The Cryosphere Discuss., 8, C1715–C1723, 2014
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The Cryosphere
Discussions

Interactive comment on **"Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya"** by **A. Racoviteanu et al.**

Dec 10th, 2014

Dear Tobias,

I am pleased to let you know that the TC paper has been thoroughly revised, and re-submitted in its new form. We are grateful for the helpful and constructive comments from the reviewers, which have helped substantially improve this paper. I think the revised manuscript is much more clear and focused, and it is a better contribution in its revised form.

We made significant changes (content as well as smaller edits). Some of the major changes in content include:

Abstract and introduction:

- These were re-written to better explain the rationale behind the study, and clarify the objectives

Methods:

- We removed the area change from 2000 to 2006 due to the short time span and image resolution, and focused the discussion on area change from 1962 to 2006.
- Based on the arguments from reviewer 2, we removed the elevation change analysis, given the uncertainties in the baseline dataset (topographic map)

Results:

- These were re-written and re-organized, and the results are presented in a more concise way (we have integrated the glacier area changes overall with glacier changes on a glacier-by-glacier basis so now it reads more fluidly)

Discussion:

- This was significantly improved and re-organized
- We have added a discussion on the role of lakes, as well as an assessment of the area covered by lakes- also see answers to short comment by Mauri Pelto.
- We have improved the discussion of topographic and climatic controls on area change, focusing the discussion on each important variable and comparing with other studies as suggested by the reviewers
- We have added references from similar studies, notably Takuri et al. 2014, Nuimura et al 2012 and other studies suggested by the reviewers. The discussion

and conclusions were focused on putting this study into context and comparing with other studies east and west of our study area.

Tables and Figures:

- We revised the tables and figures according to reviewer's comments (Fig.1, and 6, 8-11 were revised). We replaced fig 11 with a new figure (Fig. 8) showing temperature along longitudinal tracts on 3 glaciers rather than one; the elevation changes were removed and replaced with ASTER temperature (Fig. 9)
- We added the complete list of all ASTER datasets actually used in the study (table 1)
- We have revised the style and the language, according to reviewers comments (comments related to 1960's vs 1960s, decimal numbers and other style comments).

I believe the manuscript is now much clearer. I look forward to your comments.

Sincerely,

Adina Racoviteanu

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Interactive comment on **"Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya"** by **A. Racoviteanu et al.**

Anonymous Referee #1

Received and published: 4 September 2014

Review of paper on "Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya" by Racoviteanu et al.

General remarks

Racoviteanu et al. (2014) analyse spatial patterns in glacier area and elevation changes in the eastern Himalaya using remotely sensed products and the topographic map. The manuscript is interesting and deals with a topic of much interest. In general, I have an impression that the paper addresses the state of glaciers in detail, but weakly on the drivers of change. The work is of good scientific potential for publication with such a suitable topic in a data scarce region of the Himalaya, however there are plenty of space for further improving and making the paper more informative and well-organized contents. In fact, this should not be so difficult to fix.

We thank the reviewer for these helpful comments. We have thoroughly revised the manuscript according to reviewer's suggestions. Some of the major changes made to address reviewer #1 suggestions are listed here, and explained in the text (bold font):

- **We removed the area change from 2000 to 2006 due to the short time span and image resolution, and focused on area change from 1962 to 2006.**
- **We removed the elevation change analysis**
- **We have added a discussion on the role of lakes, as well as an assessment of the area covered by lakes- also see answers to short comment by Mauri Pelto.**
- **We have completely re-organized the results and discussion sections, and we have improved the discussion of topographic and climatic controls on area change, comparing with other studies as suggested by the reviewer**
- **We revised the tables and figures according to reviewer's comments**
- **We have revised the style and the language, according to reviewer's comments.**

The glacier analysis in the manuscript is limited to 2006. Though the time frame of the analysis is significant, it is not clear to me why do the authors decided to restrict their analysis until 2006. There are enough potential for extending the analysis until recent year (2013 or 2014) using freely available additional Landsat data. Adding an image of recent year make the paper much worthy with the latest information on the state of the glaciers.

We agree with the reviewer that adding another decade would provide additional information. However, there are time constraints to this. The analysis for this paper started in 2007, and involved many re-iterations to ensure the quality of the glacier outlines. We already added two datasets, which were time consuming, for the 1960 and 2006. We thing it is important to publish the results while it is timely.

The paper needs editing and thorough check for english language to ensure the clarity, correctness, and consistency in language, and for improving communication of work. Authors should be careful in while presenting data using "retreat" or "loss" or simply, "change" for glaciers. No need of negative (–) sign when using retreat or loss. I suggest for checking the appropriate use of the terminologies like, "spatial pattern", "trend", "inventory" in the manuscript.

We have checked the manuscript for the language style. We have replaced "retreat" with "surface area loss" in most cases, or referred to "area change" as negative.

Looking into the title and objective of the study, I expect some results on the elevation changes in the result section, but nothing is presented there in result section about elevation change. I read interesting results in the discussion section. The author can simply separate the results from discussion and make a new section in the results for the glacier elevation change. Furthermore, I expect brief statement on the rationale of this study in the introduction and also in abstract. The study output would be much usable and supportive for future studies by providing glacier datasets for this part of Himalaya, if the glaciers datasets for each glacier (inventory) are tabulated in the Supplement.

Given the reviews received, we have decided to remove the elevation change analysis from this paper.

Specific remarks

P3950
L2: not only deal with eastern Nepal and Sikkim, but include also China and Bhutan (as in Table 4), right?

Correct. Change made.

L7-L13: here objectives are explained in detail, but the presented results afterward do not address systematically to the objectives.

The objectives have been revised, and the introduction re-written.

L8: why is there, new “reference” geospatial?

This is not necessary, so we have removed this term.

L9: why “_” before 2000 when both the Landsat and ASTER imagery are of 2000? It is not necessary. - “glacier surface area” would be more appropriate.

Agree, we have made this change throughout the manuscript.

L12: include the time period; Can “debris-covered tongue” be written as “ablation area”?

Mostly, yes- but we want to clarify that here we are looking at debris cover specifically. In any case this part of the manuscript, related to elevation change, was removed.

L14, L16 and else where in the manuscript: Avoid repeating of unit while reporting uncertainty. Eg, remove km2 after 1463. Check in the whole manuscript.

Changes made, the repeating unit was removed.

L19: as pointed out in the general remark, here not necessary to include “–“ sign when writing “loss of. . .” “retreat”, Check the use of sign over whole manuscript.
- 1960s, not 1960’s, please check in the whole manuscript

Agree, removed " ' " from the 60s.

- Instead of 2010's in the sentence, use 2010s. It is really 2010s or 2000s?

" ' " was removed. We agree, we can say that 2006 is mostly the 2000s decades.

- Instead of "retreat" for surface area change, "surface loss" is appropriate. Ensure consistent word in the whole manuscript.

We agree and we have checked the whole manuscript.

L20: Use the same number of significant digits after decimal point for the values and its uncertainty reporting. Check in the whole manuscript.

Checked and changes made.

L25: I suggest including a brief concluding remark in the abstract.

Added the following phrase to compare with other areas and state the limitations: ***"These rates are similar rates to the ones reported elsewhere in the eastern Himalaya, but individual rates of change vary widely within the study area due to local topographic or morphologic conditions, which need to be further investigated."***

P3951
L2: "raised" or some other word may sound good for "aroused".

Good point. Change made, we used the word "generated"

L5-L7: these citations are not complete list. use "eg.," instead.

Done.

L21: hampers quality satellite image acquisition.

Change made.

L10-L21: These descriptions are more methods than introduction.

Agree, we removed them and incorporated in the introduction.

L18: Why the elevation change analysis only focused in the debris-covered tongues? Authors should briefly mention this consideration.

Originally, it was due to the quality of the topographic maps and because we were interested in the behavior of the debris covered tongues. In the new version, this part of the paper was removed.

L5: topographic relief

Changed.

L18: not “May”, it’s “June”, right?

Correct, change made.

L16: it is commonly known that the Himalayan high mountains act as a barrier for monsoon, but also Tibetan plateau? Any reference?

Agree- we have removed “Tibetan Plateau”- this was not clear.

L21: from 500 to 5000 m yr-1. Would be valuable information to indicate also the locations of these precipitation measures?

It is already mentioned in the text, it is from Gangtok station.

“In Sikkim, rainfall amounts range from 500 to 5000 mm per year, with annual averages of 3,580 mm recorded at Gangtok station (1,812 m) (1951 to 1980) (IMD 1980), and 164 rainy days per year (Nandy et al. 2006).”

L5: change 1960’s to 1960s; remove “decade”.

Done.

L6: why “reference”?

We thought of calling it “reference” since it covered the largest surface and e considered it as “baseline” for future analysis. This is not needed here, so we removed.

L6: remove “year”, not necessary before “1962”.

Done.

L15: I am not clear, why did the authors calculate an actual pixel size of approximately 2 m using the scale of the photos and the scan resolution?

The question here is: what is a reasonable orthoimage resolution? The Corona images were canned at USGS at 7 micros, which is 3629 dots per inch (DPI). Generally speaking, negatives or prints can be scanned at 1400 dpi or even 1800 dpi, the latter being close to the resolution of the original print or negative. In this case, given the DPI (3928) and the flight altitude (300,000km), calculating the desired

output resolution was a mathematical operation, ie: desired image pixel resolution (m) = scale denominator / (DPI * 0.00254) = 1.93 m, or about ~ 2m.

In summary, for the Corona stripes scanned at 7 microns, given the scale, the optimal pixel resolution is ~ 2m.

Reference at: http://www.pcigeomatics.com/pdf/airphoto_pixel_resolution.pdf

L17: Are there also processed Corona images available? Otherwise, "Raw, unprocessed" can be removed.

Removed.

L2: trend

OK.

L10: why did the authors use cubic convolution method for resampling?

We chose the cubic convolution method for resampling during orthorectification because this approach is appropriate for continuous data and produces sharper results than with bilinear interpolation.
See the ArcGIS help reference:
http://resources.arcgis.com/en/help/main/10.2/index.html#//018700000006000000
"Bilinear interpolation or cubic convolution should not be used on categorical data since the categories will not be maintained in the output raster dataset. However, all three techniques can be applied to continuous data, with nearest neighbor producing a blocky output, bilinear interpolation producing smoother results, and cubic convolution producing the sharpest."

C1718
L16: why SRTM DEM was hydrologically-sound? Is it void filled SRTM?

Correct, this is void-filled. We have added this.

Authors should be aware of the use limitation of SRTM DEM in the high elevation mountain region. Uncertainty related to the elevation change, especially the c-band penetration (Gardelle et al 2012) and the huge data gaps in the higher elevation in the original SRTM DEM (Bolch et al., 2011) need to be acknowledged.

We have added:
"The SRTM dataset is known to have biases due to topography (steep slopes) and elevations (Berthier et al. 2006; Fujita et al. 2008; Nuth and Kääb 2011) as well as due to radar penetration on snow (Gardelle et al. 2012)."

L18: remove “decade”.

Removed.

L25 and else where: 1960s or 1960’s? They have different meaning, use consistently.

Here it is 1960s. We have fixed this throughout the manuscript.

P3958
L2: here “1960s” appropriate for “1960’s decade”.

Changed.

L25: QB (2000) and WV2 (2009)

- clean-ice surfaces were delineated using. . ..

Change made.

L27: Did the authors use information on the lateral and frontal moraines for delineating the debris-covered tongues?

We have used visual clues, including lateral and frontal moraines as well as supra-glacial features. We have added this.

P3959
L28: The authors have discussed well in sufficient details about the uncertainties, however can the authors present little statement on the formulas and equations that they used for associating uncertainties in the observed values, so that the approach can be easily replicable in the future studies to evaluate the errors?

We have used the root mean square of the errors due to: 1) inconsistencies in internal rock and 2) errors from classification, using epsion band. We have added the equation: $E = \sqrt{E^2{}_{rock} + E^2{}_{classif}}$

P3960
L7: a total area of

Changed

L9: is the % of supraglacial debris comparable with the previous studies? The % debris coverage were published in Scherler et al., 2011; Nuimura et al., 2012, Thakuri et al., 2014.

Our estimates of supra-glacial debris in Sikkim were lower than those published in

other studies, for Khumbu. We have added text to compare with other studies in the results section, on p 14 of the revised manuscript:

"The percent debris cover estimated here is lower than those reported for other areas of the southern slopes of the central Himalaya by Scherler et al. (2011) (36% debris cover), or from the Khumbu region, west of our study area, by Fujii and Higuchi (1977), Nuimura et al. (2012) (34.8%), Racoviteanu et al. (2013) (27 %) and Thakuri et al. (2014) (32%)".

C1719
P3961
L2: "frequency histogram" or simply "histogram"?

Removed "frequency".

P3962
L25: again here when you write area loss "-" not necessary, check in the whole manuscript.

Ok.

L27: - 0.16% yr-1

Change made

P3963
L1-L3: I suggest for checking the sentence structure.

The phrase was removed and rephrased in the new version of the manuscript,

L6-L8: Have they been preserved more than other areas? Compare the surface area change and elevation change with the other studies in the Himalaya region. The result is in line with the conclusion in the recently published paper of Thakuri et al (2014). Thakuri et al extensively evaluated the glacier surface change in the entire Himalaya and have summarized the glacier status in the Himalaya and Tibetan Plataeu. Further, the discussion in the 5.1 section has been addressed in the Thakuri et al for the Mt Everest region. Here authors can compare the finding with that of glaciers in the Everest region as the glaciers characteristics they considered are similar.

We have revised the discussion section, which now includes: 5.1 Glacier area changes, 5.2 Topographic and controls on area change, 5.3 Surface temperature distribution on debris cover tongues and 5.4 Glacier lakes.

We have compared our results to the above-mentioned studies, as well as Salerno et al (2008). Most of p.3963 was moved to results, and then those results were discussed in section 5.

L19: The larger glaciers have a higher accumulation zones and lower elevation termini. It would be useful to evaluate the glacier dividing into two parts for surface area change.
L26: It would be interesting to see the relationship glacier area change separately for accumulation and ablation areas' elevation and their slope.

We agree with the reviewer. However, in the interest of time and also to compare with other studies, we have considered the glaciers with accumulation and ablation areas not separated.

P3964
L10: Does the higher area losses of small glaciers suggest that they have the lowest elevation accumulation zones and they are most impacted by climate change?

Small glaciers tend to have most area (including the accumulation area) below the regional ELA, and hence may be more sensitive to change. This was also noted in Racoviteanu et al. (2008) for Cordillera Blance of Peru, as well as other studies.

P3967
C1720
L18: Can be reorganized contextual part. eg Section 5.4 may be suitable to present in the method section.

The entire section 5.4 was moved to methods, and improved.

P3968
L10: root mean square error?

Correct.

P3971
L11: what is the significance of repeating the summary again in the conclusion section? Abstract itself provides the summary of the paper.

We agree, and have removed this.

P3972
L25: you mean, "can be further applicable to understand"?

Good point, we added this.

The tables and figures are quite good. Herewith, presented some suggestions for some improvements.

Table 1: Add a column "Image type" after "Spatial resolution" field to present image

types: PAN, VIS, SWIR,. . ...

Ok, done.

- include all ASTER data used in the study in the Table.
- Use a same format for the date (see Date column of QuickBird and WorldView-2).

Checked the date format and added all the ASTER imagery used.

Table 2: Is it possible to make spatial domain 3 for elevation change study?

This is not applicable anymore since we removed this section.

Table 3: caption: only “topographic zones” enough. Are the four zones presented here exactly corresponds the region presented in table 4?

Yes, these correspond to the results in Table 4. We removed unnecessary text.

Table 4: L2: why _ ?

I don’t know what the reviewer means here, there is no “_”. Maybe referring to table 5?
We removed “-“.

Table 6: reporting p-value as < 0.001 or < 0.01 for significant values would be enough.

Agreed, change made.

Table 8: why “# glcrs” in column heading? Use full description.

Done.

Why are there different in column headings ? “% area change” and “Rate of loss yr-1”?

We changed to “%” and % yr^{-1}”

C1721
“Rate of change % yr-1” is correct, right? Also, not necessary to put unit in each value and also in column heading.

Removed the units.

Figure 1: Not much visually promising and informative with all the data overlaid. I would suggest to use only one image as a base layer and draw spatial domain, glacier outline, country boundary, and label them.

The figure was redone using Landsat and ASTER as background, with the two spatial domains shown.

However, since glacier outlines and country names are shown on Fig.2, and to keep the figure simpler, we have not included glacier outlines and country names here.

Caption L1: which six 2000-2006 ASTER scenes? They are not listed in Table 1.

Fixed.

Figure 4: x-axis, why sq.km? else where written km2; slope (degree).

Revised.

Figure 5 Caption L2: remove "two direction". L3: Is it necessary to put "corresponding to topographic/climatic barriers"?

Changes made.

Figure 6 Caption L1: why is there WV2? Typo?; L2: remove "shown on a glacier-by glacier basis".

We agree, perhaps not necessary to write it here since the main data source was QB. We used WV2 only for the tip of 2 glaciers, which were not covered in QB data, as explained in methods.
We removed "on a glacier-by-glacier basis"

Figure 8 Caption L2: why is there WV2? Typo?; L3: Did you also analyzed terminus retreat?

For WV2: same as above.
We agree, we have not analyzed terminus retreat, this is only based on visual interpretation. Removed.

Figure 9: Label the glacier names mentioned in the caption.

Done.

Caption L: can use "1962 to 2006" in place of "1962 to 2000 and 2006",
Done.

L4: Did you test also acceleration of pro-glacial lakes?

No- this is beyond the scope of the current paper but a good point for a future paper. We removed the statement. However we have added some more discussion in section 5.4 (Glacier lakes)

Figure 11: The primary Y-axis show positive elevation change, is it true?

The elevation change analysis was removed.

Caption L1: 1960s. “surface temperature distribution” instead of “day temperature trends”.

Changed.

Bolch, T., Pieczonka, T., and Benn, D. I.: Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery, The Cryosphere, 5, 349–358, doi:10.5194/tc- 5-349-2011, 2011.
Gardelle, J. E., Berthier, E., and Arnaud, Y.: Impact of resolution and radar penetration on glacier elevation changed computed from DEM differencing, J. Glaciol., 58, 419–
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422, 2012.
Nuimura, T., K. Fujita, S. Yamaguchi, and R. R. Sharma (2012), 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.
Scherler, D., Bookhagen, B., and Strecker, M. R.: Spatially variable response of Himalayan
glaciers to climate change affected by debris cover, Nat. Geosci., 4, 156–159, 2011.
Thakuri, S., Salerno, F., Smiraglia, C., Bolch, T., D’Agata, C., Viviano, G., and Tartari, G.: Tracing glacier changes since the 1960s on the south slope of Mt. Everest (central Southern Himalaya) using optical satellite imagery, The Cryosphere, 8, 1297-1315, doi:10.5194/tc-8-1297-2014, 2014.
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C1723

We included these references and discussed our results in the text in light of these other studies.

Thank you,

Adina Racoviteanu

The Cryosphere Discuss., 8, C1787–C1796, 2014
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The Cryosphere
Discussions
Interactive comment on **"Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya"** by **A. Racoviteanu et al.**
Dr. Lamsal (Referee)
lamsal@nagoya-u.jp
Received and published: 12 September 2014

Comments on "Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya", by Racoviteanu et al., submitted to The Cryosphere Discussion Damodar Lamsal, September 2014

General comments

This paper presents spatial patterns of glacier area and elevation changes in a region in the eastern Himalaya since 1960s to 2000s, and discusses the results in the light of topographic (e.g. elevation, slope, aspect, portion debris cover) and climatic (e.g. precipitation and temperature) variables. The study used a) multi-temporal satellite imageries to delineate glaciers in 1962 (Corona KH4), in 2000 (Landsat/ASTER) and 2006/09 (QuickBird/WorldView2), b) digital elevation data generated from the 'The Swiss topographic map' from 1960s compiled from Survey of India and SRTM DEM (2000), c) ASTER imageries (_2000) to extract glacier surface temperature, and d) Tropical Rainfall Measuring Mission (TRMM) data for precipitation estimation. Undoubtedly, there is a great need to have more research on glaciers in the Himalayas for the better understanding of response of glaciers to climate change and also for a sound estimation of glacier mass balance, leading up to an improved insight into glacio-hydrological systems in the region. Glaciers in the target area are relatively less studied in comparison to the glaciers in other part of the world and maybe even within the Himalayas. This study provides results of glacier area change over a longtime span (1962 to 2006/09), probably one of the longest time periods of glacier change study in the Himalayas. The findings of area change of glaciers for over 40 years will definitely add to our current knowledge; however, the result of glacier elevation changes are open to a high degree of uncertainty, and thus may not be encouraging (see below for expanded comments). In this paper, main data source for delineating glaciers in 1962 is Corona KH4, with spatial resolution (SR) = 7.5 m, in 2000 is Landsat, SR = 30 m, and in 2006, QuickBird, SR = 2.4 m (later resampled to 3 m). Considering a long time span (44 years), and high and comparable spatial resolution (7.5 m for Corona KH4 and 3 m for QuickBird), a study of glacier area changes from 1962 to 2006 is highly relevant and worth to analyze change pattern of glaciers. However, a change study of glaciers from 2000 to 2006 may not be promising, basically keeping in mind a short time span (6 years) in view of (i) inherent errors in data, their processing and glacial delineations, (ii) very diverse spatial resolution (10 times difference), susceptible to remarkable delineation discrepancies (it occurs even if image data of same date but with markedly diverse spatial resolutions are used), and (iii) presence of considerable debris cover in the ablation area of the glaciers that really troubles to exactly recognize debris-covered glacier fronts, obviously more severe for a shorter period. Combined effect of them can be seen with results in Table 5. Glacier surface area in 2000 is 551±34 km2 (i.e. between 517–585 km2) and in 2006 is 537±8 km2 (i.e. 529–545 km2) that means surface area (range) in 2006 completely falls within the surface area (range) in 2000, and may imply that glacier area change might have or not have occurred. However, if one considers glacier surface area in 1962 (581–617 km2) and in 2006 (529–545 km2), the result of glacier area changes is unequivocal. A change or trend analysis based solely on the glacier area in 2000 and 2006 might lead to erroneous conclusions; in fact, authors also have had similar views (P3969 L24-28), but still asserted a higher (glacier) retreat rate in last decade (e.g. P3971 L22). I would recommend to consider only the glacier area in 1962 and 2006 for the study of glacier change. I acknowledge that authors have allocated a section to present uncertainty associated with the elevation data; however, important processes related to accuracy assessment of DEMs have been overlooked or neglected. Further, a few major issues also remain on the results of elevation change investigation. Points below need to be addressed: (I) For the estimation of glacier elevation changes with DEM differencing, (relative) DEM offsets in stable terrain outside of glaciers (off-glaciers) needs to be evaluated and reported for uncertainty/accuracy assessments of the elevation data or results of glacier elevation change (e.g. Bolch et al. 2011, Lamsal et al. 2011, Gardelle et al. 2013), which is not carried out here. This is really a critical issue to be taken into account. Further, it is not mentioned in the paper whether the elevation reference (datum) of original topographic maps was same to the SRTM DEM (WGS 1984)? If not, it may be a source of DEM offsets or uncertainty, and to tackle it, relative adjustment of DEMs may require.

We thank Dr. Lamsal for this thorough, well-thought review and for the suggestions provided for this manuscript, which we have taken into account.

These issues were addressed as follows:
I) Regarding area change from 2000 to 2006: We fully agree with the reviewer that the time span is too short, and that the errors inherent in the datasets from classification, the differences in spatial resolution might amount to larger differences than the actual change. For these reasons, initially this change was not included in the manuscript, however it was added later at the suggestion of the main editor. For the corrected manuscript, we have removed this 2000 – 2006 comparison, and the hints of accelerated glacier change from 2000 to 2006.

(II) Another issue is on results of elevation changes (e.g. as shown in Figure 10). The study found up to >150 m thickening and thinning of glaciers and authors noted ‘a general tendency of glacier thinning in the mid-, upper zone of ablation area and

thickening in glacier termini'. A study of Gardelle et al. (2013), using SPOT5 derived DEMs (40 m) and SRTM DEMs (90 m, later resampled to 40 m) and conducting extremely rigorous
DEM processing (biases correction and accuracy assessment), presented a comprehensive picture of regional-wise glacier elevation changes (and mass balance) over the Pamir-Karakoram-Himalaya including Bhutan (to the east from the present study site) and Everest region, Nepal (to the west). The study indicated glacier thinning throughout the ablation area of debris-covered glaciers in the eastern Himalaya with no clear sign of glacier thickening. Findings of the two catchment scale studies of Bolch et al. (2011) and Nuimura et al. (2012) in the Everest area, by carrying out detailed investigations with the use of higher spatial resolution data and thorough uncertainty assessment, did not indicate glacier thickening (or was very small or less than uncertainty values) in ablation area of debris-covered glaciers. On one hand, procedural limitations (point II) exist on the glacier elevation change investigation, one the other hand, the reasons behind the strong glacier thickening in the lower area of several glaciers (e.g. about 60-120 m for glacier D, about 60-200 m for glacier C in Figure 10) have not been well explained. Do the glaciers hint at or show characteristics of surge-types glaciers, such as those in the Karakoram as discussed by Hewitt (2007), Gardelle et al. (2013) and Pieczonka et al. (2013)? If they do, it is really an interesting result, and possibly the first study indicating glacier surges in recent decades in the eastern Himalaya; however, it needs to be confirmed with more detailed investigation. Authors speculated that 'thickening wave' might be behind the glacier thickening (P3966 L16); however, its process and supporting evidences have not be discussed. Further, it is asserted 'here we consider that high rates of thinning of > 150 m, which are observed towards the rock walls in the upper (glacier denoted by C), steep parts of the debris-covered area, are most likely due to errors in the topographic map in these areas' (P3966 L17-20). If >150 m thinning in that area is suspected to be errors in the topographic maps, other values such as >150 m thickening in ablation area (and tributary glaciers) of some other glaciers (Figure 10), might have also arisen from similar errors in the maps. My suspicion is that unusually high glacier thickening (or may be thinning as well) in the area compared to neighboring regions, might have occurred due mostly to errors in topographic maps, in line with the authors' doubt, but errors might not have confined to that particular area. Considering all these things, I wonder if the elevation data pair, particularly more doubt on the topographic maps, are really suitable for the elevation change investigation of glaciers to meet the needs of this study. I wish the suspicion is refuted, one way may be to carry out offset assessments of DEMs in the off-glacier area surroundings of the target glaciers and see whether the DEMs offsets in stable ground is close to zero (ideally) or relatively small or otherwise and then evaluate the results.

Thank you for these careful argumentations on the accuracy of elevation changes. This part of the analysis was limited by the availability of the data, ie we used a topographic maps which was hard to process, and hard to assess for accuracy. We have tried our best to extract elevation patterns using the available datasets. Unfortunately, we cannot provide a reliable accuracy assessment of this elevation dataset, and therefore we chose to remove this part of the manuscript and focus on

the topographic controls on area change, and the differences between debris cover and clean glaciers instead. However we will aim for this in a future study, should we be able to create accurate DEMs from stereo Corona imagery.

(III) As this study aims to understand spatial patterns glacier changes (area and elevation) in the eastern Himalaya, why only the ablation area/lower part of glaciers was investigated excluding accumulation area? Further, what is the rationale behind choosing only 21 glaciers of 50 glaciers in Domain 2? The incomplete results cannot provide a general picture of spatial patterns of glacier elevation changes in the region, representativeness of the entire eastern Himalaya is further away.

Here the purpose was to understand the heterogeneous behavior of debris covered glacier tongues. However, this part of the analysis was removed as mentioned above, and we focused on the 50 glaciers in the Kanghenjunga/Sikkim area, which have enough topographic and climatic variability to provide a picture of glaciers in this part of the Himalaya.

Specific comments

P3950 L2, L14-16 and elsewhere: please be consistent on the naming of study site. As the study site lies mainly in 'Kangchenjunga-Sikkim region', I would suggest 'Kangchenjunga-Sikkim region in the eastern Himalaya'. Above all, findings from the current study site may not be representative of the entire eastern Himalaya(central Nepal in the west to Myanmar in the east?)

We agree with the reviewer, changes might not be the same as other areas further east. We have changed this to "Kangchenjunga-Sikkim area", including in the title.

L14 & 15: in Tamor basin (Nepal), Zelu basin (Sikkim)

Change made. We note that the basin concerned is "Zemu"

L24: here, 1960's and 2000's represent year 1960 and 2000, no? Please be exact and consistent while writing the dates 1960, 1960's, and 1960s or 2000, 2000's and 2000s or similar sets of dates throughout the MS.

Correct. This phrase has been removed along with the elevation change, but we have checked the manuscript for consistency, eg. we removed "1960's" and "2000's".

P3951

L13-16: the sentence is not clear.
Rephrased. It now reads:

"Recent glacier inventories were constructed for the western part of the Himalaya (e.g. Bhambri et al. 2011; Kamp et al. 2011; Frey et al. 2012), but glaciers in the eastern

Himalaya were less inventoried (e.g. Bahuguna 2001; Krishna 2005; Bajracharya and Shrestha 2011; Basnett et al. 2013)".

P3952
L8-12: topographic maps and SRTM DEM also need to be included.

Added.

L7 and L13: glaciological/glacier parameters, same meaning? If they carry different meanings, define them and specify what parameters are included within? Otherwise, use only one terminology.

Good point. We mainly refer to glacier parameters (on a glacier-by-glacier basis), so we replaced "glaciological".

L11: please be consistent on either QuickBird (here) or Quickbird (e.g. P3959 L28); most likely the former is more correct.

We checked the manuscript and made these changes. QuickBird is correct.

L17: behavior such as?

"patterns in glacier area and elevation changes" was added instead.

L21-26: I wonder how this study (using 90 m Å~ 90 m resolution elevation data) can represent and demonstrate ablation on 'ice cliffs and ablation cones' to complement the results of Sakai et al. (1998 and 2002). The authors carried out very detailed ground observations of ablation of ice cliffs on debris-covered Lirung glacier and discussed their possible association with concomitantly collected climatic data on the glacier surface, particularly with short and long wave radiation. If this study really complements to Sakai et al. (1998 and 2000), please discuss them further in the relevant section afterwards and also demonstrate them (ice cliffs, ablation cones) on the elevation change map.

We have completely revised the introduction and removed this statement. We agree with the reviewer, though we never claimed to determine ablation from ice cliffs cones in this paper. We only point to features visible on the high resolution imagery. Nevertheless, this statement was removed.

P3953
L4: replace 'Ganges and Brahmaputra basin' by 'Kangchenjunga-Sikkim region' or by some localized names.

Change made.

L5: from 300 m (where it is, you mean minimum elevation in the SRTM tile?)

Added "at the valleys" and "based on SRTM data".

L5/6: 'long valley glaciers cover about 68% of the glacierized area', should be 'valley glacier . . .'

Change made.

L10/11: 'mapped in 1970 by Survey of India' is not contextual here.

Removed.

P3955

L1: model parameters: please specify what they are, and elaborate how these parameters were calculated based on 117 GCPs.

This was rephrased to:
"We used the bundle block adjustment procedure in LPS to estimate the orientation of all the CORONA stripes simultaneously on the basis of 117 ground control points (GCPs) extracted from the panchromatic band of the 2000 Landsat ETM+ image (15 m spatial resolution)."

L5: tie points were digitized or automatically generated?

Tie points were digitized. This was already written, but we added "manually" digitized.

P3956
L18: 'for the 2000 decade' or for 2000?

For 2000. We have corrected this.

L23-28: here, 1960's is meant for the year 1960 or decade 1960s? It is stated that exact date of each quadrant of topographic map is unknown: only days/months of a year or entire year(s)? Does the compilation period of topographic maps from 1960s (1960-1969?) to 1970s (1970-1979?) also refer to acquisition dates of air photos? On the MS, it lacks clarity whether the elevation data represent 1960 or 1960s or else.

This is meant for the decade1960s (the maps were based on 1960 to 1970 though the exact date, month or year is not known). We do not know with certainty the acquision of the air photos. We have rephrased this and tried to clarify.

P3957 L25/26: 1960s and 2000s, right?

Correct. Changed this.

P3958 L3: please tell something more about efficacy of the threshold value 'DN>200 =

snow/ice'to demarcate glaciers from non-glaciers using panchromatic imageries. How were debris-covered area and snow on steep walls handled?

This is the threshold we came up with based on visual interpretation and based on the author's experience in other areas. There is perfect way to do this, particularly for Corona panchromatic imagery. We have added in the text that debris covered areas was delineated manually, on the basis of lateral moraines and other visual clues.

L4: what exactly was 'remaining noise?' please clarify it. Please also specify the minimum size of glaciers mapped or considered for change analysis. Is it 0.05 km2?

A 5x5 median filter was used to remove noise (isolated pixels from snowfields or internal rocks).

P3960 L1-3: I wonder if this is the right way to assess uncertainties of elevation data (topo-map derived DEMs and SRTM DEMs) for glacier elevation changes unless their absolute height reference (datum) is same. Understandingly, the uncertainty values stated here (±25 m for the topo-derived DEMs and ±31 m for SRTM) represent possible absolute errors within the data, but what really needs here is to evaluate relative accuracy of the pair (DEMs) in stable terrain (off-glacier), this process may be required even when elevation data pair have had same height reference.

We agree with the reviewer.
This part of the paper was removed since a proper uncertainty analysis of the elevation data was not feasible at this point.

L7: in Sikkim (India) or in India

L25: 'glacier size ranged from 0.05–105 km2' or glaciers _ 0.05 km2 were mapped or mappable?

"Mappable" glaciers started had area > 0.02 km2. Previously four glaciers > 0.02 km2 were considered separately. We have clarified this.

P3962 I would suggest to add a figure (immediately before Figure 6) showing all the glacier outlines in 1960 and 2006, and outlines of supra-glacial ponds/pro-glacial lakes in 2006/09 (in the entire Domain 2) superposed on Corona Imagery in 1960.

We agree this would be an interesting figure, but in this paper we are not dealing with lake area changes, and have not specifically delineated the areas of pro-glacial lakes. This issue was dealt with in a different paper (Basnett et al. 2013).

P3963
Findings of 'glacier elevation changes' should also be presented in the result section before discussing them.

Not relevant anymore since this section was removed.

L8-11: also include glacier area change rate for those study areas you cited here (Alps, the Tien Shan and Peruvian Andes) and Thakuri et al. (2014) in Mt. Everest region.

This was mentioned, but maybe not clear (it was same as in the Andes, 0.7%/yr-1). Ae have added it. The area changes from Thakuri et al, was discussed at various points in this revised paper.

P3964
L9/10: south-facing slopes!
Changed.

L10: at lowest/lowermost elevation!
Unlike the clean type glaciers, outlines of frontal position of debris-covered glaciers are extremely difficult to demarcate unless large pro-glacial ponds/lakes are in contact with them (still retreat may not be purely linked to climate change) or extremely high resolution imageries are used. Therefore, horizontal retreat may not be an effective mode of change investigation of heavily debris-covered glaciers in the Himalayas (or making comparison to clean type glaciers), rather elevation change study will do. However, I admit that practices of carrying out investigations on horizontal retreat of debris-covered glaciers (or their comparison to clean glaciers) do exist. Probably, we all concerned scholars have to contend against or discourage such practices in the future.

We agree with the reviwers, the frontal position of glaciers is not an indicator of glacier mass balance due to the response time of the glaciers, and therefore a less sensitive indicator of a glacier's response to climate. In this study we brieftly presented glacier length for inventorying purpose, but we are not using this parameters to infer changes.

P3965 L21-23: maybe all glaciers experiencing elevation changes. Do not cleantype glaciers experience elevation changes?

Correct. Maybe some more than others, but overall all glaciers.

P3966 L3-8: glacier elevation change to be −30.8m±39 m: the error/uncertainty value is excessively large that makes results
overwhelmingly uncertain. Further, as the study area is located in the eastern Himalaya between Bhutan (to the east) and Everest region (to the west), comparison of glacier lowering from within the regions in the eastern Himalaya incorporating previous studies (e.g. Bolch et al. 2011, Nuimura et al. 2012) would be more meaningful than comparing with the glaciers in Karakoram. Such a comparison within the eastern Himalaya may help to see possible influence of weakening tendency of monsoon from east to west on glacier elevation changes.

The elevation analysis was removed. However, we kept in mind the comparison with the areas to the west (Everest region) and to the East (Bhutan).

L24-26: Does the temperature pattern for Zemu Glacier represent general trend of all the glaciers? It would be nice if surface temperature of all the glaciers (21) is shown in a separate figure (raster map).

We have extracted temperature patterns for several tongues, and have intended to present them all in the same graph, but this was not very illustrative. The short answer is that the surface pattern is not the general trend, as it depends on the glacier area, the presence/absence of pro-glacial lakes, etc. Here we chose a representative glacier, which we estimate to be similar in characteristics as Khumbu or Ngozumpa glacier in the Khumbu Himalaya.

At the suggestion of the reviewer, we are showing the surface temperature of the debris-covered tongues as raster map. We have also discussed these patterns more at length in the text.

L26-28:
temperature also decreases with increasing altitude (lapse rate), even on surfaces of clean-type glaciers. You mean decrease in temperature here is higher than lapse rate? It has been already established, qualitatively though, even without having knowledge of heat index that debris cover generally thickens toward glacier termini. But, does higher (or lower) temperature on a glacier surface conclusively indicate thicker (or thinnerr how thick) debris mantle? I felt the assertion 'indicating' is a quite strong word here, rather weak words such as 'might indicate' would be a fair choice.

We agree, and have rephrased this.

P3967 L2-4:
please show supra-glacial ponds/lakes and prominent ice cliffs on the map (their outlines in Figure 10) so that ice ablation associated with them could be seen. It's fine with large supra-glacial lakes; however, DEMs with spatial resolution of 90 m (or 8100 m2) cannot well represent micro-landforms such as ice cliffs and ablation cones, and their elevation distribution on the glacier surfaces. As a result, a detailed understanding of elevation change or change patterns of glaciers at micro-level (e.g. ablation on ice cliffs) is largely difficult with the current datasets (DEMs).

The elevation change section was removed so this is no longer relevant.

L7-17: arguments (elevation
change and surface temperature, and their dependency) are self-contradictory: The relationship between elevation changes and surface temperature is more clear in the middle-upper debris area mentioned above, where we also note larger elevation differences (thinning). There is less variability of surface temperature than the lower part, probably associated with thin supra-glacial debris in this area. Regression analysis

using surface temperature as explanatory variable for Zemu showed a non-significant dependency of elevation changes on surface temperature ($p > 0.05$). An ordinary leastsquared regression using all 21 debris-covered tongues showed a weak dependency of elevation changes on surface temperature (R2 = 0.01).

Same as before-
We focused our discussion on temperature patterns and area changes of debris covered tongues only.

P3970/71 Glacier (number) counts or number comparison among glacier inventories may not be a meaningful measure as discussed in the paper. Total surface area is generally expected to be a more reliable measure, but sadly, also remained not so consistent. It's good to see this paper pointing such an unreliable estimates out (P3971 L6). It's really a big challenge to the glaciological community to overcome problems associated with discrepancy in definition of glaciers, (wrong) classification, delineation error, and the like among operators. These kinds of inconsistencies may lead to a huge difference in glacier surface area and numbers among the glacier inventories. More serious problem arises when such a discrepancy (difference in glacier delineation, not by actual change) is also counted in glacier changes. Glacier outlines/inventories of this study may differ from other inventories due to the various factors mentioned above. However, authors here in this paper have had more control over their data (i.e. both inventories, 1962 and 2006 were produced by themselves using high resolution data). As a result, findings of glacier surface changes from 1962 to 2006 should be very reliable.

We agree with the reviewer.

P3979 L8: coauthors'
names are left out; should have been Sakai, A., Nakawo, M., and Fujita, K.: Distribution characteristics . . . Arc. Antart. Alp. Res., 34, 12–19, 2002. Table1: ASTER data used for temperature extraction have been missed.

Fixed.

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Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/8/C1787/2014/tcd-8-C1787-2014-C1795 supplement.pdf
Interactive comment on The Cryosphere Discuss., 8, 3949, 2014.
C1796

Basnett, S., Kulkarni, A. and Bolch, T. (2013). "The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya, India." Journal of Glaciology **59**(218): 1035 - 1046.

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Thank you very much,

Adina Racoviteanu

TCD
8, C1814–C1816, 2014
Interactive
Comment

The Cryosphere Discuss., 8, C1814–C1816, 2014
www.the-cryosphere-discuss.net/8/C1814/2014/

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Discussions

Interactive comment on "Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya" by A. Racoviteanu et al.

D. Loibl
d.loibl@geo.rwth-aachen.de
Received and published: 17 September 2014

Dear colleagues,

I just stumbled upon this very interesting contribution and would like to concisely give some ideas, since I widely agree with the reviewers' comments. We conducted a quite similar study for the eastern Nyainqêntanglha Range at the eastern syntaxis of the Himalayas, approximately 600 km east from your study area (Loibl et al., 2014). Even though the investigated timespan differs (LIA maximum - 1999), I think a comparison of the trends evident in the data sets and the interpretations regarding the forcing mechanisms would be highly valuable.

Thank you for these comments, we appreciate it. This is an important point, than you for bringing it out. It is true we have not compared our results with areas much further east, but we agree that a comparison is valuable, given that the time span and the methodology are very relevant. This is a good point also since we have focused the discussion so that we out our results in the larger context of the Himalaya. We have made reference to Loibl et al, 2014 in the revised version of the manuscript, and have presented our area changes with respect to surrounding areas, Khumbu to the west, Bhutan to the east and further east in Tibet.

For example, you speculate that the location of your study area in the monsoon-influenced area may be leading to lower sensitivity toward climate change. In contrast, our results indicate increasing sensitivity with increasing monsoonal influence (cf. also Loibl and Lehmkuhl, 2014). This also seems to be in accordance with large-scale studies (e.g., Gardelle et al., 2013; Neckel et al., 2014 and references therein) and local ground measurements (e.g., Zhou et al., 1991; Zheng et al. 1999). I am also not sure, whether it is correct to assign your study area and the eastern Nyainqêntanglha (falsely called 'Hengduan' by Gardelle et al., 2013, in my opinion) to the "same climatic zone" (cf. 3966L5), because there are noticeable differences in precipitation (cf. Maussion et al., 2014). Nevertheless, the conclusions drawn regarding the influence of topographic factors are widely similar.

We agree with these two points, particularly that glaciers in the monsoon-influenced areas experience more sensitivity to climate, with perhaps different impact of changes in precipitation and/or changes in temperature. We had speculated that the role of precipitation may be an important factor here, and that glaciers might be less sensitive because their accumulation areas might be better maintained. However, do not have good support nor evidence for the impact of climate factors in this area of the Himalaya, so we have revised our statement (see section 4.2). This part now reads:

Precipitation was also found to be significant in controlling glacier area loss, but the correlation was less strong than the glacier elevation factors mentioned above (Pearson's r = -0.25). In contrast, Loibl et al. (2014) showed that glaciers located in a monsoon-influenced area were more sensitive to climate change. This is in agreement with larger-scale studies (Gardelle et al. 2013), which indicated a tendency for enhanced glacier wastage in the eastern, monsoon-influenced parts of the Himalaya. With respect to climatic factors in this area, Basnett et al. (2013) reported an increase in mean annual temperature, more significantly in the winter (+2°C yr^{-1} in the last four decades). Increasing temperatures on the south slopes of the Himalayas were noted in other studies (Shrestha et al. 2000; Thakuri et al. 2014) based on instrumental data, but were estimated to have less effect on glacier area than changes in precipitation because of the orientation of these glaciers towards the prevailing monsoon circulation. In our study, the climatic control on glacier area is not conclusive, and finer-resolution, more accurate temperature and precipitation datasets would be needed. Furthermore, similarly to areas further east (Loibl et al. 2014), average annual solar radiation and latitude were not found to be significant controls on glacier area change in our study. Other factors such as supra-glacial debris cover might have a more important role than climate controls in preserving glacierized areas.

Further, I have only some remarks regarding your figures:
Fig. 3: Coarse resolution of climate data – why not use the freely available HAR data?

At the time this paper was started, we were not aware of this dataset, nor have we tested its accuracy for this area. It is a good point for a future paper, in which we plan to include a few more variables in a more sophisticated model.

Fig. 4a: I suggest a different grouping/logarithmic scaling to make this more figure more informative.

Good point, but a little late to change now. Left as is.

Fig. 4b: Isn't it km?

Changed.

Fig. 5: Labeling of axis?

I think labeling of rose chart axis is not necessary. You mean perhaps "N", "S"? We labeled the axis using the 0 – 360 degrees.

Fig. 7: We used similar diagrams in Loibl et al. (2014) but used symbols for clean and debris-covered the other way (i.e., triangle for debris-coverd, circle for clean). Maybe similar usage would be beneficial?

It would be nice, but at this point we don't consider necessary given the time constraints.

Fig. 10: Many glaciers show thickening at glacier termini, which I found very interesting I would like more ideas on this phenomena in the discussion.

Unfortunately this section is not mature/conclusive yet due to the uncertain quality of the topographic map, and therefore we have removed this section. We will address this in a different paper using perhaps different (an hopefully more accurate) elevation datasets.

I'm looking forward to the final version of your manuscript.
Kind regards,
David Loibl

Thank you very much,

Adina Racoviteanu

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Loibl, D., Lehmkuhl, F., Grießinger, J., 2014. Reconstructing glacier retreat since the Little Ice Age in SE Tibet by glacier mapping and equilibrium line altitude calculation. Geomorphology 214, 22–39. doi:10.1016/j.geomorph.2014.03.018

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The Cryosphere Discuss., 8, C1839–C1843, 2014
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The Cryosphere
Discussions
Interactive comment on **"Spatial patterns in glacier area and elevation changes from 1962 to 2006 in the monsoon-influenced eastern Himalaya"** by **A. Racoviteanu et al.**
M. Pelto
mauri.pelto@nichols.edu
Received and published: 20 September 2014

Racoviteanu et al (2014) provide a useful inventory of glacier change from 1962-2006 in the region along the Nepal-Sikkim border. They further relate the observed changes to basic glacier characteristics further enhancing the paper's value. The satellite image analysis approach is sound and well described. This comment focuses on just one key point glacial lakes with a few minor points.

Thank you for these useful comments. We have added a short discussion section in the new version of the manuscript to incorporate these suggestions (section 5.4, Glacier Lakes). See our answers below.

3963-22 and 3965-7: Glacial lakes at the terminus can affect terminus retreat. This should be an additional parameter to include. Must distinguish between supra-glacial lakes that have developed on the surface of a glacier, from pro-glacial lakes that are at the terminus. In spatial domain 2 a series of glaciers just north of Zemu Glacier: Changsang, East Langpo, Jongsang, Middle Lhonak, South Lhonak all terminate in glacial lakes, and some have had rapid retreat during recent decades. Some like Changsang Glacier have seen a recent merging of supra-glacial lakes into a single more appropriately termed pro-glacial terminus lake. Jongsang has a section of terminus that only has supra-glacial lakes. The impact of these lakes on retreat is worth including as a parameter. South and Middle Lhonak in particular have retreated rapidly with lake expansion. The lakes that have developed may have some relict ice cored moraine on their banks, but it is not plausible that the larger lakes indicated by red arrows in Figure 2 are underlain by glacier ice at this point (Figure 1 and 2).

We fully agree that glacier lakes constitute an important parameter, and should be included. For this paper, we have not included the lakes since we have not fully mapped the pro-glacial lakes. A recent study by Basnett et al. (2013) investigated at the effect of glacier lakes on glacier area changes, by separating glaciers with lakes and no lakes, debris cover etc. Including the lakes in the analysis is beyond the scope of this paper, but it would be a good parameter to include in the future, perhaps as a parameter for a multiple regression analysis.

3966-9: Does refer to the South Lhonak as pro-glacial.

Change made.

Minor Points: 3959-6: The average slope is one useful parameter; however, most of the debris covered glaciers have very low slope ablation zones. Is the slope of the ablation zone a more useful parameter on these? If too difficult to address should at least be mentioned.

We agree with this point. We included the average slope in order to be able to compare with other studies. We have mentioned the impact of glacier-wide slope in the results and discussion. At this point it is too complex to do the analysis separately.

3690-24: There is no Section 4.3

The sections have been revised and re-numbered.

3963-11: Why is climate seen as the key instead of the heavier debris cover? What about comparison to the Bhutan record of Bajracharya et al (2013)? This likely supports your point.

We have revised this statement. Glacier elevation is actually the key parameter, and we have emphasized this in the new version of the manuscript.
Also, we have added the comparison with the mentioned studies. Our results are indeed in agreement with these studies.

3964-22: Are not clean glaciers more sensitive to climate change because of a faster response time and hence more useful as a focus for purely climate change purposes?

We agree- however, we are not stating that we are assessing climate change.

3967-7: How valid is such a comparison from one day of temperature reconstructed data that is not from the principal melt season event?

We agree. We have removed the elevation difference section so this is no longer relevant here.

Figure 1: Map of glaciers with glacial lakes at their termini north of Zemu Glacier.
Figure 2: Landsat image from 2103 of glacial lakes north of Zemu Glacier: C=Changsang, E=East Longpo, J=Jongsang, MS=South Lhonak, M=Middle Lhonak.
Bajracharya, S.R., Maharjan, S.B., and Shrestha, F.: The status and decadal change of glaciers in Bhutan from 1980's to 2010 based on the satellite data. Annals Glaciology. 55(66): 159-166. doi: 10.3189/2014AoG66A125, 2014.
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Fig. 1. Map of glaciers with glacial lakes at their termini north of Zemu Glacier.
Fig. 2. andsat image from 2013 of glacial lakes north of Zemu Glacier: C=Changsang, E=East Longpo, J=Jongsang, MS=South Lhonak, M=Middle Lhonak.
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Thank you for these references. We have labeled some of these glaciers in the revised figure, and have also revised the discussion.

Sincerely
Adina Racoviteanu