The authors thank Frank Paul for his review and the effort going through the text and images a second time. We followed his suggestions as far as feasible, and mentioned in the text the question where we could not include a quick answer. Frank Pauls comments are underlined.

General comments

The study by Fischer et al. has been extensively revised and has now a clear focus on the creation of the various inventories for the glaciers in Austria, the various uncertainties of the digitizing and the derived area changes for different mountain ranges. In my opinion, the applied modifications and the removal of the climatic interpretation of the observed area changes has been very beneficial for the ms. I would also like to acknowledge the addition of new figures which better allow to trace what has been done.
My major objections are related to wording issues, a partly missing depth of the presentation (e.g. in the discussion), sometimes in favour of points that I would consider as being less important (e.g. the influence of drainage divides on the area instead of the attached snow fields), and the rather unfocused conclusion (the paper offers more than this). I have listed them along with some other comments below. As most of the suggested changes are minor and can very likely be easily addressed by the authors, I recommend accepting the ms once these minor revisions are implemented.

We rewrote the conclusions, and followed all other suggestions. Our editorial office, Dr. Scott, did another language correction.

Specific comments

In the following, I do not distinguish between typo / wording issues and some larger issues that should be addressed.
General: Considering the uncertainties of the derived values, I recommend removing the second decimal in most cases (e.g. L33, L38, L242/3). Please also consider editing the English by a native speaker, it partly sounds German.

The article has been edited twice by our professional english editoral office, Dr. Scott, usually doing literature translations. As I am not I native English speaker myself, in the moment I see no further options to improve the language of the article. Dr. Scott had another review round on that.

L1: Title suggestion “Tracing glacier changes in Austria from … a LIDAR-based inventory”

done

Abstract

L32: Has an inventory been digitized (i.e. incl. all the attribute information) or only the outlines?

The outlines, changed.

L35/36/37: I think it is ok to mention here that advance periods have taken place in-between. But I think it would be even nicer to add numbers that result when such periods are removed
(e.g. GI 1 to GI 2 being 13 years long instead of 29). That would give values that are comparable.

This is an interesting idea, but not straight forward to implement. As it is clearly evident from the following graph of the glacier report 2013, the length of the advance periods of the <100 glaciers being monitored is rather different, and not even all glaciers do even advance. So what we basically could to is to calculate the length of advance periods for every surveyed glacier, set up a dynamic model and calculate the length of advance period for every individual glacier. This would be the basis to remove advance periods and calculate new annual area change rates on a glacier by glacier base. If I understand you correctly, the average of these glacier by glacier advance period corrected annual area changes is the quantity you want to read here. This would be basically possible, not within this paper, but after a three years project. As already mentioned in our last reviewers response to the same reviewer question, also glacier which do not advance show a decelerated area retreat, and glaciers which do advance show a decelerated area retreat before and after actually advancing.
How would you suggest to remove these periods – setting up a mass balance model and removing periods with positive mass balances? And what would be the sense of such an approach? The basic purpose of an glacier inventory is to provide snapshots of glacier states, a course of glacier changes can be calculated with different methods, i.e. mass balance records, models or length change records and models. The idea is nice, but what we have develop first is i)the research questions and the overarching goal and ii) a research project until we can put reliable numbers in here.
We added 'of variable length' to this sentence to address the problem.

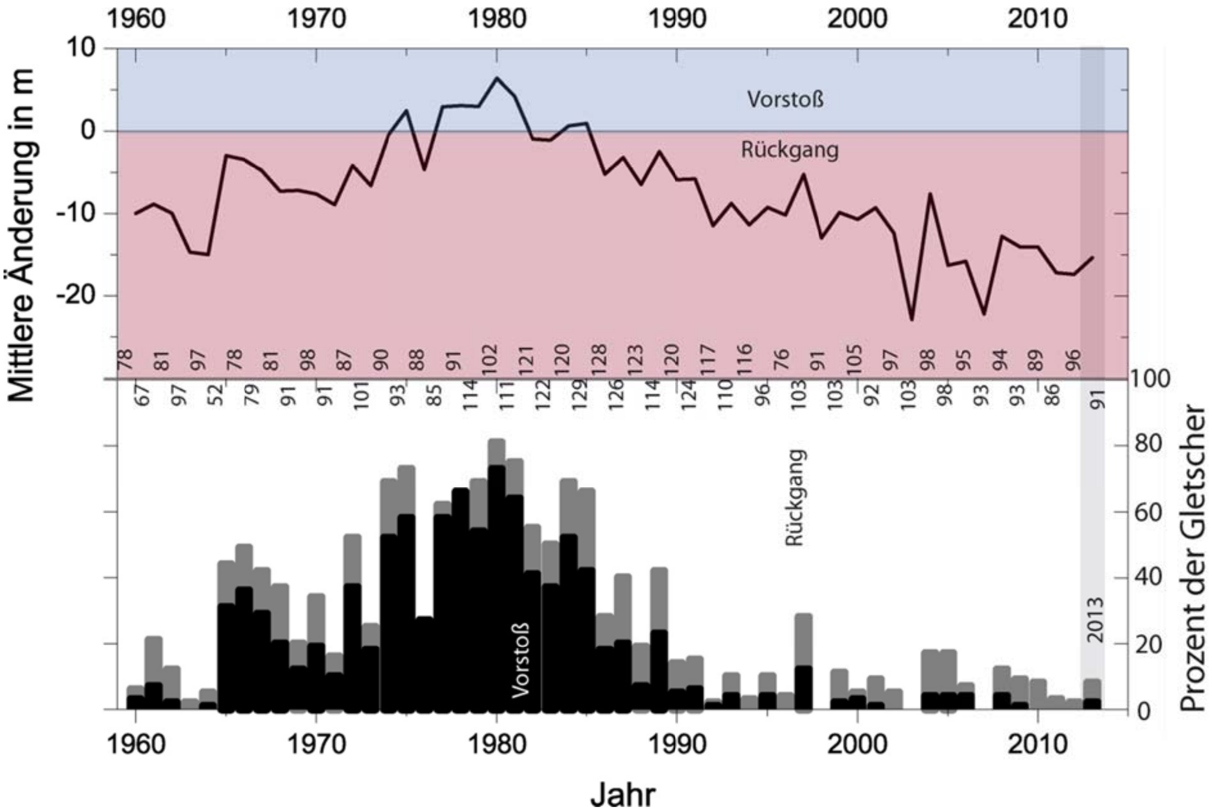


Figure 1: Length change records showing different period lengths of advances of Austrian glaciers (Fischer, 2015).

L37: Typo between year and . (remove space)
done

L38: This statement will likely change once only periods without an advance phase are compared (e.g. GI 1 to GI 2 has then also -1.3%).

Deriving advance corrected annual changes makes this statement based on the not-advance corrected annual means not wrong. It is interesting to hear that you already did the analysis described above for this data, would be interesting to read about that! Meanwhile, we can only describe the results available.

L39/40: This sentence reads strange ad misses some numbers: I suggest writing "The mean size decreased from xx km^2 (LIA) to xx km^2 (GI 3) with 47% of the glaciers being smaller than 0.1 km^2 in GI 3 (xx% in GI 1).

The sentence was changed to:
The mean glacier size decreased from 0.69 km² (GI 1) to 0.46 km² (GI 3) with 47% of the glaciers being smaller than 0.1 km² in GI 3 (22%).

Ch. 1
L54: I suggest writing: "world glacier inventory … and the one compiled by participants of the GLIMS initiative (Kargel et al., 2014)"
done:
In recent years the information available on global glacier cover has increased rapidly, with global glacier inventories compiled for the IPCC Report 2013 (Vaughan et al., 2013) complementing the world glacier inventories (WGMS, 2012) and the one compiled by participants of the GLIMS initiative (Kargel et al., 2013).

L57: Maybe cite the more recent one (from 2014) in Surveys of Geophysics

we cited the more recent one:
Radić, V. R. Hock 2014 Glaciers in the Earth's Hydrological Cycle: Assessments of Glacier Mass and Runoff Changes on Global and Regional Scales
Surveys in Geophysics, 35, 3, 813-837

L58: I suggest removing Linsbauer et al. (2012) here and adding Grinstedt (2013) instead as the former study is not related to future sea level.

We added Grinsted, 2013
Based on the glacier inventories, ice volume has been modelled with different methods, partly as a basis for future sea level scenarios (Huss and Farinotti, 2012; Linsbauer et al., 2012; Radić et al., 2014, Grinsted, 2013).

Grinsted, A.: An estimate of global glacier volume. The Cryosphere, 7, 141-151, www.the-cryosphere.net/7/141/2013/, doi:10.5194/tc-7-141-2013, 2013.

L61: I suggest adding "2012), as well as future glacier evolution."

Changed to
On a regional scale, these glacier inventory data are used for calculating future scenarios of current local and regional hydrology and mass balance (Huss, 2012), as well as future glacier evolution.

L64: I suggest citing here Andreassen et al. 2008 and maybe Paul et al. 2011a and b. Paul et al. 2010 and 2013 are not really related to the creation of glacier inventories from satellite data. There are a large number of further studies that can be cited here that are not from Paul (e.g. Bolch et al., 2010).

This initial sentence addresses remote sensing as method for deriving glacier outlines and is not directlay reloated to glacier inventories. It was reworded to

Satellite remote sensing is the most frequently applied methodfor large-scale derivation of glacier areas and outlines, (Rott, 1977, Paul et al., 2010, 2011b, 2013).

to make clear that at this sentence is saying nothing about glacier inventories.

L66: Glacier inventories are in particular needed to up-scale the always-limited field measurements to entire mountain ranges.

The sentence was changed to: For direct monitoring of glacier recession over time, the linkage of the loss of volume and area to local climatic and ice dynamical changes, and the spatial extrapolation of local observations, time series of glacier inventories are needed.

L70: I suggest giving at least on example "… data such as topographic maps with …"

Done: Longer time series (Nuth et al., 2013; Paul et al., 2011a; Andreassen et al., 2008) can only be compiled from additional data, such as topographic maps with varying error characteristics (e.g. Haggren et al., 2007) and temporally and regionally varying availability.

L74: "Apart from the Randolph Glacier Inventory (Pfeffer et al. 2014) …"

Pfeffer et al added, date removed.
Apart from the Randolph Glacier Inventory (Pfeffer et al., 2014, Ahrendt et al., 2012) and a pan-Alpine satellite-derived glacier inventory (Paul et al., 2011b), several national or regional glacier inventories are available for the Alps.

Pfeffer, W.T., Arendt, A.A., Bliss, A., Bolch, T., Cogley, J.G., Gardner, A.S., Hagen, J.O., Hock, R., Kaser, G., Kienholz, C., Miles, E.S., Moholdt, G. ,Mölg, N., Paul, F., Radić, V., Rastner, P., Raup, B.H., Rich, J., Sharp, M.J., and the Randolph Consortium: The Randolph Glacier Inventory: a globally complete inventory of glaciers. Journal of Glaciology, 60 (221), 537-551, doi: 10.3189/2014JoG13J176, 2014.

L76: "… are available for the Alps."
done, see above

L81: When this list goes back in time, I suggest starting with the latest inventory compiled for Switzerland by Fischer et al. (2014a).

This list is ordered by geographical regions and not by time, so that the above comment does not apply.

L85: I suggest adding "… and recently by Fischer et al. (2014b) for the c. 1985-2010 period."

period added.

L90: I suggest adding "1969. However, the outlines were not published then and the related change assessment with later inventories difficult."

This would be not correct, as the outlines have been published in Kuhn et al, 2008.

For the Austrian Alps, glacier inventories so far have been compiled and published for 1969 (Patzelt, 1980, Kuhn et al., 2008; GI 1) and 1998 (Lambrecht and Kuhn, 2007, Kuhn et al., 2008; GI 2) on the basis of orthophoto maps.

L 101: I suggest adding "… question that should be answered by this study is the …"

The overarching research question answered by this study is the variability of Austrian glacier area changes and change rates by time, region, size class and elevation.

Ch. 2
L111-120: This description of the previous inventories is very close to what has already been written in the introduction (L86-92). I suggest either extending it there and shorten it here or vice versa.

We shortened the description here by skipping the introductory description. This paragraph describes some important points necessary for the discussion and part of some of your later comments, so that we do not think it should be further shortened.

L119: "i.e. perennial snow patches"

changed

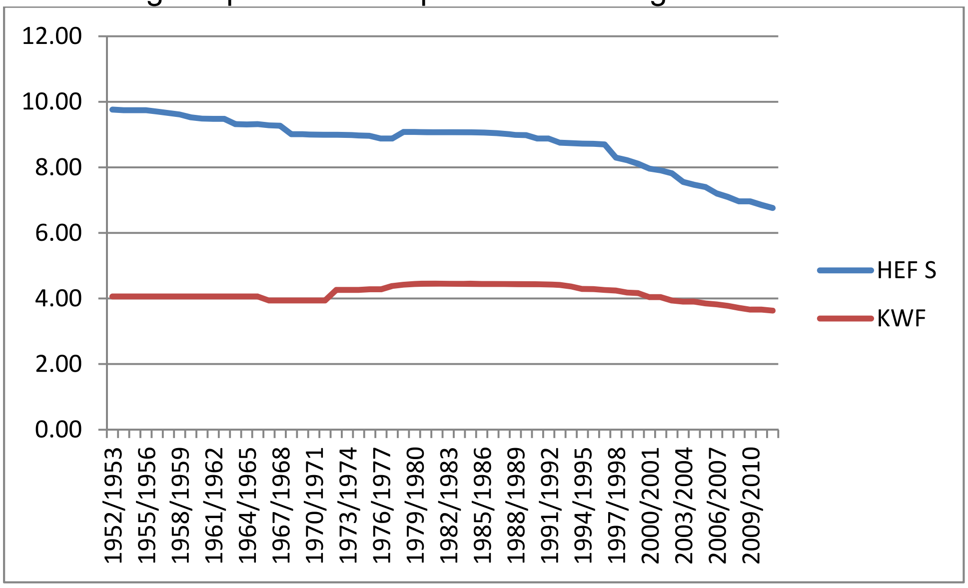
<u>L123: “so that”: I do not see the cause and effect relation to the contents of the previous sentences. Why does the number of flight campaigns depend on the glacier definition?</u>

Including snow fields attached to the glacier stresses the need for data with minimum snow cover, which is not the case in every year and difficult for planning campaigns. Two flight campaigns had to be done twice to get snow free images.
The sentence was changed to
For the GI 2 (Kuhn et al., 2013), Lambrecht and Kuhn (2007) used the same definition. A number of different flight campaigns was necessary to acquire cloud-free orthophotos with a minimum snow cover.

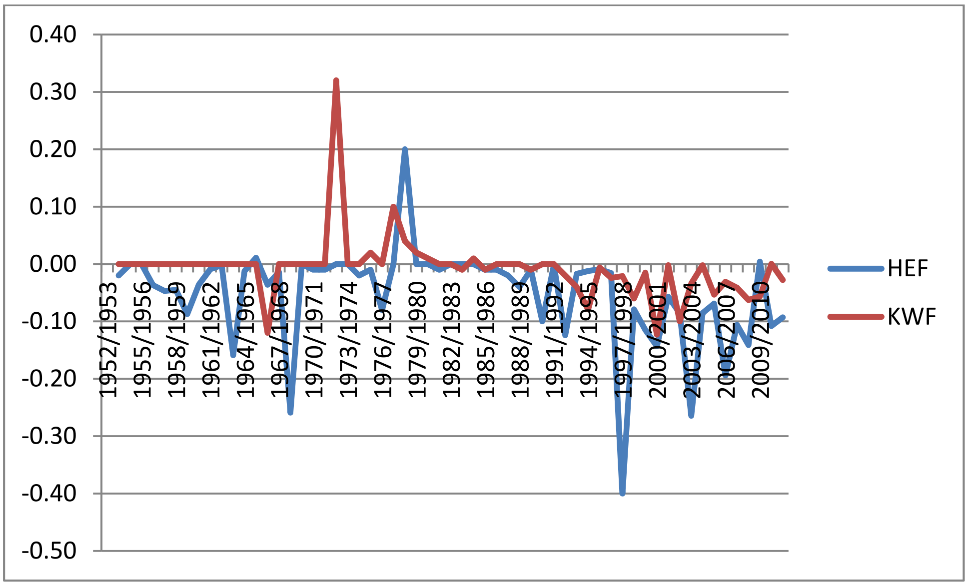
<u>L129: I know that this has been done in the cited previous study to homogenize the dates. However, I think that multiplication with size class specific annual area change rates would give a good approximation as well. Can this method be added here to see the difference?</u>

This is basically the description of the work of Kuhn and Lambrecht, so that I understand that as a suggestion for the discussion. What I do not really understand right now: How should we validate the resulting comparison as we do not have a ‘true value’? Here some short comments:

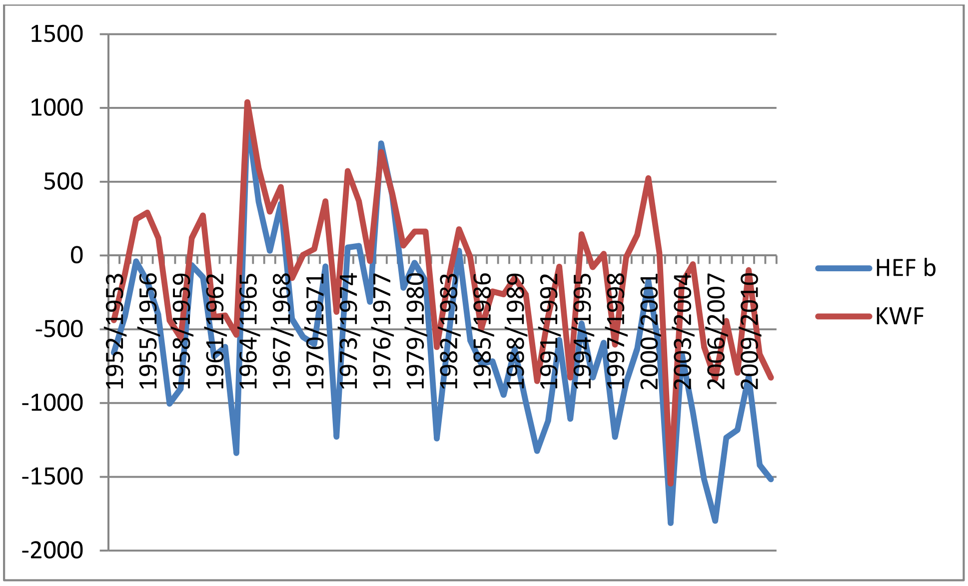
Having a look at area changes, annual area changes and specific mass balances of Hintereisferner and Kesselwandferner I do neither see the decrease in difference as proposed in your above comment, nor the direct relation between the area change and a measure of mass balance. What is evident from the graphs is that the annual area change depends on the period and changes with time.



Area Changes



Annual area changes in km²



Specific mass balance.

<u>L131: “km$_2$. They …” (dot missing)</u>

<u>L133: I think in particular in the 1999 imagery there was quite a lot of seasonal snow left in some of the regions resulting in too large glacier extents. Maybe this can be added as a note of caution and for the later discussion.</u>

<u>. added</u>

<u>L134: “The maximum error of the …”</u>

Thank you! changed .

L134: Can you the method for the error (or uncertainty?) estimate be added?
Yes, it could, but it is lengthy and already reported in much more detail in the cited paper.

L137: Can the spatial resolution of the GI 1 and GI 2 DEMs be added?

Yes, but as these requires a lot of space we refer to the literature. A thorough description of the generation of the method is needed for capturing not only a nominal pixel size, but also the spatial resolution, which is done by Würländer et al., cited in Lambrecht and Kuhn 2007. It makes no sense to put just a number referring to pixel size of 5 m here.

L142-144: the "so that" "although" sentence structure reads 'bumpy'. Maybe the English can be improved?
We asked our editor

L153: Are snow free glacier margins really the case for all years investigated? I remember that some end of summer conditions were not that good for glacier mapping.

yes.

L153 & 156: The large temporal heterogeneity of the image/LIDAR acquisition dates for GI 3 should get a more in depth description in the methods and discussion sections.

ok, but as I understand, there is no change recommended for lines 153 and 156

Ch. 3

L170-180: The ice divide issue is all fine and should be mentioned. However, I think the most important issue requiring a short discussion is the consideration of attached perennial snowfields that were included in both GI 1 and GI 2 but might have disappeared in GI 3 due to the summer of 2003. The key issue here is that these snowfields do not change their extent for decades as their existence is strongly related to topographic characteristics.

We have no empirical evidence for reproducing your statements in article. Yes, basically it can be the case that perennial snow field evolve and melt. But I do not think that this is a relevant statement for the article.

So keeping them included for consistency among the inventories is fine, but results in an underestimation of glacier area changes. When they disappear a related overestimation would result. I do not say that one method is better than the other, but I think the consequences of this decision should be clearly communicated here.

Following sentence was added:

Mapping snow fields connected to the glacier as glacier area leads to an underestimation of glacier area changes if they increase in size, and an overestimation if they melt.

L185: an excellent solution => a good solution? (The disadvantage already follows in the next sentence.)

excellent changed to good.

L186-188: An even better solution might be to start an inventory with the LIA extents.

If not analysing Egesen or LGM areas.

L188: What has finally been done here? Have grandparent IDs been introduced?
We could not decide if we should use Egesen oder Dryas forefathers.

L193: Should this read “was also quantified”? What does the sentence mean?

This sentence mean that we calculated the area covered by glaciers smaller than 0.01 km², as you recommended, and wrote it down in the results section.

L201: “with different illumination angles”

illumination added

L205/206: What about advancing glaciers?

Unfortunately, we had no glacier advance during this period. I suppose the pattern of volume change will depend on the way of advance (rapid surge or just a small advance). Sorry, now evidence on that.

L210/211: This sounds good but was it a challenging region or easy to see in the LIDAR hillshade? Maybe it can be indicated where this test site is located?

I hope I got the point indicating that Figure 6 shows the same region as Figure 2 in the caption (location of the test site). The maximum usually it easy to find.

L207/216: Accuracy estimates: Is there a chance to also provide a ‘real’ assessment of the uncertainty, for example by using a multiple digitizing experiment as outlined in Paul et al. (2013)? I think for outlines that are fully based on manual delineation and have some flexibility in interpretation, it would more useful to provide an accuracy estimate for the analyst rather than a nominal or theoretical one. I am aware that this might require some extra days of work but I think it is worth doing here.

This study is not based on deriving and validating the method, which is subject to the paper of Abermann. We have had a ‘Master Observer’ who controlled all outlines, so that there is no need for including errors caused by observer changes in this study. We added this sentence:

. Within this study, no experiment on quantifying differences between manual digitizing of different observers has been performed, as a number of studies with a high number of participants has been already been carried out for VIS remote sensing data (e.g. Paul et al, 2013).

L219: Should this be section 3.3.1?

My numbering of section 3 contains subchapters 3.1,3.2, 3.3., 3.4., 3.5., in the moment I see no evidence that this should be 3.3.1??

L226: digitization & the position (remove one space)

done

L233: which had wasted down until 1969 => which disappeared until 1969?
changed

L233: might be missing (is still required?)
still removed

L236: Why is this a fairly accurate estimate? How has it been derived?
Groß (1987) accounted for these disappeared glaciers by adding 6.5% to the LIA area, estimated from a comparison of historical maps and images as well as moraines. We decided to include this consideration in the discussion on uncertainties, although we think that this estimate is based on the best available evidence.

Ch. 4

L242: remove at least the second decimal (941.13 => 941.1), maybe also both?
ok
L244: a bit lower: Is this the 6.5% mentioned above? If yes, maybe just write it.
It is 4.4 km – we wrote that. No, it is not 6.5%.

L248: I suggest extending this section a little bit with further inventory information, maybe all related to GI3. For example, the area and number distribution per size class, the aspect distribution per number or area covered, the mean (or median) elevation vs aspect, elevation range vs glacier size, etc. These must not be assessed also vs time, but for mean or median elevation this would certainly be interesting (even for mid-point elevation in case a LIA DEM is not available).

This is the section on total glacier area in various inventories, I do not think that this would fit in here.

L250: I would say that from a hydrologic perspective the loss of glacier volume is more interesting than glacier area. However, I would suggest moving the motivation for calculating area changes in the introduction or methods section rather than in the results.
This part of the sentence was removed.

L258: I would not say neglecting, I would say including. When neglecting this period it should be taken out, i.e. the duration of the advance period should be subtracted from the total duration.
changed to including

L261: I suggest writing "In the first half of this period …"
The advances lasted until 1996 in Silvretta, so that I do not think that this is still the first half of 1969-1998. We changed the sentence to "Within this period….

L262: I would add how these numbers change when the advance period (say 1969-1985) is subtracted, i.e. annual change rates refer to a 13 rather than 28.7 years period. This can be taken up in the discussion.

I do not really get the calculation of the length of the advance period, see the discussion above. Is this number based on evidence, and if yes, on which?
We added: The glacier inventory periods can include subperiods with glacier advances and retreats, so that the calculated annual mean area change can only be considered an average value.
So that we can take this up in the discussion.

L262: I suggest writing: "showed no significant advances"
The latest period, GI 2 to GI 3, showed a general glacier recession without significant advances,
.. I do not get the difference?

L265: see comment above: when area changes are calculated for the advance-free period only annual change rates are likely as high for GI 1 to GI 2. The change for the first period (GI LIA to GI 1) might be not as high but the 119 year period might be reduced to 100 or 105 years when excluding the 1890s and 1920s advance periods.

That is correct, we added the sentence: Excluding retreat or advance periods for individual glaciers could show different annual area gain or loss rates. Excluding retreat or advance periods for individual glaciers could show different annual area gain or loss rates. The numbers shown here represent the average annual area changes, without distinguishing between advance or retreat periods.

L273/4: I suggest writing “glacier area, but only 60.4% to the area loss.”

‘but’ included

L284/5: It would be nice to provide some explanations for this in the discussion, also in view of the temporal heterogeneity of the input data used for GI 3.
ok, but this refers to the discussion part

L289: I suggest adding a scatter plot showing initial glacier size vs relative changes in glacier area (annual rates) for one or two periods and all individual glaciers. A potential dependency can be nicely used for up-scaling trends to unmeasured samples.
As nicely shown by Abermann et al., the relative area changes for specific size classes do change with time. Thus this relationship changes with time, and can not be used for upscaling. We added:
As shown by Abermann et al. (2009), relative area changes differ for specific glacier sizes and periods, so that regional differences can be also considered to be related to the specific glacier types and their geomorphology.

L301: I would add in this section how mean (or mid-point) elevation has changed through time. If interesting, also spatial trends could be shown on a map. As a further possibility, it could be shown what the AAR is when the mid-point elevation is used a proxy for the balanced budget ELA and how this AAR has changed through time.

We did not consider elevation changes in this article; this article is dedicated to area changes. We are fully aware that volume changes and elevation changes are an interesting topic, but not in the focus of this article.
From the area altitude distribution shown in Figure 11, a proxy for the AAR as suggested above is evident and is already described in this paragraph.
Added:
The area weighted mean elevation of the glacier area is 2921 m a.s.l. in GI 2 and 2943 m a.s.l in GI 3. As an approximation to a theoretical AAR, 70% of the glacier area is located abvove 3029 ma.s.l. in GI 2 and above 3046 m a.s.l in GI 3.

L297: most severe loss: In absolute or relative terms?

‘absolute’ added

L298: “Fifty percent of the area loss”?

‘percent’ added

L308: Please add what the largest size class is.

(> 10 km²) added

L312-315: I think it would be better to have the total area in km^2 here rather than the percentage (or maybe both numbers).

both number given now

Ch. 5

L327: Is this for GI2 or GI 3?
The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and lowest for GI 3.

➔ It is not clear what in this sentence refers to GI 2?

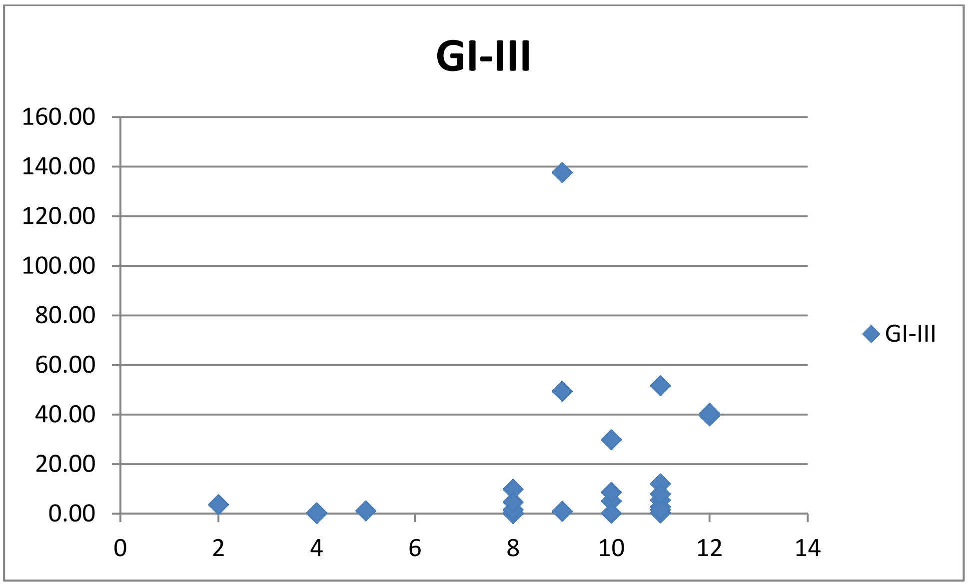
changed to
The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and decrease with time beeing lowest for GI 3.

L328: Please add a discussion of the uncertainties derived from multiple digitizing experiments here.

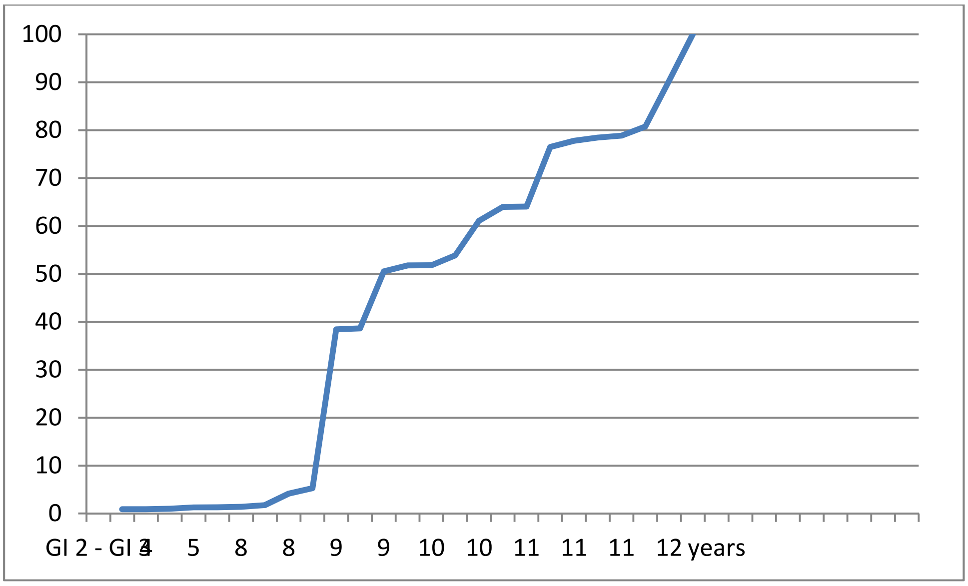
This fits better a few lines below, here these sentences was added:
In case of changing observers, differences in the interpretation of the glacier boundaries has to be taken into account. Various studies exist on that topic, e.g. by Paul et al. (2013) investigated the accuracy of different observers manually digitizing glacier outlines from high (1 m) and medium resolution (30 m) remote sensing data and automatic classification. They found high variabilities (up to 30%) for debris covered parts and about 5 % for clean ice parts. As in the presented study, the data has a spatial resolution lower 5 m, GI 1 and GI 2 have been digitized manually by two observers and GI 3 followed their basic interpretation with having the data available, the results of Paul et al. (2013) for changing observers, resolutions or methods do not directly apply to this study.

L332: Maybe add a citation here. I also suggest discussing what the impact of the partly very short time periods between GI 2 and GI 3 is. A similar effect of highly increasing area change rates towards shorter time periods was also found in the study by Gardent et al. (2014) and Paul et al. (2011a) and might not be realistic (as uncertainties in the area assessment are higher than the change). I suggest adding a histogram displaying the temporal difference vs the number of glaciers.

The information of the histogram is displayed in Table 2 and three: the scatter plot looks like this:



showing that <1% of the area has periods shorter than 5 years, 1.3% of the area shorter than 8 years and 5,3% the glacier area has periods shorter than 9 years.



Following sentences have been added:

The period length between GI 2 and GI 3 differs, as both glacier inventories show some temporal variability. The shortest period length was two years in the very small Verwall group (3.66 km², 0.88% of the total glacier area). Only 1% of the total area of GI 3 show period lengths shorter than five years, 1.3% shorter than eight years and 5.3% shorter than nine years. Gardent et al. (2014) and Paul et al. (2011) found increasing change rates for shorter periods, as they found the uncertainties in the area assessment higher than the change rates. For the present study, the change rate in the shortest periods GI2 to GI 3 (<5 years) is -18% to -22% of the GI 2 area, and thus much larger than the mapping accuracy of 2.7%. As the contribution of areas with short periods to the total area is small, the effect on the total area is also small.

L342: I suggest discussing the impact of the attached perennial snowfields in GI 1 and GI 2 on the derived area changes here. Maybe it can even be calculated what the area changes are with and without them for a smaller sub-region. That would allow us for the first time to see what the impacts of such a decision for the comparably small Alpine glaciers are.

Unfortunately, currently no method exist to identify perennial snow fields and distinguish them from glacier ice covered by snow. This might be the reason why no such numbers are available so far, and I am afraid that we can not develop a method to identify them within this study, as this needs, at the current state of the art, drilling of cores.
Following sentences have been added to address the problem:
Snow covering glacier margins or including perennial snow fields attached to the glacier can introduce significant errors in calculating the glacier areas, affecting also area change rates when comparing inventories. The errors depend on the extent of the snow cover. As currently no operational method is available to identify snow covered ground or perennial snow fields from VIS imagery, the only possibility to minimize these errors is to use remote sensing data with minimum snow cover, which requires some additional information on the development of snow cover in the respective season by meteorological or mass balance time series being available. For future developments, radar imagery in either L band or tomographic radar as well as airborne ice thickness measurements could fill this gaps. An application to temperate glacier as it is the case in the Alps still might be doubtful, as the firn and snow at the end of ablation season, when the minimum snow cover occurs and the perennial snow fields should be identified, still contains a high amount of liquid water decreasing penetration depth. Another important point is the often small extent of perennial snow fields and their location in small structures as gullies or throughs, which might be beyond the spatial resolution of low frequency airborn or spaceborn radar systems.

L342: Maybe insert a new paragraph before “Moreover”
ok
L348: Taking this and a general … into account, we estimate …
‘and’ included

L351: Maybe insert a new paragraph before “In”.
ok

L352-355: I think the former method is the standard (summing up all parts). The latter has been tried by Maisch et al. (1999) by introducing ‘Totalgletscher’ and ‘Teilgletscher’, but the challenge is that the split of glaciers does not always follow

along the position of the medial moraines. What I am not quite clear here: What has been used in this study?
Sentence added:
In the present studies, only the total glacier area in the mountain ranges has been compared.

L359/360: Yes indeed. Please calculate them and compare the rates to those published in the cited literature (e.g. Paul et al. 2004).

This is the sentence in line 359/60:
Thus a higher temporal resolution of inventories might result in different absolute and relative annual area change rates, as the length change rates, for example during the 1940s, have previously been in the same range as those after 2000.

As we have only data for LIA, 1969, 1998 and 2006 available, unfortunately we can not increase the temporal resolution of the data. I do not even think that it makes sence to present time series of area changes for the mass balance, as apart from Jamtalferner, Kesselwandferner and Hintereisferner for the period of my responsibility, one can not be sure that the areas have been measured every year.

L363: Please do not compare total area changes as these always depend on the size distribution of glaciers under consideration. Please use annual relative area change rates for comparison.
As shown by Abermann et al, also the relative changes depend on the sizes.

L369: There are several studies for Alpine glaciers having compared relative area change rates for glacier outlines starting at the LIA (e.g. Maisch et al. 1999, Paul et al. 2004). It would be nice if the results obtained here could also be compared to these (and maybe some others) studies.

added:
Maisch (1999) found for the Swiss glaciers an annual relative area change of 0.2%/year for 1850 to 1973 and about 1%/year between 1973 and 1999. Paul et al. (2004) reported for the Alps an annual relative area change rate of -1.3%/year for the period 1985 to 1999. All the above named periods differ, and the length and time of advance and retreat of glaciers vary. Therefore, even annual relative area change will not be fully comparable for the varous inventories, but include also regional and geomorpholocial variabilities.

L370: I would remove the “global”. Most satellite-derived inventories have a regional scale. Please also note that outlines are these days directly digitized in Google Earth using highresolution (50 cm) satellite imagery, i.e. the spatial resolution effect no longer applies. What is more important for the inventories derived from aerial photography (in specific flight campaigns) is spatial completeness and a better flexibility with an optimal date.

I removed the first part of the sentence. I am really impressed on the spatial resolution of 50 cm, which I did not find on Google Earth. Is these data restricted to special users, and why do Randolph outlines still seem to have not very smooth outlines?
Point iv addresses the timing.

L371: i) Not the inventories have a high spatial resolution (as they are vector outlines) but the input data used.
added: of the data base used to derive the glacier outlines
L371: ii) What is the additional information that can be included in the inventories presented here and why can this not be included in inventories derived from satellite imagery?
such as ground truth data, snow cover maps from mass balance surveys and time lapse cams as well as meteorological data
With the first part of the sentence remove, it is now stated that these additional data is used for this study. There is nothing to say against including these data in remote sensing inventories.

L372: iii) If carefully selected yes, but also satellite scenes can be selected in this regard and also aerial photography might have to acquire data in a year with adverse snow conditions (such as 1999 for GI 2). So to me this is not really an advantage.
The comparison was dropped, as it was not the intention. As I suppose repeat cycles are much shorter than 16 days now, daily satellite images might be as helpfuls as one airborne campaign at the right time.

L372: iv) This is mandatory for all datasets to be handled in a GIS and does apply to satellite derived inventories in the same way. So this is also not an item of distinction. Altogether, I suggest using the points mentioned above (L370 comment) as an important advantage and contrast this with the disadvantage of the comparably high costs for a flight campaign and the required orthorectification (satellite data are available for free and come already orthorectified), as well as the impossibility to acquire aerial photography in some countries (so satellite data are the only possibility to map glaciers).

There is no comparison any more. Sentence added:
Considering legal and monetary limitations, it might be difficult or even impossible to acquire the data used for this inventory time series for all glaciers in the world.

L375: Also the global inventories are compiled from regional scale (or national) inventories, and satellite data can have similar spatial resolutions. So I suggest arguing that the typically used medium resolution (or Landsat type) satellite images have the special advantage of covering large regions at once (e.g. 180 by 180 km in case of Landsat) and thus map all glaciers on the same day or compile an inventory over large regions (e.g. Greenland's local glaciers) within a reasonable amount of time, but on the expense of a reduced quality in regions where the majority of glaciers is very small (see Fischer et al. 2014b). Something like this.

Sentence added:

The acquisition of airborne data might be more expensive and time consuming than buying satellite data.

L382: The differences in spatial scale and the related visibility of details will certainly play a role. But the main reasons for the smaller glacier area in the RGI are likely missing glaciers under debris cover and in shadow as well as unconsidered perennial snowfields (i.e. a different glacier definition).

With a spatial resolution of 0,5 m, which you introduce above for Google Earth images, there are no differences in spatial scale. I do not want to speculate about reasons as I had no look on the remote sensing images used for RGI.

sentence changes to:
This is might be a matter of spatial scales, debris cover, shadows and different definitions applied, and has no further implication.

Ch. 6
L386ff: I suggest completely rewriting the Conclusions section. The current version is listing (repeating) rather specific details from the main text (L390-392), is speculating about causes of specific differences in L397 (this should be in the discussion) and comes several times back to mass balance observations that have not been performed (or discussed) in the study. In short, it reads like an extended discussion section. My suggestion is to add some main results from the more detailed analysis mentioned before (e.g. the mean elevation increase) and structure the Conclusions in the main findings and what these imply. L392: of 6.2% and will thus likely vanish in the …

L400: "We encourage using the presented data basis for …"

Apart from the two sentences mentioned above, the conclusions have been rewritten.

Tables

Table 1: Sensor, Point density (capitalize)
ok
Table 2: Heading: capitalize Group, Year, Data source and change GI II and GI III to GI 2 and GI 3. Last row: capitalize Total area and write "Percentage of LIA area". As a small note: I would prefer to give the respective loss in percent rather than the remaining percentage (i.e. -40, -50, -56).
ok

Table 3: Heading: Mountain group
ok

Table 4: I suggest adding percentages to the number of glaciers and absolute values in km^2 to the % of total section.

changed

Figures

General comment:
I suggest removing the outline overlays depicted in Figs. 2 (top) and 6 as all glacier extents well visible in Fig. 8. This Figure should thus be moved forward.

Fig. 1: This figure is nicely illustrating the complexity of the analysis performed here. However, colour coding of the polygons does not really work (i.e. the colours are basically invisible) and another way of symbolizing the mountain ranges should be found. I suggest adding a colour-filled circle of constant size under the two-letter abbreviation of the respective mountain range (or two circles for Schober, Venediger and Zillertal). I also suggest extending the range of colours, as many of them are difficult to distinguish. This can include a range of grey values from white to black (providing maybe 5 to 6 additional shades) and fully saturated primary colours (red, green, blue).

It is not possible to display every little mountain range with glacier areas and survey polygons in one graph. We added following sentence:

(Mountain ranges and survey dates can also be found in Fischer et al. submitted)
So that everybody could quickly download the shapes and find all the information. Circles are not feasible, as the mountain ranges are not far away enough.

Fig. 2: remove the top panel (shown in 8). I like the photo but would say it is a little bit difficult to use. It has deep shadows (hiding some glaciers) and has lots of non-glacier area included (i.e. glaciers are rather small). Maybe another one of that region could be found?

The top panel shows the orthophoto of 1998, which is not displayed in Figure 8. This is the only aerial photo we do have very close to the LiDAR Dems.

Fig. 3: The black annotations on the top panel are difficult to see, maybe change to yellow? I would also suggest adding (not too thick) glacier outlines on the hillshade to ease orientation.
Colors changed to yellow.

L582: The red squares show the position of …

Fig. 4: I suggest increasing the thickness of the red lines somewhat. If possible, I think it would also be good to show the same region on the aerial photograph (CIR) to the right of each hillshade. This might ease interpretation of the hillshades.

Line thickness increased to 2pt, unfortunately we have no simultaneous CIR data to show. Cir has been acquired several years later, then the ice was nearly gone.

Fig. 5: The red line should be a little thicker.

Both lines are thicker now.

Fig. 6: Please remove (see General comment).

The general comment says:
‘The study by Fischer et al. has been extensively revised and has now a clear focus on the creation of the various inventories for the glaciers in Austria, the various uncertainties of the digitizing and the derived area changes for different mountain ranges. In my opinion, the applied modifications and the removal of the climatic interpretation of the observed area changes has been very beneficial for the ms. I would also like to acknowledge the addition of new figures which better allow to trace what has been done.
My major objections are related to wording issues, a partly missing depth of the presentation (e.g. in the discussion), sometimes in favour of points that I would consider as being less important (e.g. the influence of drainage divides on the area instead of the attached snow fields), and the rather unfocused conclusion (the paper offers more than this). I have listed them along with some other comments below. As most of the suggested changes are minor and can very likely be easily addressed by the authors, I recommend accepting the ms once these minor revisions are implemented.
’

I can not find the hint on removing Figure 6???

Fig. 7: Please increase the thickness of the outline and annotate on the photo and the hillshade where the terminal moraines from 1850, 1920 (1930?) and 1980 (1985?) are.
ok

Fig. 8: Can label points and glacier IDs be added on this figure (maybe in black)?
Glacier names in black added

Fig. 9: I suggest using a logarithmic scale for the y-axis (rename to “Area (km_2)”). Currently the bars for some mountain ranges are close to invisible. I also suggest adding minor tick marks and use of dotted grid lines.
Scaling changed, although it was the intention that small groups are visible at the first glance.

Fig. 10: I am not sure what the message of this graph is. Data extraction and interpretation is rather difficult. I suggest replacing it with a scatter plot area vs relative change in area (annual or decadal rates) for the GI 1 to GI 2 and GI 2to GI 3 (with a different symbol) period. For the former it could be interesting to divide values by 13 instead of 28 years. It might reveal a size dependent increase or decrease of the change rates.

We think that this graph nicely shows the variation of relative area changes in the specific mountain ranges. We have no idea why we should divide absolute area changes by 13, which is half of the measured period. I suppose then the change rate doubles.
Figure labels changed.

Fig. 11: Maybe add some more tick marks and add major grid lines (dotted).
Dotted grid lines added

Fig. 12: I suggest moving this image to Fig. 2 and introduce it early (e.g. in the Introduction or L113) as I see it as an important input dataset. The snow issue could be described as is.

We do not think that the size then is sufficient to see the details.

Literature

Bolch, T., Menounos, B., Wheate, R. (2010): Landsat-based glacier inventory of western Canada, 1985-2005. Remote Sensing of Environment 114 (1): 127-137.

Fischer, M., Huss, M., Barboux, C. and Hoelzle, M. (2014): The new Swiss Glacier Inventory SGI2010: Relevance of using high-resolution source data in areas dominated by very small glaciers. Arctic, Antarctic, and Alpine Research, 46(4), 933-945.

Grinsted, A. (2013): An estimate of global glacier volume. The Cryosphere, 7, 141-151.

Pfeffer, W.T., et al. and the Randolph Consortium (2014): The Randolph Glacier Inventory: a globally complete inventory of glaciers. Journal of Glaciology, 60(221): 537-552.

You correctly remember that the conditions for glacier mapping have not been good in all summers (autums) as a result of the variability of weather and climate. Regarding the glacier inventory records and their timing and snow content: Snow cover was the reason why in two regions (Silvretta and Hallstätter Glacier) have been recorded twice, with the snow free image used for compiling the inventory. I attached a citation with all the orthophotos and a number of images to the last reviewer response, clearly indicating good, more or less snow free conditions. This is all I can say about that, and I would highly recommend that you refer to these data (time, location) when asking these questions again, or maybe give any proof of your statement of snow cover in the orthophotos.

Tracing ~~glacial disintegration~~ glacier changes in Austria from the LIA to the present using a LIDAR-based hi-res glacier inventory in Austria

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Abstract

Glacier inventories provide the basis for further studies on mass balance and volume change, relevant for local hydrological issues as well as for global calculation of sea level rise. In this study, a new Austrian glacier inventory has been compiled, updating data from 1969 (GI 1) and 1998 (GI 2) based on high resolution LiDAR DEMs and orthophotos dating from 2004 to 2012 (GI 3). To expand the time series of digital glacier inventories in the past, the glacier ~~inventory~~ outlines of the Little Ice Age maximum state (LIA) have~~s~~ been digitalized based on the LiDAR DEM and orthophotos. The resulting glacier area for GI 3 of 415.11±11.18 km² is 44% of the LIA area. The annual relative area losses are 0.3 %/year for the ~119 year period GI LIA to GI 1 with one period with major glacier advances in the 1920s. From GI 1 to GI 2 (29 years, one advance period of variable length in the 1980s) glacier area decreased by 0.6 %/year –and from GI2 to GI 3 (10 years, no advance period) by 1.2 %/year . Regional variability of the annual relative area loss is highest in the latest period, ranging from 0.3 to 6.19 %/year. The ~~specific~~ mean glacier size~~s~~ decreased from ~~LIA~~0.69 km² (GI 1) to 0.46 km² (GI 3) ~~the latest period, so that~~ with 47% of the glaciers ~~are~~being -smaller than 0.1 km² in GI 3 (22%).

1 Introduction

The history of growth and decay of mountain glaciers affects society in the form of global changes in sea level and in the regional hydrological system as well as through glacier-related natural disasters. Apart from these direct impacts, the study of past glacier changes reveals information on palaeoglaciology and, together with other proxy data, palaeoclimatology and thus helps to compare current with previous climatic changes and their respective effects.

Estimating the current and future contribution of glacier mass budgets to sea level rise needs accurate information on the area, hypsography and ice thickness distribution of the world's glacier cover. In recent years the information available on global glacier cover has increased rapidly, with global glacier inventories compiled for the IPCC Report 2013 (Vaughan et al., 2013) complementing the world glacier inventories (WGMS, 2012) and the one compiled by participants of the GLIMS initiative (Kargel et al., 2013). These global inventories serve as a basis for modelling current and future global changes in ice mass (e.g. Gardner et al., 2013; Marzeion et al., 2012; Radić and Hock, 201~~1~~4). Based on the glacier inventories, ice volume has been modelled with different methods, partly as a basis for future sea level scenarios (Huss and Farinotti, 2012; Linsbauer et al., 2012; Radić et al., 2014, Grinsted, 2013). On a regional scale, these glacier inventory data are used for calculating future scenarios of current local and regional hydrology and mass balance (Huss, 2012), as well as future glacier evolution. All this research is based on the most accurate mapping of glacier area and elevation at a particular point in time.

Satellite remote sensing is the most frequently applied method~~F~~ for large-scale derivation of glacier ~~surfaces~~areas and outlines, ~~satellite remote sensing methods are most frequently applied~~ (Rott, 1977, Paul et al., 2010, 2011b, 2013). For direct monitoring of glacier recession over time, ~~and~~ the linkage of the loss of volume and area to local climatic and ice dynamical changes, and the spatial extrapolation of local observations, time series of glacier inventories are needed. Time series of remote sensing data naturally are limited by the availability of first satellite data (e.g. Rott, 1977), so that time series of glacier inventories have been limited to a length of several decades (Bolch et al., 2010). Longer time series (Nuth et al., 2013; Paul et al., 2011a; Andreassen et al., 2008) can only be compiled from additional data, such as topographic maps, with varying error characteristics (e.g. Haggren et al., 2007) and temporally and regionally varying availability.

Although the ice cover of the Alps is not a high portion of the world's ice reservoirs, scientific research on Alpine glaciers has a long history which is important in the context of climate change. Apart from the Randolph ~~g~~Glacier ~~i~~Inventory ~~data~~ (Pfeffer et al., 2014, Ahrendt et al., 2012) and a pan-Alpine satellite-derived glacier inventory (Paul et al., 2011b), several national or regional glacier inventories are available for the Alps. For Italy, only regional data are available, for example for South Tyrol (Knoll and Kerschner, 2010) and the Aosta region (Diolaiuti et al., 2012). For the five German glaciers, time series of glacier areas have been compiled by Hagg et al. (2012). For the French Alps, glacier inventories have been compiled for ~~4~~four dates between 1967/71 and 2006/09 by Gardent et al (2014). For Switzerland, several glacier inventories have been compiled from different sources. For the year 2000, a glacier inventory has been compiled from remote sensing data (Kääb et al., 2002; Paul et al., 2004), for 1970 from aerial photography (Müller et al., 1976) and for 1850 the glacier inventory was reconstructed by Maisch et al. (1999). Elevation changes have been calculated between 1985 and 1999 for about 1050 glaciers (Paul and Haeberli, 2008) and recently by Fischer et al. (2014) for the period 1985-2010.

For the Austrian Alps, glacier inventories so far have been compiled and published for 1969 (Patzelt, 1980, Kuhn et al., 2008, Patzelt, 2013; GI 1) and 1998 (Lambrecht and Kuhn, 2007, Kuhn et al., 2008; GI 2) on the basis of orthophoto maps. Groß (1987) estimated glacier area changes between 1850, 1920 and 1969, mapping the extent of the Little Ice Age (LIA) and 1920 moraines from the orthophotos of the glacier inventory of 1969. As the Austrian federal authorities made LiDAR data available for the major part of Austria after years of very negative mass balances after 2000, these data have been used for the compilation of a new glacier inventory based on LiDAR DEMs (Abermann et al., 2010). As the high resolution data allow detailed mapping of LIA moraines, the unpublished maps of Groß (1987) have been used as the basis for an accurate mapping of the area and elevation of the LIA moraines, based on the LiDAR DEMs and the ice divides/glacier names used in the inventories GI 1 and GI 2.

The pilot study of Abermann et al. (2009) in the Ötztal Alps identified a pronounced decrease of glacier area, but differing for different size classes. The aim of this study was to update the existing Austrian glacier inventories 1969 (GI 1) and 1998 (GI2) to a GI 3 and complement this as consistently as possible with a LIA inventory based on new geodata (Figure 1) and the mappings of Groß (1987). The overarching research question answered by this study is ~~-~~the variability of Austrian glacier area changes and change rates by time, region, size class and elevation.

2 Data

2.1 Austrian Glacier inventories

Lambrecht and Kuhn (2007) used othophotos between 1996 and 2002 to update the glacier inventory 1969 (GI 1), which they also digitized (Figure 2). In the first, analogue, evaluation of the 1969 orthophotos the glacier area in 1969 was determined as 541.7 km². The glacier areas have been delineated manually by Lambrecht and Kuhn (2007) and Kuhn et al. (2008) as recommended by UNESCO (1970), i.e. perennial snow patches directly attached to the glacier have been mapped as glacier area. The digital reanalysis of the inventory 1969 (GI 1) by Lambrecht and Kuhn (2007) found a total glacier area of 567 km², including also areas above the bergschrund. For the GI 2 (Kuhn et al., 2013), Lambrecht and Kuhn (2007) used the same definition.~~;~~ ~~so that a~~A number of different flight campaigns were~~as~~ necessary to acquire cloud-free orthophotos with a minimum snow cover. Therefore, GI 2 dates from 1996 to 2002, but the main part of the glaciers were covered during the years 1997 (43.5% of the total area) and 1998 (38.5% of the total area). Lambrecht and Kuhn (2007) estimated the effect of compiling the glacier inventory from data sources of different years by calculating an area for the year 1998. The temporal homogenization of glacier area was done by upscaling or downscaling the recorded inventory area in specific altitude bands with a degree day method to the year 1998. The difference between the recorded area and the area calculated for the year 1998 was only 1.2 km². They found a glacier area of 470.9 km² for the summed areas of different dates, and 469.7 km² for a temporally homogenized area for the year 1998. All the orthophoto maps and glacier boundaries are published in a booklet (Kuhn et al, 2008), showing also the low amount of snow cover on the orthophotos. The maximum ~~area~~ error of the glacier area is estimated to be ±1.5% (Lambrecht and Kuhn, 2007). About 3% of the glacier area of 1969 have not been mapped and several very small glaciers were still missing in GI II. GI I and GI II comprise surface elevation models, with a vertical accuracy of ±1.9 m (Lambrecht and Kuhn, 2007).

2.2 LiDAR data

Airborne laser scanning is a highly accurate method for the determination of surface elevation in high spatial resolution, allowing the mapping of geomorphologic features, such as moraines (Sailer et al., 2014). The recorded glacier elevation by LiDAR DEMs was~~ere~~ compiled from a single date per glacier~~campaign. Therefore so that the recorded glacier elevation corresponds to one date only~~, although ~~the~~ acquisition times of the DEMs vary from glacier to glacier~~differ for the specific mountain ranges~~. The sensors and requirements on point densities are listed in Table 1. Vertical and horizontal resolution also depends on slope and elevation, nominal mean values for flat areas are better than ±0.5 m (horizontal) and ±0.3 m (vertical) accuracy.

Kommentar [x1]: reads bumpy ...

The point density in one grid cell of 1x1 m ranges from 0.25 to 1 point per square metre. The vertical accuracy depends on slope and surface roughness and ranges from few cm to some dm in very steep terrain (Sailer et al., 2014). LiDAR has a considerable advantage over photogrammetric DEMs where fresh snow or shading reduce vertical accuracy. As the high spatial resolution also reflects surface roughness, smooth ice-covered surfaces can be clearly distinguished from rough periglacial terrain. The flights were carried out during August and September in the years 2006 to 2012, when snow cover was minimal and the glacier margins snow free.

2.3 Orthophotos

Orthophotos were used for the delineation of glacier margins where no LiDAR data were available. All orthophotos used are RGB true colour orthophotos with a nominal resolution of 20x20 cm. Orthophotos from 2009 were used for Ankogel- Hochalmspitzgruppe, Defreggergruppe, Glocknergruppe, Granatspitzgruppe, the western part of Schobergruppe and the East Tyrolean part of Venedigergruppe. Glacier margins in the eastern part of Zillertaler Alpen and the northern part of Venedigergruppe, located in Salzburg province, were determined using orthophotos from the year 2007. Orthophotos from 2012 were used for Dachsteingruppe.

3 Methods

3.1 Applied basic definitions

The compilation of the glacier inventory time series aims at monitoring glacier changes with time. Therefore, ice divides and specific definitions regarding what is considered a glacier were kept unchanged, although they could have been changed for compiling single inventories. To make the definitions used in this study clear, the definition of glaciers, as well as glacier area and the separation by ice divides are specified here. Naturally, inventories which serve purposes other than compiling inventory time series will use other definitions, for example mapping changing ice divides instead of constant ones.

The ice divides remain unchanged in all glacier inventories and are defined from the glacier surface in 1998. Although ice dynamics are likely to change between the inventories, leaving the position of the divides unchanged has the advantage that no area has shifted from one glacier to another. Mapping snow fields connected to the glacier as glacier area leads to an underestimate~~ion~~ of glacier area changes if they increase in size~~,~~ and an overestimate~~ion~~ if they melt.

The parent data set for this study is the GI 1, so that the unique IDs in GI 1 were kept in later inventories. If a glacier had disintegrated in the inventory of 2006, one ID refers to polygons consisting of several parts of a formerly connected glacier area. For the disintegration of glaciers, the parent and child IDs as used in the GLIMS inventories (Raup et al, 2007; Raup et al, 2010) are a~~n~~ ~~excellent~~ good solution. Going backwards in time, e.g. to where several parents of the GI 1 are part of a larger LIA glacier, would consequently need the definition of a grandparent or the division of the LIA glacier in different tributaries to allow a glacier-by glacier comparison of area changes.

No size limit was applied for the mapping of glaciers in the 2006 inventory, i.e. glaciers whose area has decreased below a certain limit are still included in the updated inventory. This avoids an overestimate of the total loss of ice-covered area as a result of skipping small glaciers included in older inventories. The area of glaciers smaller than 0.01 km², which is often considered ~~as~~ a minimum size~~threshold~~ for including glaciers in inventories, was also quantified.

3.2 Mapping the glacier extent in GI 3 from LiDAR

Abermann et al. (2010) demonstrated in a pilot study for the Ötztal Alps that LiDAR DEMs can be used with high accuracy for mapping glacier area. Figure 3 shows a LiDAR hillshade of glaciers in the Ötztal Alps dating from 2006 with orthofotos in VIS and CIR RGB from 2010 for comparison. The update of the glacier shapes from the inventory of 1998 was done combining hill shades with different illumination angles calculated from LiDAR DEMs (Figure 4, location of the subset see Figure 3), analysing the surface elevation changes between the GI 2 and GI 3 inventories (Figure 5, location of the subset see Figure 3) and by comparison with orthophoto data, where available. The surface elevation change shows a maximum close to the position of the GI 3 glacier margin and should be zero outside the GI 2 glacier margin (apart from permafrost phenomena or mass movements). The resulting glacier boundaries are shown in Figure 6. Abermann et al. (2010) quantify the accuracy of the areas derived by the LiDAR method to ±1.5 % for glaciers larger than 1 km² and up to ±5% for smaller ones. The comparison with glacier margins measured by DGPS in the field for 118 points showed that 95% of these glacier margins derived from LiDAR were within an 8 m radius of the measured points and 85% within a 4 m radius. Within this study, no experiment on quantifying differences between manual digitizing of different observers has been performed, as a number of studies with a high number of participants haves ~~been~~ already been carried out for VIS remote sensing data (e.g. Paul et al, 2013).

3.3 Mapping the glacier extent in GI 3 from orthophotos

Where no LiDAR data was available (cf Figure 1, Table 2), the GI 2 glacier boundaries have been updated with orthophotos. As the nominal resolution of the orthophotos used for the manual delineation of the glacier boundaries is similar to GI 2, the estimated accuracy of the glacier area of ±1.5% is considered to be valid also for GI 3.

3.4 Deriving the LIA extent

The LIA maximum extents were mapped based on previous mappings by Groß (1987) and Patzelt (1973), which were adapted to fit the moraine positions reorded in modern LiDAR DEMs and orthophotos. Groß and Patzelt mapped the LIA extents of 85% of the Austrian glaciers based on field surveys and the maps and orthophotos of the 1969 glacier inventory. Their analogue glacier margin maps had been stored for several decades and suffered some distortion of the paper, so that the digitalization could not reproduce the ~~-~~position of the moraines according to the LiDAR DEMs. Therefore we decided to remap the LIA glacier areas, basically following the interpretation of Groß and Patzelt, but remaining consistent with the digital data. Figure 7 shows the hillshades of the tongues of Gaißbergferner with pronounced LIA, 1920 and 1980 moraines, which are ice cored on the orographic left side. The basic delineation of Groß (1987) was adapted to fit the LIA moraine in the LiDAR hillshade (Figure 8).

Nevertheless, some smaller glaciers, which ~~had wasted down~~disappeared by~~until~~ 1969, might ~~still~~ be missing in the LIA inventory. Groß (1987) accounted for these lost~~disappeared~~ glaciers by adding 6.5% to the LIA area, estimated from a comparison of historical maps and images as well as moraines. We decided to include this consideration in the discussion on uncertainties, although we think that this estimate is ~~fairly accurate~~based on ~~the~~ the best available evidence.

4 Results

4.1 Total glacier area

Austrian glaciers cover 941.1~~3~~ km² (100%) in GI LIA, 564.~~88~~ 9 km² (60%) in GI 1, 471.~~67~~ 7 km² (50%) in GI2 and 415.1~~1~~ km² (44%) in GI 3 (Table 2). The GI LIA was not corrected for glaciers which completely disappeared before GI 1, so that the area in this study is ~~a bit lower~~4.4 km² smaller than the 945.5~~0~~ km² found by Groß (1987). Only four glaciers have wasted down completely between GI 2 and GI 3.Shape files of GI 3 can be downloaded via the Pangaea data base (Fischer, in prep).

Kommentar [x2]:

4.2 Absolute and relative changes of total area

The absolute loss of glacier area~~, which is interesting from a hydrological perspective,~~ was 376 km² between GI LIA and GI 1, 94 km² between GI 1 and GI 2, and 55 km² between GI 2 and GI 3 (Table 2). Relative changes of the total area are 40% (GI LIA to GI 1), 17% (GI 1 to GI 2) and 12 % (GI 2 to GI 3). These numbers need a reference to the different period length for a comparison or interpretation, which is usually ~~-~~done by calculating relative changes per year~~, neglecting glacier advances in the periods.~~The glacier inventory periods can include subperiods with glacier advances and retreats, so that the calculated annual mean area change must ~~can only~~ be treated as ~~considered~~ an average value. The calculation of annual relative losses between GI LIA and GI 1 is based on the simplification that the LIA maximum occurred in 1850, so that the length of this period is 119 years. Then the ~~-~~relative area change per year is calculated to be 0.3 %/year, ~~neglecting~~ including glacier advances around 1920 (Groß, 1987) and the temporal variability of the occurrence of LIA glacier maximum. The area weighted mean of the number of years between GI 1 and GI 2 is 28.7, resulting in an anual relative change of total area of 0.6 %/year. ~~In~~ Within this period, a high portion of Austrian glaciers advanced (Fischer et al., 2013). The latest period, GI 2 to GI 3, showed a general glacier recession without significant advances, resulting in an annual relative area loss of 1.2%/year for the area weighted period length of 9.9 years. Therefore, overall annual relative area losses in the lastest period are twice as large as for GI 1 to GI 2 and four times as large as GI LIA to GI 1. Excluding retreat or advance periods for individual glaciers could show different annual area gain or loss rates. The numbers shown here represent the average annual area changes, without distinguishing between advance or retreat periods.

4.3 Results for specific mountain ranges

The absolute areas recorded for specific mountain ranges are shown in Figure 9 and Table 2. Highest absolute glacier area decrease between GI 2 and GI 3 was observed in the Ötztaler Alpen (-13.9 km², 24% of total area loss), the Venedigergruppe (-11.7 km², 20.9% of total area loss), Stubaier Alpen (8.2 km², 4.5%) and Glocknergruppe (-8.17 km², 14.6% of total area loss). These mountain ranges contribute 74.2% of the total Austrian glacier area. Their contribution to the area loss is lower than their share of glacier area, ~~and is~~but only 60.4% of the area loss. The contribution of the Ötztaler Alpen, Silvretta, Zillertaler Alpen and Stubaier Alpen to the total Austrian area loss decreased between the LIA and today, the contribution of Glocknergruppe and Venedigergruppe increased by more than 4% of the total area loss for each mountain range. The relative area loss since the LIA maximum differs between the specific groups: Whereas only 11% of the LIA area is left in the Samnaun Gruppe, 51 to 45% of the LIA area is still ice covered in Rätikon, Ötztaler Alpen, Venedigergruppe, Silvretta, Glocknergruppe and Stubaier Alpen (Figure 10).

While the annual relative area losses in the first period vary between -0.3 and -0.6 %/year, the regional variability of the relative annual area loss in the two latest periods is much higher the later (and shorter) the period (Table 3). As shown by Abermann et al. (2009), relative area changes differ for specific glacier sizes and periods, so that regional differences can ~~be~~ also ~~considered to~~ be interpreted as related to the specific glacier types and their geomorphology.

The highest annual relative area loss was observed in Karnische Alpen (-4.5%/year), Samnaungruppe (-5.6%/year), and Verwallgruppe (-5.9%/year) for GI 2 to GI 3. These are groups with a high portion of small glaciers.

4.4 Altitudinal variability of area changes

In GI 2, 88% of the total area was located at elevations between 2600 and 3300 m.a.s.l (Figure 11). In GI 3, the proportion of glacier area located at these elevations was still 87%. The largest portion of the area is located at elevations between 2850 and 3300 m.a.s.l (41% in GI 2 and 58% in GI 3), 42% of the area was located in regions above 3000 m in GI 2, decreasing to 39% in GI 3. The area-~~-~~weighted mean elevation of the glacier area is 2921 m a.s.l. in GI 2 and 2943 m a.s.l in GI 3. As an approximation to a theoretical AAR, 70% of the glacier area is located abvove 3029 ma.s.l. in GI 2 and above 3046 m a.s.l in GI 3.

The most severe absolute losses took place in altitudinal zones between 2650 and 2800 m.a.s.l., with a maximum in the elevation zone 2700 to 2750 m.a.s.l. Fifty percent of the area losses happened~~took place~~ at altitudes between 2600 and 2900 m.a.s.l. Therefore the main portion of the glacier covered areas are stored in regions above the current strongest area losses.

4.5 Area changes for specific glacier sizes

The interpretation of the recorded glacier sizes has to take into account that not all glaciers which are mapped for newer inventories are part of the older inventories, as the total number of glaciers in Table 4 shows. Although some smaller glaciers are missing in GI 1, the number of glaciers smaller than 0.1 km² has been increasing, replacing the area class between 0.1 and 0.5 km² as the most frequent one. At the other end of the scale, 11 glaciers were part of the largest size class (> 10 km²) in GI 1 and only 8 were left in GI 3.

For GI 3, the glaciers in the largest size class of 5 – 10 km² cover 41% of the area (Table 4). All other size classes range between 8 and 17% of the total area, but glaciers of the smallest size class cover only 9% of the total glacier area.

The percentage of area contributed by very small glaciers (<0.01 km²) is small. In GI 1, 1 glacier covers 0.~~0015~~002% (0.01 km²) of the total glacier area. In GI 2, 16 very small glaciers cover 0.024% (0.11 km²) of the total glacier area, and in GI 3 26 very small glaciers contribute 0.033% (0.14 km²) of the total glacier area.

5 Discussion

The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and decrease with time to ~~beeing~~ lowest for GI 3. For all glacier inventories, debris cover and perennial snow fields or fresh snow patches connected to the glacier are hard to identify, although including information on high resolution elevation changes and including additional information from different points in time reduces this uncertainty (Abermann et al., 2010). The high-resolution data were only available for GI 3, so that the interpretation of debris and snow can still be regarded as an interpretational range of several percentage points for the area in GI 1 and 2. The nominal accuracy of the method (Abermann et al., 2010) results in an area uncertainty of ±11.2~~%~~ km² or ±2.7%.

In case of changing observers, differences in the interpretation of the glacier boundaries must~~has to~~ be taken into account. Various studies exist on that topic, e.g. by Paul et al. (2013) who investigated the accuracy of different observers manually digitizing glacier outlines from high (1 m) and medium resolution (30 m) remote sensing data and from automatic classification. They found high variabilities (up to 30%) for debris~~-~~covered parts and about 5 % for clean ice parts. ~~As~~ In contrast, in the presented study, all ~~the~~ data have~~s~~ a spatial resolution of less than~~lower~~ 5 m, GI 1 and GI 2 have been digitized manually by two observers and GI 3 followed their basic interpretation. ~~with having the data available,~~ T~~t~~he results of Paul et al. (2013) for changing observers, resolutions or methods thus do not directly apply to this study.

The period length between GI 2 and GI 3 differs, as both glacier inventories show some temporal variability. The shortest period length was two years in the very small Verwall group

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(3.66 km², 0.88% of the total glacier area). Only 1% of the total area of GI 3 was recorded less ~~show period lengths shorter~~ than five years after GI 2, 1.3% less ~~shorter~~ than eight years later and 5.3% less ~~shorter~~ than nine years later. Gardent et al. (2014) and Paul et al. (2011) found increasing change rates for short~~er~~ inventory periods, as they found the uncertainties in the area assessment higher than the change rates. For the present study, the change rate in the shortest periods GI2 to GI 3 (<5 years) is -18% to -22% of the GI 2 area, and thus much larger than the mapping accuracy of 2.7%. As the contribution of areas with short periods to the total area is small, the effect on the total area is also small.

~~Snow covering glacier margins or~~ I~~i~~ncluding seasonal or perennial snow fields attached to the glacier can introduce significant errors in calculating the glacier areas, affecting also area change rates when comparing inventories. The errors depend on the extent of the snow cover. As currently no operational method is available to identify snow covered ground or perennial snow fields from VIS imagery, the only possibility to minimize these errors is to use remote sensing data with minimum snow cover, which requires some additional information on the development of snow cover in the respective season from~~by~~ meteorological or mass balance time series~~ beeing available~~. For future developments, radar imagery in L-~~-~~band or tomographic radar as well as airborne ice thickness measurements could fill these~~is~~ gaps. As the firn and snow at the end of ablation season, when the minimum snow cover occurs and the perennial snow fields should be identified, still contains a high amount of liquid water, radar penetration depth decreases. An application to temperate glaciers as found ~~it is the case~~ in the Alps is therefore not feasible. ~~till might be doubtful, as the firn and snow at the end of ablation season, when the minimum snow cover occurs and the perennial snow fields should be identified, still contains a high amount of liquid water decreasing penetration depth~~. Another important point is the often small extent of perennial snow fields and their location in small structures, such as gullies or t~~h~~roughs, which might be beyond the spatial resolution of low frequency airborne or spaceborne radar systems.

For the interpretation of the LIA inventory, temporal and spatial indeterminacy has to be kept in mind. The temporal indeterminacy is caused by the asynchronous occurrence of the LIA maximum extent. In extreme cases the occurrence of the LIA maximum deviated several decades from the year 1850, which is often used as synonymous with the time of the LIA maximum.

The spatial indeterminacy varies between accumulation areas and glacier tongues: The moraines which confined the LIA glacier tongues give a good indication for the LIA glacier margins in most cases as they are clearly mapped in the LiDAR DEMs and changing

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vegetation is visible in the orthophotos. In some cases, lateral moraines standing proud for several decades eroded later, so that the LIA glacier surface will be interpreted as wider, but also lower than it actually was. In some cases, LIA moraines were subject to mass movements caused by fluvial or permafrost activities. In a very few cases, ice cored moraines developed and moved from the original position. Altogether these uncertainties are small compared to the interpretational range at higher elevations, where no significant LIA moraines indicate the ice margins.

Moreover, historical documents and maps often show fresh or seasonal snow cover at higher elevations. For example the federal maps of 1816-1821 and 1869-1887 in Figure 12 show surfaces where it is not clear if they are covered by snow, ice or firn. Therefore we cannot even be sure to have included all glaciers which existed during the LIA maximum. Groß (1987) calculated LIA maximum glacier areas of 945.50 km² without, and 1011.0 with disappeared glaciers (i.e. 6.5 % disappeared glaciers). ~~-~~According to this estimate, ~~-~~6.5 % of the LIA maximum area is possibly missing from our inventory. Taking this and a general mapping error of 3.5% into account we estimate the accuracy of the total ice cover for the LIA as ±10%. Figure 12 illustrates that the maps of the third federal survey, together with other historical data, provide some information on the glacier area also in higher elevations.

In any investigation of large system changes, as between LIA and today, the definition of the term ‘glacier’ is difficult, as it is not clear if it makes sense to compare one LIA glacier with the total area of its child glaciers with totally different geomorphology and dynamics, or if it would make more sense to split the LIA glacier into tributaries according to the present situation. In the present study~~ies~~, only the total glacier area in the mountain ranges has been compared.

Regarding the presented annual rates of area change, it has to be born in mind that all periods apart from GI 2 to GI 3 contain at least one period (around 1920 and in the 1980s) when the majority of glaciers advanced (Groß, 1987; Fischer et al, 2013). Thus a higher temporal resolution of inventories might result in different absolute and relative annual area change rates, as the length change rates, for example during the 1940s, have previously been in the same range as those after 2000.

The development of area change rates is similar to the ones found for the Aosta region by Diolaiuti et al., (2012), who arrived at ~~2.8~~1.7 % ~~km²~~/year for 1999 to 2005, and ~~1.1~~0,8 % ~~km²~~/year for 1975 to 1999. The maximum relative area changes in the period of the Austrian

GI 2 to GI 3 exceed the ones summarized by Gardent et. al. (2014). The periods for which area changes have been calculated for the French Alps by Gardent et al. (2014) are no exact match of the Austrian periods, but the total loss of 25.4% of the glacier area between 1967/71 and 2006/09 is similar to the Austrian Alps, despite the higher elevations of the French glaciers. A common finding is the high regional variability of the area changes. For the Swiss glaciers Maisch (1999) found ~~for the Swiss glaciers~~ an annual relative area change of -0.2%/year for 1850 to 1973 and about -1%/year between 1973 and 1999. For the Alps Paul et al. (2004) reported ~~for the Alps~~ an annual relative area change rate of -1.3%/year for the period 1985 to 1999. All the above named periods differ in length and temporal occurrence, and the length and time of advance and retreat of glaciers vary. Therefore, even annual relative area change will not be fully comparable for the various inventories, but also include ~~also~~ regional and geomorpholocial variabilities.

~~Compared to global satellite remote-sensing-based glacier inventories, t~~The glacier inventories presented here show ~~-~~i) high spatial resolution of the data base used to derive the glacier outlines ii) inclusion of additional information, such as ground truth data, snow cover maps from mass balance surveys and time lapse cameras as well as meteorological data iii) minimal snow cover at the time of the flights and iv) consistent nomenclature and ice divides for all four inventories. Given~~Considering~~ legal and monetary limitations, it might be difficult or even impossible to acquire the data used for this inventory time series for all glaciers in the world. The acquisition of airborne data might be more expensive and time-~~-~~consuming than buying satellite data. The high resolution data used in this study is neither available for a global inventory, nor is the high resolution beneficial for global studies, so that global inventories will naturally use satellite remote sensing data. As the Alps often are used as an open space laboratory in glaciology, it nevertheless might make sense to compare results of global inventories with this regional inventory. The Randolph inventory RGI Version 3.2, released 6 September 2013 and downloaded from http://www.glims.org/RGI/rgi_dl.html contains 737 glaciers and a glacier area of 364 km² for the year 2003. These numbers are lower than the ones recorded in the Austrian inventories (GI 2 before 2003 and GI 3 after 2003), although cross-border glaciers were not delimited for the comparison. This ~~is clearly~~ might be a matter of spatial scales, debris cover, shadows and different definitions applied, and has no further implication.

6 Conclusions

This time series of glacier inventories presents a unique document of glacier area changes since the Little Ice Age. Total glacier area shrunk by 66 % between LIA maximum and GI 3, at increasing annual rates rising from 0.3%/year (LIA – GI 1), 0.6/year (GI1 – GI 2) to 1.2%/year (GI 2 – GI 3). During parts of the first two periods, some of the Austrian glaciers advanced, so that the latest period is the only one without glacier advances. The area changes vary for different mountain ranges and periods, with highest annual relative losses in the latest period GI 2- GI 3 for the small ranges Verwallgruppe (-5.9%/year) Samnaungruppe (-5.6%/year) and Karnische Alpen (-4.5%/year). Nevertheless, for some of the largest glacier regions, like Stubaier Alpen, Ötztaler Alpen and Silvrettagruppe, as well as for the small Rätikon, annual relative changes, even for the latest period, are smaller than 1%/year. Although the relative annual losses have generally increased since the LIA, some groups, for example Silvrettagruppe and Rätikon, exhibit a decrease in the latest period. The only glacier in Salzburger Kalkalpen region, Übergossene Alm, is currently disintegrating with annual relative area losses of 6.2 % and will thus likely vanish in the near future. The area-weighted mean elevation increased from 2921 m a.sl. in GI 2 to 2943 m a.sl. in GI 3, with highest absolute area losses taking place in elevations between 2700 and 2750 m a.s.l. The number of glaciers in the smallest size class (< 0.1 km²) increased between GI 1 and GI 3, the number of glaciers in the largest size class (> 10 km²) decreased. The 10 glaciers in the two largest size classes still cover 25% of the total glacier area. In GI 3, 49% of the glaciers are in the smallest size class, but cover only 5% of the total glacier area.

For deriving a statistics for specific glaciers, a discussion of the implications of disintegration of glacier tributaries is needed, including more data from various climate regions. We encourage the use of the presented data basis for further studies and investigations of glacier response to climate change.

~~This time series of glacier inventories presents a unique document of glacier area change since the Little Ice Age. The regional variability of glacier area loss since the LIA maximum is high, ranging from 89% loss of LIA glacier area for the small glaciers of the Samnaun group to half of the LIA glacier area remaining in a number of other groups. Small groups like Salzburger Kalkalpen and Karnische Alpen show the highest annual losses. The only glacier in Salzburger Kalkalpen region, Übergossene Alm, is currently disintegrating with annual relative area losses of 6.2 %. It seems likely to vanish in the near future. Nevertheless,~~

for some of the largest glacier regions like Stubaier Alpen, Ötztaler Alpen and Silvrettagruppe as well as for the small Rätikon, annual relative changes even in the latest period are smaller than 1%/year. Although generally the relative annual losses increased since the LIA, some groups, for example Silvrettagruppe and Rätikon, exhibit a decrease in the latest period. The reason for that might be found in small scale mass balance variabilities in the shortest period analysed, or topographic or dynamical responses. For a meaningful interpretation of annual relative losses the length of the periods and the occurrence of positive mass balances and advances must be taken into account. We hope that the presented data basis will be used for further studies and investigations of glacier response to climate change.

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Table 1: Sensor and point densities.

	sSensor	pPoint density/m²
Tirol	ALTM 3100 and Gemini	0.25
Salzburg	Leica ALS-50, Optech ALTM-3100	1.00
Vorarlberg	ALTM 2050	2.50
Kärnten-Karnische Alpen	Riegl LMS Q680i and Riegl LMS Doublescansystem	1.00
Kärnten-other	Leica ALS-50/83 and Optech Gemini	1.00

Table 2: Acquisition times of the glacier inventories with glacier areas for specific mountain ranges shown in Figure 1; L means LiDAR ALS data and O means orthophoto.

gGroup	GI II yYear	GI III yYear	dData source	LIA km²	GI-I km²	GI-II km²	GI-III km²
Allgäuer Alpen	1998	2006	L	0.29	0.20	0.09	0.07
Ankogel-Hochalmspitzgruppe	1998	2009	O	39.94	19.17	16.03	12.05
Dachsteingruppe	2002	2012	O	11.95	6.28	5.69	5.08
Defregger Gruppe	1998	2009	O	2.01	0.70	0.43	0.30
Glocknergruppe	1998	2009	O	103.58	68.93	59.84	51.67
Granatspitzgruppe	1998	2009	O	20.08	9.76	7.52	5.48
Karnische Alpen	1998	2009	L	0.29	0.20	0.18	0.09
Lechtaler Alpen	1996	2004/06	L	2.09	0.70	0.69	0.55
	1996	2006	L				0.36
	1996	2004	L				0.19
Ötztaler Alpen	1997	2006	L	280.35	178.32	151.16	137.58
Rätikon	1996	2004	L	3.12	2.19	1.65	1.61
Rieserfernergruppe	1998	2009	L	8.07	4.60	3.13	2.75
Salzburger Kalkalpen	2002	2007	L	5.68	2.47	1.68	1.16
Samnaungruppe	2002	2006	L	0.59	0.20	0.08	0.07
Schobergruppe	1998	2007/09	L/O	9.88	5.60	3.49	2.57
	1998	2007	L				0.96
	1998	2009	O				1.61
Silvrettagruppe	1996	2004/06	L	41.27	23.96	18.97	18.48

		2006	L				9.86
		2004	L				8.62
Sonnblickgruppe	1998	2009	L	24.81	12.76	9.74	7.91
Stubaier Alpen	1997	2006	L	110.10	63.05	53.99	49.42
Venedigergruppe	1997	2007/09	L/O	145.20	93.44	81.01	69.31
	1997	2007	O				29.85
	1997	2009	L				39.47
Verwallgruppe	2002	2004/06	L	13.41	6.70	4.65	4.08
	2002	2006	L				3.66
	2002	2004	L				0.41
Zillertaler Alpen	1999	2007/11	L/O	118.42	65.64	50.64	45.24
	1999	2007	O				4.73
	1999	2011	L				40.51
total area				941.13	564.88	470.67	415.47
% of LIA area				100.00	60.02	50.01	44.15

Table 3: Relative and relative annual area changes.

Mountain group	GI 1-GI 2	GI 2 - GI 3	LIA-GI 1	GI 2-GI1	GI3-GI2	LIA-GI 1	GI 1-GI2	GI2-GI3
	years	years	%	%	%	%/year	%/year	%/year
Allgäuer Alpen	29	8	-31	-55	-22	-0.3	-1.9	-2.8
Ankogel-Hochalmspitzgruppe	29	11	-52	-16	-25	-0.4	-0.6	-2.3
Dachsteingruppe	33	10	-47	-9	-11	-0.4	-0.3	-1.1
Defregger Gruppe	29	11	-65	-39	-30	-0.5	-1.3	-2.7
Glocknergruppe	29	11	-33	-13	-14	-0.3	-0.5	-1.2
Granatspitzgruppe	29	11	-51	-23	-27	-0.4	-0.8	-2.5
Karnische Alpen	29	11	-31	-10	-50	-0.3	-0.3	-4.5
Lechtaler Alpen	27	8,10	-67	-1	-20	-0.6	-0.1	-2.2
Ötztaler Alpen	28	9	-36	-15	-23	-0.3	-0.5	-2.6
Rätikon	27	8	-30	-25	-25	-0.3	-0.9	-3.1
Rieserfernergruppe	29	11	-43	-32	-22	-0.4	-1.1	-2.0
Salzburger Kalkalpen	33	5	-57	-32	-18	-0.5	-1.0	-3.5
Samnaungruppe	33	4	-66	-60	-22	-0.6	-1.8	-5.6
Schobergruppe	29	9,11	-43	-38	-19	-0.4	-1.3	-1.8
Silvrettagruppe	27	8,10	-42	-21	-25	-0.4	-0.8	-2.7
Sonnblickgruppe	29	11	-49	-24	-21	-0.4	-0.8	-1.9
Stubaier Alpen	28	9	-43	-14	-23	-0.4	-0.5	-2.6
Venedigergruppe	28	10,12	-36	-13	-22	-0.3	-0.5	-2.0
Verwallgruppe	33	2,4	-50	-31	-22	-0.4	-0.9	-5.9
Zillertaler Alpen	30	8,12	-45	-23	-23	-0.4	-0.8	-2.0

Table 4: Absolute and relative number and areas of glaciers per size class.

Size classes [km²]	<0.1	0.1 to 0.5	0.5 to 1	1 to 5	5 to 10	>10	Total
Number of glaciers							
in GI 1	177	401	116	99	11	5	809
in GI 2	401	343	92	79	7	3	925
in GI 3	450	307	77	77	8	2	921
Number of glaciers in %							
in GI 1	22	50	14	12	1	1	100
in GI 2	43	37	10	9	1	0	100
in GI 3	49	33	8	8	1	0	100
% of total area in class							

in GI 1	2	17	14	39	15	13	100
in GI 2	4	17	14	41	14	10	100
in GI 3	5	17	12	41	17	8	100
Area in class in km²							
in GI 1	11.30	96.03	79.08	220.30	84.73	73.43	564.88
in GI 2	18.83	80.01	65.89	192.97	65.89	47.07	470.67
in GI 3	20.77	70.63	49.86	170.34	70.63	33.24	415.47

Size classes [km²]	<0.1	0.1 to 0.5	0.5 to 1	1 to 5	5 to 10	>10	total
number of glaciers							
in GI 1	177	401	116	99	11	5	809
in GI 2	401	343	92	79	7	3	925
in GI 3	450	307	77	77	8	2	921

% of total area in class							
in GI 1	2	17	14	39	15	13	100
in GI 2	4	17	14	41	14	10	100
in GI 3	5	17	12	41	17	8	100

Figures

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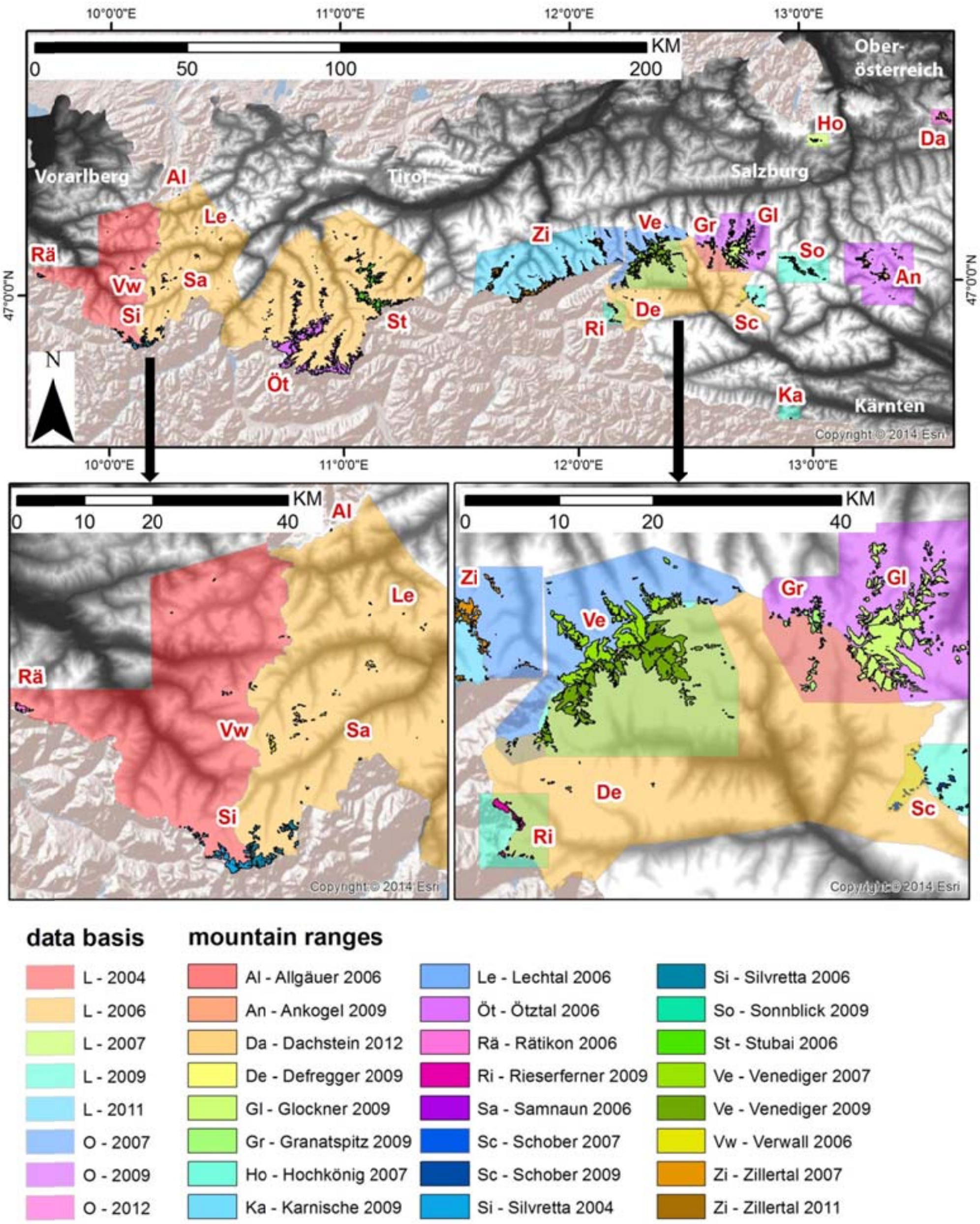


Figure 1: Austrian glaciers displayed on a DEM (Jarvis et al., 2009) color-coded by mountain ranges, with polygons showing data type and date used for deriving GI 3 and GI LIA (Mountain ranges and survey dates can also be found in Fischer et al. submitted).

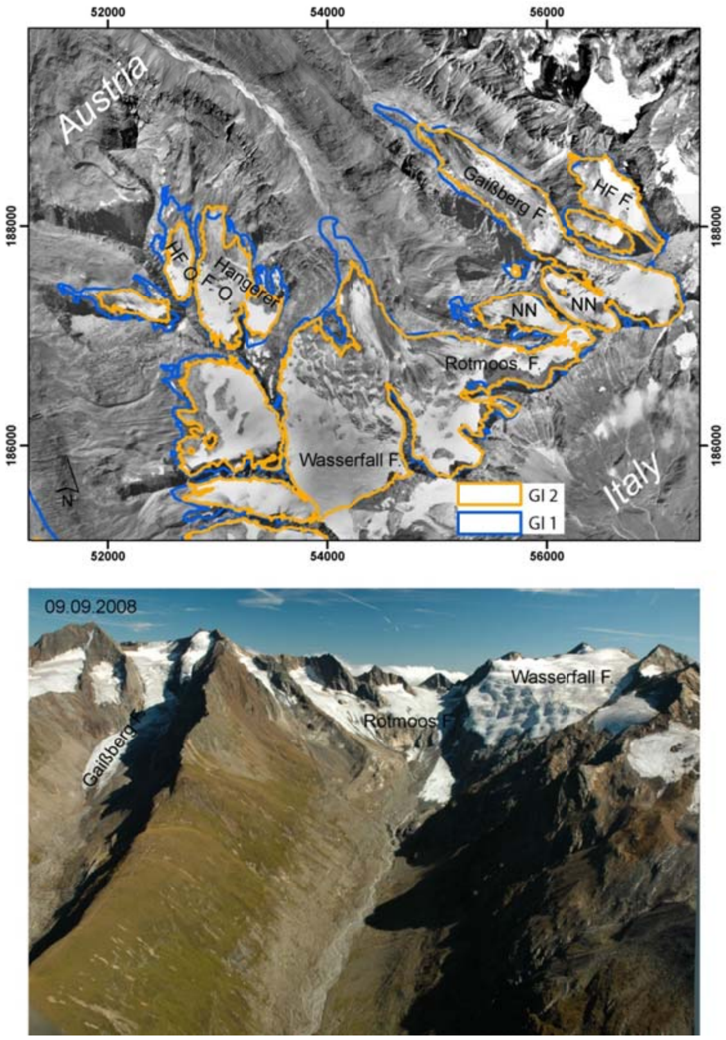


Figure 2: GI 1 and GI 2 glacier margins superimposed on a GI 2 orthophoto with an oblique photograph of the area in Ötztal Alps. HF O…Hangerer Ferner Ost, HF F…Hochfirst Ferner, NN …not named.

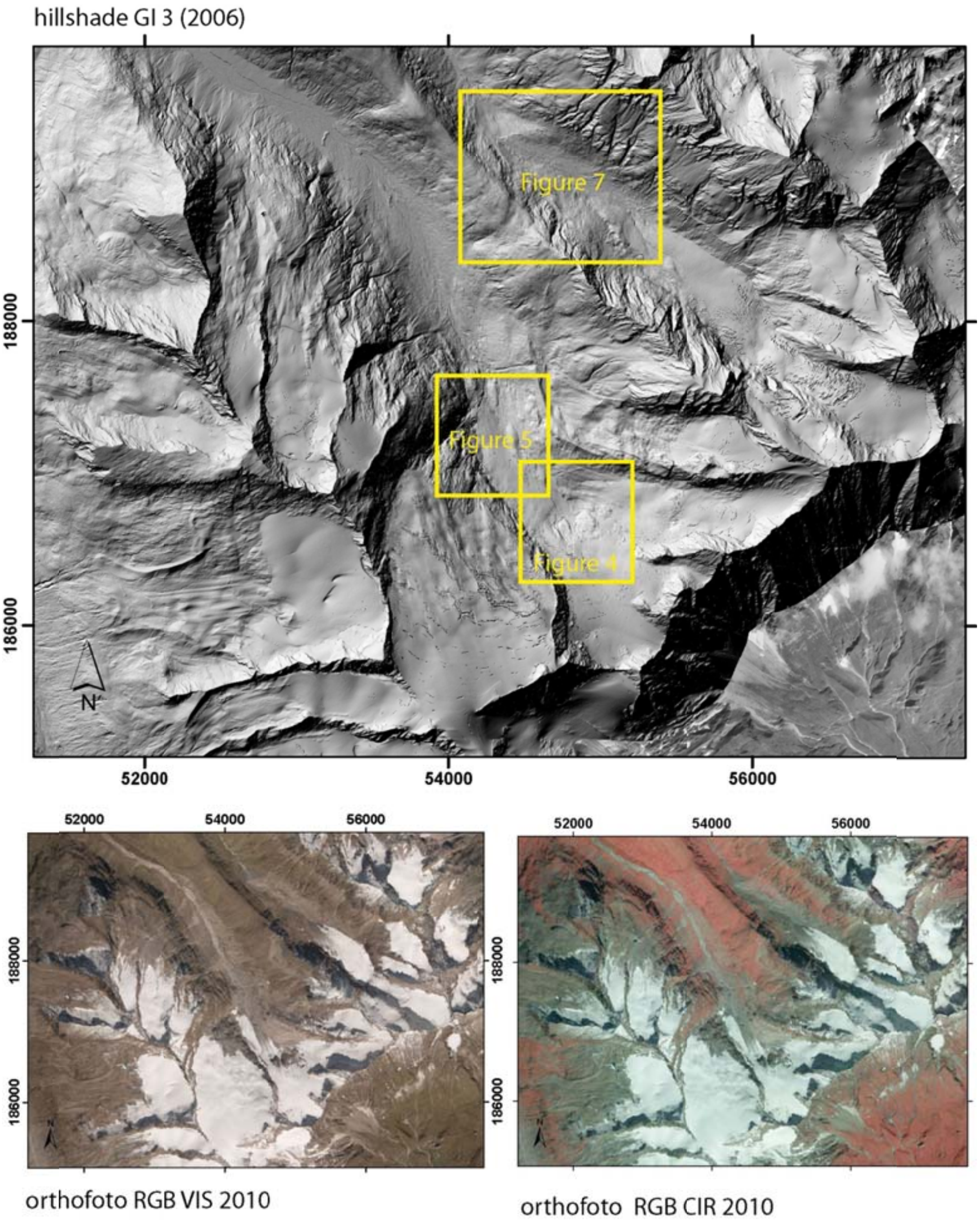


Figure 3: Example of an LiDAR hillshade (2006) of the same area as in Figure 2 with VIS and CIR RGB orthophotos from 2010 for comparison. The inserts show the position of the subsets shown in Figure 4 (lower right rectangle) and Figure 5 (upper left rectangle).

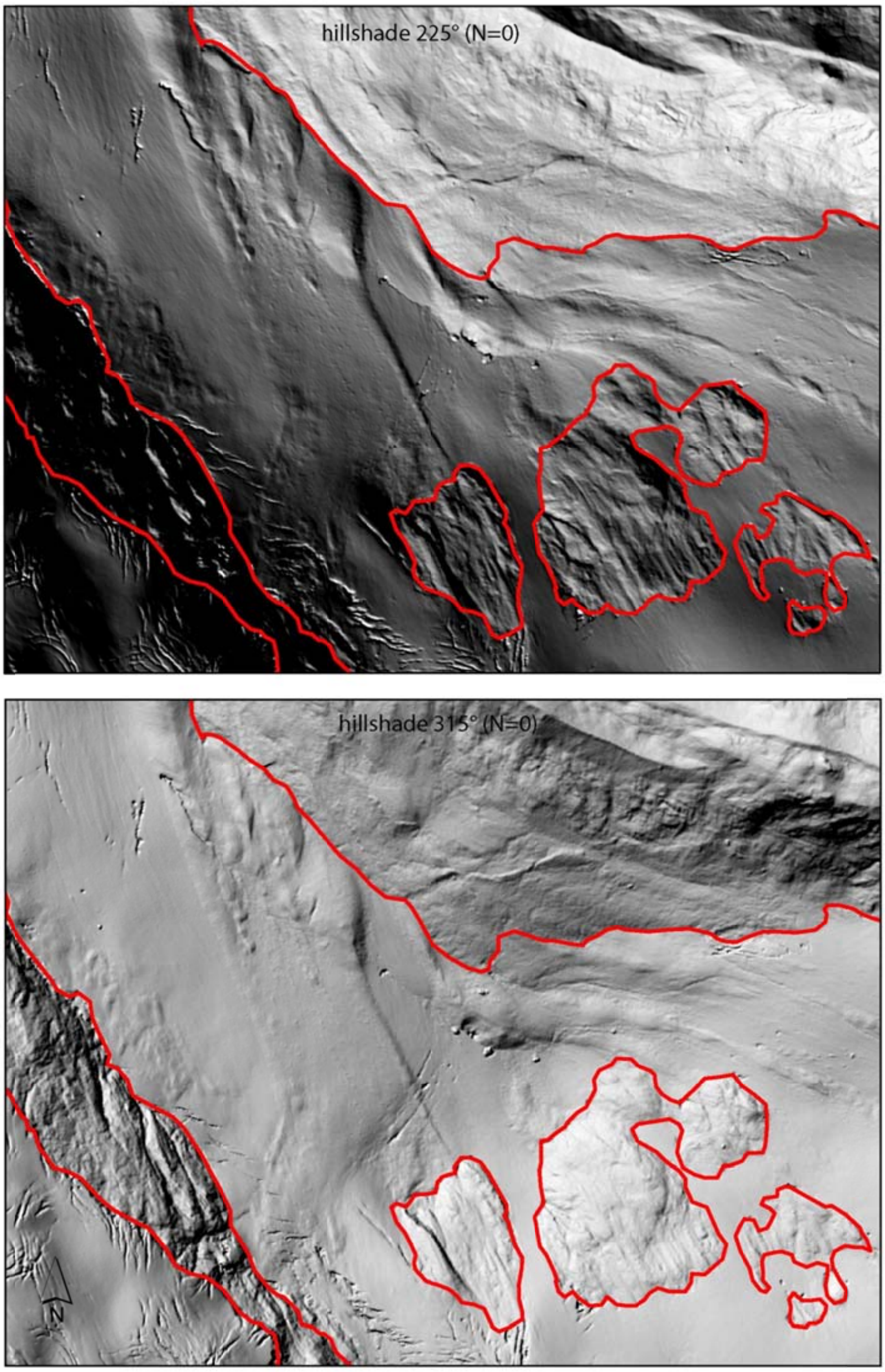

hillshade 225° (N=0)
hillshade 315° (N=0)
N

Figure 4: Hillshades from different view angles allow to distinguish smooth glacier surfaces from bedrock (position of the subset shown in Figure 3).

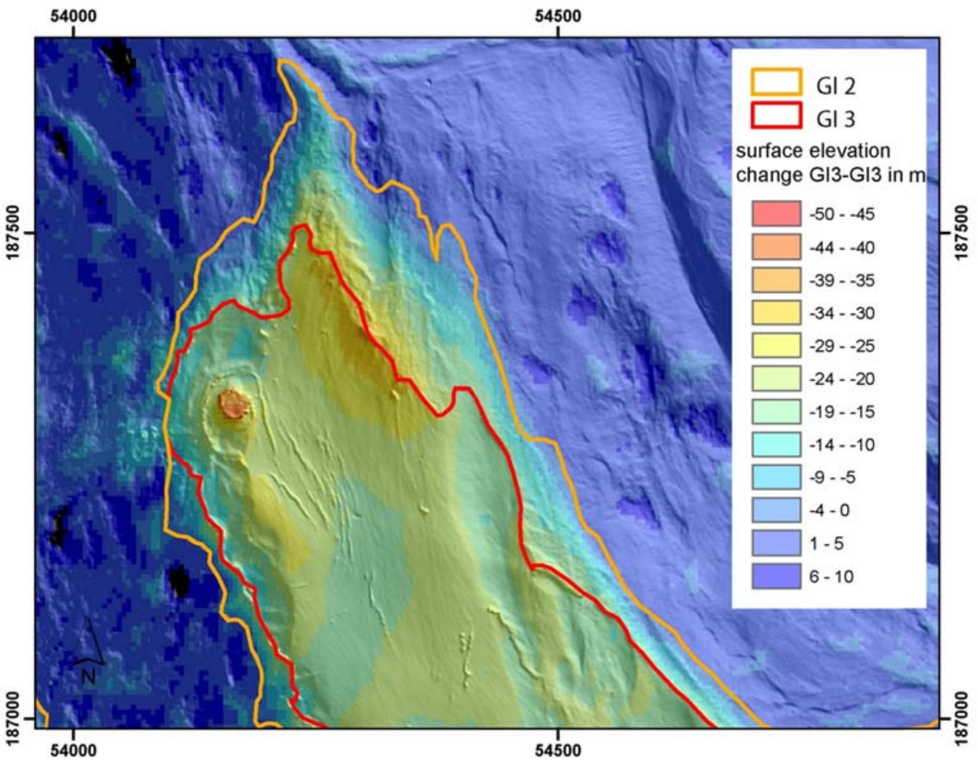
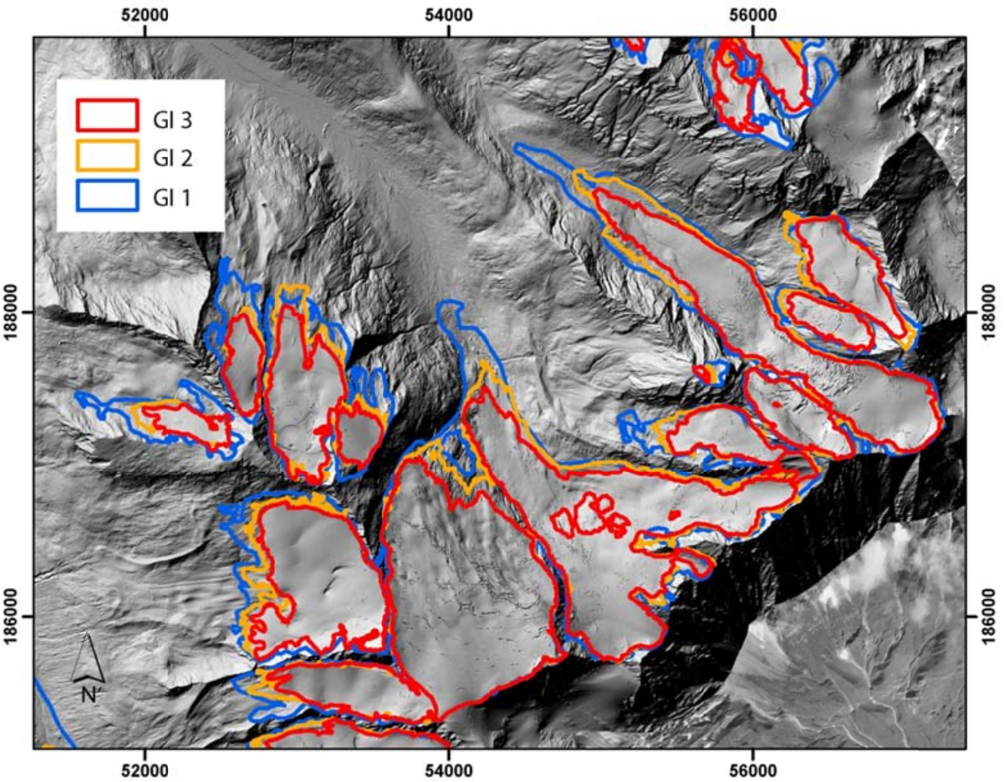


Figure 5: The elevation change between GI 2 and GI 3 superimposed on a hillshade shows that the elevation changes can help to delineate the actual (maximum elevation change) and previous (outer minimum of elevation change) position of the glacier margin (position of the subset shown in Figure 3).



52000
54000
56000
GI 3
GI 2
GI 1
188000
186000
N

Figure 6: GI 3 glacier boundaries superimposed on LiDAR hillshade with GI 1 and GI 2 boundaries (same site as in Figure 2).

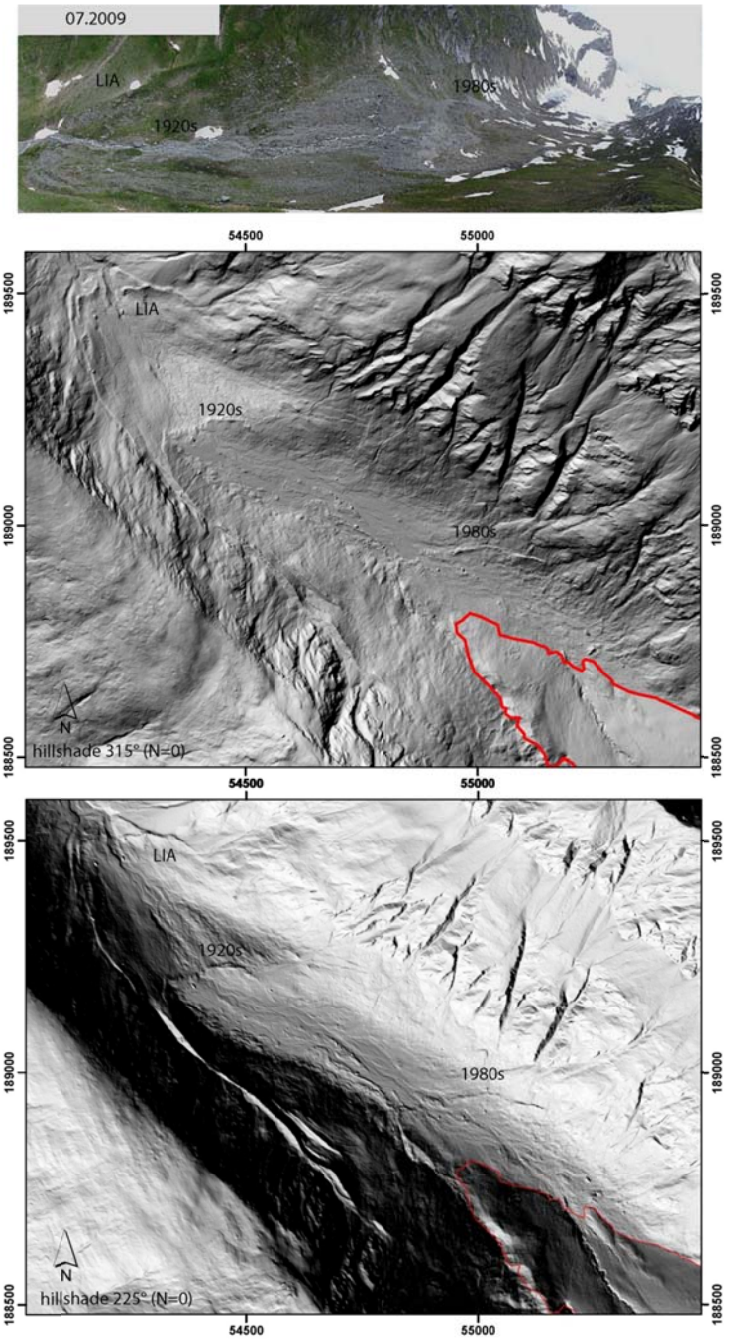


Figure 7: Periglacial area of Gaißbergferner with moraines dating from LIA, 1920 and 1980 (position of the subset: see Figure 3).

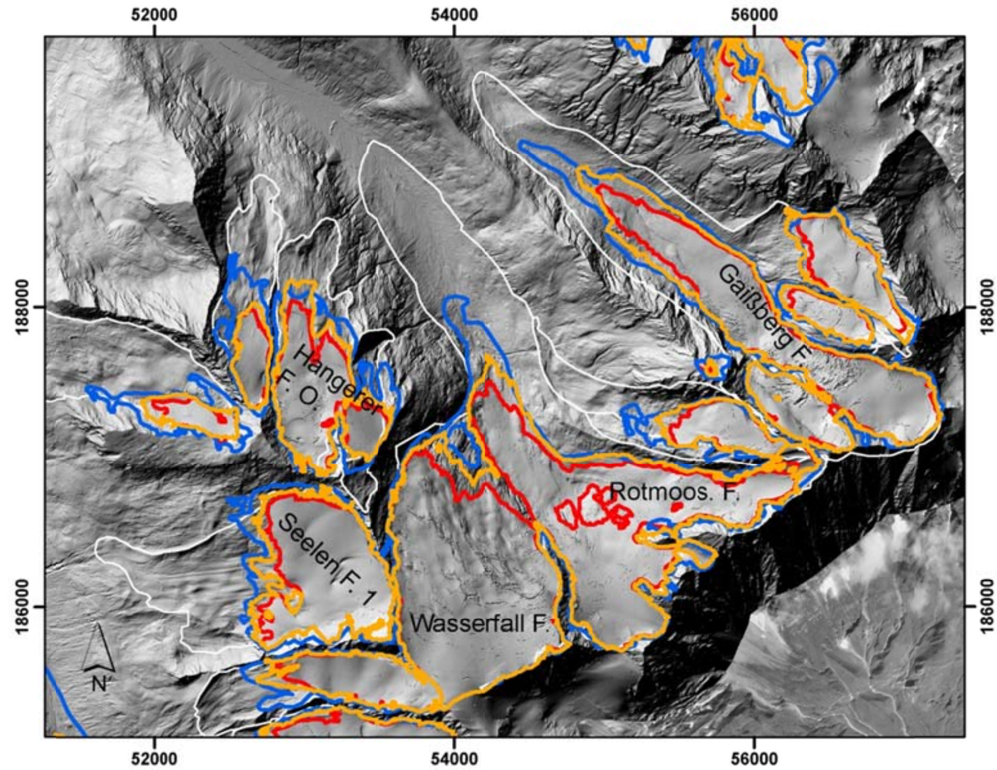


Figure 8: Resulting LIA glacier areas (white) with several modern glaciers contributing to the LIA Rotmoos Ferner and LIA Gaißbergferner (all glacier names: see Figure 2).

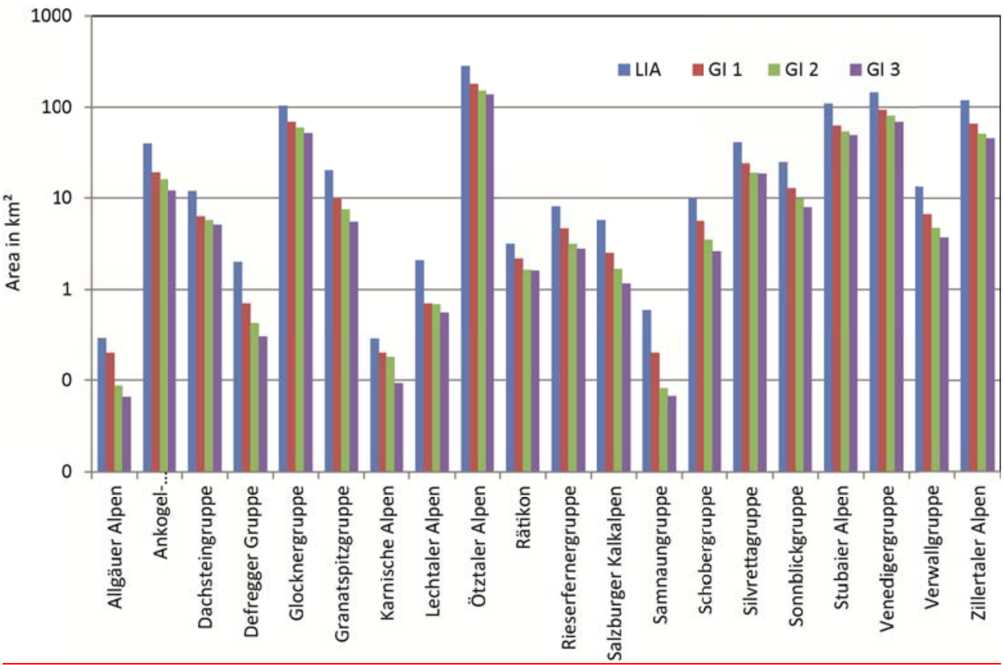


Figure 9: Glacier areas for specific mountain groups in GI LIA to GI 3.

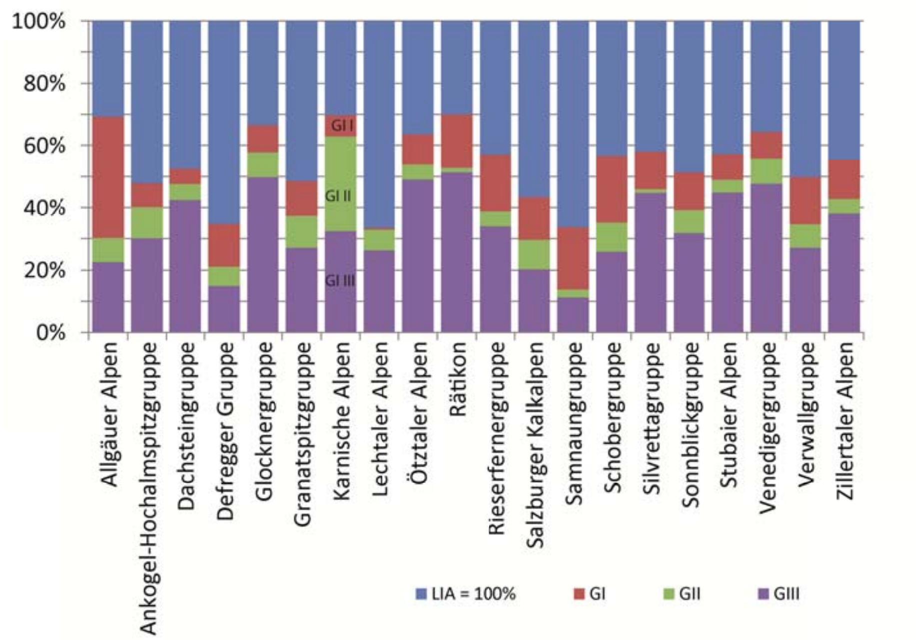


Figure 10: Area changes of specific mountain ranges in percentage of their LIA area.

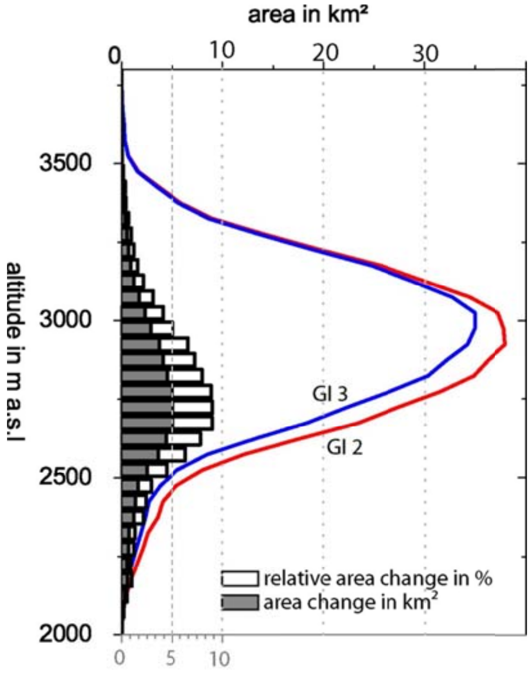


Figure 11: Altitudinal distribution of areas in GI 2 and GI 3 with absolute and relative area changes.

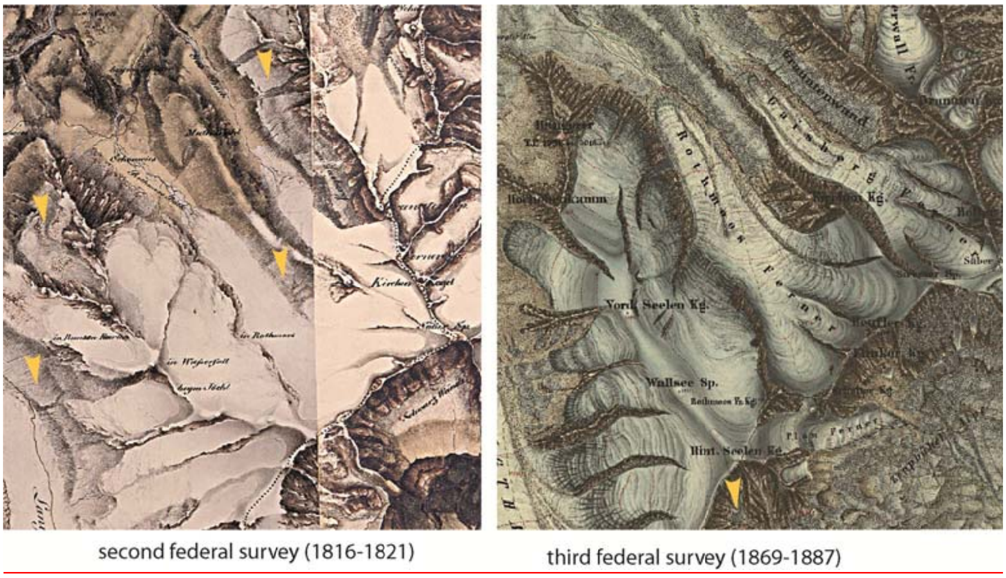


Figure 12: Federal maps of the second and third federal survey (before and after the LIA maximum) show uncertainties in differentiation of snow, firn and glacier (arrows) but give some general impression on LIA glaciers.