Review TC-2016-48

General Comments

The potential of declassified optical stereo satellite imagery for glacier change detection is undisputed. Several studies quantified glacier volume changes using declassified Corona and Hexagon data, mainly focusing on small basins or individual glaciers only. For the processing nearly all of the studies used commercial software packages. From this point of view the study of Maurer is highly welcomed as it proposed an independent workflow for DEM generation. Moreover, the study of Maurer closes a gap of knowledge in terms of region-wide glacier mass balance investigations in Bhutan using declassified imagery.

The workflow of DEM generation has already been published in the ISPRS Journal of Photogrammetry and Remote Sensing (Maurer and Rupper, 2015). This paper builds upon this previous paper and presents an application in the field of glacier volume change assessment. All in all it is a nice paper and worth of prompt publishing.

Thank you for your positive comments on the approach and results. We also appreciate your careful consideration of the manuscript and your detailed comments/criticisms. We have carefully considered your comments, and address all of them directly below.

Specific Comments

P 3, L 29. How were the blocks selected? Were they defined with respect to the glacier extent?

Blocks were selected to maximize coverage of large glaciers across the region, and avoid regions with cloud cover. We have clarified this point in the text on P3, L30.

P 4, L2. "Points located on unstable terrain were excluded" – Based on ICIMOD glacier outlines?

The ICIMOD glacier outlines were used to exclude glacier terrain during optimization. The glacier outlines were first converted to a raster binary mask at the spatial resolution of the reference DEM used during optimization (SRTM in this case). Next, dilation (a morphological operation which adds pixels to edge boundaries) was used to slightly enlarge the glacier boundaries in the raster mask, which helped to eliminate any unstable glacier pixels not quite contained by the ICIMOD outlines, as well as possibly unstable moraines.

Additionally, in the optimization routine, any elevation change pixels outside of 3 standard deviations are excluded at each iteration, which effectively eliminates other unknown sources of large error during optimization.

We have updated the text in section 2.1 on P3-4 to more precisely explain our methods.

P 4, L 21. Hexigon -> Hexagon

Thank you for correcting this typographical error.

P 4, L 29. I am not familiar with glacier elevation changes in Bhutan. Comparing with the Everest

Region 100 m seems to be suitable. However, the strong elevation change for glacier "k" and "i" might also justify a threshold of 150 or 200 m.

After checking thickness changes for the two glaciers with strongest changes (glaciers i and k), we find that for glacier i, the largest magnitude thickness change is -104 m (negative meaning the glacier has thinned), and only 24 pixels out of 6939 are more negative than -100 m (0.4%). For glacier k, the largest magnitude thickness change is -93 m, thus 0 pixels out of 57182 are more negative than -100. Given the uncertainties in the elevation change measurements, we find that the few excluded pixels in glacier i exhibiting thickness changes slightly more negative than -100 meters do not significantly affect results.

P 5, L 2. “Greatest accuracy” – What does it mean? Did you use a slope threshold to correct the outlines with regard to steep parts in the accumulation regions which have erroneously been delineated as part of the glacier? The delineation of debris-covered glacier tongues is often ambiguous. How did you cope with uncertainties in these regions (e.g. glacier “f” in Figure 3 shows a strong glacier thinning at the end of the tongue outside the glacier outline)?

At that time we inspected glacier polygon outlines from both the Randolph Glacier Inventory and ICIMOD. We found that polygons from the Randolph Glacier inventory had significant georeferencing errors in the Bhutan region, while those from ICIMOD appeared more detailed and accurate, based on visual inspection after overlying the outlines on high resolution Google Earth imagery. Recently these exact same ICIMOD outlines have been incorporated into the GLIMS database, but at that time they were not. We have updated the text on P5 L10.

As suggested, we have updated our workflow to include a slope threshold, to correct glacier areas by removing erroneously delineated parts (i.e nunataks, rock cliffs, etc.). We found that a threshold of 45 degrees was optimal, and have updated our results with this correction included. The text has also been updated on P5 L 13.

As noted in our uncertainties section, we expect relative vertical errors to occur between the Hexagon and ASTER DEMs, i.e. apparent elevation changes where no actual changes have occurred. This is due to different sensor characteristics, viewing geometries, sun position, cloud cover and atmospheric conditions, etc. between Hexagon and ASTER imagery. It is entirely possible these errors occur near a glacier toe, making it appear as though the change is part of the glacier, when in fact it is not. Further complicating this are actual non-ice elevation changes such a landslides and glacial-lake outburst floods, which can be triggered as glaciers recede and alter stress regimes along valley walls and moraine ridges, exposing unstable slopes, and reorganizing large volumes of unconsolidated sediment (e.g. Richardson, Shaun D., and John M. Reynolds. "An overview of glacial hazards in the Himalayas." Quaternary International 65 (2000): 31-47). Therefore, we base our glacier outlines primarily on the satellite imagery, with the thickness change maps as a secondary source. We also include a new supplementary figure, S6, which illustrates some unstable moraines which have since collapsed in the region, leading to non-ice elevation changes near glaciers. The associated text has been updated in the paragraph starting on P5 L16.

We agree regarding the common problem of ambiguous debris-covered glacier tongues. We have manually adjusted the ICIMOD glacier outlines to capture glacier extents to the best of our ability, however it is entirely possible (indeed likely) that some debris-covered toes are slightly inaccurate, as is the case for every previous study using remote sensing methods to study debris-covered glaciers. Unfortunately there is no easy way of eliminating ambiguity regarding the separation of inaccurate glacier outlines, DEM errors, or reorganization of unconsolidated sediment, especially regarding glacier extents during the 1970's. We now discuss this problem in the text, and suggest a possible route for future studies to better delineate debris-covered glaciers (P5 L16).

P 5, L9-11. Data gaps in the accumulation regions are characteristic for DEMs generated using optical satellite imagery. Closing these gaps is indispensable for glacier mass balance calculations. Several approaches can be found in the literature, e.g. based on TINs (Surazakov and Aizen, 2006) or using the regional mean/median for individual elevation bands. Other studies assumed no change in the accumulation regions replacing missing data values by zero (Pieczonka and Bolch, 2013). Using the regional mean the authors assume a similar behavior for all glaciers of the same type. However, this must not necessarily be true. Taking this into account the proposed method allows the calculation of regional glacier volume changes but might not be suitable to calculate glacier volume changes for individual glaciers (e.g. P 10, L 4). Can you provide a difference image after extrapolation to judge the meaningfulness of the approach? You could also add a figure showing all three stages for an example glacier (difference image before hole interpolation, after hole interpolation, after extrapolation).

We now include results using both gap-filling methods in Table S3 (regional extrapolation for individual elevation bands and assuming zero change) in order to facilitate comparison. In addition, 3 new supplementary figures are included which show each glacier at each processing stage (Fig S3-S5).

The text has been updated in the paragraph starting on P6 L3, and a brief discussion of the observed impacts of extrapolation vs. assuming zero change is included on P9 L6.

P 8, L12. The results from this study are not comparable to the results of Kääb et al. (2012) and Gardelle et al. (2013) due to different time periods. The authors should add other references when writing "is comparable to other estimates derived from remote sensing […]". Compared to the Everest Region (Bolch et al., 2011) the regional mass budget is less negative. Zemp at al. (2009) give annual mass balances based on in-situ observations on a broader scale. For Southeast Asia they found a moderate mass loss until 1995 with a subsequent acceleration since 1996, reflecting the higher mass loss found by Kääb et al. (2009) and Gardelle et al. (2012) for the last decade.

We agree that the wording of this statement is inaccurate, as different time periods prevent direct comparison. The text has been updated accordingly in section 4.1 on P8-9, and results from the other studies mentioned have been added.

P 9, L 20. What is the source for the information regarding melt ponds? Did the authors use Google Earth for a visual inspection of the glaciers?

The source of the information was imagery viewed in Google Earth (updated on P10 L10).

P 10, L 15 and L 20. In my opinion it is a decrease from -35 to -10 m in line 15 and an increase from 0 to -10 m in line 20 as the values are related to glacier thinning.

We agree the wording was confusing, and have updated to more clearly describe the profiles in section 4.3 on P11.

P 11, L 7. “Low slope and low surface velocity” – This is imprecise and some further information is needed.

The statement has been updated to provide more information on P11 L33.

P 11, L 9. “Near stagnant flow velocities” – This statement is not supported by any figure or by a reference.

The reference to (Kaab, 2005) has been added on P12 L3.

P 11, L 14. “heavy debris” and “lighter debris” – What does it mean in terms of absolute debris thickness?

We mean that certain regions appear to have more or less area covered by debris, based on visual inspection of the satellite imagery. Darker = relatively more area covered by debris, lighter = relatively more area covered by ice.

The text has been updated to more precisely define our meaning on P12 L9.

Figure 2. 8 different Hexagon DEMs are mentioned. Figure 2 shows only 3 polygons. This needs to be changed to 8 polygons to get the link between Table S1 and Figure 2.

Labels for the 8 different Hexagon DEM regions have been added to Figure 2.

Figure 3. The chosen color for the investigated glaciers is unfavorable in comparison to the bright background color. A different color for the outlines would improve the readability of the figure significantly (in particular for the glaciers “q”-“u”).

We agree, and have changed the color of investigated glacier outlines from white to blue.

Figure 3. The current visualization using a continuous color coding shows an almost perfect fit between both models but conceals uncertainties in the data. The authors should use classes instead of a continuous color coding in order to allow a better distinction between areas of higher and lower deviations from zero, in particular for the stable terrain.

We now include a version of Figure 3 with classes in the supplement (Fig S7). However, we feel that a version with continuous color coding is essential for clearly illustrating the various spatial patterns of thinning with the most detail. Thus, we have retained the continuous version, but have improved it by enhancing the contrast to better highlight the elevation differences.

Figure 3. Glacier “a” shows a strong surface lowering in the middle part of the tongue followed by sudden elevation uplift at the end of the tongue. At the same time there is a strong thinning right next to the outline not mapped as a glacier.

On close inspection, we find a lateral moraine ridge has collapsed along the west margin of the glacier tongue, which likely caused the apparent elevation change there (Fig S6).

As Fig. S6 shows, the polygon does contain ice at the end of the tongue. We hypothesize that the apparent slight elevation uplift may be due to emergent velocities associated with glacier dynamics.

Figure 3. Considering glacier "k" and "i" I would expect a surface lowering of more than 100 m. The threshold of 100 m used to exclude outliers might be too low. A value of 150 or 200 m might be more suitable, in particular for the ablation regions. Can the author provide a difference image before gap interpolation in the supplements?

See previous comment regarding P4, L 29. We also now include Figs S3-S5 to show difference images at various stages, including before and after gap interpolation.

Table S2. Area uncertainties for 1974 are missing.

The area uncertainties have been added.