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Interactive comment on "Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st century observed with ASTER satellite imagery and aerial photography" *by* M. Shahgedanova et al.

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Response to the Reviewers' Comments

We are very grateful to the Reviewers for their most helpful and constructive comments. We have addressed the suggested changes incorporating most in the revised text. Ours responses are shown below the reviewers' comments. We have made all the suggested stylistic changes.

Reviewer 1 (Professor Cogley)

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Interactive Discussion

Discussion Paper

P4161 L17-20 Perhaps it would be prudent to mention here two other strong contributors to area measurement error: sensor resolution and glacier size.

Done

P4163 L14-16 These critical remarks should probably be omitted here. That about “the use of snow-covered areas” is not mentioned in section 6, and the other two are details that are best left until later. My impression as a reader is that Holobaca’s results are “OK”, but if they are compromised by inadequate correction for seasonal snow that should be documented more thoroughly.

The critical remarks have been removed.

P4164 L16-18 Oops! The Randolph inventory simply took the Caucasus outlines from GLIMS on the assumption (evidently wrong) that they covered the region completely. This will be corrected in future versions.

We take it as a comment. We haven’t made any change to the text but we can remove reference to the Randolph Inventory if required.

L9-10 I do not know what an “interactive” ground control point is.

“Interactive” has been removed

P4166 L28 Mention the number of surging glaciers that were excluded, and possibly the criteria that were used to identify them. And if the number is significant, it would be of interest to know roughly how this paper’s area changes might have been affected by their inclusion.

We have added information on the number of glaciers with a reference to a review paper on surging glaciers in the Caucasus: “Within the study area seven glaciers have been identified as surging by Rototaeva (2006).” The excluded glaciers are small and would not significantly affect the results but they were excluded in order to comply with the standard procedures.

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P4168 Ll3 Increasing the buffer width on debris-covered parts of glacier margins is a common practice, but it may not address the real problem, which is that the debris creates a risk of gross error (mistakes many pixels wide).

We agree with this comment and can only add what is already said in the text: Most glaciers in the Caucasus, as opposing to many other regions such as Central Asia, have well-defined margins even if they are debris-covered. This does not resolve the problem of dead ice whose existence can only be assessed using radar surveys which is outside the scope of this paper.

P4168 L15 Donguz Orun: Figure 3 is a superb illustration not just of what "debris-covered glacier" means but also of where the debris might come from. A remark would be appropriate to explain that the debris derives (or is presumed to derive) from the headwall by avalanching.

We added: "One of the most heavily debris-covered glaciers in the Caucasus is Donguz-Orun where supra-glacial debris cover approximately 70% of the glacier map area as a result of avalanche nourishment supplying debris from the headwall exceeding 4400 m a.s.l. (Fig. 3)."

P4168 L18-20 For how many glaciers was the error due to debris cover calculated? Change "the overall majority of" to "most". (Here, as in most of its other occurrences in scientific writing, "overall" is meaningless.)

67 glaciers; we changed 'overall' to 'most'

Fig. 1 The Baksan, Kuban, Inguri and Kodori catchments should be delineated in Figure 1.

Done. We have added the Malka basin, which we missed, and changed the statistics of glacier distribution in Table 1 accordingly.

P4171 2 L23 I suggest "0.1–1.0" and "1.0–5.0". Everybody would know what you mean, and you would avoid awkward questions about glaciers with areas of 0.105 and 1.05

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km2.

Done

P4175 L2 Debris cover of 3–25%: this conflicts with the statement of the extent of debris on Donguz Orun Glacier on P4168.

There is no conflict; we stated that Donguz Orun is an exception and it is a glacier with the largest extent of debris cover in the region. This has been clarified in the text.

10-12 The discussion is rather hard to follow here. I suggest writing a separate sentence about the valley glaciers.

This section has been re-phrased.

P4176 L1-7 As suggested at P4163 L14-16, this discussion should be either reduced or extended. The inclusion of seasonal snow, for example, ought to be either documented with examples or dropped.

We have removed the comments.

L11 Change "on glacier tongue" to "near the glacier terminus".

Done

P4184 Table 2 The errors of the areas are not retrievable from the errors of the area changes. If finding space for them is difficult, they are probably more important than the (admittedly convenient) percentages, which could be sacrificed. The same comment applies to Table 4, where space could certainly be saved by putting a line break between "Number" and "(Fig. 4)".

We included errors on glacier change and not areas because the errors are small and will be less important for the total areas but very important for the changes which are relatively small too. We prefer to keep the tables as they are, however, if Reviewer insists, we will add errors to areas too.

P4193-4194 Tables 6, 7 The lines in these graphs ought not to be smoothed.

Corrected

Reviewer 2 (Dr Bhambri)

P 4160, L 6: Include no of sub-sample was investigated using aerial photography and ASTER.

Done

P 4160, L 8-10: Include the total area out which the loss and recession has been analyzed.

Done

P 4160, L 15: What is the possible cause of tripled rate of increase in glacier termini retreat on the southern slope? Describe in 1-2 sentences. Several studies in northern hemisphere also found (e.g. Bhambri et al. 2011) higher recession rate on southern slopes.

A brief explanation is given in the last sentence of the Abstract and is included in the Discussion. We prefer not to make comparisons with other regions where more rapid recession was observed on the southern slopes (e.g. the Himalayas as in Bhambri et al., 2011 or the Altai as in Shahgedanova et al., 2009) because although the outcome is the same, the processes are different. The only potentially valid comparison is with the European Alps because climate in both, the Alps and the Caucasus, is affected by the North Atlantic Oscillation. A general comparison with the Alps is presented in the Discussion but we stopped short of making slope-to-slope comparison because of the heterogeneity of NAO impacts and other factors which make it very hard to select comparable samples from publications.

P 4161, L 1: There are several peer-reviewed references on temperature increase. So, use peer-reviewed reference instead of website.

We have added a reference to IPCC 2013 which shows temperature anomalies (The Physical Science Basis; Chapter 2; Fig. 2.19), however, we decided to retained the web reference too because the Met Office provides most up-to-date information with anomalies for specific decades and years.

P 4162, L 14-15: ' Stokes et al. (2006) reported the average glacier termini recession rates of 8 ma−1 between 1985 and 2000.' Shift these sentences on line 7 before the 'Panov's (1993) analysis of the field measurements and data derived.....' and make change accordingly.

No change is required as we initially introduce the main studies and then present their findings in chronological order.

P 4162, L 14-15: Show on fig 1 subdivided parts of western, central and eastern sectors of greater Caucasus for the more understanding of region.

We prefer not to show this 'borders' on the Fig. 1 because this is not a formal division, just commonly accepted terminology. Instead, we have made it clearer in the section Study Area where the main points of geographical reference are located.

P 4164, L 21: Include exact number instead of 'several'.

We can't do this because it depends which exactly point in MCR you take measurements from! Figure 1 shows location of Mt. Elbrus.

P 4164, L 25-27: Not understandable. Improve the sentence.

Done

P 4165, L 15-21: Glacier outlines.......... was 0.02 km2. Shift these lines in 3.1 Satellite imagery and glacier mapping as these belong to glacier mapping.

We moved the sentence on size of smallest glacier (added on instructions from the Editor) in the section to make it more logical. We prefer to leave the explanation as to why we did not use automated techniques in at the start making our position clear and not to mix it with the detailed methodology.

Delete 'procedures'. Glacier mapping is sufficient here.

Done

I would suggest authors can merge 3.3 Assessment of changes in positions of glacier termini using aerial photographs with this section.

We prefer to keep these sections separately as different variables are measured and different types of imagery are used.

P 4165: Describe the procedure of debris-covered glaciers tongue in section 3.1 Satellite imagery and glacier mapping. P 4167: Section 3.2 quantification of errors. This section only considered error estimation for area changes and errors related with terminus changes reported in other 3.3 section. Generally, papers on glacier area and length changes (e.g. Bolch et al. 2010, Bhambri et al. 2013) included error estimation in a single section. I would suggest that authors should include error estimation of terminus and area changes in single section.

We are not sure that restructuring our text will improve the paper. Both this text and the cited papers (Bolch et al. 2010, Bhambri et al. 2013) address the same issues outlying them in different format and neither is preferable.

P 4169, L 1-3: These lines related with introduction, so shift in introduction and add length area changes are indirect response of glaciers.

Done

P 4169, L 11: Describe scale of aerial photographs if possible.

The scale of aerial photographs changes depending on the altitude of the aircraft. Instead or scale, resolution of aerial photographs is used and this is stated in the text.

P 4169, L 25: 'five measurements were taken across the length of each glacier terminus along flow lines and an average value was calculated.' cite here Koblet et al., 2010; Bhambri et al. 2012.

Done

P 4170, L 4-5: Location of meteorological stations show on fig 1.

We have chosen not to show locations of weather stations on Fig. 1 because the size of Fig.1 is quite small. One of the stations (Terskol) will be too close to Mt. Elbrus on the figure and it will look crowded. Coordinates of the stations are given in the text instead.

P 4170, L 8-10: Include period of used meteorological data.

Done.

P 4170: Section 3.4 Meteorological data. Non-parametric test performed in this study to observe the significance of climatic trends. This information should be presented in this section.

We are not certain what is required. Linear trends are calculated and their significance is assessed as well as significance between the means in Results. These techniques are hardly worth explaining in the Methods as it will only inflate the text but we can add a brief explanation if the Reviewer insists.

P 4170: 4 Results, there is confusion in structure of result section. I would suggest to change the structure of results. 4 Results, 4.1 Area change, 4.1.1 The Main Caucasus Ridge, 4.1.2 Mt. Elbrus, 4.2 Terminus retreat, 4.3 Climatic variability.

Done.

P 4170, L 20-25: Long phrase. Split it.

Done

P 4171, L 4-5: Define here glaciers of other types.

We have added reference to Table 3 which summarises area reduction of different types of glaciers.

P 4171: Section 5 Climatic variability, Include this section in results section as suggested above.

Done

P 4171: Section 5. For the interest of readers mention in this section magnitudes of the climatic trend by linear regression analysis.

We are not sure which climatic trend requires further explanation. We deliberately have not included temperature increase per year but compared averages for different time periods instead because of the clear step changes in the time series. We have added an interpretation of precipitation trend between 1951 and 2011 at Terskol: "At Terskol, a positive linear trend for the 1951-2011 period was statistically significant. It indicated a 35 mm increase in the accumulation season precipitation per decade and explained 19% of the total variance in the data set."

P 4173, L 7: 'rates of" typo error.

Corrected

P 4173, L 13: 'two periods' respectively. What periods?

The time periods are stated at the beginning of the section, 7 lines above.

P 4174: Section 6 Discussion and conclusions. Both sections are important. Arrange in two different sections. I would suggest authors should see role of elevation range, slope, aspect on glacier retreat results and discuss in discussion (e.g. Bolch et al. 2010, 2011, Bhambri et al. 2011).

We have separated Discussion and Summary.

Results are discussed in the paper for different slopes and summarised in Tables 2

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and 5. We agree that aspects and elevation are important controls. However, we have decided not to include aspect (which is not the same as slope) because (i) position on the northern or southern slope results in a more significant difference and (ii) the data set becomes very fragmented especially if we account for two other variables such as slope and type. We have not included analysis by elevation range for the same reason: it will have to be done by type, slope and also sector (Central and Western) because both ELA and glacier tongue elevations differ significantly between slopes and sectors (see text of the paper). As a result, we will not get sufficient statistics for a reliable analysis. An automated inventory using Landsat has been performed on the Caucasus resulting in a larger sample and elevation range will be considered when these data are prepared for publication.

P 4184: Table 2 Include region wise no. of glaciers with combined area in table.

These data are given in Table 1.

P 4188: Improvement is needed in Fig 1 for more understanding of region. Location of Fig 2, 3, 4 and 5 include in fig 1. Location of climatic stations also show in fig 1.

Figures 2, 4 and 5 refer to Mt. Elbrus and its location is shown on Figure 1. Donguz-Orun (Fig 3) and Terskol station is too close to Mt. Elbrus at this scale and their inclusion will make Figure 1 very crowded. We have given coordinates of these locations in the text instead.

P 4189: Fig 2, P 4190 Fig 3. Include year/date of photography.

Done.

P 4189: Fig 4 and 5, Include details/type of satellite images (date).

These are given in Table 1 but we specified the details in the figure captions too.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/8/C2231/2014/tcd-8-C2231-2014-

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Interactive Comment

supplement.pdf

Interactive comment on The Cryosphere Discuss., 8, 4159, 2014.

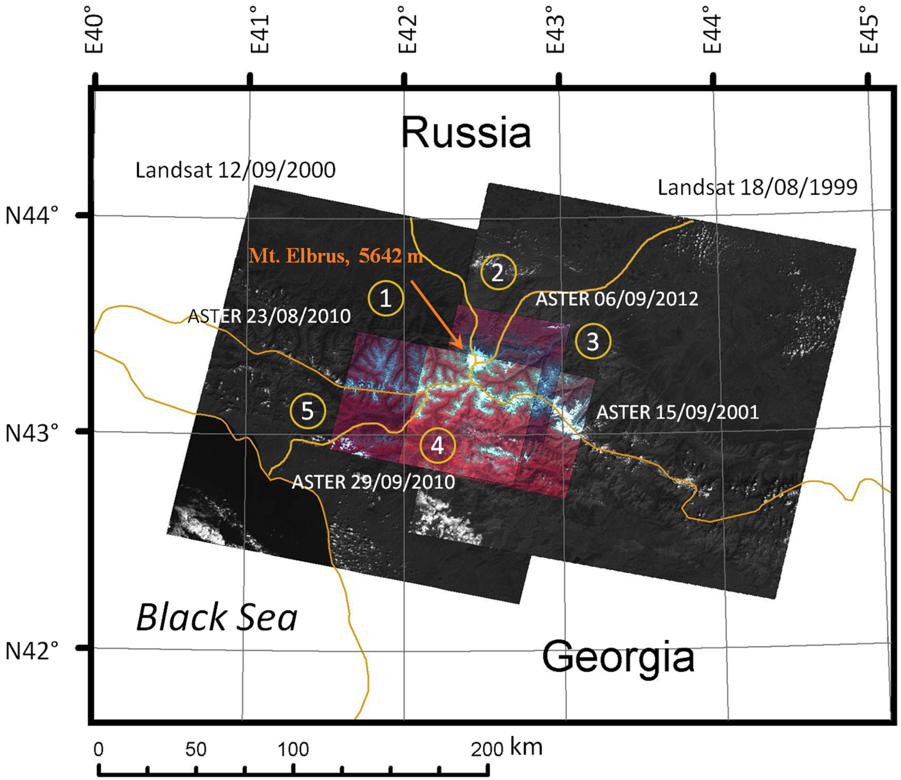

Fig. 1. Study area and satellite imagery used for the analysis. The yellow lines show the Black Sea coastline, the MCR, and the catchment boundaries. The catchments are numbered as follows: (1) Kuban; (2) Mal

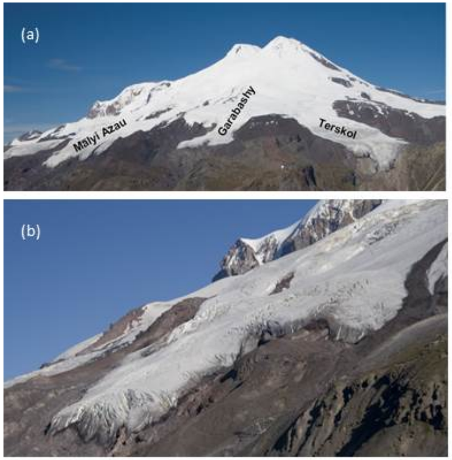

Fig. 2. Oblique aerial photograph of (a) glaciers on Mt. Elbrus and (b) snout of the Malyi Azau glacier. Note the clearly defined glacier boundaries and a very limited extent of debris cover. Photograph by I.

Fig. 3. Oblique aerial photograph of the Donguz-Orun glacier which has the highest extent of debris cover in the sample. Photograph by I.I. Lavrentiev (25 August 2009).

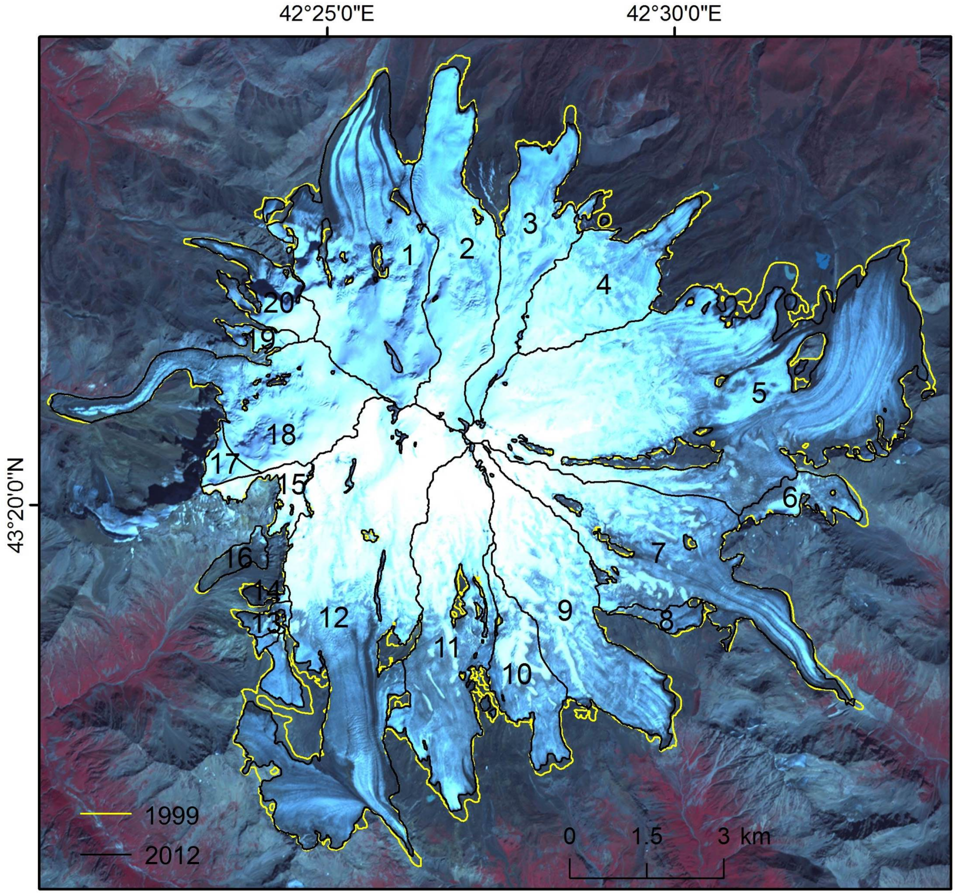

Fig. 4. Changes in glacierised area of Mt. Elbrus between 1999 and 2012. See Table 4 for the statistics of changes in areas of individual glaciers. The 1999 Landsat ETM+ image (Table 1) is used as background.

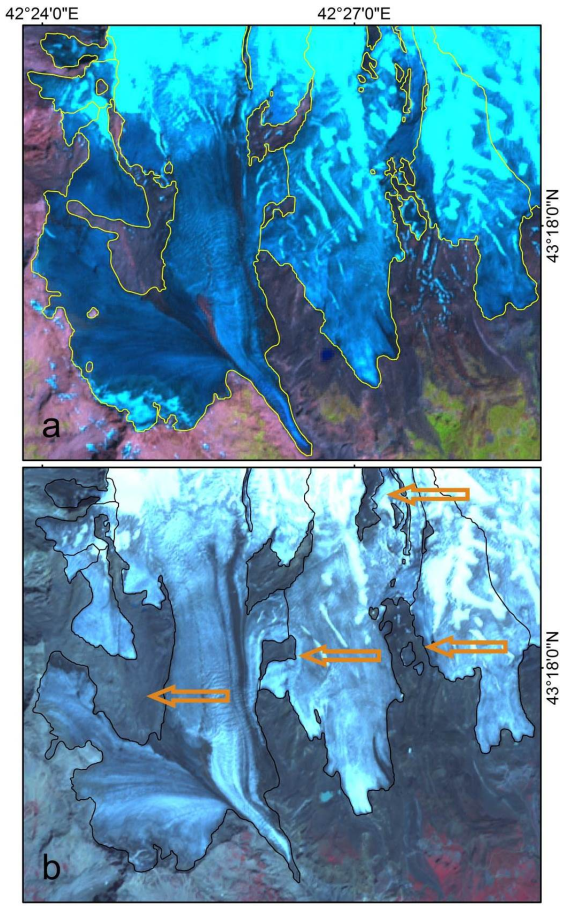

Fig. 5. Expansion of exposed rocks on the southern slope of Mt. Elbrus: (a) 1999 and (b) 2012. Arrows point at the expanded areas of exposed rocks. The 1999 Landsat ETM+ image (Table 1) is used as background.

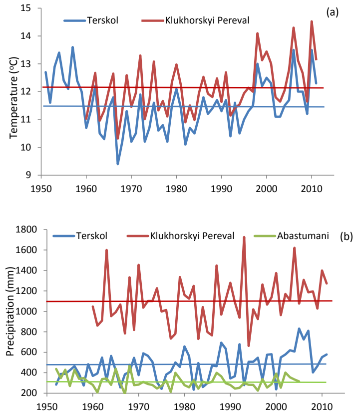

Fig. 6. (a) JJA temperature and (b) October-April precipitation for Abastumani, Klukhorskyi Pereval and Terskol stations. Horizontal lines show record averages for each station.

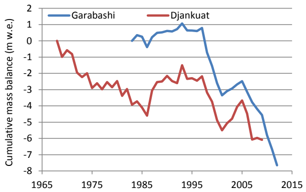

Fig. 7. Cumulative mass balance of Garabashi and Djankuat glaciers (WGMS, 2013; unpublished records from the Institute of Geography, Russian Academy of Science for Garabashi in 2012).