We thank Frank Paul for his extensive and thorough review, which will definitely help us to improve and focus the contents of the paper.

The main suggestions of Frank Paul, to skip the climate part and add some more explanations and illustration of the data, are in line with the suggestions of the two other reviewers. We will follow this recommendation, including a more detailed description of the analysis, and add illustrations which are in the cited literature in the current version.

We apologize for not having been aware that the GLIMS outlines also describe a backwards evolution of 'parent' to 'grandparent' IDs, as we did not find the explicit description for that in the literature. We will do our best to try to find out more details, and also the recommendations for describing areas for more than one generation of parents and childs. We also apologize for not delivering relative area changes in all places. We thought the derivation of relative changes in relation to LIA or one of the inventories would be self-evident from Table 2, page 5218, and relative changes are given in the last line of Table 3 for the total data set (as well as in the text).

It was not our intention to downplay shortcomings of the data or avoid any discussion, and we will do our best to help the reader make up their mind by illustrating the data set in additional Figures. The mapping of snow fields attached to the glacier area is mentioned on page 5201 in an extra section, as we agree with Frank Paul that this is an important point. We can add an estimate of the total effect of seasonal snow for GI I and GI II.

We are grateful to Frank Paul for making these general points in numerous specific comments. We are confident that we will end up with a detailed and balanced description of our work.

(1) I suggest removing the climate data sections (2.4, 3.4, 4.3). As far as I can see, they have not really been used to explain any of the observations and a study showing that there is a relation between changes in temperature and/or precipitation and area changes is yet missing (what about response times?). Demonstrating that glaciers are shrinking because temperature is rising is not required here.

> We will follow the recommendation to skip the climate section, as the facts described in the submitted version are generally well known, and a more specific treatment would take up much more space, which is more usefully spent on a more detailed description of method and data (as suggested by the reviewers).

(2) Please show the datasets and the result of the digitizing work for at least a few examples (LIA, GI I, GI II, GI III). This should also demonstrate how disintegration looks like (it is in the title!) using overlay of outlines and how seasonal / perennial snow fields have been interpreted and distinguished in the various data sources.

> (1) We can provide data sets and results (including perennial snow patches attached to the glacier) as well as disintegration.

Please go for a more systematic and scientifically sound presentation and analysis of the observed area changes. It currently reads like a random collection of numbers without a clear message. Please also compare only relative area changes and add some analyses to the numbers (e.g. change rates vs original glacier size, slope, aspect or median elevation).

> (2) Thank you for these valuable suggestions. At the moment, we find it difficult to define the original glacier size (i.e. LIA/LGM/? glacier size?) and the relevant slope, aspects and elevations. But we will think about that and eventually come up with some

examples of our concerns about the definition (e.g. loss of flat tongues or loss of firn areas with a certain aspect), if we do not succeed in finding that in the GLIMS outlines. We agree to present relative changes in every place, but would still like to present absolute numbers also.

(4) Please discuss the problems of using two datasets as a reference (GI II and GI III) for change assessment when they cover a 7-year time-period and mean annual area change rates are -1.2% per year. In some regions there are only 2 years between the inventories and the homogenization procedure might result in rather high uncertainties.

That was in fact the reason for not extrapolating the whole data set to one date per inventory. In this respect, the LIA inventory refers to a timeframe of several decades. We can discuss that more explicitly.

(5) Please check how the concept of parent IDs is set up in the GLIMS database and how previous studies have performed area change assessment in case of disappearing and disintegrating glaciers. There is actually quite a lot around that can also be applied here.

We will do our best to find best practice examples for that.

(6) Please take more care for the quality of all figures (and extend their number to better illustrate the results).

We can do that.

Specific comments:

P5196

L5 / 9: suggest using other abbreviations for the four inventories (and also to include the one from LIA), as the 'I' in GI and the numbers I, II, III are too similar and with too little relation to the specific year. Maybe use AGI-1850, AGI-1969, AGI-1998 and AGI-2009 instead? I would also recommend introducing the abbreviations in the introduction rather than in the abstract and use in the abstract only the years.

We decided to use the numbers as we think that the reference to single years is misleading, as the LIA inventory contains LIA maxima that were reached in different decades and all but the GI I data have been acquired during more than one year. A name convention as 'AGI $_{1996-2002}$' would be quite long, and is not really straightforward for LIA. As a compromise, we suggest replacing the Roman numbers by Arabic ones, so that readers of previous papers are not confused by a sudden renaming.

L8: Have orthophotos not been used to identify anything?

It is correct that here the few glaciers mapped with orthophotos should also be named.

L10: Please check the 11% annual loss (e.g. the maximum is 7.8% on P5205, L6). These values are incredibly high and point to seasonal snow that has been mapped in AGI 1998.

We will check the number and consider this example for an illustration.

This sentence says that nearly half of Austria's glaciers in GI III are smaller than 0.1 km². Here we can also add the number of glaciers that have decreased below the size limit of 0.01 km², and the size of their total area.

Yes, this actually was the intention to write the next sentence, line 16 to 19. We can also switch the two sentences, starting with globally and coming down to the regional effects, which have in fact triggered the first glaciological investigations in Austria, so that we followed a time line in our arguments here.

We can replace balances by budgets without losing any information.

We will add the terms 'hypsography' and 'ice thickness distribution' to the list in this sentence.

We will gladly do that, the paper was not available when we compiled ours.

Yes, that is correct. Sorry, that maybe happened during spell check.

We can add that point here. In the current version, this is partly addressed in page 5196, line 25,26.

We can specify length changes, mass budget data, and ice thickness data here.

We can shift that paper to the Swiss inventories starting in line 27.

We cited

Citterio, M., Diolaiuti, G., Smiraglia, C., D'Agata, C., Carnielli, T., Stella G., and Siletto, G. B.: The fluctuations of Italian glaciers during the last century: a contribution to knowledge about Alpine glacier changes, Geogr. Ann. A, 89(3), 167–184, 2007.

in Abermann et al (2009), but not here, as the main focus of the paper area length fluctuations. But we can add this citation as area changes of Lombardia are also part of the presented analysis.

Fischer et al (2014) is already cited in this sentence on the next page, line 5. We can shift the Paul et al (2004) from line 22 to line 29.

We can do that, as this is also one of the previous suggestions to give this topic more room (which we can as we will skip the climate part).

As before, we suggest to use Arabic numbers and refer to Table 3 in the text. It is transparent from the presentation which years and periods we refer to, so that we do our best to find a clearly readable naming. A convention AGI-1877 vs AGI-1840 could be apply to individual glaciers, but not the total LIA inventory. It will be difficult as well that the term AGI 2002 refers to the same GI II as AGI 1999 for the specific ranges, and a $AGI_{1996-2002}$ will make it necessary to look up the periods listed in Table 3 anyway.

In the first version, we cited the paper Abermann et al (2010) in this sentence, accessible via http://www.the-cryosphere.net/4/53/2010/tc-4-53-2010.pdf and containing the information in Figure 5 and 6, page 57 as well as 7 on page 58, 8 and 9 on page 59, 11 on page 61. We will show further examples in extra Figures as suggested.

Reformulating research questions is necessary in any case, as the climate chapter will be skipped. We will recheck the wording as suggested.

This research question is obsolete, as the climate chapter will be skipped.

We apologize, since this is a remnant of an earlier version.

This mainly refers to regional differences in precipitation changes, which result in quite quick responses in terms of length changes as the fluctuation data shows. But this would need much more additional data and analysis. As we decided to skip that climate chapter, this problem should be avoided.

It was part of an earlier version, we apologize for that.

Ok. A detailed description including further literature is given in Groß, 1987. We will include additional information and illustration on this topic.

This gives us an estimate of the area change between the acquisition dates of the data – we will further explain that, as we should explain the method in more details (suggested by other reviewers).

Ok, we can do that.

This is part of the analysis of Lambrecht and Kuhn, which is cited here. But we can skip the citation of this specific result here.

The missing data are not included in RGI. Would it help to add a glacier by glacier list? We can add the error estimates by Lambrecht and Kuhn (2007) here, currently they are cited in the discussion.

Because the DEMs are basic data used in this study, and therefore we describe them in the data section. The delineation method is described in section 3.2, the resulting outlines are shown in the results section. We understand that we have to describe the method and the results in more detail.

We will show some examples and describe the procedure in more detail.

The information requested here is found in Table for each specific mountain range.

P5200

L2: Please explain why snow-free glacier margins are important to map glacier extents with LiDAR. This sounds like LiDAR data have the same problems like optical data. But how can seasonal snow patches then be distinguished from perennial ones? I assume this works better with optical data?

We currently don't know any method to distinguish perennial from seasonal snow with singular remote sensing data. In the cited paper Abermann et al (2010) you find the explanation that changes in surface roughness help to delimit the glacier margins. We can add this explanation with an illustration, and add additional references showing that the length change surveys found most of the 100 surveyed glaciers tongues snow free during the acquisition dates of the LiDAR campaigns.

L9: Any chance to illustrate the regional coverage on a map and show or describe how these orthophotos look like (e.g. in regard to snow conditions). To be ok with the mixture of LiDAR data and orthophotos it would also be nice to illustrate that results (glacier outlines) derived from either source are about the same.

We can provide examples but for a look at all orthophotos we must refer to a book and a sample of articles in an extra number of the ZGG to have. The cited book is

Kuhn, M., Lambrecht, A., Abermann, J., Patzelt, G., and Groß, G.: Die österreichischen Gletscher 1998 und 1969, Flächen und Volumenänderungen, Verlag der Österreichischen 20 Akademie der Wissenschaften, Wien, 2008.

and we will add the papers in the special number of ZGG to the reference list.

L11: RGB colour is nice but not sufficient as a description. Please add if these were true colour or false colour infrared (which often have better contrast for glaciers).

ok

L18: Please remove this section, as climate data are not really used here (see above).

ok

P5201

L11: I think this should be plural (Methods).

ok

L13-15: Please rephrase to make clear what the problem is.

This is just an introductory sentence, we may rephrase or skip or it, as it seems that you do not get any information from it.

L19: Please introduce abbreviation (ELA) and make sure that it is really an ELA derived from mass balance measurements. Otherwise clarify that it was an AAR derived (67%?) value that can be seen as a proxy for a balanced-budget ELA.

It is AAR derived, as clearly defined in the cited publications. But we can emphasize that here again.

This is currently part of the discussion, page 5208, lines19 to 26.

Currently we do not know any method to distinguish seasonal or perennial snow fields from snow covered glacier area in the necessary spatial resolution with singular remote sensing data. We can qualify that by pointing out thatthis might be possible in the future, using e.g. high res multi frequency or polarimetric airborne SAR data.

The problem of snow cover itself is currently part of the discussion, page 5208, lines19 to 26, and we agreed to add additional Figures before. From the data, we have no evidence from our analysis for the drastic snow effect you describe in your review. We would be glad if you could inform us, maybe referring to the data published in the Kuhn et al book.

We opt for removing the comment on geomorphological parameters, as a comparative analysis of mean slope, median elevation, distribution of aspects is clearly not feasible within this paper, because we would have to add a number of illustrations and explanations to follow the above suggestion. We promise to keep that point in mind for a further stage of analysis.

All we want to say is that there are several possibilities of comparing glacier area, glacier by glacier or total area, relative or absolute. We can add some references on examples. We will rephrase this sentence.

==L9: Maybe it would also be useful to just refer here to the concept of parent-IDs as established in the GLIMS database (see Raup et al. 2007) for exactly this purpose?==

Yes, we will refer to this concept and add an example illustrating the situation for the LIA glacier systems.

==L11: I assume many ice divides were also defined by rock outcrops that have nothing to do with the glacier surface from 1998 and changing ice dynamics? Please add how they have been calculated (watershed algorithm or manually with a flow-direction grid?).==

We will add an example illustrating the position of the ice divides and explain their calculation.

==L14-17: The line of arguments seems to be unconnected here. Why are surface roughness and optical images required when volume change alone ('subsidence of the surface') allows the identification? And what has manual delineation to do with it (grid cells with decreasing elevations can also be selected automatically)? It would be helpful to illustrate how the combination of datasets finally results in correct outlines for debris-covered glaciers.==

We will add some examples, currently only cited in the Abermann et al. 2010 paper.

==L17: Is it possible to add how ice-cored lateral moraines have been identified and maybe separated? They might also show volume reduction but no longer be connected to active ice thus not belonging to the glacier (e.g. at Hintereisferner).==

There are some examples of ice-cored moraines or dead ice, we will show some examples.

==L20: On the other hand it might result in an underestimation of the real loss if all the pieces below 0.01 km2 are seasonal snow only. For being more transparent on this decision, I recommend just adding what the effect of including / excluding areas smaller than this normally applied threshold is.==

We will illustrate the effect and give an estimate of the results without all small glacier areas.

==L28: I think this comparison does not fully work. When the terrain is snow covered as in optical images (I assume this is meant by 'photogrammetry', please clarify), the terrain should be smooth as well and the glacier perimeter invisible. In other words, a high accuracy can only be achieved under optimal mapping conditions==

We agree that a high portion of seasonal snow cover reduces the accuracy of every type of glacier mapping algorithms. Therefore, it is important to choose a suitable date for data acquisition.

L4/5: As mentioned above, can a figure be added illustrating how this works?

yes

L6-10: As the 2006 inventory (AGI-2009 above) is a mixed product from orthophotos and DEMs, it would be good adding an accuracy estimate for the orthos, maybe based on an independent multiple digitization of the same glaciers (as suggested elsewhere)?

We can add an error estimate for mapping from orthophotos.

L11: As mentioned above, this section is more a dataset description rather than a description of what has been done to digitize the extents. Please move this to datasets and illustrate here (with a figure!) how the DEMs / maps have been transformed into outlines.

yes, as above we can do that.

P5204

L1: I suggest removing this entire section.

We will follow this recommendation

L10ff: Please present the results in a more systematic way for each of the four inventories and focus on the scientifically interesting numbers. Changes should only be given as annual change rates in percent, the km2 changes have no meaning at all (as they depend on the area considered). Please also have a careful look at all calculations, the numbers partly makes no sense (e.g. the 0.02% in L17 should be 0.6% and the 0.05% should be 1.2%). I would also add that the relative annual area loss rate from AGI-1969 to AGI-1998 is 1.2% when the advance period of glaciers until about 1985 is removed from the period. This means that there is no acceleration of the shrinkage in the last period and that the values match very well with other change rates from the Alps (see Gardent et al. 2014).

We will rephrase this chapter. In the moment it is not clear for us how we could remove the effect of the period of mid 1980s, when some glaciers advanced and others showed reduced decreases. For ~ 100 glaciers, length change data would be available to show which glaciers advanced for which periods, but for the other glaciers, no data is available. The focus of the current draft is a time series of glacier inventories, and not modelling the course of decrease and advance of glaciers from inventories and length change data. We believe that this would demand a study and a paper for its own, and is not within the scope of the current paper.

L22: Please decide using either (Alpen / Gruppe) or (Alps / Group).

ok

L26: It might be useful to already add here (or later in the discussion) that this is due to the larger number of larger glaciers in this region and the dependence of the relative area loss on glacier size (decreasing towards larger sizes). I recommend supporting this with a scatter

We will include the suggested Figure.

P5205

L1-16: Please reconsider what is important to report here. It reads arbitrarily picked. What should the important message be?

We will try to focus this paragraph.

L14: Any chance to report how much of the area was lost instead of what remains?

This is the subject of the next sentences.

L17: Entire section 4.1: as above, please sort out what is important here and present it in a more structured way. Please also calculate the relative area loss for each elevation band and show it in Fig. 4 as bars. These are likely the more interesting numbers.

ok

L26/7: should be 'glacierized' and 'area loss'.

We would prefer glacier covered rather than glacierized. 'Area loss' is part of the sentence?

P5206

L1-11: as above: It is unclear on which base these numbers have been selected from the various inventories. Can the description be more systematic? I would also suggest to better contrast the number (with large changes) and area distribution (with minor changes). In this regard I also recommend using either percentages as in Table 5 or absolute numbers as in Table 4 and list both in the same table. As the number of glaciers is rather arbitrary in this study, I finally recommend setting a minimum size threshold (e.g. 0.01 km2) for better comparability of the different datasets and thus a more sound evaluation of trends.

We can do this comparison.

12-27: I suggest removing this part (and expanding some others). There is no useful link between area changes and climatic trends given in the study.

ok

P5207

L4: Does this also apply to the LIA extent? Why and how?

Yes, because contemporary documents show a high portion of snow cover at the highest elevations. We will illustrate that.

L9: Please explain how 'nominal accuracy' is calculated (e.g. in methods) and why this is providing a sound estimate for the entire sample (that also uses aerial photography).

It is currently part of the data description and explained in Abermann 2010, but we can include that here again.

We can give a bandwidth for the LIA maximum where datings are available.

As the position of moraines in historical documents is less accurate than today's LiDAR data, the derivation of erosion is not possible as no data are available. The current rate of erosion/creep can be estimated but varies, e.g. with hydrological conditions.

ok

We can give a number here.

We can add some more details

ok

We can add some figures and numbers.

ok

ok

L22: Please report what the impact of this is is (in km2 and percent)! It is fundamental to understand the differences in the mapped glacier area in other studies that had better snow conditions (and compare them here).

ok.

L24/25: What 'changes'? Where does the 3% come from? The overestimation of glacier area in the AGI-1998 due to seasonal snow is for some regions maybe more close to 10-15%.

We will illustrate the number, 10 to 15 % is clearly a too high estimate.

L27: What is a 'significant decrease'? Please quantify it for both number and area of glaciers.

We will quantify that.

P5209

L1: This is fine in general, but by just including everything (i.e. snow patches) the estimate for the glacier area is not getting better. If it is important for other (e.g. hydrological) purposes to just include everything, that's fine but it should be clearly defined in the beginning. Assuming that a glacier has to flow by definition, the 'units' smaller than 0.01 km2 are likely not glaciers and should thus be distinguished (e.g. marked in the attribute table) to consider them separately (see Paul et al., 2010).

as discussed above

L4/5: Please avoid comparing absolute area changes as these are not comparable among different regions.

ok

L8: Please compare annual rates rather than total changes when the time periods are different.

ok

L12: I assume 'satellite-derived' is meant here as LiDAR and aerial photography is also remote sensing?

yes

L13-15: This list is rather one-dimensional and in my opinion partly wrong. First, there is a number of (a) advantages of satellite-derived inventories and (b) disadvantages of the here-used datasets that should be mentioned as well. Examples for (a) include: free availability (maybe add a price tag to the datasets used in this study), fast and largely automated processing for clean ice thanks to a spectral band in the shortwave-infrared, a possibility for annual repetition (snow and cloud conditions permitting), and the complete coverage of all glaciers in Austria in a single day (or the entire Alps in six weeks). In particular the latter benefit is key for a number of applications. Examples for (b) certainly include the high workload for data processing, high costs, reduced contrast in panchromatic imagery, adverse snow and cloud conditions and the small area covered requiring the creation of mosaics with data from different years and a rather difficult calculation of changes. The individual points listed do also not really apply in my opinion: (i) High-resolution (0.5 m) satellite data as

We can add a paragraph on alternatives to LiDAR here (and we are well aware that LiDAR data are not available for the major part of the world). Nevertheless we think it is justified to use LiDAR data if available.

we will add some information that i) the high spatial resolution of Lidar is remarkable in terms of the vertical accuracy, ii) refers to additional historical data field surveys. iii) we will quantify snow cover and iv) we found that remote-sensing-derived inventories used other glacier definitions, also regarding ice divides, names, and IDs, which made a direct comparison of the data difficult. But we can rephrase that, as we did not want express a criticism of remote sensing data, which are of course valuable.

We find that it is difficult to carry out a glacier by glacier comparison of area decrease if the glaciers in various data sets have different IDs or some are missing. We suggest that for the compilation of repeat inventories it makes sense to agree on a parent data set.

We will check that and add some illustrations.

ok, as above

Could be the case.

yes, as above

We will add the information

We will check that

I think there is some misunderstanding, but as the conclusions will be rewritten, this sentence will be removed anyway.

as above

We will illustrate the problem

It might help to detect system switches if flagged out by a change in the ID

right.

Tables

T1: Maybe add dates of acquisition to the table and a letter for identification. Show in Fig. 1 which regions are covered by each sensor.

ok

T2/T6: Please remove; this study is about area changes of glaciers.

ok

T3: Add the identification letter from T1 here to properly trace the sources. Please add relative area changes and/or annual (or decadal) change rates for the three periods.

ok

T4/5: Please merge and use either totals or percentages for better comparability.

ok

Figures

F1: Please make the figure larger, add outlines of Austria and use a darker colour for the glaciers (to see them also in b/w). Show the boundaries of the individual mountain groups and add the footprints of the LiDAR DEMs used (as marked in T1).

We will check the maximum possible size with the journal, add boundaries and colorcode the glaciers in specific mountain ranges. With 'LiDAR DEM footprints' you possible refer to the boundaries of the individual DEMs referring to a specific date? This will include an additional number of lines, so that we might come up with a new suggestion or even subfigures to make the content clear.

F2: As these data are all in T3, I think this graph is not required. Please check adding a scatterplot with size vs relative (decadal) area changes for the different periods.

Yes, we could add a scatter plot.

F3: I think this one is ok, but it requires a more detailed description in the main text.

ok

F4: Please capitalize axes titles and place units in brackets. Add 100 m minor tick marks on the y-axis and add labels to all major tick marks. Place area in km2 at bottom (this is the main point of a hypsometry plot) and the area change at top. Add relative changes in percent (as bars) and indicate with a symbol (on the lines) to which elevation bins the respective values refer to. Consider using a more professional software for creating the plots.

We could do that. This is Origin Lab, which is more often used in physics, but we could switch to Matlab which might more familiar in Earth Sciences.

F5: Please remove.

That comes along with skipping the climate chapter.

Cited references

Fischer, M., M. Huss, C. Barboux and M. Hoelzle (2014): The new Swiss Glacier Inventory

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global projections of twenty-first century glacier mass changes in response to climate scenarios

from global climate models. Climate Dynamics, 42, 37–58.

Raup, B.H., A. Racoviteanu, S.J.S. Khalsa, C. Helm, R. Armstrong, and Y. Arnaud (2007):

The GLIMS Geospatial Glacier Database: a new tool for studying glacier change. Global

and Planetary Change, 56, 101-110.

Schmid, M.O., P. Baral, S. Gruber, S. Shahi, T. Shrestha, D. Stumm and P. Wester (2014):

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