Reply to comments by Anonymous Referee #3:

1) The study is solid overall. Most comments are minor and given below in the "Specific comments" section. The accuracy assessment has the most room for improvement, although it is extensive already. At this point, it calculates the DEM uncertainties in two different ways, by using the DEM accuracies provided by swisstopo, and by conducting an independent DEM comparison over unglacierized terrain. While this is good, the study applies two extreme approaches for determining uncertainties (resulting in 'nominal' and a 'stochastic' uncertainty, assuming either fully correlated or completely uncorrelated errors). The study does not apply a third approach, which quantifies spatial correlation in the difference grid through variograms. This approach has been used in recent work and should be implemented here as well. See Truessel and others (2013, J.Glac, 59 , p.153) and references therein (Motyka and others, 2010, Rolstad and others, 2009) for more information.

Chapter 4 (accuracy assessment and validation) will be changed and extended as we will reassess the uncertainties of our methods and results according to all reviewers comments on these issues, including a re-evaluation of the question whether errors of the DEMs used are spatially correlated or not. We will try to apply the approach by Rolstad et al. 2009 and applications thereof (e.g. Motyka et al. 2010) to our study.

P 4584: 'within only some few' –> in only a few

According to the comments of reviewer #1 on P 4584, Lns 16-17, we rewrote the corresponding text passage. Now, the sentence containing "within only some few" is omitted.

P 4585, Line 15: Figure 6 indicates that there is some glacierized area below 2000 m asl. What DEM is used there, which technique, and which date?

Below 2000 m a.s.l., it is also a 2 m DEM but of even higher accuracy because it was created with airborne laserscanning (ALS). We complemented this accordingly but do not give too much detail/answer all the questions of reviewer #3 here because it only concerns a minor fraction of the glacierized surfaces analyzed in our study. We further refer to the product information of the swissALTI^{3D}, where detailed descriptions of the whole data set can be read.

"For areas below 2000 m a.s.l., the swissALTI3D DEMs are of even higher vertical accuracy (±0.5 m 1σ) since they were created based on airborne laser scanning data (swisstopo, 2013)."

P 4585, Line 22: Mention why: Because the errors are not systematic, they get reduced when averaging over an entire glacier. This finding should be considered in your error assessment.

These comments of reviewer #3 will be implemented accordingly.

P 4586, Line 1: There is some DEM data from the 60s. A 1960 DEM in conjunction with the smaller 1970 mask will underestimate the volume loss. Or were areas and mass balances stable between the 1960s and 1970s?

Yes, for very few and mostly very small glaciers the combination of a 1960s DHM25 Level 1 DEM with the 1973 outlines might actually underestimate the volume loss. For these glaciers, however, this underestimation is most likely smaller than the uncertainty of the volume change itself. Actually, the mass budget of glaciers in the entire European Alps were close to balanced conditions between 1960 and the mid-1980s, and area changes during this period were only minor, in particular for small glaciers (Huss, 2012, TC). We extended the corresponding text passage accordingly.

"The considerable time difference between the acquisition of the SGI1973 source data and individual DHM25 Level 1 DEMs used for t_1 (Fig. 1) is acceptable as only small area changes and an almost balanced mass budget of glaciers were reported for the European Alps between 1960 and the mid-1980s (Glaciological Reports, 1960-2013; Paul et al., 2004; Huss, 2012).

P 4586, Line 20: 'Due to' –> Thanks to

According to the comments of reviewer #2 on P 4586, Ln 20, we rewrote the corresponding sentence. Now, "due to" is omitted.

P 4587, Line 18: 850 +-60: add something like "according to Huss (2013)"

Implemented, also according to the comments of reviewer #1 on P 4587, Ln 18.

"…is set as a constant of 850±60 kg m^{-3} (Huss, 2013), which is consistent with…"

P 4588, Lines 1-11: Add a sentence of justification for this approach. Why is this approach valid? –> If the mountain range balance has a positive anomaly, then glacier A is also likely to have a positive anomaly. In general, this paragraph reads less well than other parts of the paper. Rephrase/add information so that the reader grasps the idea more quickly. Possibly add another equation: B_norm = sum B_i,g from i = 1980 to 2010 divided by 30.

Please refer to our answer on reviewer #2s comments to P 4588, Ln 5. We reworded and changed the corresponding text passage in order to be clearer.

"The deviation of the glacier-individual average mass balance $\dot{B}_g$ (dashed grey line in Fig. 3) from the mountain range mean (black line in Fig. 3) over the respective observation period overline_B_{t2}– B_{t1} is used as a scaling factor to account for glacier-wide mass balance variability (Kuhn et al., 1985). The mean mountain-range mass balance from Huss (2012) for an individual year i, $B_{i,\mathrm{mr}}$, accounts for temporal mass balance variability. The annual mass balance $B_{i,g}$ for year i and any glacier g is thus calculated with:

Equation (3)

Because 2010 is the reference year t_2 for most of the investigated glacier entities and the mean observation period is ≈30 years (Fig. 1), the hydrological years 1980/81–2009/10 are defined as the reference observation period over the entire Swiss Alps over which annual mass balances for individual glaciers $B_{i,g}$ are cumulated (grey line in Fig. 3). By this means, mass changes are temporally homogenized, can be compared and further analyzed."

P 4588, Line 20: simplify to 'which can explain this variability to a certain extent.'

Done.

"Different factors have been identified which can explain this variability to a certain extent."

P 4589: Equation 4: Add reference. For example (Etzelmueller, 2000: "On the quantification of surface changes using grid-based Digital Elevation Models"). What does it stand for? –> Standard propagation of random errors What does it yield? –> The combined per pixel uncertainty. Note that there are other (better) ways to obtain delta sigma z, using variograms (e.g., applied in Motyka and others, 2010).

According to comments of all reviewers, these issues will be implemented as the accuracy and uncertainty assessment will be re-evaluated.

P 4589, Line 24: What do the vertical accuracies provided by swisstopo (2000) stand for? (one sigma?)

Following also to the comments of reviewer #2 on P4589, L19, we added information on what reviewer #3 is referring to here. From section 2.2 it should now be more clear that σ_{DEM1} and σ_{DEM2} refer to the average error (except for areas below 2000 m a.s.l. of the swissALTI^{3D} DEMs). This is all we get from the product informations of the DHM25 Level 1 and the swissALTI^{3D} DEMs (swisstopo, 2000; swisstopo, 2013).

P 4590, Line 7: "multiplying with the initial glacier area". A simple multiplication would mean that the per pixel uncertainties are correlated across the glacier area, which is probably not the case given your statement on p. 4585, Line 22 (i.e., your error bounds would be too high). On the other hand, treating the per pixel uncertainties as random would yield errors that are probably too low (as shown in your Eq. 8). The recommended intermediate approach would be that applied by Motyka and others (2010).

Chapter 4 (accuracy assessment and validation) will be changed and extended as we will reassess the uncertainties of our methods and results according to all reviewers comments on these issues, including a re-evaluation of the question whether errors of the DEMs used are spatially correlated or not. We will try to apply the approach by Rolstad et al. 2009 and applications thereof (e.g. Motyka et al. 2010) to our study.

P 4590: Equation 5: How do you justify that the sigmas are not just summed up? Assuming that the measurements of individual glaciers are uncorrelated? Add a reference if this equation was used in previous work.

Together with changes to the whole chapter 4 according to all reviewers comments , we will reassess if it's correct to calculate the uncertainty of the total volume change in this way or not.

*P 4590: Equation 6: May be more readable if you combine factors 1 and 2 as well as 3 and 4 into (F1*F2)^2 + (F3*F4) ^2*

Implemented as suggested.

P 4590, Line 16: make clear that the uncertainty comes from Huss (2013).

Implemented accordingly (similar to reviewer #3s comments on P 4587, Ln 18).

"…with a mean density of volume change $f_{\Delta V}$ = 850 kg m^{-3} and a corresponding uncertainty $\sigma_{f\Delta V}$ = ±60 kg m^{-3} (Huss, 2013)."

P 4591: Equation 7: Again, clearly justify why the numerator is not just summed up.

Together with changes to the whole chapter 4 according to all reviewers comments, we will reassess if it's correct or not to calculate the uncertainty of the mean average mass balance for all glaciers in the Swiss Alps over our reference period as we.

P 4591, Line 9: "over stable terrain" How much terrain did you consider (how many km2, is the area evenly distributed among the aspect categories? Etc.).

We considered about twice the total area glacierized at t_1 for DEM comparison over stable terrain. Because we analyze DEM differences within a mask around glacier entities, we know that different aspect categories are representatively distributed. This should be evident from Fig. 4. We extended the corresponding text passage as follows:

"The spatial distribution of surface elevation changes outside the glaciers is calculated within a mask around every entity (Fig. 4) and over about twice the area glacierized at t_1."

P 4591, Line 11: Show the corresponding distribution in addition to Figure 4. Examples are given in Larsen and others (2007) and Truessel and others (2013). Also, state that you did not correct for this systematic shift.

These comments are now implemented accordingly.

P 4591, Line 15: ". . .literature-based uncertainty estimates." I assume you mean the values assigned by swisstopo (2000). If so, state this.

Done.

"…with literature-based uncertainty estimates (Rickenbacher, 1999; swisstopo, 2000)."

P 4591: Equation 8: You calculate the stochastic uncertainty without explaining your motivation for doing so. Also you don't discuss why you refrain from using the stochastic uncertainty for your final error estimates. In fact, the stochastic error is likely too low, because the elevation changes of individual pixels are correlated to some extent. Again, the approach applied in Truessel (2013) and Motyka (2010) would yield error estimates that lie somewhere between the two extreme cases calculated in your work.

The whole chapter 4 (accuracy assessment and validation) will be changed and extended as we will reassess the uncertainties of our methods and results according to

all reviewers comments on these issues, including a re-evaluation of the question whether errors of the DEMs used are spatially correlated or not. We will try to apply the approach by Rolstad et al. 2009 and applications thereof (e.g. Motyka et al. 2010) to our study.

P 4591, Line 23: Discuss reasons for this increase with elevation. I would have assumed that this is due to the more rugged terrain (i.e., steeper slopes), but you rule that out in the next sentence. Other reasons?

Implemented as suggested.

P 4592, Line 8: Elaborate on the Nuth and Kaeaeb approach: Did the approach suggest any shift, etc.

We calculated the influence of co-registration according to Nuth and Kääb (2011) for the 45 largest glaciers. Because the co-registration of the source DEMs prior to the DEM differencing had only a negligible influence on resulting mass changes (changes inferior to uncertainty of the mass changes), we did not co-register the source DEMs prior to DEM differencing. We reformulated the corresponding text passage (also according to the comments of reviewer #1 on P 4592, Lns 8ff) in order to be clearer.

"We assume this shift to originate from the creation of the DHM25 Level 1 source data and therefore calculate the influence of its correction via co-registration according to Nuth and Kääb (2011) for the 45 largest glaciers spread over the entire Swiss Alps and covering 650 km^2 at t_1. Because the effect of this correction on the average mass balance of individual glaciers turns out to be in the order of $\pm 10^{-4}$ to 10^{-2} m w.e. yr^{-1} and is always smaller than the uncertainty in the derived average mass balance from 1980 to 2010, i.e. smaller than ± 0.03 m w.e. yr^{-1}, we consider the effect of the detected DEM shifts on calculated surface elevation, volume and mass changes as negligible and therefore do not co-register the source DEMs priorto DEM differencing."

P 4592, Line 20: 'considerably' rather than 'significantly'

Changed accordingly.

"For individual glaciers, mean mass balance from Huss et al. (2010a,b) partly differs considerably from our results…"

P 4592, Line 22: It would help if error bars were integrated into Fig. 5. This would indicate how reasonable your error estimates are.

Now error bars are included in Fig. 5.

P 4592, Line 26: 'same order of magnitude'. Is this something you assume based on Figure 5? If so, you should add a 'likely'. Or do you have additional analyses that would support this statement?

Yes, indeed, we assume this based on Figure 5. Now, a "likely" is added.

"…the accuracy of the average geodetic mass balance is likely in the same order of magnitude as if derived with…"

P 4592, Line 27: Delete 'for instance, by photogrammetric techniques.'

We prefer not to do so because otherwise it makes no sense to write '…is likely in the same order of magnitude…' before. We wrote '…for instance, by photogrammetric techniques…' because we validate our results with data derived from differencing of photogrammetrical DEMs (see also Fig. 5).

P 4593, Line 8: 'whereof' –> of which

Done.

"…for the measured period, of which glaciers still present in 2010 account for…"

P 4593, Line 11: 'lowermost elevations'. Maybe mention that you have this typical 'knee' in the curve, with max. elevation changes above the lowermost elevation, due to the glacier retreat.

We extended the corresponding text passage as follows:

"Corresponding average elevation changes were in good agreement with theoretical considerations by Schwitter and Raymond (1993) and continuously decreased from largest changes nearly at lowermost elevations (terminus of valley glaciers) towards zero in the accumulation area."

P 4593, Line 16: "state of disequilibrium". Elaborate a little more on this. What are the reasons for the elevation changes above 3500 m asl (Surface mass balance? influence of flow dynamics?)

We rewrote the corresponding sentence as follows:

"The observed thinning at high altitudes and over the accumulation areas of glaciers results from a combination of ice flow dynamics and reduced accumulation and emphasizes the current state of disequilibrium of glaciers in the Swiss Alps."

P 4594, Line 24: 'is a good example to explain'–> 'illustrates the influence of '

Implemented accordingly.

"…a medium-sized valley glacier, illustrates the probable influence of both glacier hypsometry and…"

P 4595, Line 8: What does significant mean here? Did you test for significance or does it stand rather for 'considerable'? In general, make sure to calculate significance levels and be careful with interpreting non-significant relationships.

Here, "significant" refers to the significance level of the correlations mentioned (and shown in Fig. 10). To clarify this (also according to reviewer #1), we computed p

values for all correlations and added them to Figure 10.

P 4595, Line 9: Elaborate how you obtained the correlations for the aspects. Did you fit a straight line into the points, previously sorted by eight aspect bins? Or did you actually use the sine and cosine components as done in previous work (Evans and Cox, 2005)?

We actually rearraged the initially eight classes of dominant aspect (N, NE, E, SE, S, SW, W, NW) into five new classes of equivalent potential clear sky radiation (N, NW/NE, W/E, SW/SE, S) prior to the correlation analysis. We extended the corresponding text passage in section 3.2 (methods chapter):

"…For mean aspect, the initially eight classes were rearranged into five classes of equivalent potential clear sky radiation (N, NW/NE, W/E, SW/SE, S) prior to the correlation analysis."

P 4595, Line 10: 'a good one' –> the strongest one. An r = 0.42 indicates that about 18% of the variability can be explained with the slope variable. Also, state why you used the slope of the lowermost 25%? Huss (2012) used the slope of the lowermost 10%.

Implemented accordingly, also reffering to comments of reviewer #2 on P 4595, Ln 10.

"A weak correlation (r=0.22) was found for median elevation (Fig. 10b), and a stronger one (r=0.42) for mean slope over the lowermost 25% of the glacier (Fig. 10c).

We tested different values for which we found the highest correlation for slope over the lowermost 25% of the surface at t_1. 50% would correspond to the whole ablation area at t_1, i.e. to far more than the glacier terminus, if we consider the midpoint elevation of a glacier to be a proxy for the climatic equilibrium line altitude (ELA). In regard to the fact that small glaciers with rather low elevation ranges dominate the sample of glaciers in the Swiss Alps, it is reasonable to assume that the elevation range over the glacier terminus corresponds to more than only the lowermost 10% of the surface at t_1. These rather qualitative arguments provide further support for 25% as a reasonable value. In consequence, we rewrote and extended the 2nd paragraph of section 3.2. as follows:

"In order to identify the controlling factors and to better understand the spatial variability of the observed surface elevation ans mass changes, a correlation analysis between the average mass balance over the reference period 1980–2010 and classes of mean area 1973–2010, median elevation, surface slope of the glacier terminus, and dominant aspect, hereafter referred to as mean aspect, was performed. Huss (2012) showed that these four geometrical indices can explain some of the variability of observed long-term mass balances. For the surface slope of the glacier terminus, the testing of different values indicated that taking the average surface slope over the lowermost 25% of the glacier at t_1 resulted in the highest correlation."

P 4595, Line 13: '5-% quantiles'. Explain how you obtained them (I assume sorted by the respective variable and then filled into the 5% bins by number).

Text passage now rewritten accordingly, also reffering to comments of reviewer #2 on P 4595, Ln 13.

"Because part of the significant scatter in Figure 10a-c is likely caused by glacier-individual uncertainties and local effects, we also calculated the respective mean values for 5%-quantiles of the data (triangles in Fig. 10a-c) by computing the mass balance average for 20 classes of equal sample size.

P 4595, Line 15: Did you conduct a correlation analysis for those binned values? Are the fits significant? What are the corresponding correlation coefficients?

Correlation coefficients for 5% quantile mean values and corresponding p values of are now included in Figure 10 (also according to reviewer #2s comments on P 4595, Lns 11-15).

P 4595, Line 17: 'longer response times' implying that they are 'more out of equilibrium' or 'lag behind the climatic forcing '. State that here.

Also due to our implementations of reviewer #1s comments on P 4595, Lns 15-16, we deleted the sentence reviewer #3 is referring to here.

P 4596, Line 17: 'the same methods as ' –> our method for

Reworded accordingly.

"Applying our method for temporal homogenization of mass changes…"

P 4596, Line 18: '-0.65' add error

Referring also to our answer to a similar comment of reviewer #1, we did not report error bounds for two reported values because they were not directly derived from the DEM differencing but from our time series of annual mass balance (see section 3.1, temporal homogenization via mountain-range mass balance data) in order to compare to reported values of other studies over the same time intervals. These values have an additional uncertainty component resulting from the temporal homogenization which we can not determine.

P 4596, Line 23: '-0.39' add error

See our answer above.

P 4597, Line 5: Combine the two paragraphs.

Done.

P 4597, Line 7: significantly –> considerably

Changed accordingly.

"Over glacierized areas in Switzerland, however, it is probably considerably higher (Paul, 2008)."

P 4598, Line 6: What percentage is due to outline quality and what percentage due to DEM quality?

Unfortunately we do not know this. Neither can we give reasonable estimates here.

Figure 3. add t_1 and t_2 to the plot replace "measured period" with "observation period", "measured" with "observed"

Implemented as suggested.

Figure 4. Discussed above. Add an additional figure with error distribution. Is there a small polygon in Griesgletscher that should not be in there? (the one intersecting the 2700 m contour)?

Figure 4 is now corrected and extended according to the comments of reviewer #3.

Figure 4. The slopes to the NW of Griesgletscher appear to have a systematic shift while the slopes to the SE do not (admitting that the slopes in the SE sections are flatter, implying that the same shift may show up as smaller elevation difference). Nevertheless, this begs the question whether the shifts are systematic over large areas or systematic only on a "local scale". The latter case would not be corrected with the approach of Nuth and Kaeaeb, I think (in general, such errors would be difficult to correct properly). Also, Fig. 4 indicates that an additional buffer around the 1970 outlines would have been appropriate, as the terrain is particularly unstable in recently deglacierized areas.

These points are now briefly addressed in the text.

Figure 5. Discussed above. Add bars with uncertainties.

Now error bars are added to Figure 5.

Figure 7. No need to show all of Switzerland. Crop the left side and the top and so that you can show the glacierized areas larger.

Changed accordingly.

Figures 8. and 9. Is there a way to add uncertainties for each or selected glacier(s), which would allow the reader to better interpret the results?

Adding uncertainties to all glaciers shown in Figures 8 and 9 will not be possible as it would hamper the visibility. In general, uncertainties decrease with increasing glacier size. We will try to implement this either in Figures 8 and 9, in the text or with a new table. – Otherwise uncertainties in average mass balances of all glaciers will be visible

and accessible to anyone as we plan to publish the entire dataset via the WGMS webpage after final publication of the paper.

Figure 10. Hard to read as is. Increase thickness of box plots, increase point size. d) Does a linear correlation coefficient make sense for aspect categories? What do the whiskers stand for? 1.5 IQR?

We implemented the suggestions by reviewer #3 accordingly. A linear correlation does indeed not make much sense for aspect categories, but for classes of equivalent potential clear sky radiation as for what we computed it for Figure 10d does.