

Dear reviewer,

We appreciate the thorough review and we believe the manuscript will improve as a result of your suggestions. Below we have addressed all your comments point-by-point and our reply is provided in *Italics*.

With kind regards,

Walter Immerzeel

General comments

The article 'Use of an UAV to assess recent surface elevation change of Storbreen in Norway' by Immerzeel et al. describes the results of one UAV campaign and the technical aspect of DEM and orthoimage processing. The author furthermore compare the derived DEM with an independent source (LIDAR) and derive volume changes. They compare the volume changes with the glaciologically derived surface mass balance using a rough density conversion method. The Article is well written and shows the potential of high-resolution and low-cost DEMs and is methodologically sound. The climatic interpretation is largely missing and the comparison with the glaciological method is rather crude and contains a major source for misinterpretation. The value of the article is thus primarily of methodological nature and as such it deserves publication in TC after applying some major revisions. A way to improve the comparison significantly would be a point-wise assessment of glaciological balance vs geodetic balance. Furthermore, decadal mass changes of other areas/studies could be compared in more detail. There is room for shortening it significantly, both in number of figures, and by adding a table. Some English formulations may be improved.

Thank you. In the revised manuscript we will improve the climatic interpretation and we will also add a comparison with other regions where decadal mass changes based on geodetic studies are available. As for the point-wise assessment suggestion: we did initially consider this, however there were two major issues that prevented such a comparison. First many of the stakes were re-drilled over the course of 6 years and secondly, a correction is required to correct for glacier flow, which is not straightforward. Therefore we decide to constrain the comparison to the overall glaciological mass balance, in addition to the comparison with the GCPs, the GNSS profiles and the off-glacier elevation differences.

Specific comments and technical corrections

L19: 'routinely . . . monitoring' sounds weird to me. The first sentence of the abstract could be deleted without losing info.

OK

L26: remove: under the yielding conditions?

OK

L27: LIDAR-DEM?

OK

L28-29: see below, but I fear that the agreement is actually worse than that if you consider the glaciological b applied for the entire glacier vs the geodetic for 77% (i.e. the more negative part of the glacier). This likely would make the geodetic balance of the entire glacier less negative and would increase the difference of geodetic vs glaciologic more.

The reviewer is correct that the 23% of the masked area is mostly in the higher part of the glacier. However, the glaciological mass balance is based on a limited number of stakes (~6-10) in the compared period and none of them are located in the masked area. The 77% of the glacier area that is used for the geodetic mass balance contains thousands of points, so therefore we respectfully disagree that the mask we have used causes a negative bias relative to the glaciological balance. The advantage of the glaciological method is that it can cover the entire glacier. Although our survey does not cover the whole glacier, we have added text to address this problem in the discussion.

L31: Is that a strong mass loss and retreat? The retreat seems very moderate, the mass loss significant but not very strong either?

The mass loss is strong compared to the mean of the whole period, the retreat is comparable to average retreat. This part will be reformulated accordingly.

L34: are glaciers characterized. . .? Reformulate?

OK. Changed to facing

L37: what is meant by 'likely play a major role'?

This will be reformulated to be a major cause

L34-41: condense to 1 sentence?

This paragraph will be reformulated.

L74: supraglacial?

OK

L79: why 'largely'?

Largely will be removed

L86: typo: monitor

OK

L93: . . .of UAVs for mass balance monitoring

OK

L96-99 can this be combined to one sentence? Section 3.1.: could the info be included/condensed into Tab1, i.e. include LIDAR survey date, resolution, point density, GCPs, etc? Then the text could be reduced significantly.

We will combine it in one sentence. However, we propose to keep table 1 as it is, as this really summarizes our observations and the LIDAR description now only covers a few lines, which given the relatively limited length of the paper is acceptable.

L142: Why haven't the corners of the bag been measured? I guess it is too late but this could maybe yielded to a higher precision?

This is indeed too late, but we measure the center of the bags because they need to be identified on the imagery during the processing. A bag is just a few pixels on the imagery, so using a single point in the center provides the best accuracy.

L156: The title is misleading as it does not include meteorological surveys here, right? I guess snow is in this case part of the glaciological survey. Later you use some AWS data. It may be worthwhile presenting it here.

We use meteorological data from Sognefjellshytta and Bøverdalen, which are standard stations, and are used to confirm the snow depth estimate in 2009.. We added a sentence at the end in this section: To check for snow depths on the time of laser scanning in 2009, we used data from two nearby weather stations of the network of The Norwegian Meteorological Institute. The data were downloaded from the service seNorge.no.

L162: is that justified? When I look at Fig 2 and Fig 7 I am not sure if the strong gradient just below the center of the fig is not an artefact simply because of the one point that lies in ca 1650 at the Eastern lobe (2B)

We believe it is correct. The strong gradient in snow depth coincides with a steep drop in elevation (see Figure 3B). The western large plateau is about 200 meters higher than the lower eastern tongue. We also observed this snow depth pattern in the field.

Section 3.3.: I am not sure if I understand method (1): if used as GCPs in the DEM Generation shouldn't it then be 100% the same as the DEM/orthophoto is fitted through them? And as for (2) how do you account for antenna height over surface? I guess when moving this can vary quite a bit, say ± 0.3 m?

The fit between GCPs and the generated DEM do not have to be match 100% because the Agisoft algorithm optimizes the point cloud orientation based on all GCPs . Therefore the comparison with the GCPs says something about the accuracy of the SfM optimization. The comparison with the GNSS track in the snow is independent as these points are not used in the processing and this provides information about the spatial accuracy. We outline this in lines 188-190. The antenna is indeed moving and this causes an extra error and we acknowledge this in lines 273-276. We added (± 0.2 m).

L195: what do you mean by trail here? The tracks in the snow? Specify.

Yes, tracks in the snow. We have rephrased this to 'tracks in the snow'.

L225: Typo: upper part

Corrected uppers->upper.

L230: postprocessed?

OK

L234: why 2m grid?

The differences are computed directly on the pointcloud using the M3C2 algorithm. This may cause some local noise. By re-gridding the difference point cloud to a 2 meter resolution this is largely resolved. We will update the manuscript accordingly to explain this: 'To reduce undesirable local noise effects the determined differences were gridded to a 2 m grid for further analysis.'

L238: Why does Fig7 appear here? Be consistent in Figure labelling, f. ex. Compare L239 with L250

This cross reference to Figure 7 will be removed and we have checked the consistency of the labelling.

L241: was corrected

OK

L242: I would add the methodological part of the density conversion here.

OK, this will be moved here.

L250: a.s.l.

OK

L251: really ablation measurements? Or at the time of the summer balance survey?

This will be rephrased to "at the time of the summer mass balance surveys"

L264+: here starts again a methodology section that fits better to 3.3. The paper would benefit if the methodology part would be combined and shortened and the climatic interpretation (incl climate data, weather patterns, reanalysis data, etc.)

The methods part the accuracy assessment is described in 3.3. Here we briefly summarize the four steps of the assessment and then we discuss the results. Since the paper is largely methodological we propose to keep it as is.

L267: reference to Fig. inconsistent, see above.

We will systematically use Figure.

L271: see previous comment of section 3.3.

See our earlier response.

L280: using the GNSS between XX and XXX?

OK

L282-283, I am surprised, that the RMSE is that much higher here than for the GCPs. Any idea?

Yes, the comparison with the GCPs does say something only about the processing accuracy, whereas the stake comparison and the comparison with snow tracks indicate the spatial accuracy. The snow track comparison results in a RMSE of 0.41 mete (excluding one outlier)r, whereas the stake comparison results in an RMSE of 0.44 meter and these are very comparable values.

L295: Delete sentence starting with However, . . .?

OK

L298: automated weather station?; m a.s.l.

OK

L299: negative temperatures?

OK

L300: confusing with varying units. mm w.e.?

OK

L311: are varied

*We keep 'is varied' as it is The number (**singular**) of markers that **is** varied*

L312: 'impact' instead of bearing?

OK

L318: glacier

OK

L319: even though there are only half as many markers?

OK, this has been reformulated.

L324: lowered over the entire area surveyed with more thinning near the snout. – and remove the next sentence?

OK

L325: reference to fig 7 here?

OK

L325-326: overuse of word 'lower'

This will be rephrased

L333: was used

OK

L336: consider removing one sign digit

OK

L336- 349: should appear in methods.

We propose to keep it as it is, as it is directly linked to the interpretation of the results.

L339: (e.g., Zemp et al. 2016)

OK

L350-351: out of place, remove?

This will be rephrased.

L357-368: This part is problematic as stated above and I recommend a stake-by-stake intercomparison. Then of course you open up for new issues, such as emergence velocity. If it is left as it is, the statement that they fit together reasonably (abstract L28) has to be weakened.

See our earlier response on stake-by-stake comparison which is problematic due to emergence velocity and redrilling of stakes. Line 359-368 comment on length change and terminus retreat . We do believe that the geodetic and glaciological mass balance are in agreement and within each other's error margins. We will rephrase it in the abstract and remove the word good, but stick to agreement only.

L359: reveals

OK

L360: terminus

OK

L362: consistent significant digits.

OK

L367: The area change does not appear very high; suggest adding a literature review of recent mountain glacier change and put into context Reference to Fig 8?

This will be added.

L399: seems to provide or better: provides

OK

L406: OBIA? Explain abbreviation

OK

L408-409: Appears without being mentioned before.

This was mentioned on line 222-224 and is a result we think could be kept also in the conclusion.

Figures:

Figure 1: should be removed. The only extra info is the map of Norway. That fits into 2B

OK

Figure 2A: Add coordinate grid Figure 2B, 3A: scale bar: remove comma in 1,000

OK

Figure 3A and 3B could be merged by adding contour lines to A. I don't get much more info from 3B. m a.s.l. Remove resolution from caption. This appears in text and can not be seen in image anyway.

OK

Figure 4 caption: (a,b) or A,B? I don't understand why c does not use the same points as D, i.e. $n=150$?

OK. We will use capitals consistently. The number of points used to assess the horizontal error is less because we have used only those points when the snow tracks were clearly identifiable. We will add this to the text.

Figure 7: Adjust scale: i.e. -15 until -3 or so. See comment about kriging. Add snow measurements from 2B in this figure?

OK