

**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 long-time 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  $551 \pm 34 \text{ km}^2$  (i.e. between 517–585  $\text{km}^2$ ) and in 2006 is  $537 \pm 8 \text{ km}^2$  (i.e. 529–545  $\text{km}^2$ ) 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  $\text{km}^2$ ) and in 2006 (529–545  $\text{km}^2$ ), 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.

(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, on 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 been 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.

(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.

### # 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?)

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

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.

P3951

L13-16: the sentence is not clear.

P3952

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

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.

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

L17: behavior such as?

L21-26: I wonder how this study (using 90 m × 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.

P3953

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

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

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

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

P3955

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

L5: tie points were digitized or automatically generated?

P3956

L18: ‘for the 2000 decade’ or for 2000?

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.

P3957

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

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?

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 km<sup>2</sup>?

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 ( $\pm 25$  m for the topo-derived DEMs and  $\pm 31$  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.

L7: in Sikkim (India) or in India

L25: ‘*glacier size ranged from 0.05–105 km<sup>2</sup>*’ or glaciers  $\geq 0.05$  km<sup>2</sup> were mapped or mappable?

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.

P3963

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

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.

P3964

L9/10: south-facing slopes!

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.

P3965

L21-23: maybe all glaciers experiencing elevation changes. Do not clean-type glaciers experience elevation changes?

P3966

L3-8: glacier elevation change to be  $-30.8\text{m} \pm 39\text{ m}$ : 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.

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).

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 thinner or 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.

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 m<sup>2</sup>) 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).

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 least-squared regression using all 21 debris-covered tongues showed a **weak dependency** of elevation changes on surface temperature ( $R^2 = 0.01$ ).*

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.

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.

#### Additional references

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