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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 scanned at USGS at 7 microns, 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 epsilon 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 Plateau. 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 Blanca 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–C1722

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.

Interactive comment on *The Cryosphere Discuss.*, 8, 3949, 2014.
C1723

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

Thank you,

Adina Racoviteanu