Comments on the revised version of the manuscript on "Spatial patterns in glacier area changes from 1962 to 2006 in the Kangchenjunga-Sikkim area, eastern Himalaya", by Racoviteanu et al., submitted to The Cryosphere Discussion
Damodar Lamsal, December 2014

After the revision, this paper is notably improved. I commend the authors for its revisions. Specific comments given were mostly addressed. However, general comments were partly addressed: i) uncertainty/validation of elevation change was not carried out leading to authors' opting to taking out that part from the MS, ii) potentially erroneous surface area change analysis from 2000 to 2006 was removed as advised, and iii) issues on (in-) adequacy of spatial extent of glacier change analysis to draw conclusion on spatial pattern of change in the region and issues on debris-covered glaciers were not sufficiently addressed. There is still ample space to make the paper stronger, by clarifying and resolving some remained issues (see below). It would be nice if authors address below points carefully, taking enough time for manuscript improvement.

We thank the reviewer for this review and the previous one. With respect to (i) and (ii), this was already justified in our previous replies. Regarding (iii), this was addressed at length to address the reviewer's concerns in this version of the manuscript. Please find below our answers in more detail.

Please note also that improvements were made to the results and discussion section, particularly with respect to area changes for clean vs debris covered glaciers and for east versus west, as well as one table added.

1. Central idea of the paper needs to be clarified and story should progress methodically to support that idea. Although the paper presents considerable amount of data, how the individual component support and connect with the main idea has not been well discussed/established. Very first line of the abstract states and gives impression that main aim of the paper is to analyze spatial pattern of glacier changes; however, in the introduction section (aim of the paper), it states that 'primary goal is to estimate current glacier distribution and parameters'. If the main idea behind this paper is to present spatial pattern of glacier area change and to examine dependency of the glacier change/loss on climatic and topographic variables/settings, data and results should be presented accordingly in the right order and discuss the association of glacier change/loss with governing variables, providing only the strong evidences, relevant and substantial information. At times, arguments are not strongly supported by the data and discussion are rather qualitative and general: for instance, discussion in section 5.3 and 5.4 do not add significant knowledge to existing understanding due to nature of (constrain in) data in hand despite the lengthy arguments.

We revised the abstract and introduction to clarify the objective of the paper. We considered the reviewer's suggestions to better clarify the objectives in the abstract and introduction, and made the following changes:

In the abstract:

- First line and title changed to "spatial distribution of glacier characteristics".
- First paragraph of the abstract now reads:

> ***L 14- 21: "This study investigates spatial patterns in glacier characteristics and area changes at decadal scales in the eastern Himalaya: Nepal (Arun and Tamor basins), India (Tista basin in Sikkim), and parts of China and Bhutan based on various satellite imagery: Corona KH4 imagery, Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Advanced Spaceborne Thermal Emission Radiometer (ASTER), QuickBird (QB) and WorldView-2 (WV2). We compare and contrast glacier surface area changes 1962 – 2000/2006 and their dependency on glacier topography (elevation, slope, aspect, percent debris cover), climate (solar radiation and precipitation) on the eastern side (Sikkim) versus the western side (Nepal)"***

In the introduction, we state and clarify the two-folded objective of the paper:
P 2, l 4 – 14:
"While significant progress has been made in the recent years on remote sensing glacier mapping in the Himalaya, some of the sub-regions still need updated glacier area and surface characteristics including debris cover. The objective of this study is two-fold: (1) present the current glacier distribution and characteristics in a data-scare area of the eastern Himalaya based on an updated 2000 Landsat ETM+ and ASTER inventory, along with elevation data from the Shuttle Radar Topography Mission (SRTM); (2) investigate spatial patterns in glacier surface area changes from 1962 (Corona KH4) to 2000 (Landsat/ASTER) and 2006 (QB) 2006 (WV2) and their dependence on topographic and climatic factors, with a particular emphasis on debris-covered glacier tongues. These updated glacier datasets help fill a gap in global glacier inventories such as the RGI (Pfeffer et al. 2014), as well as for subsequent future mass balance applications at regional scales."

With respect to sections 5.3 and 5.4, these were added at the suggestion of reviewers and comments. While some of the discussion is qualitative, we consider it valuable as a base for a future study.

2. Only 50 glaciers in domain 2 is largely insignificant numbers to examine spatial pattern of glacier surface loss in the region. Moreover, rationale behind assigning domain 1 and domain 2 in the same paper is not justified/justifiable and it may be confusing to the readers to grasp the story. I suggest to make only one domain (wider) to examine both glacier area change/loss, and topographical and climatic controls on glacier changes. So I would recommend to expand domain 2, at least of the size of domain 1 (487

glaciers) at present, or preferably wider, so that (real tendency of) spatial pattern of glacier loss and their dependencies (on topographic and climatic) might be examined and inferred.

Concerns about the analysis wxtent were not raised in reviewer's previous comments. The rationale behind this was to use only quality-controlled outlines based on high resolution Corona and QB imagery. While the number of glaciers in the Kangchenjunga-Sikim area (50 glaciers) may seem insignificant, these glaciers cover 38% of the spatial domain 1. We added the area covered by these glaciers in table 1. As the reviewer noted previously, the number of glaciers is subjective, and previous studies have split glaciers in this area into more glaciers. See table 8 on inconsistencies in glacier numbers. Also we note that other studies have based estimates of area change on a small sample of glaciers, notably in the Khumbu area (Thakuri et al 2014: 29 glaciers, 400 km^2 , Nuimura et al, 2012: 10 glaciers, 183 km^2 and others quoted on this study). We point out that our previous version of the paper referred to changes in glacier area in the Kangchenjunga-Sikkim area.

That being said, to address the reviewer's concerns we have made the following changes to the manuscript:

- ***We expanded spatial domain 2 to include all glaciers covered by Corona and Landsat/ASTER. This comprises 232 glaciers, located in Sikkim and Nepal. Note that we cannot extend the analysis to include China and Bhutan because these are not covered by Corona. Instead, we focused the analysis on the E vs. W sides of the divide (sub-regions as suggested by the reviewer).***

- ***Spatial domain 2 became spatial domain 3 (50 glaciers in the Kanchenjunga-Sikkim area) and we are using this sample of glaciers as a case study, to (i) present changes to 2006 based on high resolution imagery; (2) discuss particularities of these glaciers (surface temperature, lakes etc) and also iii) show some of the mapping challenges pointed out by the reviewer.***

As authors said (in P8 and P9), study region has topographical and climatic variability (east west and/or north-south) and its division into 4 sub-regions (as in Table 3) is reasonable/justifiable (P9 L8-9). But the sub-regions were not taken up for analyzing glacier area change. I recommend to consider either these four sub-regions or some other meaningful sub-regions/classes for analyzing such spatial patterns of glacier change.

Concerned addressed. See comment above regarding two of the sub-regions not covered by the 1962 Corona extent.

3. Exact delineation of debris-covered glacier (front) is extremely difficult job due to debris mantle, resulting in obscure glacier front; delineation is usually based on rather subjective judgment of the operators. Moreover, although area change/loss may be a (highly) reliable parameter or mode of investigation of clean type glaciers and for assessing their response to climate change, but less effective (sometimes it might be ineffective too) for debris-covered glaciers unless debris-covered glaciers accompany pro-glacial lakes. Through volumetric/elevation change studies, it has been already demonstrated and becoming increasingly clearer that debris-covered glaciers have been losing ice mass similar to those of clean type glaciers (e.g., Bolch et al. 2011, Kääb 2012, Nuimura et al. 2012). With keeping above facts in mind, I would reiterate that studies of surface area change of debris-covered glaciers generally do not manifest real glacier changes/loss and may not be comparable with clean type glaciers. I would suggest to analyze only the sub-region-wise (4 sub-regions!) area changes of clean type glaciers or to consider, though less preferable alternative, clean type and debris-covered glaciers separately (analyze/compare only clean type vs. clean type and only debris-covered vs. debris-covered glaciers) across sub-regions.

We agree with the reviewer and we are not stating by any means that the smaller rates of retreat of debris-covered tongues reflect a state of health of these glaciers. As a matter of fact, for clean glaciers as well, area changes do not reflect either the true state of the glacier due to a glacier's response time. We are simply showing that for debris covered glaciers, we do not see high rates of retreat (yet most likely these glaciers may be thinning, as noted in nearby Khumbu area). Our approach is similar to that of Scherler et al. who reported the rates of retreat of the debris covered tongues at regional scales, except we focus on the area at sub-regional scale.

At the suggestion of the reviewer we present separately the area changes of debris glaciers vs. clean glaciers, as well as debris vs. debris and clean vs. clean in Sikkim vs. Nepal (the two sub-regions in spatial domain 2 now).

We also added this point in the discussion section, 5.1 last paragraph:
"Area changes for debris-covered glaciers need to be interpreted with caution, due to the wide variability in debris cover characteristics such as thickness. Furthermore, these stagnating or less retreating tongues may not reflect the true state of the glaciers, for example patterns of glacier thinning, which may occur at similar rates to clean glaciers (Gardelle et al. 2012a; Kääb et al. 2012)."

4. It seems (seeing Figures 10 and 11) glacier delineation/outlines may yet be improved: please see below image, a small portion of figure 11 for illustration. Small polygons inside the glacier outlines are not always exposure/rock out crops. Seeing on Google Earth image 2010, it is apparent that the small polygons inside the

main glacier polygon in 2006 glacier outline (as shown within dotted oval in black) are not outcrops, but the glacier surface: such erroneous polygons need to be cleaned/removed from throughout the maps. Further, 2006 glacier front (Jongsang Glacier) extends below the 1962 glacier front, is it really a glacier terminus advancement? or mis-delineation? Further, inside the dotted red circle, the 2006 glacier polygon (in bright green) most likely should have been drawn along the dotted green line: median moraine on the glacier surface is apparently considered as non-glacier surface (moraine). Therefore, careful quality or cross-check of delineated glacier outlines (e.g., against Google Earth images) has not been fully carried out, but if doing so, it would improve quality of glacier outlines, producing more accurate glacier change estimation.

Specific comments:
P2
L11 'glacier area and elevation changes' -> 'glacial changes'

Removed "area and elevation changes". However, "glacial" is not the correct term.

L13 'helped improve estimates' -> 'helped estimates' or 'helped improve estimates over …?'

Grammar is correct. Left as is.

L20 '… may not be suitable … glacier parameters' -> citation; how about the quality of the RGI or other regional glacier inventories in the current study area, were not those inventories suitable for extracting glacier parameters? Any quality check or comparison with them?

The author is well familiar with the glacier inventories in this area. This comparison has been done and the inconsistencies were explained in detail in answers to editor's comments in the first round of revisions. We considered more appropriate to construct our own inventory, for the area of interest.

L22 GAMDAM (Glacier Area Mapping for Discharge in Asian Mountains) glacier inventory, Nuimura et al. 2014 in TCD is relevant here

Reference added

P3
L22 if mixing up area change and mass/volume change of debris-covered glaciers, influence of debris-cover on glacier change might be debatable as stated in the manuscript citing Scherler et al. 2011 and Kääb et al. 2012, otherwise, recently it has been increasingly clear that debris-covered glaciers have also been experiencing similar mass loss/change that of non-debris covered glaciers (e.g., Kääb et al. 2012, Nuimura et al. 2012).

We generally agree with this, but the reviewer's comment is unclear. This is only a general literature review for the introduction, and we are not elaborating on the role of debris for melt here.

L23-24 'Modelling of melt under the debris cover is subject to uncertainties' -> is this uncertainties due to unviability of updated and precise glacier inventories or other reason?
Added:
"..is subject to uncertainties due to limited field-based measurements of debris thickness needed for model parameterization"

P4
L19 'valley'!

New phrase started, so "Valley" is appropriate. Not sure what the reviewer means here.

P5
3.1 Data sources: shorten general information about satellite images as much as possible, as are available elsewhere

The reviewer did not comment on the length of section 3.1 in the first review. Information about Corona images and its processing is not easily available, and it is important to detail how the orthorectification was done.

We removed the following information from the text, which is included in Table 1:
Removed:
"The Landsat ETM+ scene has seven spectral channels at 30 m spatial resolution, a thermal channel at 60 m and a panchromatic channel at 15 m, a revisit time of 16 days and a large swath width (185 km)."
"The ASTER scenes have 3 channels in the visible wavelengths (15 m spatial resolution), 3 channels in the short-wave infrared at 30 m, and four thermal channels at 90 m, a swath width of 60 km and a revisit time of 16 days."

L20 '1960s decade' may not be right choice as data were acquired in 1962 only-> 'year 1962'

Removed "1960s decade"

P6
L4 due to

added

L13-14 'GCPs were identified on the Landsat image' -> is not fully correct as there is no elevation information in Landsat imageries. Normally GCPs represent long., lat., and elevation information (X, Y, and Z) together, so please clearly state that long. (X), lat. (Y) values were collected from the Landsat scenes and the elevation information (Z) was extracted from SRTM DEM

We agree with the reviewer. The paragraph now reads as:

GCPs (x,y) were identified on the Landsat image on non-glacierized terrain including moraines, river crossings, and outwash areas, and elevation information (z) were extracted from the SRTM DEM v.4 (CGIAR-CSI 2004).

L15-16 LPS automatically (though manual is also possible) generates a large number of tie points in the overlapped area of the images being processed using 'image matching technique (IMT)' module. Here, authors stated that tie points (number?) were manually digitized taking Landsat image as a reference data. Although automatically generated tie points may contain some erroneous match (operators should remove them later), it generally produces very accurate object match. I wonder why the authors opted to manual tie point generation, was there any issue with automatically generated tie points?

Correction: The authors did use the automatic TP generation tool. While this works fairly well, these points have to be checked manually. We double-checked the location of each of the TP for improved accuracy, plus some TP were added manually. We rephrased to clarify this process:

"Tie points (TPs) were automatically extracted in LPS and visually checked from overlapping Corona strips, on the Landsat image."

P8
L1-10 SRTM DEM is now used only for ortho-rectification of imageries (not for the elevation change study), detail information about SRTM and its uncertainty is not needed as nothing additional processing has been carried out on the DEM to improve its quality.

Correction: the SRTM was used here to extract 2000 glacier parameters. One reviewer asked for additional information on SRTM DEM.
Left as is.

L11-16 According to the authors (in p3), quality of the topographic maps (1960s and 1970s) remain uncertain. I did not understand why the maps were used and how the maps helped improve the glacier outlines delineated from Corona images.

It was stated that the map was used only for visual comparison and manual adjustment, for example to discard seasonal snow, or to correct some water

bodies that were reflective on the Corona images and could have been misclassified as snow. We added this on p.8.

P9
L4-7 Authors noted 'well-known biases in the TRMM data' and asserted 'they were not concerned with absolute values' citing its purpose was for only characterizing the sub-regions. It would be worth to add a few lines on how much biases are expected in the data in the region, this is because in the later part precipitation data (Table 7 and in the discussion) have been used as one of the factors to see glacier change dependency on it.

***We do not have any means of characterizing biases in the TRMM data in this region, due to lack of ground-based climate data. The reader is referred to Bookhagen papers and others* (Bookhagen and Burbank 2006; Andermann et al. 2011; Palazzi et al. 2013).**

L17 'elevation change' by Thakuri et al. 2014? You mean SLA (snow line altitude) change?

This paragraph was re-written and the reference was removed as it is discussed later.

L18-20 'To facilitate comparison with this study and others from the same climatic area, we excluded glaciers from China and Bhutan from the glacier area change analysis': wider area including China and Bhutan would be better to see glacier change pattern, should not have restricted analysis extent only for the sake of comparison.

As explained earlier, our analysis extent was determined by the extent of the Corona imagery, which did not cover the parts of China and Bhutan. We clarified this in the new version of the manuscript, and as noted, we extended the analysis to the full Corona extent (Sikkim and Nepal, total of 232 glaciers). We added:

"Glaciers from eastern Bhutan and China were not covered by the Corona image, so the area change analysis focused on glaciers of Sikkim and eastern Nepal"

P10
L22-24 'Some transient snow persisting in the deep shadowed valleys was manually removed from the glacier outlines on the basis of the topographic map': to check 2006 glacier outline quality, Google Earth Images would be better than using topographic maps of 1960/70s, whose quality is, as stated by the authors (p3), uncertain.

We'd like to point out that 1) Google Earth are <u>not</u>t the actual images, they cannot be used as full resolution images. We had the high resolution Quickbird images which Google earth uses and 2) Google earth images do not go back to 1960s decades. So, high-resolution imagery was indeed used to check the glacier outlines but of course uncertainties remain.

P11
L13-15 Glacier thickness calculation? Don't really understand how well the model fits in this region with high relief and rugged topography, relatively smaller glaciers, many with debris-covered types. How much uncertainty is expected?

This is something which is addressed in Huss et al papers and we are not estimating the uncertainty here. We cannot answer this question. We are using the output of this model as order of magnitude.

3.4 Uncertainty estimates: shorten the description of error types, particularly, which is not considered, for instance, Geolocation error.

At the suggestion of a different reviewer we detailed the uncertainty estimates. We shortened the geolocation error section and moved it to 3.1 where we describe the orthorectification of Corona.

L10-12 'The error in glacier surface area change (E) was computed from the errors due to rock inconsistencies (Erock) and classification errors (Eclassif) embedded in each dataset as the RMSE' -> it seems that only Eclassif is considered based on P13, L5 (image classification error 3-6%) and P14 L3 (total uncertainties ±3%, ±6% and ±3%): don't they represent the same thing/value? Here also, if the uncertainty/error is not taken into account (Erock?), shorten its description.

The errors to internal rock inconsistencies were actually used in the RMSE calculations. For the glacier area estimates, we used $E_{classif}$ (revised values are ±3%, ±6% and ±2%) plus E_{rock} (1.3%). All these were computed it as RMSE. The section was re-written to clarify this (p. 12-13).

P14
L14-18 (and elsewhere when relevance) this comparison fits/goes to discussion section.

Moved to discussion (section 5.1 "Spatial distribution of debris cover")

L19- (whole paragraph and elsewhere when relevance) -> Please move your interpretation of the results to discussion section.

Moved to discussion (section 5.1 now)

P16
L10-14 It would be worth of specifying how (manual or automatic and how is it determined) the length of glaciers were calculated.

Glacier length was an output of the model by (Huss and Farinotti 2012) , based on (Farinotti et al. 2009). The reader is referred to those papers for details of the model. Added this on p.11

L20 Obviously, glaciers follow (local) topography. So more meaningful and insightful analysis is needed, particularly, in relation with glacier area loss. Showing portion/percent loss, with excluding absolute loss, not necessarily represents the degree or severity of loss. In the paper, all the glacier losses are shown in percent to show small glaciers have experienced larger losses. Note that in terms of total surface area loss, larger glaciers have lost considerable area. So it would be nice to show absolute change/loss as well.

Ok, we added the absolute changes.

P24
Section 5.3: surface temperature distribution on debris cover tongues: as argued here and based on already established knowledge, higher temperature towards glacier termini may indicate thicker debris cover. To characterize debris-covered glaciers, temperature profiles/maps definitely help, but how is the temperature data/results relate to current purpose, the glacier area change. Also please show the temperature pattern on clean type glaciers, particularly in the same elevation range of debris-covered glaciers, so that the true contrast could be seen.

Here we show that temperature data may be used to understand why some of those debris covered glacier tongues behave differently (e.g. stagnating tongue vs. developing large pro-glacial lakes). We present it as a further improvement in the model for a future paper. Here we only present a first step to understand whether these data can be used.

P26
Section 5.4: role of glacial lakes: discussion here is mostly referring to the findings of the previous studies (Basnett et al. 2013, Bajracharya et al. 2014 and Gardelle et al. 2011, Fujita and Sakai 2014). I don't think this section/study adds any new knowledge to existing understanding on the subject.

We responded to comments by Mauri Pelto who suggested a comparison with these studies, as well as a summary discussion. We considered it relevant. Left as is.

Table 8: % glacier area change from 1962 to 2000 (this study) -> sign should be negative (-13.5 ± 6.4)

Correction made.

Figure 7: % area loss from 1962-2000 (figure caption)? But 1962-2006 (y-axis label)?

Correction made, should be 2000.

Figure 9: It would be better to measure the distance/profile from terminus (0 m) to up-glaciers, to see temperatures (variation) pattern. Common/same x-axis scale should work fine. It would be nice to present surface temperature variation of clean and debris-covered glaciers so that the contrast could be seen.

This is a matter of preference, for this paper we preferred to show the distance going downglacier. It would be nice, but presenting surface temperature variation for clean glaciers is out of context here, we are only focusing on debris covered glaciers tongues in the discussion.

Figure 11: 2000 glacier outline (and legend) is not contextual here.

OK.

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, The Cryosphere Discuss.,8, 2799–2829, doi:10.5194/tcd-2799-2014, 2014.

Andermann, C., Bonnet, S. and Gloaguen, R. (2011). "Evaluation of precipitation data sets along the Himalayan front." Geochemistry, Geophysics, Geosystems **12**(7): Q07023. 10.1029/2011gc003513.

Bookhagen, B. and Burbank, D. W. (2006). "Topography, relief and TRMM-derived rainfall variations along the Himalaya." Geoph Res Lett **33**(L08405): doi::10.1029/2006gl026037.

Cgiar-Csi (2004). "Void-filled seamless SRTM data V1." International Centre for Tropical Agriculture (CIAT), available from the CGIAR-CSI SRTM 90m Database: http://srtm.csi.cgiar.org and http://www.ambiotek.com/topoview. Last accessed: 2014-04-01.

Farinotti, D., Huss, M., Bauder, A. and Funk, M. (2009). "An estimate of the glacier ice volume in the Swiss Alps." Global and Planetary Change **68**: 225 - 231.

Huss, M. and Farinotti, D. (2012). "Distributed ice thickness and volume of all glaciers around the globe." Journal of Geophysical Research **117**(F04010). DOI: 10.1029/2012JF002523.

Palazzi, E., Von Hardenberg, J. and Provenzale, A. (2013). "Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios." Journal of Geophysical Research: Atmospheres **118**(1): 85-100. 10.1029/2012jd018697.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., Hagen, J. O., Hock, R., Kaser, G., Kienholz, C., Miles, E. S., Moholdt, G., Mölg, N., Paul, F., Radić, V., Rastner, P., Raup, B. H., Rich, J., Sharp, M. J. and Randolph_Consortium (2014). "The Randolph Glacier Inventory: a globally complete inventory of glaciers." Journal of Glaciology **60**(221). doi: 10.3189/2014JoG13J176.