$) of all debris-covered areas were affected by avalanches according to this definition. To calculate the deposited volumes we first estimate the volume loss between April 2014 and April 2015 (pre-earthquake), considering the mean annual thinning rates of the identified avalanche affected areas between Oct 2006 and Feb 2015. We then sum these volumes with the volume change measured by DEM differencing between 21 April 2014 and 7 May 2015 to obtain accumulated avalanche material volumes.~~

~~We calculate a total volume of avalanche material that accumulated on debris-covered area of 2.49*10$^7$ m$^3$, which is equivalent to a cube length of 292 m. 40% of the avalanche material~~

remained until 6 Oct 2015 (Table 6). The two glaciers which were most affected by avalanches were Langtang Glacier (receiving 58% of the total volume) and Lirung Glacier (29%). Figure 12 shows that the avalanche cone at Lirung Glacier piled up to a height of nearly 60 m, while the avalanche material at Langtang Glacier was more spread. Consequently, more material remained until 6 Oct 2015 at Lirung Glacier (57%), while at Langtang Glacier only 31% remained (Table 6). Field visits at the end of October 2015 revealed that a smooth debris layer melted out of the avalanche material and covered the surface uniformly with a thickness of a few centimeters (P. Buri an P. Egli, personal communication).

Considering the calculated volumes of avalanche deposits divided by the total debris-covered area we can compare the deposited volumes to average annual volume loss. The avalanche deposits remaining on 6 Oct 2015 are equivalent to an average surface elevation change by +0.52 m (Table 6). Given the average $\Delta h/\Delta t$ rates between October 2006 and February 2015 of -1.03 m/a (Table 5), the avalanches after the earthquake compensated by about 50% the volume loss of one average year. Over periods of several years, the effect of the post-earthquake avalanches on the altitudinal thinning profiles such as presented in Figure 8 is therefore only minor. It is best visible at Lirung Glacier at 4350 m asl (dark red and orange lines in Figure 8d), and slightly at Langtang tongue at about 4650 m asl (Figure 8a).

# 65 Discussion

## 6.1 Spatial and temporal elevation change patterns

## 5.1 Elevation change rates of changes of debris-covered glaciers

Elevation changes in the debris-covered area which are not primarily independent of elevation dependent (Figure 8), as previously identified in the Langtang catchment (Pellicciotti et al., 2015) and elsewhere in high-mountain Asia (e.g. Bolch et al., 2011; Dobhal et al., 2013; Pieczonka et al., 2013; Pieczonka and Bolch, 2015; Ye et al., 2015). Such patterns have usually been explained by downglacier increase of debris thickness and by ablation associated with supraglacial lakes and exposed ice cliffs. Our analysis shows that, with few exceptions, the highest thinning rates and the strongest increase in thinning rates can be associated to areas with a high concentration of ice cliffs and supraglacial ponds (Figure 12, Figure S4). While previous studies have pointed out that debris-covered areas with a large presence of supraglacial cliffs and lakes make a disproportionately large contribution to ablation (Reid and Brock, 2014; Buri et al., 2016; Miles et al., 2016; Thompson et al., 2016), this is the first study which documents the relation between accelerations in volume loss rates and the large presence of supraglacial cliffs and lakes.

~~, Figure 10c) have already been identified in previous studies for glaciers in the Langtang catchment (Pellicciotti et al., 2015) or elsewhere in high-mountain Asia (e.g. Bolch et al., 2011; Dobhal et al., 2013; Pieczonka et al., 2013; Pieczonka and Bolch, 2015; Ye et al., 2015). Such patterns have usually been explained by downward-increasing debris thickness and by ablation associated with supraglacial lakes and exposed ice cliffs. Our analysis shows that the highest thinning rates and the strongest increase in thinning rates can be associated to areas with patchy, spatially highly variable elevation change patterns, characteristic of areas with a high concentration of ice cliffs and supraglacial ponds (Figure 2, Figure 10). While previous studies have pointed out that debris-covered areas with a large presence of supraglacial cliffs and lakes make a disproportionately large contribution to ablation (e.g. Bolch et al., 2011; Zhang et al., 2011; Juen et al., 2014; Reid and Brock, 2014; Buri et al., 2016; Miles et al., 2016a), this is the first study which shows the correlation between complex thinning patterns and accelerations in volume loss rates at the scale of multiple glacier tongues.~~

Accelerated thinning of debris-covered area in the Upper Langtang catchment does not take place ~~at~~on stagnating parts of the tongues, but ~~in~~on the contrary at areas where debris-covered glacier area is dynamically active (Figure 12~~e), and where the transition between the active and the stagnant ice can be expected. Compressive stresses in the down-glacier direction associated with flow deceleration~~), and where the transition between the active and the stagnant ice can be expected. Supraglacial cliffs seem to appear more frequently on slowly moving ice (5-10 m $a^{-1}$, Figure 12) and not where the glacier is stagnant (Sakai et al., 2002; Bolch et al., 2008; Thompson et al., 2016). This can be explained by compressive stresses associated with flow deceleration that may initiate fracturing (Benn et al., 2009). Such stresses are usually not large enough to initiate open surface crevasses, but in combination with elevated water pressure ~~below the margins of supraglacial lakes~~due to local water inputs lead to hydrologically driven fracture propagation (hydrofracturing) and englacial conduit formation (Benn et al., 2009). The collapse of large englacial voids destabilizes the debris layers and ~~may lead to the formation of new ice cliffs. This explains why high values of σ~~

Δh/Δt and thus thinning accelerations are associated to active glacier dynamics. Higher ablation rates up-glacier than at the terminus cause a reduction of the glacier surface gradient, which in turn leads to further glacier slowdown and stagnation due to reduced driving stresses (Quincey et al., 2009; Jouvet et al., 2011; Benn et al., 2012). It is therefore likely that reduced ice fluxes and enhanced melt at supraglacial cliffs/lakes both contribute to the observed thinning accelerations at debris-covered tongues. Reduced ice flux could explain why the areas of maximum thinning migrated to slightly higher elevations on Langtang Glacier (Figure 8a), and why a new local maxima at 4650 m – 4750 m asl emerged on Shalbachum Glacier (Figure 8c). In order to assess which of the two factors contribute most to the observed accelerations in thinning, it would be necessary to quantify changes in ice flux over time. For such an assessment informationleads to the formation of new ice cliffs.

The appearance of supraglacial lakes, on the other hand, is strongly related to the surface gradient (Sakai and Fujita, 2010; Miles et al., 2016b). Large supraglacial lakes can only form where the slope is less than 2° (Reynolds, 2000) and where local water input is high. These conditions are not met on debris-covered glacier sections in the Upper Langtang catchment, since local surface slope is consistently above 5° (Pellicciotti et al., 2015). It is interesting to note that the highest lake area fractions (Lake Area > 6%) are found on avalanche deposition zones at Langtang Glacier (4750-4800 m a.s.l., Figure 9a and Figure 12a) and at Lirung Glacier (4300 m a.s.l., Figure 9d and Figure 12d). This is likely related to high local surface water inputs from melting of avalanche snow and ice. On Langtang Glacier frequent avalanche inputs may explain why thinning did not accelerate at the altitude range between 4750 m a.s.l. and 4900 m a.s.l., in spite of the presence of exposed ice (Cliff Area > 13%, Figure 12a).

Several studies suggest that lakes and cliffs are important but cannot explain the mass loss alone (e.g. Sakai et al., 2002; Juen et al., 2014). The high thinning magnitudes on the upper sections of Shalbachum tongue (4750-4800 m a.s.l.) likely cannot be attributed to lakes and cliffs (cliff/lake area fractions are below 5%, Figure S4c), and thin layers of deposited debris in the upper sections of the glacier tongue could explain such patterns.

Reduced ice fluxes also contribute to thinning accelerations. To assess how much this factor contributes to the observed accelerations in thinning it would be necessary to quantify changes in ice flux over time (e.g. Nuimura et al., 2011; Berthier and Vincent, 2012; Nuth et al., 2012). Information about the evolution of surface velocities over long time periods would be required, which our dataset cannot provide. However, given the usually very slow dynamical response of debris-covered glaciers to changes in the local temperature (Banerjee and Shankar, 2013) it can be assumed that ~~reductions in glacier uplift are~~a slowdown of the compressive flow regime is not the primary factor that ~~cause~~causes the observed thinning accelerations. Over the timescales considered in this study, on the other hand, high warming rates have been identified in this part of the Himalaya (Shrestha et al., 1999; Lau et al., 2010). The rise in air temperatures directly impacts glacier melt rates, and can explain~~s~~ rapid acceleration of thinning where ice is not insulated from warming by thick debris.

Banerjee and Shankar (2013) numerically investigated the response of extensively debris-covered glaciers to rising air-temperatures and describe the dynamical response as follows: during an initial period the fronts remain almost stationary and in the ablation region a slow-flowing quasi-stagnant tongue develops. During this period, which may last more than 100 years, glaciers loose volume by thinning. After this initial period glaciers start to retreat with a higher rate, while annual volume loss decreases because of thickening debris layers. Since thinning rates near the fronts of the large debris-covered glaciers in the valley (Langtang, Langshisha and Shalbachum Glaciers) have not yet started to significantly decrease (Figure 12a-c) and the glacier tongues are still dynamically active (Figure 13) it can be assumed that the quasi-stationary length period will persist for these glaciers in the near future. The model of Banerjee and Shankar (2013) does not account for supraglacial cliffs and lakes, which likely contribute to thinning acceleration (Figure 12). However, we have shown that they primarily appear on parts of the glacier tongues which are still dynamically active (Table 8). It can thus be assumed that they become less abundant with decreasing flow. The presence of cliffs and lakes therefore does not interfere with the dynamical response of debris-covered glaciers as described by Banerjee and Shankar (2013).

Near the snout of Ghanna Glacier a deceleration in thinning rates by -80% can be clearly identified (Figure 8e, 4800-4850 m a.s.l.). Previous studies have provided ~~numerical~~ evidence that ablation rates of debris-covered ice may decrease over time as a consequence of thickening debris cover, in spite of rising air-temperatures (Banerjee and Shankar, 2013; Rowan et al., 2015). ~~This insulating effect~~This process seems to take place currently at Ghanna tongue, but also on the lower ablation areas of Lirung, Langtang and Shalbachum Glaciers, where the ensemble of thinning rates also point to decreasing rates (Figure 12). The insulating effect of thickening debris might even lead to terminus advance during warmer climatic periods (Kellerer-Pirklbauer et al., 2008). ~~Due to long response times this somewhat counterintuitive response of debris-covered glaciers is difficult to observe.~~ However, ~~near the snout of Ghanna Glacier a deceleration in thinning rates can be clearly identified, and also in the lower ablation areas of Lirung, Langtang and Shalbachum Glaciers the ensemble of thinning rates point to a slowly decreasing trend (Figure 8). Terminus~~terminus advances~~, on the other hand,~~ have not been observed ~~(Table 7~~in the study area (Table 8) and are unlikely to occur at the five studied debris-covered glaciers due to ablation from frontal ~~ablation~~cliffs (evident from higher thinning rates at the lowest elevation ~~band at each profile in~~bands, Figure 8).

~~Other authors have suggested that slope can be used as a proxy for debris-covered glacier sections where ice cliffs are prone to form, favoring increases in ice losses (Nuimura et al., 2012; Pellicciotti et al., 2015). Most of the elevation bands of debris-covered sections are gently sloped (74% have a mean slope of less than 10°). However, we do not find a correlation between slope and thinning acceleration (Figure 10d). We explain this by the low variability in slopes at the scale of glacier tongues, whereas other studies have analyzed the connection between slope and elevation change at larger scales (Nuimura et al., 2012) or across the entire elevation range of debris-covered glaciers (Pellicciotti et al., 2015).~~

### 5.1.1 ~~Differences between individual~~Post-earthquake avalanche impacts

Accumulation by debris-laden avalanches is one of the most important processes for debris-covered glacier formation (Scherler et al., 2011a). The tongue of Lirung Glacier would likely not exist without accumulation through avalanches (Ragettli et al., 2015). It is detached from the accumulation area (Figure 1) and reaches 200-700 m lower elevations than all other debris-covered glaciers (Table 1). Our volume calculations of the post-earthquake avalanche impact allow quantifying the avalanche impact on mass balance and comparing it to mass loss during an average year. Given the avalanche deposits remaining on Lirung tongue by 6 Oct 2015 (divided by the area of the tongue: 3.87 ± 0.23 m, Table 4) and the average Δh/Δt rates between Oct 2006 and Feb 2015 of -1.64 ± 0.10 m $a^{-1}$ (Figure 10d), the avalanche after the earthquake compensated by 240% the volume loss of one average year. At the scale of all debris-covered area in the valley this value amounts to 50% (0.52 ± 0.19 m avalanche deposits and 1.02 ± 0.08 m $a^{-1}$ average thinning). According to Scally and Gardner (1989) avalanche deposit density increases until the end of the ablation season to about 80% of ice density. The mass deposits therefore compensate mass loss during a normal year by about

180% at Lirung tongue (40% at the catchment scale). Still, our analysis has revealed that the impacts are not significant in comparison to the 2006-2015 ensemble uncertainty (Section 4.1, Figure 10d and f).

### ~~6.2~~5.2 Elevation changes of debris-free glaciers

~~Debris-free Yala Glacier experienced by far the strongest increase in relative annual area loss of all studied glaciers (1974-2006: -0.43% a$^{-1}$, 2006-2015: -1.77% a$^{-1}$, Table 7). Of all glaciers in our sample, this is also the glacier for which the strongest acceleration in mean thinning is identified (Table 5). Areal changes of debris-free Kimoshung Glacier correlate with the average surface height changes only for the recent period 2006-2015. During this period the glacier area of Kimoshung Glacier decreased at a rate of 0.05% per year, which is 35 times less than at Yala Glacier. Accordingly, Kimoshung Glacier experienced much less thinning (-0.05 ma$^{-1}$, Table 5) than Yala Glacier (-1.00 ma$^{-1}$) during the same period. However, the retreat rates of Kimoshung Glacier were relatively low also during the period 1974-2006 (-0.08% a$^{-1}$, Table 7), while the calculated average elevation change rates for the same period are significantly more negative during this period (-0.55 ma$^{-1}$, Table 5). Likely, the identified average Δh/Δt values for Kimoshung Glacier for earlier periods (Figure 7c) overestimate the actual thinning rates. Presumably, unrealistically high thinning rates at high altitudes due to errors in the Hexagon 1974 DEM led to this result (Figure 6a). The actual Δh/Δt values still can be expected within the indicated uncertainty bounds but closer to steady-state conditions.~~

~~By the differences in mean elevation change rates between Kimoshung and Yala Glacier we can demonstrate how the response of debris-free glaciers strongly depends on glacier hypsometry. Almost balanced mass budgets in recent years can be associated to high accumulation area ratios such as characteristic of Kimoshung Glacier, although thinning of debris-free glacier area below the equilibrium line altitude is accelerating rapidly (Figure 9d). Only a small fraction of area of Kimoshung Glacier is exposed to rising temperatures above freezing level, and due to its steep tongue the accumulation area ratio (AAR) is not sensitive to changes in the 0°C isotherm altitude.~~2006-2015 downwasting rates on Yala Glacier are 0.5-1.2 m a$^{-1}$ higher than on Kimoshung Glacier (Table 5). However, the two glaciers have a very different hypsometry (Figure S5). Currently the estimated AAR of Yala Glacier is 40% (Table 1), which is a common value in the HKH region (Kääb et al., 2012). The estimated AAR of 86% at Kimoshung Glacier, on the other hand, corresponds to an exceptionally high value for the HKH (Khan et al., 2015). The differences in volume loss rates point to the role of glacier hypsometry to for the response of debris-free glaciers to climatic changes (e.g. Jiskoot et al., 2009). Almost balanced mass budgets in recent years (Table 5) and only minor area changes (Table 7) are associated to Kimoshung Glacier. Thinning did not increase significantly with respect to the period 1974-2006 (Figure 9g). Due to the steep tongue of this glacier the AAR is also not sensitive to changes in the ELA due to global warming (Table 6), and only a small fraction of area is exposed to rising temperatures above freezing level. The balanced conditions of Kimoshung Glacier therefore indicate that precipitation in recent decades remained approximately stable, which agrees with the findings of studies on precipitation trends in this part of the Himalaya (Shrestha et al., 2000; Immerzeel, 2008; Singh et al., 2008). Yala Glacier, on the other hand, is sensitive to fluctuations in temperature and is therefore thinning rapidly due to recent warming. A hypothetical rise of the ELA by 100 m at this glacier causes 30% of its area to turn from accumulation into ablation area (Table 6), and thinning below the ELA is accelerating rapidly (Figure 11d). Due to the common AAR of Yala Glacier it can be assumed that many other debris-free glaciers in the region are currently thinning at similar rates.

#### 6.2.1 Differences between individual debris-covered glaciers

In comparison to the current retreat rates of Yala Glacier, all debris-covered glaciers are shrinking at a much slower pace, with retreat rates between -0.04% $a^{-1}$ and -0.40% $a^{-1}$ (Table 7). It is interesting to note that the debris-covered glacier for which we currently observe the highest annual volume loss (Shalbachum Glacier, -0.70 ± 0.31 m/a, Table 5) has an almost stationary front (area loss -0.04% $a^{-1}$, Table 7). Ghanna Glacier in contrast is retreating at the highest pace of all debris-covered glaciers (-0.40% $a^{-1}$, Table 7) although the thinning rates have significantly declined near the terminus in recent periods (Figure 8e). Ghanna Glacier is also the only debris-covered glacier where average annual volume loss at the tongue did not accelerate in recent periods (Table 5, Figure 7n), although relative area loss seem to have increased slightly (from -0.33% $a^{-1}$ to -0.40% $a^{-1}$, Table 7).

Banerjee and Shankar (2013) numerically investigated the response of extensively debris-covered glaciers to rising air-temperatures and describe the dynamical response as follows: during an initial period the fronts remain almost stationary and in the ablation region a slow-flowing quasi-stagnant tongue develops. During this period, which may last more than 100 years, glaciers loose volume by thinning. After this initial period glaciers start to retreat with a higher rate, while annual volume loss decreases because of thickening debris layers. The

~~response time of such glaciers depend on local climate and geometrical properties (e.g. slope, length), but smaller glaciers with thinner initial glacier tongues and lower flow speeds can be generally assumed to pass the initial period with stationary lengths faster than large valley glaciers. Our observations therefore suggest that Ghanna Glacier, which is the smallest glacier in the sample, is already entering the second period, since annual volume loss of the tongue is decreasing but retreat rates are increasing. All large debris-covered glaciers in the valley (Langtang, Langhsisha, Shalbachum) are still responding to increasing temperatures by accelerated thinning rather than retreat. Since thinning near the glacier fronts has not yet started to substantially decrease (Figure 8) and the glacier tongues are still dynamically active (Figure 11) it can be assumed that the quasi-stationary length period will persist in the near future. The model of Banerjee and Shankar (2013) does not account for supraglacial cliffs and lakes, which likely cause an acceleration in thinning (Figure 10a and b). However, we have shown that they primarily appear on parts of the glacier tongues which are still dynamically active. It can thus be assumed that they become less abundant with decreasing flow, such as it is already the case in the lower section of Langtang Glacier (Figure 2b). The presence of cliffs and lakes therefore does not interfere with the dynamical response of debris-covered glaciers as described by Banerjee and Shankar (2013).~~

### ~~6.3~~5.3 Differences between debris-free and debris-covered glaciers

The ~~dynamical~~ response of debris-covered and debris-free glaciers to ~~a~~ warming ~~climate~~ is substantially different, as described in the two sections above and exemplified by the altitudinal elevation change profiles in Figure 11. Our observations do not support the ~~conclusion~~findings of previous studies about similar present-day lowering rates of debris-covered and debris-free glacier areas at the same elevation (Kääb et al., 2012; Nuimura et al., 2012; Gardelle et al., 2013) ~~that the present-day lowering rates of debris-covered glacier areas in high mountain Asia might be similar to those of debris-free areas at the same elevation. In the Upper Langtang catchment this might be the case only very locally, e.g. comparing the elevation change rates of large debris-covered tongues and Kimoshung tongue (Figure 6b). However, Kimoshung Glacier is rather unique, since the very high AAR of 86% (Table 1) leads to a high ice flux, which also explains why its tongue reaches to unusually low elevations (terminus at 4385 m asl, Table 1). Yala Glacier, which can be considered a benchmark glacier in this part of the Himalaya~~. Also for debris-covered elevation bands where up to 18% the area is covered by supraglacial cliffs and lakes (e.g. at Langtang tongue

5050 m a.s.l. or at Langshisha tongue 4750 m a.s.l.) thinning rates do not exceed 1.8 m a$^{-1}$, while for Yala Glacier the lowering rates are already above this value at 5250 m a.s.l. and further increase downglacier (Figure 11). Within the same altitudinal range (5200-5300 m a.s.l.) thinning rates of debris-covered glaciers do not exceed 35%-75% of the thinning rates of Yala Glacier.

Our data indeed reveal 60%-80% lower thinning rates at Kimoshung tongue with respect to Yala Glacier at 5200-5300 m a.s.l. (Figure S5). Kimoshung Glacier has a very steep tongue that reaches to similarly low elevations as the debris-covered glacier tongues (Table 1). However, a comparison of thinning rates with debris-covered glaciers is not meaningful, since the average slope of Kimoshung tongue is 32%, whereas the average slope of debris-covered area is only 8%. Glacier surface height increase as a result of compressive flow effectively compensates for lowering by ablation on a glacier with a very steep tongue, whereas this is not expected on gently sloped glacier area. We suggest that future large scale geodetic studies take this into account when comparing lowering rates of debris-free and debris-covered ice.

Regarding the mean surface elevation changes (Table 5), our observations reveal a heterogeneous response to climate of both the debris-free and the debris-covered glaciers. As discussed in the two sections above, there are examples for both types of glaciers where thinning has increased significantly or where thinning remained approximately constant. A significant difference in thinning trends between debris-free and debris-covered glaciers in our sample cannot be identified. In our sample, the best predictor for thinning accelerations seems to be the altitude distributions of glaciers. Glaciers with a high AAR (Kimoshung) or which reach the highest elevations (Lirung) have the most balanced mass budgets and show no significant changes in volume loss over time (Figure 9, Table 5). Glaciers which are most sensitive to ELA changes (more than ±10% AAR change in response to ±100 m ELA uncertainty, Table 6) such as Yala, Langtang and Langshisha Glaciers reveal the most significant thinning accelerations (Figure 9, Table 5). However, debris-free Yala Glacier is currently downwasting at 60%-100% higher rates than the large debris-covered glaciers in the valley. Considering Yala Glacier as a benchmark for debris-free glaciers in the Nepal Himalayas (Fujita and Nuimura, 2011), seems more appropriate for comparison. Due to the lower AAR (40%, Table 1) the glacier reaches only to a minimum elevation of about 5150 m asl. Note that this is the altitude where maximum thinning occurs on Langtang Glacier (Figure 8a, Figure 9a). However, maximum thinning per elevation band does not exceed 1.3 – 1.5 m/a at the main tongue of Langtang Glacier (Figure 8a), while at the same altitude Yala Glacier is thinning by about 1.8 – 2.3 m/a in recent periods (Figure 9d). This means that in spite of enhanced melt from supraglacial cliffs and at supraglacial lakes (Figure 2), within the same altitudinal range thinning rates of debris-covered glaciers do not exceed 65%-75% of the thinning rates at Yala Glacier. In addition, a comparison of thinning rates at the same altitudinal range between debris-free and debris-covered glaciers is not indicative of their climate responses, since debris-covered glaciers usually reach much lower elevations than debris-free glaciers and are often thinning less near the glacier terminus (Figure 8).our results indeed point to a difference in current volume loss of debris-free and debris-covered glaciers. It seems important, however, that this observation is confirmed by studies using larger glacier samples.

The comparison of mean surface elevation change rates 1974-2006 and 2006-2015 (Table 5) reveals that both the debris-free and the debris-covered glaciers show a heterogeneous response to climate. Considering the values in Table 5, average thinning of all glaciers has increased in the recent period (except at Kimoshung Glacier, but which likely derives from errors in the Hexagon 1974 DEM, see Section 7.1.1). However, as discussed in the two sections above, there are examples for both types of glaciers where thinning seems to increase rapidly or where thinning remains approximately constant. A main difference between debris-free and debris-covered glaciers in our sample cannot be identified with regard to average thinning in recent periods. In our sample, the best predictor for average thinning between 2006 and 2015 seems to be the altitude distributions of glaciers, since glaciers with a high AAR (Kimoshung) or which reach the highest elevations (Lirung) have the most balanced mass budgets (Table 5), whereas glaciers with low AAR and which span over the relatively small elevation ranges (Yala, Ghanna) are thinning most rapidly.

Note that lower thinning rates at debris-covered tongues are not in contradiction to the overall mass balances trends, where no major difference between glacier types can be identified. Debris-covered glaciers have low-lying tongues with shallow slopes, whereas the tongues of debris-free glaciers are shorter and often much steeper, which means that smaller areas are exposed to the high air-temperatures which cause rapid downwasting.

## ~~6.4~~5.4 Comparison ~~with~~to other studies

The four largest debris-covered glaciers in the valley (Langtang, Langshisha, Shalbachum, Lirung) have been the focus of a recent geodetic mass balance study by Pellicciotti et al. (2015), who reconstructed elevation and mass changes using the 1974 Hexagon DEM which is also used in this study (spatial resolution 30 m) and the 2000 SRTM3 DEM (90 m). They found that all four glaciers ~~were losing~~lost mass over the study period but with different rates (on average -0.32 ± 0.18 m w.e. $a^{-1}$). We find an overall glacier mass balance for the period 1974-2006 of the four glaciers which is ~~similar (-0.24 ± 0.35 m w.e. $a^{-1}$).~~probably slightly less negative (-0.22 ± 0.08 m w.e. $a^{-1}$). However, the results match within the uncertainties. A study by Kääb et al. (2015) revealed that the penetration estimate of the SRTM radar signal as applied by Pellicciotti et al. (2015) is likely underestimated. A correction of their results by a larger penetration estimate reconciles their results with ours. The lower uncertainty estimates by our study are justified by the high resolution and quality of the 2006 Cartosat-1 DEM (Table 3). Differences in the mass balance of Langtang, Lirung and Shalbachum Glacier are within uncertainty bounds and can be attributed to differences in used glacier masks, study period, outlier correction approaches and density assumptions. However, for Langshisha Glacier we calculate a mass balance which is substantially less negative than in Pellicciotti et al. (2015). While we identify almost balanced conditions for the period 1974-2006 ~~(~~(-0.~~01~~10 ± 0.~~39~~08 m w.e. $a^{-1}$, ~~Table 5~~Table 5), the mass balance indicated by Pellicciotti et al. (2015) is very negative (-0.79 ± 0.18 m w.e. $a^{-1}$). ~~The main reason for this are uncertainties in the Hexagon DEM which are accounted for differently. In the present study, volume gains in the accumulation area of Langshisha Glacier are not per se identified as outliers, whereas in~~ The discrepancy can be explained by the overestimated extent of the accumulation areas by Pellicciotti et al. (2015)~~ those areas are completely masked out (Fig. 3 in Pellicciotti et al. (2015)). Likely, the actual mass balance of Langshisha Glacier is somewhere between the two average values. Note that the higher uncertainty estimates for the present study are due to differences in the uncertainty quantification approach, and cannot be related to differences in data quality. At Langshisha Glacier the uncertainty estimates of the present study are certainly more realistic~~ (Figure S2) in combination with unrealistic lowering rates of up to -2 m $a^{-1}$ at about 6000 m a.s.l. (Figure 4d in Pellicciotti et al., 2015). The more realistic elevation change values obtained by the present study for the accumulation areas (-0.4 - 0.4 m $a^{-1}$, Figure 11b) point to the need of restrictive outlier definitions and the advantage of having information from multiple datasets available for gap filling.

Yala Glacier has been frequently visited for field measurements in the last 25 years. Sugiyama et al. (2013) calculated mean thinning rates of Yala Glacier for the periods 1982-1996 (–0.69 ± 0.25 m $a^{-1}$) and 1996-2009 (–0.75 ± 0.24 m $a^{-1}$) on the basis of ground photogrammetry and GPS surveys. The values suggest a more moderate acceleration of volume loss rates than ~~presented by~~in our study ~~(Table 5, -~~(-0.~~40~~33 ± 0.~~25~~06 m $a^{-1}$ 1974-2006 to -~~1.00 ± ~~0.~~26~~89 ± 0.23 m $a^{-1}$ 2006-2015~~).~~, Table 5). However, similarly to our study Sugiyama et al. (2013) identified a rapid acceleration of thinning rates at the lowest elevations. ~~Our ensemble of average elevation change rates representative of recent periods also suggests especially strong increases in thinning during the last couple of years (Figure 7d).~~At higher elevations the uncertainty of photogrammetric surveys increases because of low contrast due to homogeneous snow layers.

Ragettli et al. (2015) used a glacio-hydrological model to calculate the mass balances of all glaciers in the upper Langtang catchment for the hydrological year 2012/2013. They used glaciological and meteorological field data from Lirung and Yala Glacier to calibrate the melt parameters taking into account the effect of variable debris thickness and spatio-temporal changes in surface albedo. The calculated average mass balance of glaciers in the valley was -0.24 m w.e. Here we identify mass balances which were substantially more negative during recent periods (-0.~~51~~45 ± 0.~~30~~18 m w.e. $a^{-1}$, ~~Table 5~~Table 5). However, the hydrological year 2012/2013 was one of the wettest years since 1990 (Ragettli et al., 2015), which likely explains the less negative mass balances.

The acceleration in mass loss in recent periods identified by this study agrees with other studies from the Nepalese Himalaya which assess multi-temporal elevation changes (Bolch et al., 2011; Nuimura et al., 2012). Bolch et al. (2011) identify an increase in mass loss rates by 0.47 ~~-~~m w.e. $a^{-1}$ comparing the two periods 1970-2007 (-0.32 ± 0.08 m w.e. $a^{-1}$) and 2002-2007 (-0.79 ± 0.52 m w.e. $a^{-1}$). Nuimura et al. (2012) calculate increasing mass losses in the same study region between 1992-2008 (-0.26 ± 0.24 m w.e. ~~$a^{-1}$) and 2000-2008 (-0.45 ± 0.60 m w.e. $a^{-1}$). However, the uncertainties in the mass loss estimates by Bolch et al. (2011) and Nuimura et al. (2012) are higher than the identified acceleration in glacier thinning.~~$a^{-1}$) and 2000-2008 (-0.45 ± 0.60 m w.e. $a^{-1}$). However, the identified acceleration in glacier thinning is not significant given the largely overlapping error bounds. Moreover, the mass loss estimates of Gardelle et al. (2013) for the Khumbu region and the period 2001-2011 (average of -0.41 ± 0.21 m w.e. $a^{-1}$) are in the same order as calculated by Bolch et al. (2011) for 1970-

2007. The ensemble approach of this study can therefore substantially strengthen previous conclusions that mass loss of glaciers in the Central Himalaya is accelerating. ~~Although the uncertainty bounds of average elevation changes calculated for different periods overlap,~~The volume changes calculated over ~~a multitude of~~several multi-year periods between ~~1974~~2006 and 2015 consistently indicate that glacier thinning ~~is~~has indeed ~~accelerating~~accelerated (Figure 9~~a~~h).

## ~~7~~6 Conclusions

This study presents glacier volume changes of seven glaciers (five partially debris-covered, two debris-free) in the upper Langtang catchment in Nepal~~ of 28 different periods between November~~, using a digital elevation model (DEM) from 1974 stereo Hexagon satellite data and ~~October 2015 based on 8 high resolution~~seven DEMs derived from ~~high resolution~~ 2006-2015 stereo or tri-stereo satellite imagery. ~~The large dataset of elevation change maps was thoroughly checked for outliers in order to consider only those~~We carefully selected elevation change maps which are least affected by uncertainty~~. The ensemble of remaining maps provides one of~~ to obtain multiple independent DEM differences for the ~~most rigorous documentations~~period 2006-2015.

Our results point to ~~date of glacier response to climate change over the last 40 years in the Himalaya.~~

~~To analyze spatial and temporal patterns of thinning we addressed three main points. First, we assessed if thinning rates of glaciers in the region have accelerated in recent years. Second, we determined if spatial thinning patterns have changed over time and third, we addressed if there are major differences between the response of debris-covered and debris-free glaciers in the sample. Regarding the first point, we could constrain~~increasing thinning rates (from -0.24 ± 0.08 m $a^{-1}$ in 1974-2006 to -0.45 ± 0.18 m $a^{-1}$ in 2006-2015), whereas the estimated confidence level of accelerated thinning rates is higher than 99%. This study therefore supports the findings of previous studies (Bolch et al., 2011; Nuimura et al., 2012) that glacier wastage in the Central Himalaya is accelerating. ~~Glacier volume decreased during all periods between 2006 and 2015 (2006 – 2015: -0.60 ± 0.34 m $a^{-1}$) and at higher rates than between 1974 and 2006 (-0.28 ± 0.42 m $a^{-1}$).~~ However, whereas a majority of glaciers in the study region are thinning rapidly, glaciers with a high ~~percentage of glacier~~accumulation area ~~at~~

~~very high elevations~~ have almost balanced mass budgets ~~in recent years~~ and ~~experienced~~experience no or only ~~minor~~insignificant accelerations in thinning.

~~Regarding the spatial thinning patterns, the focus was on the extensively debris-covered tongues of five glaciers in the study region. In the upper reaches of the tongues,~~ Our observations also reveal that thinning has mostly accelerated in ~~recent years,~~ the upper reaches of the tongues (up to +150%, comparing the periods 1974-2006 and 2006-2015), while the nearly stagnant areas near the terminus show constant or decreasing thinning rates (up to -80%). The quality of the elevation change information is high due to good image contrast over debris, which increases the accuracy of the geodetically derived DEMs. The variations in the elevation change profiles of debris-covered tongues are mostly within ±10%, in the six overlapping periods between 2006 and 2015. The highest thinning rates and the strongest increase in thinning rates can be associated to areas with ~~complex, spatially heterogeneous elevation change patterns, characteristic of areas with~~ a high concentration of ice cliffs and supraglacial ponds. ~~Approximately constant to clearly~~Constant or decelerating thinning rates can be associated to areas with relatively homogeneous debris layers near the termini of glaciers. We conclude that the response of extensively debris-covered glaciers to global warming is largely determined by feedback processes associated to different surface characteristics.

~~Finally, regarding the third objective of this study to assess the differences between debris-covered and debris-free glaciers, we point out the importance of differentiating between spatial patterns and temporal patterns. Regarding the temporal patterns and therefore the trends in average elevation change rates, no clear difference between debris-free and debris-covered glaciers can be identified. In this respect, the~~The behavior of glaciers in the study area is highly heterogeneous, and the presence of debris itself is not a good predictor for mass balance trends. However, the spatial thinning patterns on debris-covered glaciers are fundamentally different than those on debris-free glaciers. While on debris-free glaciers thinning rates are linearly dependent on elevation, debris-covered glaciers have highly non-linear altitudinal elevation change profiles. ~~Still, throughout the entire elevation range the thinning rates of debris-covered tongues are lower than at corresponding altitudes of debris-free glaciers. Our observations do therefore~~Our observations do not provide evidence for the existence of a so-called debris-cover anomaly, where the insulating effect of thick supraglacial debris is compensated by enhanced melt from exposed ice cliffs or due to high energy absorption at supraglacial ponds. Within the same altitudinal range, lowering rates on debris-free Yala Glacier are 35%-300% higher than on debris-covered glacier area. On debris-free Kimoshung Glacier the thinning rates are similar to those of debris-covered area, but this result must be explained by compressive flows that compensate for surface lowering by ablation, since the glacier has a very short and steep tongue and a large accumulation area.

Future work should be devoted to look at larger glacier samples to compare the response of debris-free and debris-covered glaciers. Large-scale datasets of elevation change measurements (e.g. Kääb et al., 2012; Gardelle et al., 2013) have been used to compare the response of debris-free and debris-covered glaciers, but should consider also the differences in elevation distribution and the non-linearity of altitudinal elevation change profiles. Finally, for an in-depth analysis of debris-free and debris-covered glacier response to climate, also glacier uplift and therefore changes in ice flux over time should be quantified (either by englacial GPS measurements or by a modeling approach), which would enable the calculation of melt rates instead of only thinning rates. A better knowledge of melt rates, particularly in presence of supraglacial cliffs and lakes, would substantially advance our understanding of debris-covered glacier response to climate.

On 25 April 2015, triggered by a magnitude 7.8 earthquake, a large avalanche went down on Lirung Glacier and caused a strong pressure blast that devastated the trekking village of Kjangjing consisting of about 30 houses. Further down-valley co-seismic snow and ice avalanches and rockfalls destroyed Langtang Village and killed or left missing at least 350 people (Kargel et al., 2016). On the basis of two post-earthquake DEMs we quantified the avalanche impacts on the mass balance of debris-covered tongues. At the end of the 2015 ablation season, avalanche deposits outweighed by 50% the average annual volume loss of debris-covered glacier area during the last decade. We conclude that the impact of the earthquake on the cryosphere is almost as disproportional to the impact of global warming on glaciers in this region as it was disproportional to the impact on human lives.

Geodetic mass balance studies such as this have been increasingly revealing heterogeneous patterns of changes and a complex response of debris-covered glaciers that call for an enhanced understanding of processes over debris-covered glaciers. Their ablation, mass balance and response to climate is modulated by debris supply, transport, glacier flow, lakes and cliffs developments and a complex subglacial hydrology and hydraulics that all need to be understood in the future to be able to predict future changes of these glaciers over multiple time scales.

## Acknowledgements

This study is funded ~~mainly~~ by the Swiss National Science Foundation (SNF) project UNCOMUN (Understanding Contrasts in High Mountain Hydrology in Asia). T. Bolch acknowledges funding through German Research Foundation (DFG, code BO 3199/2-1) and European Space Agency (Glaciers_cci project, code 400010177810IAM). We thank Evan Miles for helping with the glacier delineations and the post-processing of surface velocity data. Jakob Steiner and Pascal Buri ~~created the map of~~manually delineated cliffs and lakes ~~on Langtang Glacier, which is~~for the inventories used in this study, and they are gratefully acknowledged. We thank Etienne Berthier for the Pléiades image data, for his useful comments regarding the DEM extraction and Fanny Brun for her help with the identification of GCPs. DigitalGlobe imagery was used to produce the WorldView-1 and 2 digital elevation models. We thank Eyjolfur Magnússon and one anonymous reviewer for extensive and thorough reviews that considerably helped to improve the manuscript.

## References


Banerjee, A. and Shankar, R.: On the response of Himalayan glaciers to climate change, J. Glaciol., 59(215), 480–490, doi:10.3189/2013JoG12J130, 2013.

Benn, D., Gulley, J., Luckman, A., Adamek, A. and Glowacki, P. S.: Englacial drainage systems formed by hydrologically driven crevasse propagation, J. Glaciol., 55(191), 513–523, doi:10.3189/002214309788816669, 2009.

~~Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, a., Nicholson, L. I., Quincey, D., Thompson, S., Toumi, R. and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Science Rev., 114(1-2), 156–174, doi:10.1016/j.earscirev.2012.03.008, 2012.~~

Berthier, E~~., Arnaud, Y., Baratoux, D., ~~. and Vincent, C~~. and Rémy, F.: Recent rapid~~.: Relative contribution of surface mass-balance and ice-flux changes to the accelerated thinning of ~~the ~~“Mer de Glace~~” glacier derived from satellite optical images, Geophys. Res. Lett., 31(17), L17401, doi:10.1029/2004GL020706, 2004.~~, French Alps, over 1979–2008, J. Glaciol., 58(209), 501–512, doi:10.3189/2012JoG11J083, 2012.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P. and Chevallier, P.: Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Remote Sens. Environ., 108(3), 327–338, doi:10.1016/j.rse.2006.11.017, 2007.

Berthier, E., Vincent, C., Magnússon, E., Gunnlaugsson, Á. Þ., Pitte, P., Le Meur, E., Masiokas, M., Ruiz, L., Pálsson, F., Belart, J. M. C. and Wagnon, P.: Glacier topography and elevation changes derived from Pléiades sub-meter stereo images, Cryosph., 8(6), 2275–2291, doi:10.5194/tc-8-2275-2014, 2014.

Bignone, F. and Umakawa, H.: Assessment of ALOS PRISM digital elevation model extraction over Japan, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., 37, 1135–1138, 2008.

Bolch, T., Buchroithner, M. and Pieczonka, T.: Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data, J. Glaciol., 54(187), 592–600, doi:10.3189/002214308786570782, 2008.

Bolch, T., Pieczonka, T. and Benn, D. I.: Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery, Cryosph., 5(2), 349–358, doi:10.5194/tc-5-349-2011, 2011.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M.: The state and fate of Himalayan glaciers., Science, 336(6079), 310–314, doi:10.1126/science.1215828, 2012.

Brun, F., Buri, P., Miles, E. S., Wagnon, P., Steiner, J., Berthier, E., Ragettli, S., Immerzeel, W. W. and Pellicciotti, F.: Quantifying volume loss from ice cliffs on debris-covered glaciers using high resolution terrestrial and aerial photogrammetry, J. Glaciol., ~~in review~~1–12, doi:10.1017/jog.2016.54, 2016.

Buri, P., Pellicciotti, F., Steiner, J. F., ~~Evan,~~Miles, E. S. and Immerzeel, W. W.: A grid-based model of backwasting of supraglacial ice cliffs on debris-covered glaciers, Ann. Glaciol., 57(71), 199–211, doi:10.3189/2016AoG71A059, 2016.

~~Cogley, J. G.: Himalayan glaciers in the balance, Nature, 488(7412), 468–469, doi:10.1038/488468a, 2012.~~

Collier, E. and Immerzeel, W.: High~~-~~-resolution modeling of atmospheric dynamics in the Nepalese Himalaya, J. Geophys. Res. Atmos., 120, 9882–9896, doi:10.1002/2015JD023266.Received, 2015.

Dehecq, A., Gourmelen, N. and Trouve, E.: Deriving large-scale glacier velocities from a complete satellite archive: Application to the Pamir–Karakoram–Himalaya, Remote Sens. Environ., 162, 55–66, doi:10.1016/j.rse.2015.01.031, 2015.

Dobhal, D. P., Mehta, M. and Srivastava, D.: Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India, J. Glaciol., 59(217), 961–971, doi:10.3189/2013JoG12J180, 2013.

Fujita, K.: Effect of precipitation seasonality on climatic sensitivity of glacier mass balance, Earth Planet. Sci. Lett., 276(1-2), 14–19, doi:10.1016/j.epsl.2008.08.028, 2008.

Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers., Proc. Natl. Acad. Sci. U. S. A., 108(34), 14011–14014, doi:10.1073/pnas.1106242108, 2011.

Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, a.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, Cryosph., 7(4), 1263–1286, doi:10.5194/tc-7-1263-2013, 2013.

~~Hewitt, K.: The Karakoram Anomaly? Glacier Expansion and the “Elevation Effect”, Karakoram Himalaya, Mt. Res. Dev., 25(4), 332–340, doi:10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2, 2005.~~

Holzer, N., Vijay, S., Yao, T., Xu, B., Buchroithner, M. and Bolch, T.: Four decades of glacier variations at Muztagh Ata (eastern Pamir): a multi-sensor study including Hexagon KH-9 and Pléiades data, Cryosph., 9(6), 2071–2088, doi:10.5194/tc-9-2071-2015, 2015.

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, Cryosph., 7(3), 877–887, doi:10.5194/tc-7-877-2013, 2013.

Huss, M., Jouvet, G., Farinotti, D. and Bauder, A.: Future high-mountain hydrology: a new parameterization of glacier retreat, Hydrol. Earth Syst. Sci., 14(5), 815–829, doi:10.5194/hess-14-815-2010, 2010.

Immerzeel, W.: Historical trends and future predictions of climate variability in the Brahmaputra basin, Int. J. Climatol., 28(2), 243–254, doi:10.1002/joc.1528, 2008.

Immerzeel, W. W., Kraaijenbrink, P. D. a., Shea, J. M., Shrestha, A. B., Pellicciotti, F., Bierkens, M. F. P. and de Jong, S. M.: High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles, Remote Sens. Environ., 150, 93–103, doi:10.1016/j.rse.2014.04.025, ~~2014~~2014a.

~~Jouvet, G., Huss, M., Funk, M. and Blatter, H.: Modelling the retreat of Grosser Aletschgletscher, Switzerland, in a changing climate, J. Glaciol., 57(206), 1033–1045, doi:10.3189/002214311798843359, 2011.~~

Immerzeel, W. W., Petersen, L., Ragettli, S. and Pellicciotti, F.: The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas, Water Resour. Res., 50(3), 2212–2226, doi:10.1002/2013WR014506, 2014b.

Jiskoot, H., Curran, C. J., Tessler, D. L. and Shenton, L. R.: Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length–slope and area–aspect relations, Ann. Glaciol., 50(53), 133–143, doi:10.3189/172756410790595796, 2009.

Juen, M., Mayer, C., Lambrecht, a., Han, H. and Liu, S.: Impact of varying debris cover thickness on ablation: a case study for Koxkar Glacier in the Tien Shan, Cryosph., 8(2), 377–386, doi:10.5194/tc-8-377-2014, 2014.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, Nature, 488(7412), 495–498, doi:10.1038/nature11324, 2012.

Kääb, A., Treichler, D., Nuth, C. and Berthier, E.: Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya, Cryosph., 9(2), 557–564, doi:10.5194/tc-9-557-2015, 2015.

Kargel, J., Leonard, G. Shugar, D. et al.: Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake, Science, 351(6269), 1–18, doi:10.1126/science.aac8353, 2016.

Kellerer-Pirklbauer, A., Lieb, G., Avian, M. and Gspurning, J.: The response of partially debris-covered valley glaciers to climate change: the example of the Pasterze Glacier (Austria) in the period 1964 to 2006, Geogr. Ann. Ser. A Phys. Geogr., 90(4), 269–285, doi:10.1111/j.1468-0459.2008.00345.x, 2008.

Khan, A., Naz, B. S. and Bowling, L. C.: Separating snow, clean and debris covered ice in the Upper Indus Basin, Hindukush-Karakoram-Himalayas, using Landsat images between 1998 and 2002, J. Hydrol., 521, 46–64, doi:10.1016/j.jhydrol.2014.11.048, 2015.

Lamsal, D., Sawagaki, T. and Watanabe, T.: Digital terrain modelling using Corona and ALOS PRISM data to investigate the distal part of Imja Glacier, Khumbu Himal, Nepal, J. Mt. Sci., 8(3), 390–402, doi:10.1007/s11629-011-2064-0, 2011.

Lau, W. K. M., Kim, M.-K., Kim, K.-M. and Lee, W.-S.: Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols, Environ. Res. Lett., 5(2), 025204, doi:10.1088/1748-9326/5/2/025204, 2010.

Leprince, S., Barbot, S., Ayoub, F. and Avouac, J.-P.: Automatic and precise orthorectification, coregistration, and subpixel correlation of satellite images, application to ground deformation measurements, IEEE Trans. Geosci. Remote Sens., 45(6), 1529–1558, 2007.

Magnússon, E., Muñoz-Cobo Belart, J., Pálsson, F., Ágústsson, H. and Crochet, P.: Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data – Case study from Drangajökull ice cap, NW Iceland, Cryosph., 10(1), 159–177, doi:10.5194/tc-10-159-2016, 2016.

Mattson, L. E., Gardner, J. S. and Young, G. J.: Ablation on Debris Covered Glaciers: an Example from the Rakhiot Glacier, Punjab, Himalaya, IAHS Publ., 218, 289–296, 1993.

Maurer, J. and Rupper, S.: Tapping into the Hexagon spy imagery database: A new automated pipeline for geomorphic change detection, ISPRS J. Photogramm. Remote Sens., 108, 113–127, doi:10.1016/j.isprsjprs.2015.06.008, 2015.

Mayer, C., Lambrecht, A., Belo, M., Smiraglia, C. and Diolaiuti, G.: Glaciological characteristics of the ablation zone of Baltoro glacier, Karakoram, Pakistan, Ann. Glaciol., 43(1), 123–131, doi:10.3189/172756406781812087, 2006.

Mihalcea, C., Mayer, C., Diolaiuti, G., Lambrecht, A., Smiraglia, C. and Tartari, G.: Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan, Ann. Glaciol., 43(1), 292–300, doi:10.3189/172756406781812104, 2006.

Mihalcea, C., Mayer, C., Diolaiuti, G., Agata, C. D., Smiraglia, C., Lambrecht, A., Vuillermoz, E. and Tartari, G.: Spatial distribution of debris thickness and melting from remote-sensing and meteorological data, at debris-covered Baltoro glacier, Karakoram, Pakistan, Ann. Glaciol., 48(1), 49–57, doi:10.3189/172756408784700680, 2008.

Miles, E. S., Pellicciotti, F., Willis, I. C., Steiner, J. F., Buri, P. and Arnold, N. S.: Refined energy-balance modelling of a supraglacial pond, Langtang Khola, Nepal, Ann. Glaciol., 57(71), 29–40, doi:10.3189/2016AoG71A421, 2016a.

Miles, E. S., Willis, I. C., Arnold, N. S. and Pellicciotti, F.: Spatial, seasonal, and interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999 to 2013, J. Glaciol. ~~J. Geophys. Res. Earth Surf.~~, under ~~review~~revision, 2016b.

Noh, M.-J. and Howat, I. M.: Automated stereo-photogrammetric DEM generation at high latitudes: Surface Extraction with TIN-based Search-space Minimization (SETSM) validation and demonstration over glaciated regions, GIScience Remote Sens., 52(2), 198–217, doi:10.1080/15481603.2015.1008621, 2015.

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, Antarct. Alp. Res., 43(2), 246–255, doi:10.1657/1938-4246-43.2.246, 2011.

Nuimura, T., Fujita, K., Yamaguchi, S. and Sharma, R. R.: Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu region, Nepal Himalaya, 1992–2008, J. Glaciol., 58(210), 648–656, doi:10.3189/2012JoG11J061, 2012.

Nuimura, T., Sakai, A., Taniguchi, K., Nagai, H., Lamsal, D., Tsutaki, S., Kozawa, A., Hoshina, Y., Takenaka, S., Omiya, S., Tsunematsu, K., Tshering, P. and Fujita, K.: The GAMDAM glacier inventory: a quality-controlled inventory of Asian glaciers, Cryosph., 9(3), 849–864, doi:10.5194/tc-9-849-2015, 2015.

Nuth, C. and Kääb, ~~a~~A.: Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, Cryosph., 5(1), 271–290, doi:10.5194/tc-5-271-2011, 2011.

Nuth, C., Schuler, T. V., Kohler, J., Altena, B. and Hagen, J. O.: Estimating the long-term calving flux of Kronebreen, Svalbard, from geodetic elevation changes and mass-balance modelling, J. Glaciol., 58(207), 119–133, doi:10.3189/2012JoG11J036, 2012.

Östrem, G.: Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges, Geogr. Ann., 41(4), 228–230, 1959.

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S. P., Konovalov, V., Bris, R. Le, Mölg, N., Nosenko, G., Nuth, C., Pope, a., Racoviteanu, a., Rastner, P., Raup, B., Scharrer, K., Steffen, S. and Winsvold, S.: On the accuracy of glacier outlines derived from remote-sensing data, Ann. Glaciol., 54(63), 171–182, doi:10.3189/2013AoG63A296, 2013.

Pellicciotti, F., Stephan, C., Miles, E., Immerzeel, W. W. and Bolch, T.: Mass-balance changes of the debris-covered glaciers in the Langtang Himal, Nepal, 1974–99, J. Glaciol., 61(225), doi:10.3189/2015JoG13J237, 2015.

Pieczonka, T. and Bolch, T.: Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~1975 and 1999 using Hexagon KH-9 imagery, Glob. Planet. Change, 128, 1–13, doi:10.1016/j.gloplacha.2014.11.014, 2015.

Pieczonka, T., Bolch, T. and Buchroithner, M.: Generation and evaluation of multitemporal digital terrain models of the Mt. Everest area from different optical sensors, ISPRS J. Photogramm. Remote Sens., 66(6), 927–940, doi:10.1016/j.isprsjprs.2011.07.003, 2011.

Pieczonka, T., Bolch, T., Junfeng, W. and Shiyin, L.: Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery, Remote Sens. Environ., 130, 233–244, doi:10.1016/j.rse.2012.11.020, 2013.

Pratap, B., Dobhal, D. P., Mehta, M. and Bhambri, R.: Influence of debris cover and altitude on glacier surface melting: a case study on Dokriani Glacier, central Himalaya, India, Ann. Glaciol., 56(70), 9–16, doi:10.3189/2015AoG70A971, 2015.

~~Quincey, D., Luckman, A. and Benn, D.: Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking, J. Glaciol., 55(192), 596–606, doi:10.3189/002214309789470987, 2009.~~

Racoviteanu, A. E., Arnaud, Y., Williams, M. W. and Manley, W. F.: Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern Himalaya, Cryosph., 9(2), 505–523, doi:10.5194/tc-9-505-2015, 2015.

Ragettli, S., Pellicciotti, F., Immerzeel, W. W., Miles, E. S., Petersen, L., Heynen, M., Shea, J. M., Stumm, D., Joshi, S. and Shrestha, A.: Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model, Adv. Water Resour., 78, 94–111, doi:10.1016/j.advwatres.2015.01.013, 2015.

Reid, T. D. and Brock, B. W.: Assessing ice-cliff backwasting and its contribution to total ablation of debris-covered Miage glacier, Mont Blanc massif, Italy, J. Glaciol., 60(219), 3–13, doi:10.3189/2014JoG13J045, 2014.

Reynolds, J.: On the formation of supraglacial lakes on debris-covered glaciers, IAHS Publ., (264), 153–161, 2000.

Rowan, A. V., Egholm, D. L., Quincey, D. J. and Glasser, N. F.: Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya, Earth Planet. Sci. Lett., 430, 427–438, doi:10.1016/j.epsl.2015.09.004, 2015.

Sakai, A. and Fujita, K.: Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya, J. Glaciol., 56(195), 177–181, doi:10.3189/002214310791190785, 2010.

Sakai, A., Nakawo, M. and Fujita, K.: Melt rate of ice cliffs on the Lirung Glacier, Nepal Himalayas, 1996, Bull. Glacier Res., 16, 57–66, 1998.

Sakai, A., Takeuchi, N., Fujita, K. and Nakawo, M.: Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas, Debris-Covered Glaciers, IAHS Publ., 265, 119–130, 2000.

Sakai, A., Nakawo, M. and Fujita, K.: Distribution characteristics and energy balance of ice cliffs on debris-covered glaciers, Nepal Himalaya, Arctic, Antarct. Alp. Res., 34(1), 12–19, doi:10.2307/1552503, 2002.

Sapiano, J., Harrison, W. and Echelmeyer, K.: Elevation, volume and terminus changes of nine glaciers in North America, J. Glaciol., 44(146), 119–135, doi:10.3198/1998JoG44-146-119-135, 1998.

Scally, F. De and Gardner, J.: Evaluation of avalanche mass determination approaches: an example from the Himalaya, Pakistan, J. Glaciol., 35(120), 248–252, 1989.

Scherler, D., Leprince, S. and Strecker, M.: Glacier-surface velocities in alpine terrain from optical satellite imagery—Accuracy improvement and quality assessment, Remote Sens. Environ., 112(10), 3806–3819, doi:10.1016/j.rse.2008.05.018, 2008.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Hillslope-glacier coupling: The interplay of topography and glacial dynamics in High Asia, J. Geophys. Res., 116(F02019), 1–21, doi:10.1029/2010JF001751, 2011a.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nat. Geosci., 4(3), 156–159, doi:10.1038/ngeo1068, 2011b.

Schwitter, M. and Raymond, C.: Changes in the longitudinal profiles of glaciers during advance and retreat, J. Glaciol., 39(133), 582–590, 1993.

Shrestha, A., Wake, C., Mayewski, P. and Dibb, J.: Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94, J. Clim., 12, 2775–2786, doi:10.1175/1520-0442(1999)012<2775:MTTITH>2.0.CO;2, 1999.

Shrestha, A., Wake, C., Dibb, J. and Mayewski, P.: Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters, Int. J. Climatol., 20(3), 317–327, doi:10.1002/(SICI)1097-0088(20000315)20:3<317::AID-JOC476>3.0.CO;2-G, 2000.

Singh, P., Kumar, V., Thomas, T. and Arora, M.: Changes in rainfall and relative humidity in river basins in northwest and central India, Hydrol. Process., 22(16), 2982–2992, doi:10.1002/hyp.6871, 2008.

Steiner, J. F., Pellicciotti, F., Buri, P., Miles, E. S., Immerzeel, W. W~~.,~~., and Reid, T. D~~. and Steiner, C. J. F~~.: Modelling ice-cliff backwasting on a debris-covered glacier in the Nepalese Himalaya, J. Glaciol., 61(229), 889–907, doi:10.3189/2015JoG14J194, 2015.

Steiner, J. F., Buri, P., Miles, E. S., Ragettli, S. and Pellicciotti, F.: Life and death of ice cliffs and lakes on debris covered glaciers - insights from a new dataset, Geophys. Res. Abstr., 18(EGU2016-13922), 2016.

Sugiyama, S., Fukui, K., Fujita, K., Tone, K. and Yamaguchi, S.: Changes in ice thickness and flow velocity of Yala Glacier, Langtang Himal, Nepal, from 1982 to 2009, Ann. Glaciol., 54(64), 157–162, doi:10.3189/2013AoG64A111, 2013.

Surazakov, A. and Aizen, V.: Positional Accuracy Evaluation of Declassified Hexagon KH-9 Mapping Camera Imagery, Photogramm. Eng. Remote Sens., 76(5), 603–608, doi:10.14358/PERS.76.5.603, 2010.

Tadono, T. and Shimada, M.: Calibration of PRISM and AVNIR-2 onboard ALOS "Daichi," IEEE Trans. Geosci. Remote Sens. Sens., 47(12), 4042–4050, doi:10.1109/TGRS.2009.2025270, 2009.

Thompson, S., Benn, D. I., Mertes, J. and Luckman, A.: Stagnation and mass loss on a Himalayan debris-covered glacier: processes, patterns and rates, J. Glaciol., 1–19, doi:10.1017/jog.2016.37, 2016.

Tiwari, P., Pande, H., Punia, M. and Dadhwal, V. K.: Cartosat-I: Evaluating mapping capabilities, Int. J. Geoinformatics, 4(1), 51–56 [online] Available from: http://creativecity.gscc.osaka-cu.ac.jp/IJG/article/view/609 (Accessed 26 January 2016), 2008.

Wang, D. and Kääb, A.: Modeling Glacier Elevation Change from DEM Time Series, Remote Sens., 7(8), 10117–10142, doi:10.3390/rs70810117, 2015.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B. and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang., 2(9), 663–667, doi:10.1038/nclimate1580, 2012.

Ye, Q., Bolch, T., Naruse, R., Wang, Y., Zong, J., Wang, Z., Zhao, R., Yang, D. and Kang, S.: Glacier mass changes in Rongbuk catchment on Mt. Qomolangma from 1974 to 2006 based on topographic maps and ALOS PRISM data, J. Hydrol., 530, 273–280, doi:10.1016/j.jhydrol.2015.09.014, 2015.

Zhang, Y., Fujita, K., Liu, S., Liu, Q. and Nuimura, T.: Distribution of debris thickness and its effect on ice melt at Hailuogou glacier, southeastern Tibetan Plateau, using in situ surveys and ASTER imagery, J. Glaciol., 57(206), 1147–1157, doi:10.3189/002214311798843331, 2011.