Authors response and changed tracked revised version to TC2014-140

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

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Inhalt

Short outline

The paper has been rewritten, most of the old figures were removed, new figures and tables have been added according to the suggestions of the reviewers.

The chapter illustrating temperature and precipitation changes has been removed. The responses are listed per reviewer with following code:

Reviewer comments

Authors response

Changes

Response to Mauro Pelto

The authors thank Mauri Pelto for his valuable comments and suggestions. We will add a comment on the differences between LiDAR and orthophotos or satellite imagery as basis for deriving inventories. If these differences will be considered as advantage or disadvantage of a specific method will depend also on the specific setting of a study. In the current version, this topic has been outsourced to the paper of Abermann et al. (2010), describing the method.

Specific comments:

Title: Austria should appear in the title.

Title: We can of course add 'Austria' to the title.

Changes:We added Austria to the title.

5204-11: This paragraph does a poor job of relating the key temporal results for all of Austria. Proceed in a logical progression from LIA are to GI than GII and finally GIII. How many glaciers were lost between LIA and GI? For example see below: The total glacier LIA area was 941.13 km2 without disappeared glaciers, which is a bit lower than the 945.50km2 found by Groß (1987). By GI the area had declined 40% to an area of 564.88 km2. There was a further loss of 94.21 km2 in the 29 years between GI and GII. In GI III, glaciers cover 415.11 km2, equivalent to 44% of the glacier area at the LIA. Only four glaciers wasted down completely since. The loss of area between GI II and GI III is 55.97 km2, which is the highest annual area loss, at: 0.23 km2 year□1. Losses between LIA and GI I averaged□0.16 km2 year□1 and exceeded the ones between GI I and GI II of 0.13 km2 year□1. There was a period when the majority of glaciers advanced between LIA and GI and GI and GII. The relative annual area loss was only 0.02% until GI II, rising to 0.05%year□1 for the latest period.

5204-11: We can reformulate the paragraph as suggested. Answering the question 'How many glaciers were lost between LIA and today' is more difficult: No exact maps of these glaciers exists, because also in contemporary maps or art snow patches in the highest elevation does not allow a reliable judgement if these snow patches cover glaciers or are only perennial snow fields. Mapping of geomorphological evidence (moraines) in highest elevations might end up in misinterpretation of early Holocene glaciers as LIA glaciers. Therefore, we follow Groß in his estimate of downwasted LIA glaciers, which is based on an extrapolation on what is actually known about downwasted glaciers between LIA and GI I. We can repeat his estimate here.

Changes: We write in the previous paragraph that we do not know the number of glaciers which disappeared after LIA, so that we are not able to give a number here. We rephrased and reorganized the full section.

5205-4: In Figure 3 and Table 3 it is evident that the change for Lechtaler is the lowest from GI to GII and form GII to GIII it is Silverettagruppe and Rakiton. Is there something about the elevation range or other characteristic of the glaciers in these areas that led so the most limited changes?

5205-4: In Lechtal Alps and Rätikon, most glaciers are very small, located in cirques and avalanche fed. In Silvretta, glaciers are small to medium size. We will try to better describe the different response characteristics of the ranges, which are always a mixture between altitude range, mass balance, ice thickness, glacier size and local topography.

Changes: The paragraph was rewritten.

5205-19: Can the shift in the area elevation curve in Figure 4 be used as an approximate indicator of ELA change? Since mass balance programs have been reporting the ELA this can be easily tested too. If not that is good to know as well.

5205-19: Yes, this is a promising parameter including mass balance as well as glacier dynamics. The data set shown here indeed is not the right one to show or proof that parameter and give a profound background. We have much more data available for the mass balance glaciers, and will work that out. In any case, we consider that an independent topic, with potential applications in multitemporal inventories.

Changes: We could not include the additional material for treating this question.

5206-27: It is worth emphasizing the difference statistically in the deviation of summer temperature versus sunshine and precipitation, which indicates that summer temperature has been the principal driver or area lost at least from GII to GIII.

5206-27: We decided to skip the climate section as suggested by the two referees.

Changes: The full section on climate was skipped

5208-16 to 28: Why is this not in section 3.3?

5208-16 to 28: Thank you, we will shift that part in the right place.

Changes: Shifted.

5208-13: Reference needed.

5208-13: We will add two references:

G. Patzelt (1970): Die Längenmessungen an den Gletschern der österreichischen Ostalpen 1890 - 1969. Z. f. Gletscherkunde u. Glazialgeologie, Bd.6 (1970): 151-159.

and

Fischer, Andrea; Patzelt, Gernot; Kinzl, Hans (2013): Length changes of Austrian glaciers 1969-2013. *Institut für Interdisziplinäre Gebirgsforschung der Österreichsichen Akademie der Wissenschaften, Innsbruck*, doi:10.1594/PANGAEA.821823

as references.

Changes: We added the second reference, but instead of the first one, we could cite as well Groß (1987) again, as he describes the sitiation LIA maximum to 1969..

5210-5: "Salzburger Kalkalpen, the plateau glacier seems likely to vanish. " Is this a specific glacier, and is this because the annual ELA has risen above the plateau glacier?

5210-5: Yes, both correct, the Übergossene Alm glacier is vanishing. We can add a reference on past mass balance measurements.

Changes. Paragraph was reworded.

Figure 5: Axis font labels too small.

Figure 5: We will increase the font size.

Changes: Figure removed

Response to S.J. Khalsa

We thank S.J. Khalsa for his suggestions to improve and strengthen this paper.

His remark that the research questions asked on page 5198 are not fully addressed in the paper is correct, and this mistake results from the fact that parts of the original paper have been removed during the discussion among the authors. The section on climate will be removed according to the suggestion of the second referee, so that the research question will be changed to sharpen the focus of the paper.

5197-line5 “All these research” should be “All this research"

5197-line5 Correct, all this research.

Changes: Corrected

5197-16 delete “of older data”

5197-16 The term ‘older data’ was placed only to stress that there is no choice on the characteristics of historical data. This sentence can be reworded.

Changes: Deleted

5198-17 “downwasting of glacier area” is incorrect. downwasting is the thinning of ice, not loss of area (only of volume)

5198-17: ‘downwasting’ can be replaced by ‘decrease’, then the wording should be ok.

Changes: ‘downwasting’ is replaced by ‘decrease’

5199-6 Avoid use of the passive voice so that it is evident who did the action. Rather than “inventories have been compiled: : :” use “X has compiled inventories: : :”

5199-6: We will split up the information in this sentence to the next two ones, as the persons who compiled the inventories are named in the next two sentences.

Changes:The sentences have been rephrased to avoid passive voice (Patzelt (1980) and Groß (1987) compiled…)

5199 Data - section 2.1 should only describe how the inventories were compiled and updated. the results should be moved to a later section.

5199: The suggestion to remove results in the specific section might concern mainly section 2.4, which will be removed according to the suggestion of the second referee. We will shift the other contents to the results.

Changes: As these are not our results, but the properties of data we work with, we decided to leave parts of the data description here, including rough numbers. It would make no sense to describe the difference between the analogue and the digital version of the GI 1 without giving at least the rough number for the total area.

5199-9 please explain what is meant by homogenized

5199-9 The term ‘homogenized’ here refer to the compensation of different dates of data acquisition in the GI II. Lambrecht & Kuhn (2007) developed an estimate for the year 1998, accounting for changes between the acquisition of the orthophotos and 1998. We can include a short description of this procedure, and an explanation that this procedure was only used for the total glacier area, but not for the individual shape files.

5201-23 “to the glacier” is repeated

5201-23 Thank you, ‘to the glacier’ indeed is repeated.

Change: ‘To the glacier’ was deleted

5202 section 3.2 needs more detail on the methodology. for example, provide a graphic illustrating delineation of glacier margins based on surface roughness in lidar data. show how orthophotos were used to update glacier margins. Move information on accuracy to data section and to uncertainty discussion in section 5.

5202: We will be glad to use the additional space we win by skipping the climate part to show in more detail the steps of the analysis of the LiDAR data, which was previously included by citing the paper on the method (Abermann et al., 2010).

Change:Figures and explanation added.

5205-24 do not begin a sentence with numerals. Spell out “Fifty percent: : :”

5205-24: We will spell the 50 % out.

Change: Fifty percent spelled out.

5205-19 GI II should be GI III

5205-19: You are right, it should be GI III

Change: changed to GI3

5207-10 two decimal places in accuracy estimates is not warranted

5207-10: It is correct that the number of decimals is too high, we will discuss if we use one or no decimal.

Changes: we skipped one decimal place.

5208-3 how was the figure of 10% arrived at? could it be 20%? 30%? In fact, isn’t there a fundamental limitation in estimating LIA glacier area (as opposed to just mapping the ablation zone margins)? i.e, there is no firm basis for estimating accumulation area.

5208-3: This number actually was derived based on Groß' estimate of the area of glaciers which disappeared between the LIA and today as well as on the accuracy of the moraine mapping at the glacier tongues and the uncertainty in the firn areas. It fact, we do not believe, that the error could also be 20 or 30 %. We can illustrate that by adding additional information on the LIA ice cover as well as by adding an example of LIA areas. The federal maps are partly available from 1817 onwards for all glaciers since 1870, as well as a number of detailed maps by e.g. Sonklar and Keil and additional images and photograph. All this is in detail explained and illustrated in the paper of Groß, (1987), but apart from citing that, we can add some of the information to this paper.

Changes: We added some of the documents available for estimating the accumulation area and how we arrived at the 10%.

5208-10 GLIMS has established a system for identifying glaciers

and parent-child relationships. Reference Raup, B.H., and Khalsa,

S.J.S. (2010) GLIMS analysis tutorial, 15 pp. Available at

http://www.glims.org/MapsAndDocs/assets/GLIMS_Analysis_Tutorial_a4.pdf

5208-10: Thank you for pointing out the parent and child system in the GLIMS Tutorial.

I found following helpful parts:

6. If no flow takes place between separate parts of a continuous ice mass, they should, in general, be treated as separate units, separated at the topographic divide. However, for practical purposes, such an ice mass may be analyzed as a unit at the analyst's discretion, if delineation of the flow divides is impossible or impractical. If the same system is analyzed in the same way later, it will have the same glacier ID, and can therefore be compared. If the system is analyzed in more detail later by breaking it into its component glaciers, those pieces will get new IDs (ID of system will be "parent icemass" ID for each part), and future analyses of those pieces, if done in the same way, will be comparable.

7. It is possible that an ice body that is detached from another may still contribute mass to the latter through ice avalanches, or it may no longer do so. It is practically impossible to tell which is the case from a single satellite image. Therefore, within GLIMS, adjacent but detached ice areas should, in general, be considered as different "glaciers", regardless of whether they contribute mass to the main glacier through snow or ice avalanches. However, at the analyst's discretion, detached ice masses may be included as parts of one glacier. This is similar to the situation described in 5 above. If the pieces are analyzed separately later, each piece should be given a new GLIMS ID, the old one being used as the "parent icemass" ID for all the pieces.

This is a very good solution for breaking up glaciers. We in fact had the problem that our later analysis did not result in new childs (smaller glaciers), but in new parents (larger glaciers). I did not find a description to handle this problem in the GLIMS outline. In fact, there is a sort of parent ID included in the GI I and GI II, by naming the rivers (and therefore parent LGM glaciers) the glaciers now drain to. Another point I did not really get reading the tutorial, is how the GLIMS recommendation is on how to calculate area changes between the parents and the childs (compare the area of the parents to all the childs, despite an possible change in ice dynamics and topography?). We will try to figure that out and cite the solution.

5210-11: no results were presented to support this conclusion

5210-11: It is correct that this conclusion is weak and not supported by the analysis, as this conclusion could be more easily drawn from the length change data, which is not subject of this paper, As the total climate section will be removed, this sentence will be removed also.

Changes: Paragraph skipped

5210-23: I did not notice any such proposed relationship between summer temperatures and area change

5210-23: The relation was part of an earlier draft, unfortunately some parts of this previous version are still in the submitted version and will be removed.

Changes: Paragraph skipped

5216 Table 1, include acquisition dates

5216: We can include the acquisition dates in the map, as there have been several campaigns per line in Table 1.

Changes: Dates can be found in Table 2 (as before) and Figure 1 (new).

Response to Frank Paul

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.

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 $_{1996\text{-}2002}$' 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.

Changes: We changed roman to Arabic numbers

P5196 L8: Have orthophotos not been used to identify anything?

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

Changes: We added 'and orthophotos'.

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.

Changes: We corrected the 11% and added a Table on relative area changes.

P5196 L11/12: This sentence is a little bit strange. Does it refer to the mean glacier size, or the size class, or the number of glaciers in this size class? When talking about glacier numbers, please consider removing all units that are smaller than 0.01 km2 from the sample (might still be ice but not a glacier). Please also consider if this is an important finding and worth mentioning in the abstract. I assume there are more interesting ones.

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.

Changes: We added 'specific': The number of smaller glaciers increases, the number of larger glaciers decreases. Of course, this is also reflected by changes in mean glacier size and numbers of glaciers in size classes. This is important for further derivation of inventories, as skipping smaller glaciers in inventories and modelling will lead to larger errors when the small glaciers have a higher contribution to total glacier area.

P5196 L14-16: What about glacier changes being indicators of climate change? I assume this is also why we look at glacier changes globally?

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.

Changes: We did not switch the two sentences for the above reason.

P5196 L20: Better use 'glacier mass budgets'.

We can replace balances by budgets without losing any information.

Changes: We replaced balances by budgets.

P5196 L21: It is hypsography rather than elevation (which one minimum, mean, median?), please also add ice thickness distribution, this is what current models are using to determine future mass changes.

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

Changes: We added the terms ‘hypsography’ and ‘ice thickness distribution’ to the list in this sentence.

P5197 L1: Instead of Radic and Hock (2010), I suggest citing Radic et al. (2014) (more up to date).

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

Changes: I suppose this was in L3 and not L1, changed as above.

P5197 L8: Please use glacial only when referring to the last glacial. For contemporary glaciers it should be 'glacier recession'.

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

Changes: to ‘glacier recession’

P5197 L10: A key reason for creation of repeat glacier inventories is to have a base-line dataset to upscale the spatially more sparse direct measurements (e.g. mass balance) to the entire mountain range.

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

Changes: As this topic is addressed a few lines above, it is not repeated here.

P5197 L20: Please shortly explain what 'glaciological data' means (length, volume, mass changes?)

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

Changes: As the purpose of this sentence was to explain why we do studies in the Alps, rather than to list types of data, it was changed to

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 still important working with time series issues of climate change.

P5197 L22: Paul et al. (2004) is only referring to the Swiss Alps rather than 'pan-Alpine'.

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

Change: Shifted to Swiss inventories.

P5197 L24: Maybe add Citterio et al. (2007)?

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.

Changes: We decided to skip length fluctuation data here and keep the focus.

P5197 L29: For the Inventory of the Swiss Alps better cite Paul et al. (2004), the Kääb et al. (2002) paper was more a preliminary assessment. Maybe also add here the recent study by Fischer et al. (2014).

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.

Changes: The Paul et al. 2004 paper is included here in the references. As the citations of the Swiss inventories here are roughly chronological, the Fischer et. al. paper ist still at the end of the paragraph, as it makes no sense to shift it to L29.

P5198 L2: I suggest having a closer look at the cited study by Maisch et al. (1999) for the various possibilities to deal with change assessment of disappearing and disintegrating glaciers (cf. comment to 5209: L23-26)

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).

Changes: The topic is included more explicitly and rephrased.

P5198 L5ff: Please use inventory abbreviations that include the year (e.g. AGI-1969).

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 $AGI_{1996\text{-}2002}$ will make it necessary to look up the periods listed in Table 3 anyway.

Changes: As described above, general comments.

P5198 L13-15: Please show it! When working with unpublished maps or LiDAR data there is a need to illustrate what has been done. Otherwise there is no possibility to agree on the methods, i.e. the study comes as a non-repeatable black box.

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.

Changes: A figure is included later in the methods section. Here, the reference with published data as Figure still is considered sufficient, as we would like to describe methods in the specific section. In case you do mean the unpublished maps of Groß: They are not even included in the original publication of Groß (1987), as they lack scale and tie points. A republication here makes no sense.

P5198 L19ff: Please use a consistent terminology: down-wasting for volume loss, retreat for length changes and maybe shrinkage or area decrease for area changes. This is totally mixed-up in the following sentences. So assuming that 'downwasting of glacier area' means area shrinkage (?), there is no need to introduce differing precipitation trends as an explanation as these have nothing to do with area changes (as the authors write themself on P5210, 3 L15). Apart from this, area changes are a combined effect of thickness changes and ice thickness distribution and thus only marginally related to large-scale climate trends or patterns. In this regard research question (i) makes no sense. Please also note: with a switch to retreat rates the topic is now length changes and 'reverse precipitation trends' would have required an explanation. I have no idea what this should be.

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

Changes: 'downwasting' is replaced by 'decrease'

P5198 L21ff: Question (ii) is justified but does not follow from the opening in L15/16 and should use 'area change rates' rather than 'retreat rates'.

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

Change: This paragraph has been reworded to 'The aim of this study was to update the existing Austrian glacier inventories 1969 (GI 1) and 1998 (GI2) to a complete GI 3 and complement that with a as far as possible consistent LIA inventory based on new geodata and the mappings of Groß (1987). This allows to answer the research question of variability of Austrian glacier area changes and change rates by time, region, size class and elevation.'

P5198 L23ff: As mentioned above, question (iii) is an interesting one to be answered, but it cannot be obtained from this dataset as there is basically no relation between area changes and climate change. It has also to be noted that this study does not even make a try to connect the two (2.4, 3.4 and 4.3 only describe the climate data). The only sentence about (iii) is popping up out of nowhere in the conclusions (L11/12) and has no information at all. In short, please remove the climate data from the study, they do not make any sense here.

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

Changes: The paragraph has been reworded as described above.

P5198 L26: What are 'respective climate changes'? Is it known which part of the climate change is related to which part of the area changes? I mean there is no mentioning of glacier response times at all, how could a 'relation' be discussed?

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.

Changes: This paragraph has been skipped

P5199 L3: I do not see this comparison with climatic changes? Where is it?

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

Changes: This part of the sentence was skipped as the climate part was skipped.

P5199 L5: Where is the description of the datasets that have been used to get the LIA extents? There is nothing in section 2.2 or 2.3 but details are given in the methods section 3.3. Please move the first paragraph from that section to datasets.

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

Changes: We included the LIA inventory in this section.

P5199 L8-10: Please explain why this is important to know when the data have not been used.

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).

Changes: We shifted that to the discussion, as this question is part of this reviewers questions.

P5199 L9/10: I suggest introducing the difference between recorded glacier area and homogenized area before numbers are given. Please also explain how they are calculated, why this is important to know in the context of this study, and which dataset has finally been used here. The text is rather difficult to read and understand in this regard.

Ok, we can do that.

Changes: We shifted that to the discussion, as this question is part of this reviewers questions, at the position where he asks for it.

P5199 L15/16: Why is volume change introduced here as a dataset? So far I thought area changes are analysed?

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.

Changes: We skipped the citation of volume change.

P5199 L17: Are these missing datasets included in the RGI? What is the frequency distribution of glacier number / area covered for each year? What is the (estimated) error of the homogenized 1998 dataset compared to reality (i.e. when used as a base for comparison)?

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.

Changes: As the number of glaciers for each year is shown in Figure 1 and the Table of results, we could not introduce a second table showing the same thing. The section has been reorganized, following also the valuable suggestion in here and by other referees.

P5199 L19: Why is this section only about DEMs rather than glacier outlines? I understand that hillshades of the DEMs have been used to trace glacier extent based on differences in surface smoothness, but this link should be made here to understand the details of the description.

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.

Changes: A paragraph has been added at the beginning of this section to explain why this information is in the data description. As this is a repetition, it was kept short.

P5199 L22: 'moraines': maybe introduce here that LIA extents were mapped based on the well recognizable lateral moraines and add where the information is described that was used for digitizing LIA extents in case they are not present.

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

Changes: This has been written several times above, and will come later again in the methods section. Therefore, we did not repeat that here.

P5199 L22/23: 'between 2006 and 2012': this is also a 7-year period (as for AGI-1998): please explain (at latest in the methods section) how the temporal homogenization was done here and what the impacts are. At the extremes, glacier changes are derived for either a 4-year (2002 to 2006) or a 16-year period (1996-2012) and it is easy to say that this makes no sense. Maybe a map (and/or a graph?) can be provided on how long the AGI-1998 to AGI-2009 period is in reality (regionally and by number/area covered) to justify it.

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

Changes: This is the data section. The requested description comes in the method, results and discussion sections.

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.

Change: This is the data section, the method section with this topic comes later. The acquisition of DEMs and orthophotos is usually done at a minimum snow cover, to keep errors due to snow cover small. In case of optical data, the reason is oversaturation, the reason for LiDAR is that usually the elevation of the ground and not of the snow surface should be measured. See Abermann et al. (2010) and the other LiDAR references given. As this is the data section, and the data was acquired at a specific time of the year as a fact, we do not think that it needs a teaching book explanation here. The focus of this paper is not the comparison of different methods.

P5200 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.

Change: The description was changed to make it easier to find the above information, Figure 1 was changed following all the suggestions.

P5200 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

Change: 'true'added

P5200 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

Changes: s added.

P5201 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.

Changes: To 'The compilation of the glacier inventory time series aims to allow monitoring any glacier changes rather than changes in basic definitions. Therefore, for example ice divides or specific definitions regarding what is a glacier, might be 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, and map for example changing and not constant ice divides'

P5201 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.

Changes: This part was skipped, as it is not important for this study.

P5201 L23: Please describe to which inventory the snow-covered area was added (1969 or 1998 or both)? This is unclear from the text. Please also add by how many percent glacier area increased by this and that a likely overestimation of glacier area resulted from this addition as snow conditions were partly not suitable for glacier mapping (dataset description).

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

Changes: There is a misunderstanding, area above the bergschrund is not necessarily snow covered. This explanation is now part of the data section. P5201 L24: 'impossible': this has actually some rather drastic implications, basically it means that a glacier inventory cannot be compiled under adverse snow conditions (i.e. seasonal snow hiding a glaciers perimeter). When an inventory is nevertheless compiled under such conditions, one can never be sure whether any changes in extent through time are glacier changes or changes in snow extent. Which basically means that observed changes have lost any significance in climatic terms. Please elaborate on this and explain why it is sensible to derive 'glacier' changes nevertheless, maybe considering that most of these 'attached' perennial snow fields (in GI I and II) melted away in 2003 thus leading to huge (and unrealistic) area loss rates between the AGI-1998 and the RGI-2003 dataset.

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.

Changes: This part has been skipped. We still have no indication that the bergschrund areas melted away between GI 1 and GI2.

P5201 L25: Possibility (1): remove the comment on geomorphological parameters as these have not been further exploited or possibility (2): add them also to the AGI-1998 (and/or AGI-2009) dataset and expand the study by also describing how these have changed through time (e.g. mean elevation as a proxy for a balanced budget ELA). I would opt for (2) to get some flesh on the bone of this study. The current focus on area changes is a bit thin.

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.

Changes: The comment on geomorphology was removed

P5202 L2ff: 'not straightforward': I would say that summing up the parts belonging to a former larger glacier to track area changes through time is at least more easy than doing this for other parameters like minimum or maximum elevation. As this has been done in the same way in earlier studies, maybe just cite them here as an example?

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.

Changes: This part has been rephrased, point out the parent and child solution of GLIMS.

P5202 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.

Changes: We added the description of parent and childs for disintegrating glaciers and the problem of defining grand parents.

P5202 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.

Changes: It is mentioned in the paper that the ice divides have been calculated as water divides from the DEM 1998 (GI 2), Figures 2 ff show the position of divides.

P5202 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 howthe 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.

Changes: This section was moved to section 3.2 describing the methods.

P5202 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.

Changes: See section 3.2 . Gaißbergferner shown in half of the Figures has a large dead ice area and an ice cored moraine.

P5202 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.

Changes: This is still the section with definitions, the suggested change takes place in the discussions

P5202 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.

Changes: photogrammetry refers to the derivation of DEMs from orthophotos. This sentence does not directly refer to mapping of glacier, but to DEM generation. We added some sentences to make that clear. The paragraph was shifted to the data section.

P5203 L4/5: As mentioned above, can a figure be added illustrating how this works?

yes

P5203 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.

Change: A 'mapping from orthophotos section' has been added to the methods section, plus a citation of the accuracy of GI II mapped also from orthophotos.

P5203 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.

Changes: We described how we mapped the LIA margins and included a Figure.

P5204 L1: I suggest removing this entire section.

We will follow this recommendation

Changes: We skipped the climate records.

P5204 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.

Changes: We reorganized the full section and added annual relative area losses. We can not add that the relative annual area loss as suggested for GI 1 to GI 2 is 1.2%, because we can not calculate a decreased retreat by positive mass balances as shown for several glacier during the advance period. This would involve detailed modelling of glacier dynamics of all Austrian glaciers, which is clearly not the focus of this paper.

P5204 L22: Please decide using either (Alpen / Gruppe) or (Alps / Group).

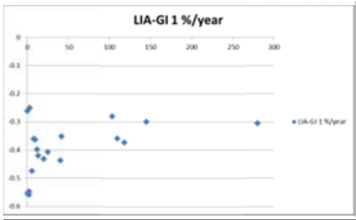
ok

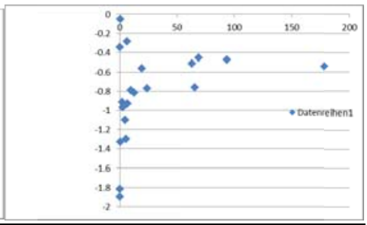
Change: We use the german spelling

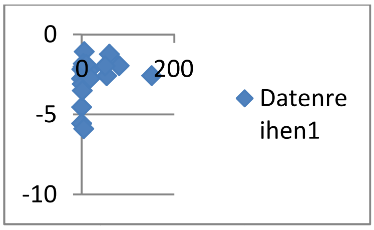
P5204 L26: It might be useful to already add here (or later in the discussion) that this is due to the larger number of larger glaciers in this region and the dependence of the relative area loss on glacier size (decreasing towards larger sizes). I recommend supporting this with a scatter plot showing glacier area vs relative change rates for various samples and/or time periods. This might lead to further interesting conclusions.

We will include the suggested Figure.

Changes: The suggested Figures show no information and have not been included. The high variability of small groups is evident from the table.







GI LIA-GI 1 GI 1-GI2 GI2-GI3

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.

Change: This paragraph has been rewritten

P5205 L14: Any chance to report how much of the area was lost instead of what remains?

This is the subject of the next sentences.

Change: Done

P5205 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

Changes: We included the relative area change.

P5205 L26/7: should be 'glacierized' and 'area loss'.

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

Changes: to 'Therefore the main portion of the glacier covered areas are stored in regions above the current strongest area losses.

'

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.

Changes: We joined Tables 4 and 5. Setting a minimum size threshold has nearly no impact, see the new paragraph in the text, where we list the numbers and areas of very small glaciers.

P5206 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

Changes: Climate part removed.

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.

Changes: Figure added.

P5207 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.

Changes: This is part of the data section.

L12: Please discuss more thoroughly how this temporal issue is related to the variable data acquisition for AGI-1998 and AGI-2009 and calculation of mean annual change rates.

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

Changes: There is no spatial and temporal indeterminacy in GI1 to 3. In contrast to the occurrence to the LIA maximum, for which the date is not known for every glacier, we know exactly when the GI 1 to 3 date from. As you suggested to calculate mean annual relative change rates, and we followed this suggestion, we had to add a short paragraph on fluctuations.

L24: This sounds if these alterations of moraines have not been considered for the mapping despite the manual delineation of the outlines (which I assume is a wrong impression)? What about the regions at the glacier terminus where LIA moraines were often eroded? How have these been identified?

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.

Changes: No changes, as this is explained in Groß (1987).

L25ff: Other studies (e.g. Maisch et al. 1999) have simply used the extents of the first inventory (here AGI-1969) as a starting point for the accumulation region. While this might underestimate the true area, it might still be in the same order as the uncertainty of the historic maps in this region. From the description I am not sure what approach has been taken here. Please describe it better (in the methods section) and add some figures.

ok

Changes: Figures added.

P5208

L3: What is the impact of this uncertainty on the derived change rates?

We can give a number here.

Changes: The annual change rates depend on the time of LIA maximum, as the length of the period is 119+-50 years, and we neglected the glacier advance of 1920, the 10 % error in area is not the major problem for the interpretation of change rates.

L4-10: This is basically a repetition of the text in the methods section. Is it possible to go beyond that and discuss the approach in the context of other studies?

We can add some more details

Changes: this paragraph was skipped.

L10: I recommend checking how the parent glacier ID concept is handled in the GLIMS database? It might be worth looking at and adapting it here.

ok

Changes: We skipped this discussion, as the problem is illustrated in a Figure. as we do not perform a glacier by glacier comparison, it is not relevant here.

L11-16: As mentioned above, please calculate these other change rates using the shorter time periods and discuss the results here in comparison to other studies that have done it already a decade ago. There is no need to stay descriptive and vague here.

We can add some figures and numbers.

L18/19: I would remove this sentence here as it breaks the flow.

ok

Changes: This paragraph had been removed

L20/21: Please report the numbers! 'differ slightly' has no meaning.

ok

Changes: This paragraph had been removed.

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.

Changes: It is not clear which study with better snow condition is meant. As the paragraph is skipped, the number is reported in the data chapter, no changes have been made.

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.

Changes: The 10 to 15 are unclear, and not evident from our data. This paragraph was moved to the data section.

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

We will quantify that.

Changes: This paragraph was skipped. There is no impact of snow cover on the number of glaciers, and the snow covered area in GI3 is less than 3%.

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

Changes: this point appeared in the suggestions.

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

ok

Changes: No changes.

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

ok

Changes: relative changes added.

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

yes

Changes: Paragraph rephrased.

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 available in Google Earth and similar tools are already used directly to digitize outlines (e.g. Schmid et al. 2014), (ii) does 'information' mean attributes in the database? In this case there is no difference to satellite derived inventories as these can host additional information as well (maybe such 'information' should be added to the here presented inventories as well?), (iii) this is possible also for satellite images and seemingly failed for several of the aerial photos used for the inventories described here, (iv) why should this not be possible for satellite-derived inventories? In short, please pick some other advantages and be fair with the shortcomings.

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.

Changes: We do not want to completely ignore global data sets, although we are well aware that they have different aims, methods and results, which is ok. The scope of this article is not a comparison of methods. Therefore we rephrased this section, showing that the results are somehow different, but with absolutely no implications as you cannot compare the scales.

L18: Please do not care about the different number of glaciers in different inventories, and maybe reduce the number of digits somewhat (384 km2 should be ok).

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.

Changes: number changed to 364 km².

L18: I am not sure if this has something to do with 'consistent data management' (or I misunderstand the meaning). Reasons for the differences are mainly missed debris-covered glaciers and removed very small glaciers (smaller 0.01 km2) in the RGI and too large glaciers in the AGI-1998 / AGI-2009 due to inclusion of perennial (and seasonal) snow.

We will check that and add some illustrations.

Changes: We can exclude snow and small glaciers as reason, and changed the paragraph so that it is clear that this is a scale problem. See the attached images (RGI: blue, GI 3, red).L23-26: Please be aware that glacier numbers have a very limited scientific meaning and that mean glacier size was not presented in this study. The issue with the multi-temporal comparison of glaciers that split through time has been presented in previous studies and I am actually not sure what the approach selected for this study was. I recommend making a reference to one of those earlier studies (e.g. Maisch et al. 1999, Citterio et al. 2007, Paul et al. 2004) and then apply the method here in the same way (and please add a figure showing how this looks like).

ok, as above

Changes: This sentence was skipped.

P5210

L1: The conclusions will certainly change once the more in-depth analysis of the four glacier inventories has been performed.

Could be the case.

Changes: Happened.

L4/5: I would prefer writing what percentage was lost (min/max for specific regions and overall) rather than what is still there.

yes, as above

Changes: Conclusions rewritten.

L7/8: Where have these numbers been presented or discussed and why 'nevertheless'? A 4% area loss per year is enormous (to what period does it belong?)

We will add the information

Changes: Conclusions rewritten.

L9: If comparable periods are compared the loss rates are likely equal (about -1.2%/year).

We will check that

Changes: Conclusions rewritten.

L11-16: Please just remove this. It has neither been shown in this study nor is there any scientific reasoning behind it. Without a clear link between temperature change and area change there is no way to present this as cause and effect. I can see such a relation for mass balance, but glaciers have a response time! I have no idea why this is still ignored in so many studies reporting glacier area changes.

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

Changes: Conclusions rewritten.

L17-20: I recommend having a look at the GLIMS database design. The parent glacier ID concept is there since about a decade.

as above

Changes: Conclusions rewritten.

L21: I am not sure if ice dynamic models require a standardized ID tracking system? I mean such models use outlines from time 1 and compare modelling results to outlines from time

We will illustrate the problem

Changes: Conclusions rewritten.

2. How does an ID help for this?

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

Changes: Conclusions rewritten.

L23-27: Please remove. There is no 'proposed relation' in this study.

Changes: Conclusions rewritten.

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

Changes: Acquisition dates are found in Table 2. we see no advantage in adding another list in Table 1 which is redundant. Figure 1 is changed.

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

ok

Changes: removed

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

Changes: As Figure 1 shows the mountain ranges and the sensor, and Table 1 the mountain ranges and the acquisition year (in the text: August or September of each year the data was acquired).

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

ok

Changes: We transposed Table 5, and merged it with table 4.

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.

Changes: Figure redone

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.

Changes: The scatter plot makes no sense – you just see scatter. See graph above.

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

ok

Changes: Done

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.

Changes: Figure redone

F5: Please remove.

That comes along with skipping the climate chapter.

Changes: removed

Cited references

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Example Comparison RGI GI3

This section shows some examples demonstrating the scale differences between RGI (blue) and GI 3 (red). The RGI as global inventory has a much larger scale as the GI 3. The glaciers are superimposed on orthofotos 2010 (affected by some snow,but suitable for a look at the differences with the help of independent data sets) of the Federal Government of Tyrol, available for free at

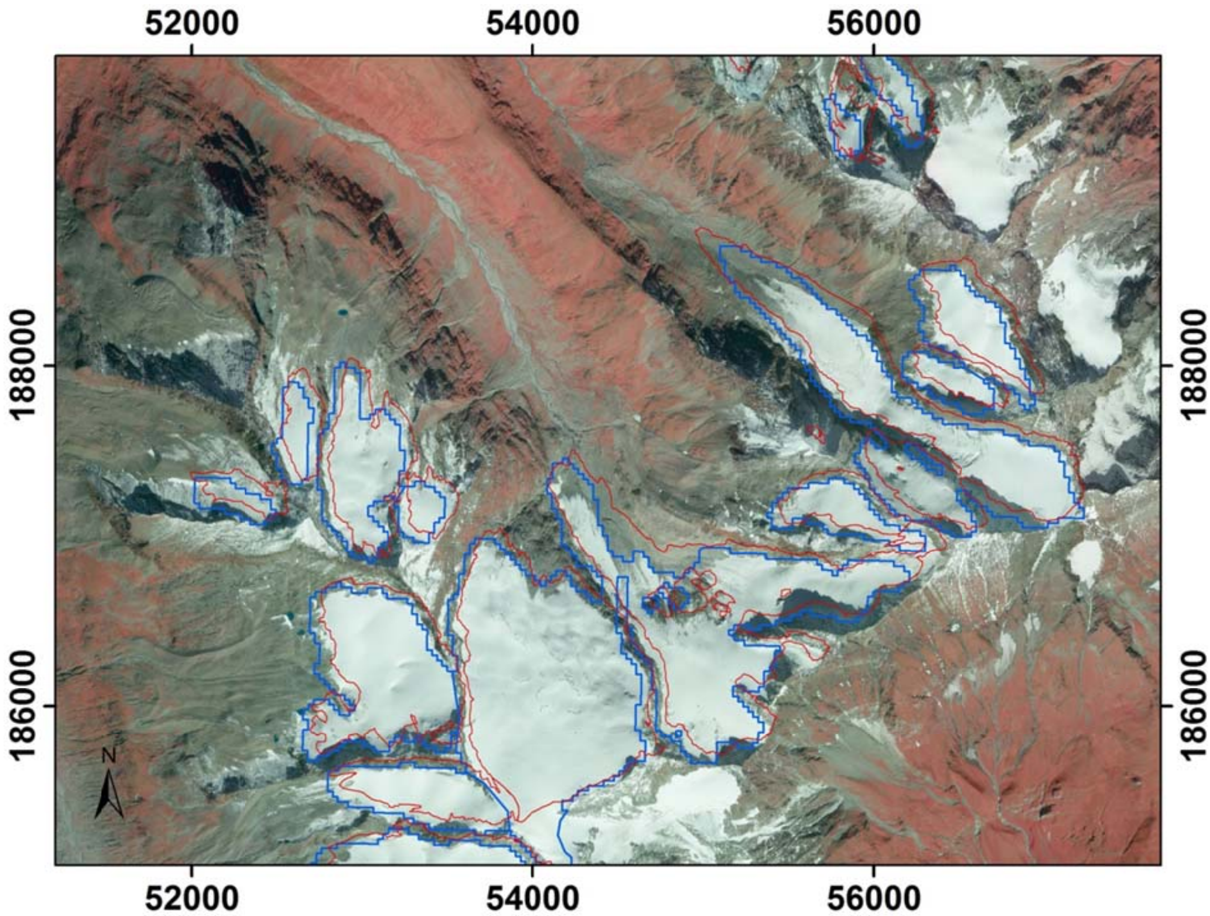
https://gis.tirol.gv.at/arcgis/services/Service_Public/oph05_wms/MapServer/WMSServer

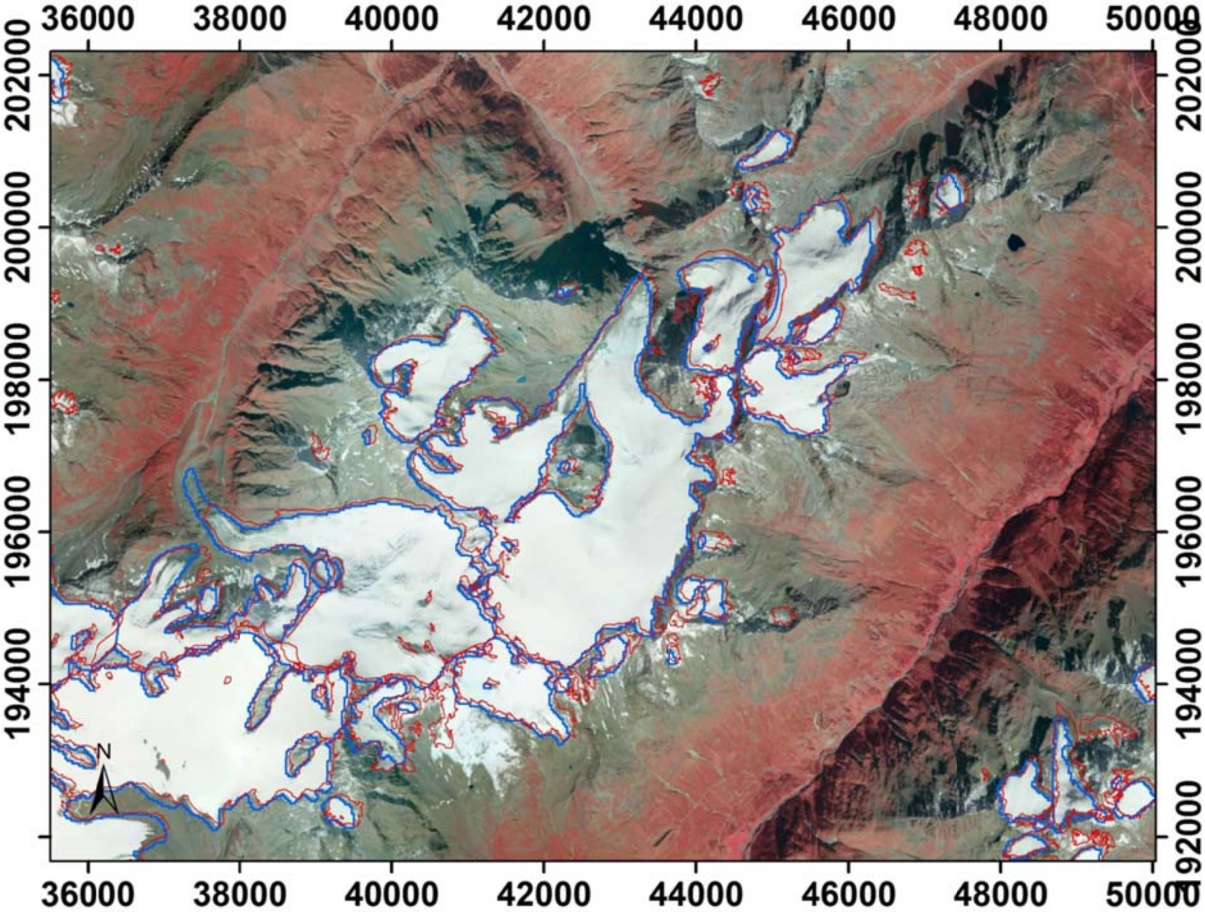
How to use the data:

https://portal.tirol.gv.at/t3tiro/fileadmin/themen/sicherheit/geoinformation/Geodaten/AnleitungWMS.pdf

For full transparancy, we added the download possibilities for data used in this study.

The data was not reprojected, but just displayed with standard parameters. This causes small shifts, which have nothing to do with data accuracy.





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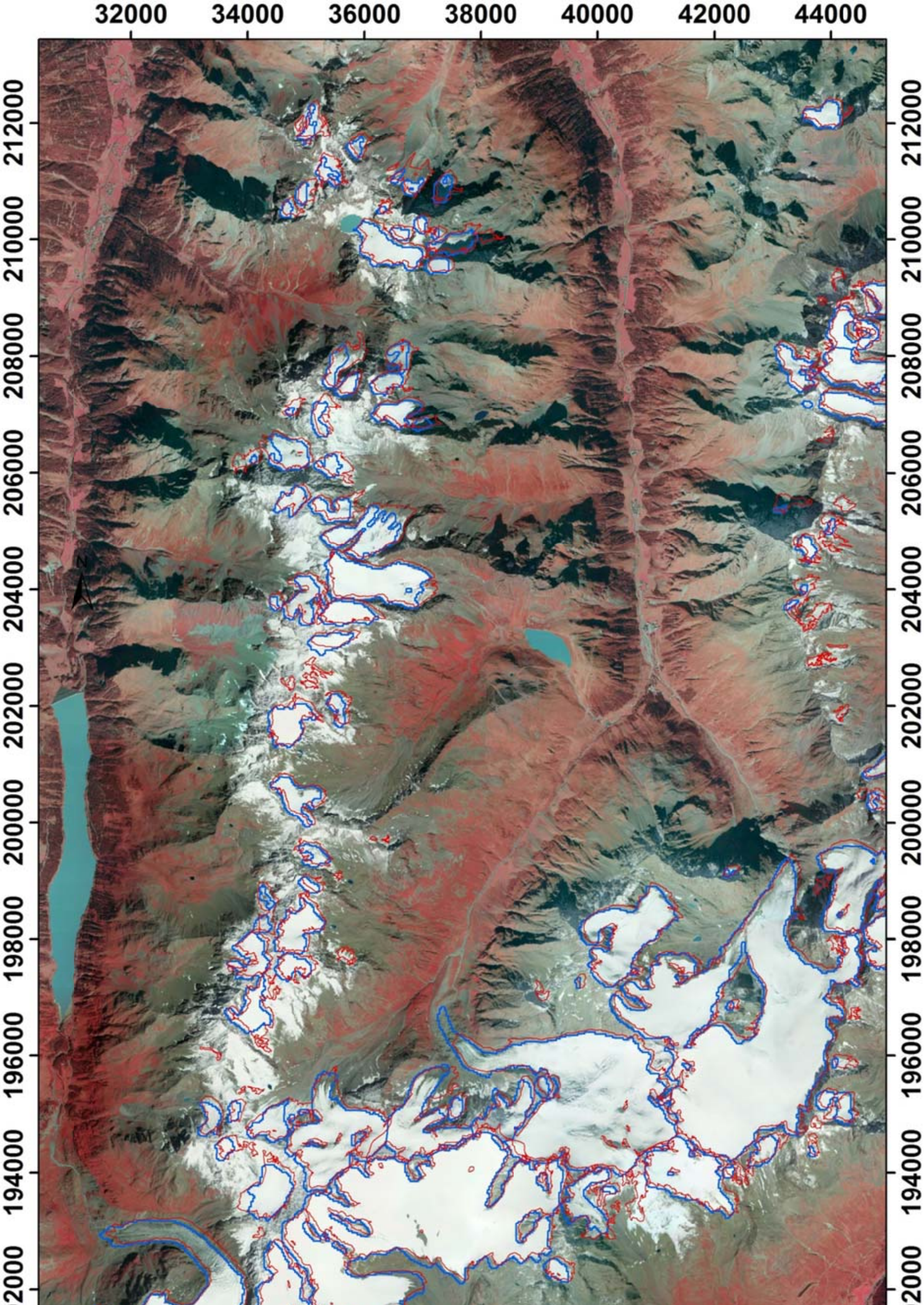
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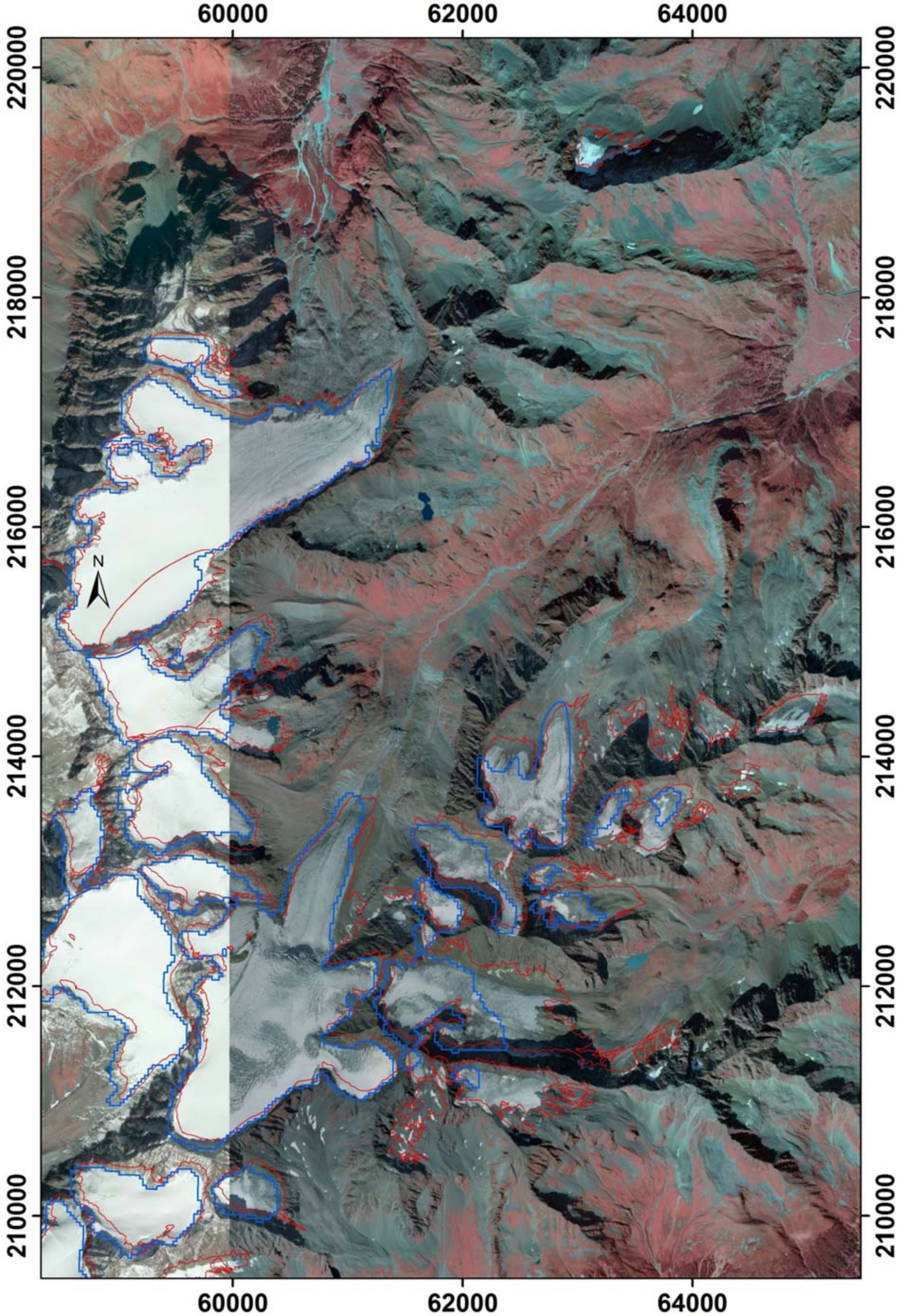

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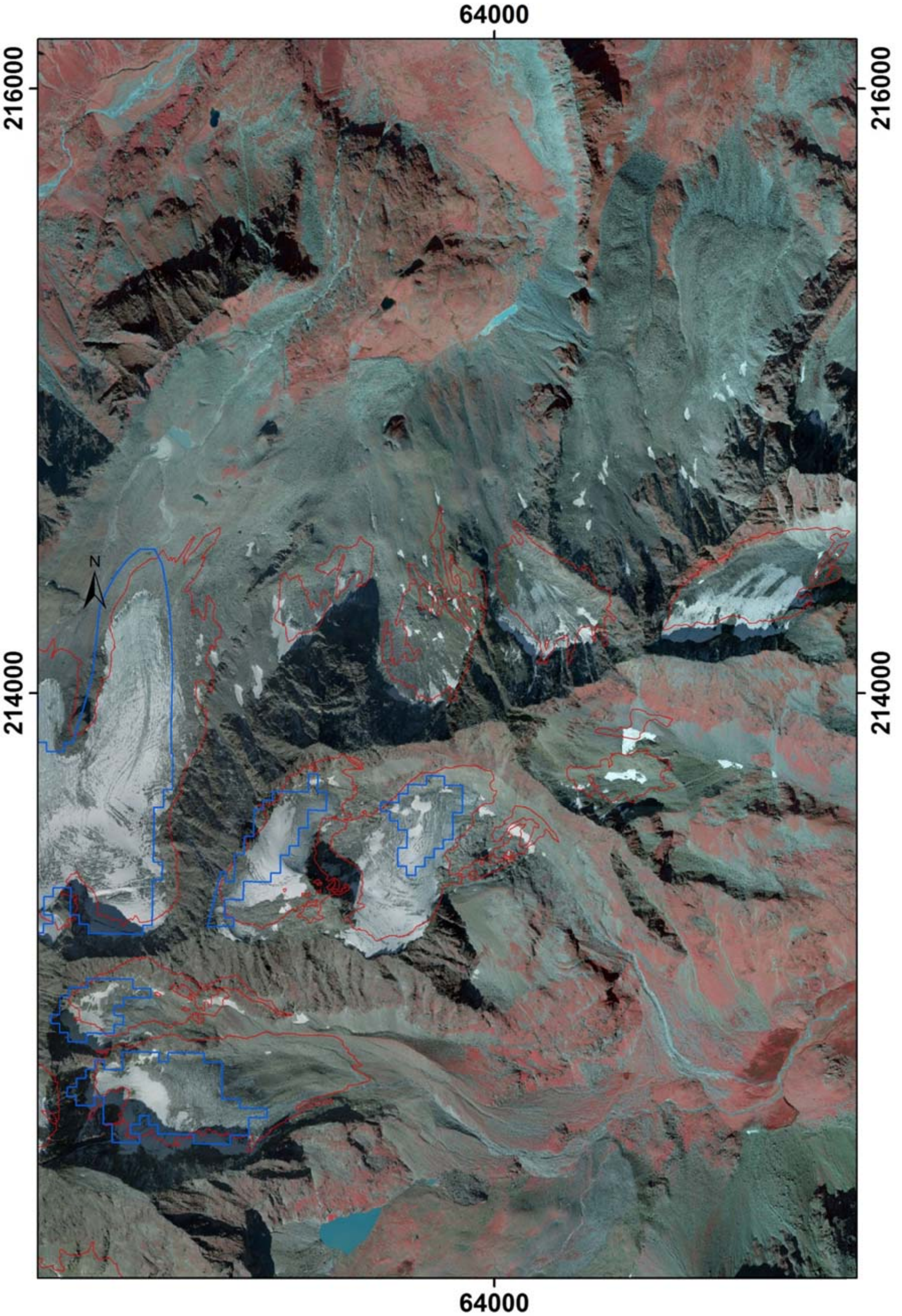
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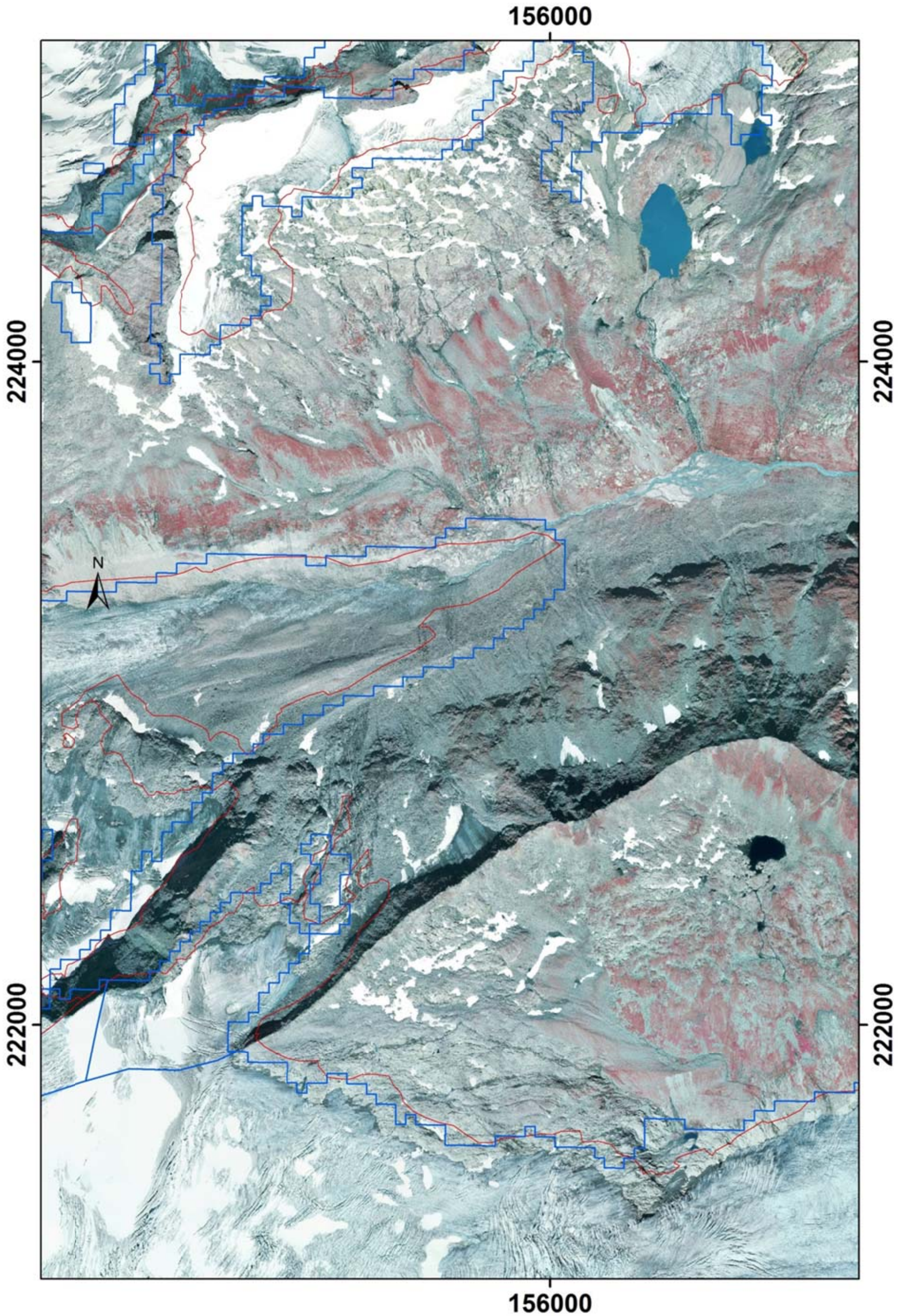
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Tracing glacial disintegration from the LIA to the present using a LIDAR-based hi-res glacier inventory in Austria

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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 updating data from 1969 (GI ~~I~~1) and 1998 (GI ~~II~~2) has been compiled, based on high resolution LiDAR DEMs and orthophotos dating from 2004 to 2011 (GI ~~III~~3). To expand the time series of digital glacier inventories in the past, the glacier inventory of the Little Ice Age maximum state (LIA) has 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, 0.6 %/year for GI 1 to GI 2 (29 years, one advance period in the 1980s) and 1.2 %/year for GI2 to GI 3 (10 years, no advance period)~~show high regional variability,~~are generally increasing from LIA to GI 3 from ~~ranging from 11% annual relative loss to less than 1 % for the latest period~~. Regional variability of the annual relative loss is highest in the latest period, ranging from 0.3 to 6.19 %/year. The specific glacier sizes reduced from LIA to the latest period, so that 47% of the glaciers' areas are smaller than 0.1 km² in GI ~~III~~3.

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 ~~balance~~ budgets to sea level rise needs accurate information on the area, ~~and~~ ~~elevation~~ 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 GLIMS initiative (Kargel et al., in press). 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; Radic´ and Hock, 2011). Based on the glacier inventories, ice volume has been modelled with different methods as a basis for future sea level scenarios (Huss and Farinotti, 2012; Linsbauer et al., 2012; Radic´ ~~and Hock~~et al., 201~~0~~4). 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). All ~~these~~ this research is based on the most accurate mapping of glacier area and elevation at a particular point in time.

For large-scale derivation of glacier surfaces, satellite remote sensing methods are most frequently applied (Paul et al., 2010, 2012, 2013). For direct monitoring of ~~glacial~~ glacier recession over time, and the linkage of the loss of volume and area to local climatic and ice dynamical changes, 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., 2011; Andreassen et al., 2008) can only be compiled from additional data with varying error characteristics (e.g. Haggren et al., 2007) and temporally and regionally varying availability~~ of older data~~, limiting the availability of global sets of historical data. Apart from the inventories mentioned above, further extra-European regional time series of glacier inventories are available, for instance, for the Cordillera Blanca in Peru (Lopez-Moreno et al., 2014).

~~Glaciological data in the~~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 still important working with time series issues of climate change.~~ Alps are among the longest and densest time series.~~ Apart from the Randolph glacier inventory data (Ahrendt et al., 2012) and a pan-Alpine satellite-derived glacier inventory (Paul et al., ~~2004,~~ 2011), several national or regional glacier inventories are available. 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 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 Austrian Alps, glacier inventories so far have been compiled for 1969 (Patzelt, 1980; GI ~~I~~1) and 1998 (Lambrecht and Kuhn, 2007; GI ~~II~~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 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 ~~I~~1 and GI ~~II~~2.

The pilot study of Abermann et al. (2009) in the Ötztal Alps identified a pronounced ~~downwasting~~ decrease of glacier area, but differing for different size classes~~, and Auer et al. (2007) found remarkably different precipitation trends south and north of the main Alpine ridge.~~ ~~.This raises several research questions: i) Is the increasing retreat rate found by Abermann valid for all Austrian glaciers, or are the reverse precipitation trends found by Auer~~

~~(2007) also reflected by glacier retreat rates? ii) How large are the current retreat rates compared to past retreat rates? and iii) Can we define a relation which allows the calculation of area decrease as a function of climate change?~~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 that with a as far as possible consistent LIA inventory based on new geodata and the mappings of Groß (1987). This allows to answer the research question of variability of Austrian glacier area changes and change rates by time, region, size class and elevation.

~~In this study, the compilation of the glacier inventories of LIA maximum state (GI LIA) and 2006 (GI III) is presented together with a comparison of area losses in the period LIA-1969, 1969-1998 and 1998-2006 with the respective climatic changes as recorded in the HISTALP climate data (Auer et al., 2007). After a short description of the method developed by Abermann et al. (2010), the resulting losses of area are presented for the specific mountain ranges and size classes.~~

2 Data

~~This study is based on glacier inventory data of 1969 and 1998, updated by LiDAR data and orthophotos and compared with climatic changes since the LIA as documented by the high quality HISTALP instrumental climate data.~~The Austrian inventories described in this section have been the basis for the compilation of the new inventory, GI 3, and the updating of the LIA inventory with the help of LiDAR data and orthophotos. LiDAR data was used to calculate hillshades and volumes changes used for updating the glacier outlines of GI 2. For a small number of glaciers, where LiDAR data was not available, orthophotos have been used.

2.1 Austrian Glacier inventor~~ies 1969 and 1998~~ies

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Patzelt (1980) and Groß (1987) derived the first Austrian glacier inventory GI 1 based on orthophotos from 1969 (shape files: Patzelt,2013). Groß (1987) compiled glacier inventories for the LIA maximum and 1920 from the GI 1 geodata and field surveys mapping the moraines of the respective glacier adavances.

Lambrecht and Kuhn (2007) used othophotos between 1996 and 2002 to update the ~~The~~ glacier inventor~~ies~~y 1969 (GI ~~I~~1), which they also digitized (Figure 2). ~~and 1998 (GI II) have been compiled from orthophotos dating from 1969 and the years between 1996 and 2002~~. In the first, analogue, evaluation of the 1969 orthophotos by ~~Groß (1987) and Patzelt (1980),~~ the area 1969 was determined as 541.7 km². ~~The digital reanalysis of the inventory 1969 by Lambrecht and Kuhn (2007) found a total glacier area of 540 km².~~ The glacier areas have been delineated manually ~~(~~by Lambrecht and Kuhn~~,~~ (2007)~~;~~ Kuhn et al., 2008) as recommended by UNESCO (1970), i.e. 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 54~~0~~67 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 number of different flight campaigns was 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 have been covered during the years 1997 (43.5% of the total area) and 1998 (38.5% of the total area). Lambrecht and Kuhn estimated the effect of compiling the glacier inventory from data sources of different years by calculating an ~~homogenized~~ area for the year 1998. They did the temporal homogenization of glacier area by upscaling or downscaling the recorded inventory area in specific altitude bands with a degree day method to the year 1998~~,~~. They found a ~~which differed~~difference of the recorded area by only 1.2 km² from area temporally homogenized to the year 1998:~~the recorded areas~~. 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 portion of snow cover on the orthophotos. The maximum area of the glacier area is estimated to be ±1.5% (Lambrecht and Kuhn, 2007). ~~The digital reanalysis of the inventory 1969 by Lambrecht and Kuhn (2007) found a total glacier area of 540 km². The glacier areas have been delineated manually (Lambrecht and Kuhn, 2007; Kuhn et al., 2008) as recommended by UNESCO (1970). The volume change was quantified as 4.9 km³, corresponding to a mean elevation change of -8.7 m in 29 years, corresponding to -0.3 m/year.~~ 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 data were recorded between 2006 and 2012 in several campaigns covering most of the Austrian glaciers~~. ~~The minimum point density is 1 point /4 m^2. The vertical resolution ranges from few decametres to several centimetres, depending on slope and surface roughness (Sailer et al., 2014).~~ ~~The flights were carried out during August and September, when snow cover was minimal and the glacier margins snow free.~~

The LiDAR DEMs have been compiled from a single campaign so that the recorded glacier elevation corresponds to one date only, although the acquisition times of the DEMs 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.

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~~y~~ 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.

~~The survey flights took place at different dates. The DEMs have been compiled from a single campaign so that the recorded glacier elevation corresponds to one date only, although the acquisition times of the DEMs 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.~~

2.3 Orthophotos

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

~~2.4 Climate data~~

~~Regional differences of glacial changes have been compared to monthly means of glacier related climate parameters such as air temperatures, sunshine duration or precipitation. Monthly homogenized records of climate data such as temperature, pressure, precipitation, sunshine and cloudiness have been compiled for the Greater Alpine Region (GAR) in the HISTALP database (HISTALP, 2014; Auer et al., 2007). These go back as far as 1760 and are available in station mode or as grid. Auer et al. (2007) identified incremental temperature increases in the 20th century (+1.2°C) with one peak in the 1950s and a second increase starting in the 1970s (+1.3°C/25a). They found a remarkable opposed development with 9% precipitation increase in the NW versus 9% decrease in the SE. For the comparison with the inventory data, mean temperatures and sunshine duration during the ablation season (May to September) were analysed as well as precipitation in the accumulation season (October of the previous year to April of the current year).~~

~~Ten stations in Austria, one in Italy and two in Eastern Switzerland (Begert et al., 2005) have been selected to represent climate and climate change in Austria's glacier covered regions for the following criteria: i) length of record, ii) availability of parameters, and iii) location within or close to specific glacier regions or shown correlation with glacier mass balance in the region (Figure 1, Table 2).~~

3 Methods

3.1 Applied basic definitions

~~As t~~The compilation of the glacier inventory time series aims ~~to allow~~at monitoring ~~any~~glacier changes with time.~~, several definitions and parameters have been kept unchanged between the inventories~~. Therefore, for example ice divides or specific definitions regarding what is a glacier, might be 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, and map for example changing and not constant ice divides.

~~The glacier inventory of 1969 Patzelt (1980) contained a number of geomorphological parameters, such as aspect, type, minimum and maximum elevations, and the ELA, as well as two different definitions of glacier areas: The area in 1969 was recorded with and without non-moving parts above the bergschrunds. The inventory of 1969 was partly reanalysed during the compilation of the glacier inventory of 1998 (Lambrecht and Kuhn, 1998), adding snow covered area connected to the glacier to the glacier area, as it is impossible to prove if the snow covers ice or ground. Geomorphological parameters are only available for the inventory of 1969.~~

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.

~~A consistent definition of specific glacier area between the LIA inventory and later inventories is not straightforward, as often several glaciers joined in one glacier tongue during LIA, but split up in later inventories.~~ The parent data set for this study is the GI 1, so ~~To avoid confusion,~~that the unique IDs in the ~~glacier inventory of 1969 and 1998 have been kept~~GI 1 was kept in later inventories. ~~,~~ ~~even if~~If ~~the~~a glacier had disintegrated in the inventory of 2006, ~~so that~~ one ID ~~can~~ 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 an excellent solution. Going backwards in time, to that e.g. several parents of the GI 1 are part of lager 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. ~~For the comparison of LIA areas on the basis of individual glaciers, the LIA glaciers have not been divided because the position of medial moraines remains unclear, but these LIA glaciers have been compared to all glaciers that are part of the LIA area today.~~

~~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.~~

~~The manual delineation of the glacier areas in GI III avoids major problems with the identification if debris-covered glacier parts, because the combination of volume change, surface roughness and optical images from various sources allows the identification of debris-covered parts of the glaciers by the subsidence of the surface.~~

No size limit was applied for the mapping of glaciers in the inventory 2006, i.e. glaciers whose area has shrunk 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 below 0.01 km², which is often considered as a threshold for including glaciers in inventories, was quantified.

3.2 Mapping ~~of~~the glacier extent ~~2006~~ in GI 3 from LiDAR

~~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 photogrammetry where fresh snow or shading reduce accuracy. As the high spatial resolution also reflects surface roughness, smooth ice-covered surfaces can be clearly distinguished from rough periglacial terrain.~~ 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 angles calculated from

LiDAR DEMs (Figure 4, location of the subset see Figure 3), analysing the surface elevation changes between the GI ~~I~~2 and GI ~~II~~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 (apert from permafrost phenomena or mass movements). The resulting glacier boundaries are shown in Figure 6. Abermann et al. quantify the accuracy of the areas derived by the LiDAR ~~their~~ 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.

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.

Kommentar [x1]:

3.~~3~~4 Deriving the LIA extent

~~LIA extents have been calculated for instance by Richter (1888) and Groß (1987), who also summarized available historical documents and maps. Richter's glacier inventory of 1888 was based on military maps, which were certainly a milestone in cartography at that time, but showed great uncertainties regarding the extent of the firn areas.~~ The LIA maximum extemts have been mapped based on previous mappings of Groß (1989) and Patzelt (1973) which have been 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. ~~As the spatial resolution of the new LiDAR DEMs is high, the position of the LIA moraines is reproduced much more accurately than in previously available elevation models. In addition to that, the~~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 ~~accurate~~ position of the ~~glacier tongues~~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, on the orographic left side ice cored. The basic delineation of Groß was adapted to fit the LIA moraine in the LiDAR hillshade (Figure 8).

Nevertheless, some smaller glaciers, which had wasted down until 1969, might still be missing in the LIA inventory. Groß (1987) accounted for these disappeared glaciers by adding 6.5% to the LIA area. We decided to include this consideration in the discussion on uncertainties, although we think that this estimate is fairly accurate.

~~3.4 Climate records~~

~~The monthly homogenized data were analysed with reference to the typical extent of accumulation and ablation seasons in the Austrian Alps, i.e. from the beginning of October to the end of April for accumulation (precipitation sums) and from the beginning of May to the end of September for ablation (mean air temperatures and sunshine duration). To separate long-term climate change within the periods of the glacier inventories, a 30-year running mean centred on the final year of the period was chosen. This method seems to be less influenced by singular extreme values than linear trend analysis.~~

4 Results

4.1 Total glacier area

Austrian glaciers cover 941.13 km² (100%) in GI LIA, 564.88 km² (60%) in GI 1, 471.67 km² (50%) in GI2 and 415.11 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 a bit lower than the 945.50 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 donloaded via the Pangaea data base (Fischer, submittes).

4.2 Absolute and relative changes of total area

~~In GI III, glaciers cover 415.11 km^2, equivalent to 44% of the glacier area at the LIA maximum determined in this study (941.13 km^2 without disappeared glaciers, which is a bit lower than the 945.50 km^2 found by Groß, 1987).~~ ~~Only four glaciers have wasted down completely.~~ The absolute –loss of glacier area, which is interesting from a hydrological perspective, -was 376 km^2 between GI LIA and GI 1, 94 km^2 between GI 1 and GI 2, and 55 km^2 between GI 2 and GI 3 (Table 3). 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 usually is done by calculating relative changes per year, neglecting glacier advances in the periods. 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 glacier advances about 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 an anual relative change of total area of 0.6 %/year. In 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 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.

~~between GI II and GI III is 55.97 km^2, which is more than half of the area loss of -94.21 km^2 in the 29 years between acquisition of GI I and GI II. Annual area losses are highest in the latest period (GI II to GI III: 0.23 km^2/year). Losses between LIA and GI I (-0.16 km^2/year) exceeded the ones between GI I and GI II (0.13 km^2/year). The relative annual area loss was only 0.02 % until GI II, rising to 0.05%/year for the latest period.~~

4.3 Results for specific mountain ranges

Kommentar [x2]:

The absolute areas recorded for specific mountain ranges are shown in Figure ~~2~~9 and Table 3. Highest absolute glacier area decrease between GI ~~II~~ 2 and GI ~~III~~ 3 was observed in the Ötztaler Alp~~s~~en (-13.94 km², 24% of total area loss), the Venedigergruppe (-11.7~~0~~ 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 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 ~~3~~10).

While the annual relative area losses in the first period vary between -0.3 and -0.6 %/year, ~~T~~The regional variability of the relative annual area loss in the ~~period GI II to GI III~~ two latest periods is much higher the later (and shorter) the period (Table, Figure). ~~The maximum relative annual area loss was observed in the Salzburger Kalkalpen, where the disintegration of the Übergossene Alm glacier results in a relative loss as high as 7.8% of the glacier area per year. While in most of the mountain ranges about 1% of the total glacier area is lost per year, in mountain ranges covered by smaller glaciers, such as Allgäuer Alpen, Karnische Alpen, Samnaun and Verwallgruppe, the annual losses may exceed 4% of the total glacier area. During earlier periods, the relative losses did not exceed 1%, although the evaluation of shorter periods might of course reveal higher rates which would be smoothed in longer periods.~~

~~The 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 3).~~

The highest annual relative area loss was observed in Karnische Alpen (-4.5%/year), Samnaungruppe (-5.6%/year), and Verwallgruppe (-5.9%/year) for G2 to GI3. These are groups with a high portion of small glaciers.

Kommentar [x3]:

Kommentar [x4]:

Kommentar [x5]:

4.4~~1~~ Altitudinal variability of area changes

In GI ~~II~~2, 88% of the total area was located at elevations between 2600 and 3300 m.a.s.l (Figure ~~4~~11). In GI ~~II~~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 ~~II~~2 and 58% in GI ~~III~~3), 42% of the area was located in regions above 3000 m in GI ~~II~~2, decreasing to 39% in GI ~~III~~3:

The most severe 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. ~~50%~~Fifty of the area losses took place at altitudes between 2600 and 2900 m.a.s.l. Therefore the main portion of the ~~glaciated~~ glacier covered areas are stored in regions above the current strongest area ~~retreats~~losses.

4.5~~2~~ 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 ~~I~~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 had been part of the largest size class in GI ~~I~~1, of which only 8 were left in GI ~~III~~3.

For GI ~~III~~3, the glaciers in size class 5 – 10 km² cover 41% of the area, which is the largest size class (Table 5). 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% of the total glacier area. In GI 2, 16 very small glaciers cover 0.024% of the total glacier area, and in GI 3 26 very small glaciers contribute 0.033% of the total glacier area.

~~4.3 Climate change~~

~~Long term climate records show an increase of air temperature since the end of the LIA, more pronounced since 1983, when the 30-year running mean was at a minimum for the years after 1942 at low elevations (Figure 5). Sunshine duration shows the same minima in the early 1980s for all stations, the early 1940s minima occur in the two stations at low elevations. In contrast to the low elevation stations, the mountain stations Zugspitze and Sonnblick recorded an increase of average air temperature and sunshine duration without a pronounced minimum at the beginning of the 1940s.~~

~~Regional variability of precipitation – as described by Auer (2007) – is higher than for air temperatures. The inner Alpine stations show an increase in precipitation in the 1930s to 1940s. A maximum of the running mean in the early 1970s has been observed in Linz, Kremsmünster and Rauris, i.e. in the northeast, but not for the inner-Alpine and southern stations. Increases in winter precipitation from around the year 2000 have been most pronounced in the north, and less so south of the main Alpine ridge. The mean values of summer temperatures, winter precipitation and sunshine duration for the inventory periods are presented in Table 6.~~

5 Discussion

The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and lowest for GI ~~III~~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 ~~III~~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 ~~I~~ 1 and ~~II~~2. The nominal accuracy of the method (Abermann et al., 2010) results in an area uncertainty of ±11.~~17~~2% or 2.~~69~~7%.

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 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 shows 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~~, as it is impossible to distinguish perennial snow fields from glacial firn~~. Groß (1987) calculated LIA maximum glacier areas of 945.50 km² without, and 1011.0 with disappeared glaciers (i.e. 6.5 % disappeared glaciers). ~~Assuming, as is the case in later inventories, that the ice cover at high elevations is small as a result of wind drift and~~

~~avalanche activity,~~According to this estimate of 6.5 % of the LIA maximum area possibly is missing in our inventory, and a general mapping error of 3.5% we estimate the accuracy of the total ice cover for the LIA as ±10%. Figure XXX 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, ~~but necessary if we aim at further modelling of parameters such as mass balance or ice thickness involving glacier dynamics.~~as it is not clear if it makes sense to compare one LIA glacier with the total area of it’s child glaciers with totally different geomorphology and dynamics,or if it would make more sense to split the LIA glacier in tributaries according to the present situation. ~~Calculating ice divides from surface DEMs for every inventory does not allow deriving glacier statistics, as ice divides and therefore glacier areas change too much. The disintegration of glaciers after the LIA could be captured best by using parent-and-child IDs, but so far no systematics have been established in the international community.~~

Regarding the presented annual rates of area change, it has to be born in mind that all periods apart from GI ~~II~~2 to GI ~~III~~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 been in the same dimension as those after 2000.

~~Groß (1987) calculated glacier areas for 1850 (945.50 km² without, and 1011.0 with disappeared glaciers), 1920 (758.60 km²) and 1969 (541.73 km²). A reconstruction of glacier areas for 1920 has not been attempted within this study.~~ .~~The figures of Groß (1987) for the glacier area in 1969 differ slightly from those given by Lambrecht and Kuhn (2007) and from those in this study, as snow patches connected with the glacier have been neglected. In order to avoid having to reanalyse the digital data compiled by Lambrecht and Kuhn (2007), the authors stuck to the same definition of glaciers as Lambrecht and Kuhn (2007). For the last decade, changes would only have amounted to 3% maximum, as a series of negative mass balance years has significantly reduced perennial snow patches.~~

~~The application of a minimum glacier size would lead to a significant decrease in the number of Austrian glaciers and of course also to a reduction of glacier area. As this study wanted to trace the changes in glacier area, no minimum glacier size was applied.~~

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 km^2/year for 1999 to 2005, and 1.1 km^2/year for 1975 to 1999. The maximum relative area changes in the period of the Austrian GI II to GI III 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.

Compared to global satellite remote-sensing-based glacier inventories~~ of the area~~, the glacier inventories presented here ~~have the advantage~~ show of i) high~~er~~ spatial resolution ii) inclusion of additional information iii) minimal snow cover at the time of the flights and iv) consistent nomenclature and ice divides for all four inventories. 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 open space laboratory in glaciology, it nevertheless might make sense to compare results of global inventories with this regional inventory. ~~The comparison with t~~The Randolph inventory RGI Version 3.2, released 6 September 2013 and downloaded from http://www.glims.org/RGI/rgi_dl.html ~~shows~~contains ~~that the number of~~737 RGI glaciers (737) ~~as well as the~~and a -glacier area of 36~~3.87~~74 km^{2}for the year 2003. These numbers are ~~is~~ lower than the ~~glacier area~~ones recorded in the Austrian inventories (GI ~~II~~ 2 before 2003 and GI ~~III~~ 3 after 2003), although cross-border glaciers have not been delimited for the comparison. ~~This shows the importance of consistent data management for deriving time series of inventories.~~This is clearly a matter of spatial scales, and has no further implication.

~~For the statistics on the number of glaciers, and therefore parameters such as the mean glacier size, a homogenous definition of a glacier as connected area together with a name convention would be an advantage, especially when comparing LIA glaciers with their split remnants of today.~~

6 Conclusions

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 ~~11~~89% of the LIA glacier ~~area still left~~gone -for the small glaciers of the Samnaun group to-half of the glacier area left for a number of other groups. ~~For some regions, like the~~ Small groups as 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 %. ~~the~~ the only ~~plateau~~ glacier there seems likely to vanish in the near future. Nevertheless, for some of the largest glacier regions as 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. ~~most regions the annual losses do not exceed 4%.~~ Although generally the relative annual losses increased since the LIA, some groups, for example Silvrettagruppe and Rätikon, exhibit a decrease in the latest period. ~~Between GI I and GI II, the loss rates were below 1%, so that the relative losses after 2000 have been rising.~~ The reason for that might be found in small scale mass balance variabilities in the shortest period analysed, or topographic or dynamical responses. For the meaningful interpretation of annual relative losses, the length of the periods and the occerence of positive mass balances and advances mut 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. ~~However, it must be taken into account that this period is rather shorter than the others and lacks glacier advances.~~

~~The comparison of area changes with changes in climate reveals that not only climate, but also the topography and glacier states, might play an important role. The significant temperature increase for the recent period GI II to GI III is reflected in an increase of area losses. The influence of regional differences in winter precipitation could not be traced back to area changes, as glacier sizes and accumulation situation might differ too much between the regions.~~

~~The compilation of time series of glacier inventories shows up the need for consistent definitions and IDs. The disintegration of glaciers, along with the separation of glacier tributaries, can only be handled with a standardized system of parent and child IDs that allow the prolongation of time series into the future and the past. This is especially important for the application of numerical models that include ice dynamics for volume calculations.~~

~~Further investigation will show if the proposed relation between mean changes in summer temperatures and area change is a reliable guide for other regions and/or time periods. The analysis of the regional variability of volume changes, together with temperature and precipitation anomalies, will be the next step to fully exploit the presented time series of glacier inventories.~~

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Table 1: Sensor and point densities.

	sensor	point density/m²
T~~y~~irol	ALTM 3100 and Gemini	0.25
Salzburg	Leica ALS-50, Optech ALTM-3100	1.00
Vorarlberg	ALTM 2050	2.50
~~Carinthia~~Kärnten-Karnische Alpen	Riegl LMS Q680i and Riegl LMS Doublescansystem	1.00
~~Carinthia~~Kärnten-other	Leica ALS-50/83 and Optech Gemini	1.00

~~Table 2: List of climate stations with available parameters and the first recorded year . p…precipitation, t…temperature, s…sunshine duration.~~

~~station~~	~~long.~~	~~lat.~~	~~height~~	-	~~1st recorded year~~				
~~name~~	~~E~~	~~N~~	~~m.a.s.l~~	-	~~p~~	-	~~t~~	-	~~s~~
~~Innsbruck~~	~~11.385~~	~~47.261~~	~~609~~	-	~~1858~~	-	~~1777~~	-	~~1906~~
~~Kötschach-Mauthen~~	~~12.998~~	~~46.678~~	~~714~~	-	~~1871~~	-	-	-	-
~~Kremsmünster~~	~~14.131~~	~~48.055~~	~~382~~	-	~~1820~~	-	~~1767~~	-	~~1884~~
~~Linz-Stadt~~	~~14.286~~	~~48.297~~	~~263~~	-	~~1852~~	-	~~1816~~	-	-
~~Mariapfarr~~	~~13.745~~	~~47.152~~	~~1153~~	-	-	-	-	-	~~1930~~
~~Marienberg/Montemaria~~	~~10.490~~	~~46.740~~	~~1323~~	-	~~1858~~	-	~~1858~~	-	-
~~Patscherkofel~~	~~11.462~~	~~47.210~~	~~2247~~	-	-	-	~~1931~~	-	~~1935~~
~~Rauris~~	~~12.993~~	~~47.224~~	~~941~~	-	~~1876~~	-	~~1876~~	-	-
~~Sonnblick~~	~~12.958~~	~~47.054~~	~~3105~~	-	-	-	~~1887~~	-	~~1887~~
~~Villacher Alpe~~	~~13.673~~	~~46.604~~	~~2160~~	-	-	-	-	-	~~1884~~
~~Zugspitze~~	~~10.980~~	~~47.420~~	~~2962~~	-	-	-	~~1901~~	-	~~1901~~
~~Davos~~	~~9.843~~	~~46.813~~	~~1594~~	-	~~1866~~	-	~~1866~~	-	-
~~Säntis~~	~~9.343~~	~~47.250~~	~~2502~~	-	~~1882~~	-	~~1864~~	-	-

Table ~~3~~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;.

group	GI II	GI III	data source	LIA	GI-I	GI-II	GI-III
	year	year		km²	km²	km²	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 4: Number of glaciers by size classes.~~

~~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 I~~	~~177~~	~~401~~	~~116~~	~~99~~	~~11~~	~~5~~	~~809~~
~~in GI II~~	~~401~~	~~343~~	~~92~~	~~79~~	~~7~~	~~3~~	~~925~~
~~in GI III~~	~~450~~	~~307~~	~~77~~	~~77~~	~~8~~	~~2~~	~~921~~

~~Table 5: Distribution of area for different size classes.~~

-	~~in % of total area~~		
	~~GI I~~	~~GI II~~	~~GI III~~
~~<0.1 km²~~	~~2~~	~~4~~	~~5~~
~~0.1 to 0.5 km²~~	~~17~~	~~17~~	~~17~~
~~0.5 to 1.0 km²~~	~~15~~	~~14~~	~~12~~
~~1 to 5 km²~~	~~40~~	~~41~~	~~41~~
~~5 to 10 km²~~	~~14~~	~~14~~	~~17~~
~~10 to 50 km²~~	~~13~~	~~10~~	~~8~~

group	GI 1-GI 2	GI 2 - GI 3	LIA-GI 1	GI 2-GI1	GI3-GI2	LIA-GI 1	GI 2-GI1	GI3-GI2
-	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
mean			-40	-17	-12	-0.4	-0.8	-2.7

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

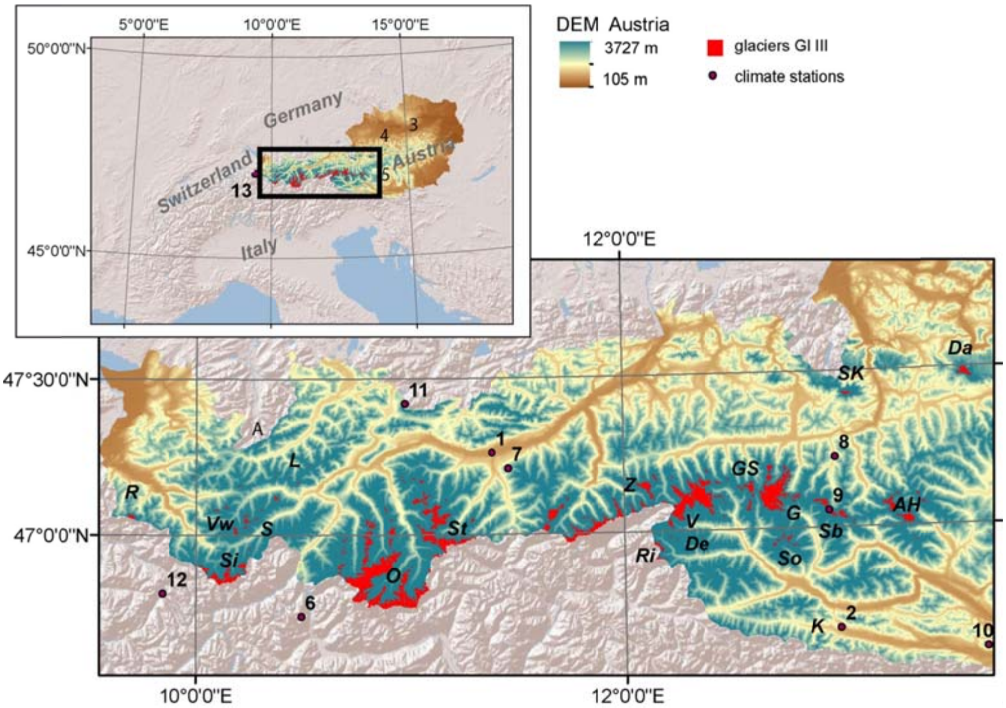
~~Table 6: Mean summer air temperatures, sunshine duration and winter precipitation sums for the glacier inventory periods.~~

~~precipitation~~	~~1850-1969~~	~~1970-1998~~	~~1999-2006~~
~~1.10.-30.04.~~	~~-~~	~~mm~~	~~mm~~
~~Innsbruck~~	~~-~~	~~343~~	~~405~~
~~Kötschach-Mauthen~~		~~594~~	~~729~~
~~Kremsmünster~~		~~451~~	~~517~~
~~Linz-Stadt~~		~~421~~	~~466~~
~~Marienberg/Montemaria~~		~~287~~	~~332~~
~~Rauris~~		~~435~~	~~424~~
~~Davos~~		~~428~~	~~467~~
~~Säntis~~	~~-~~	~~1544~~	~~1549~~

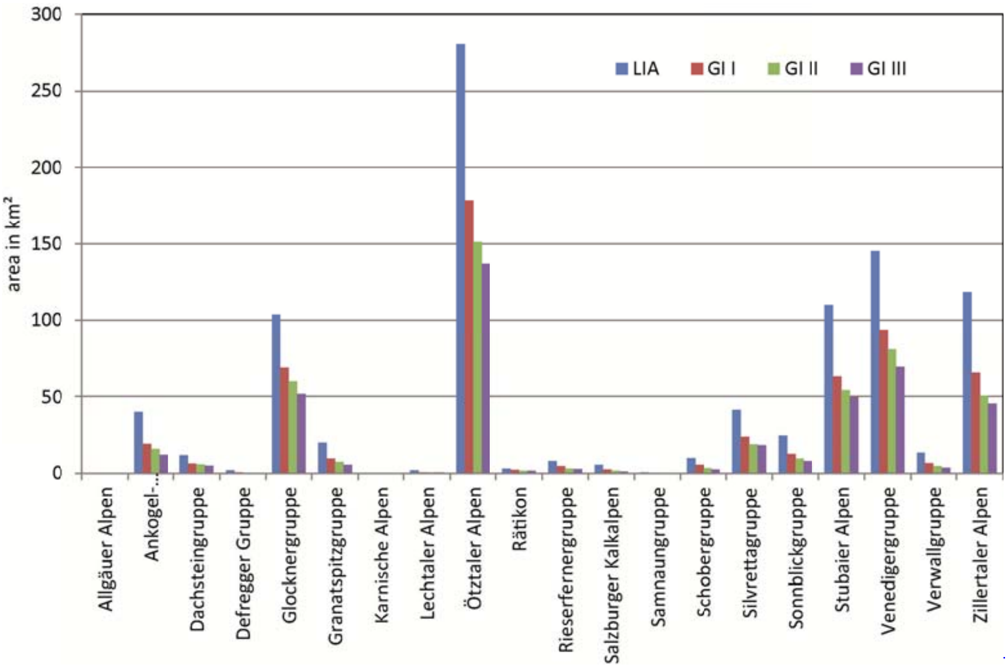
~~air temperature~~	~~1850-1969~~	~~1970-1998~~	~~1999-2006~~
~~01.05-30.09.~~	~~°C~~	~~°C~~	~~°C~~
~~Innsbruck~~	~~15.3~~	~~16.0~~	~~17.2~~
~~Kremsmünster~~	~~15.6~~	~~16.2~~	~~17.1~~
~~Linz-Stadt~~	~~16.0~~	~~16.6~~	~~17.9~~
~~Marienberg/Montemaria~~		~~12.2~~	~~13.4~~
~~Patscherkofel~~		~~5.5~~	~~6.7~~
~~Rauris~~		~~12.2~~	~~13.3~~
~~Sonnblick~~		~~0.0~~	~~1.0~~
~~Zugspitze~~		~~0.5~~	~~1.5~~
~~Davos~~		~~9.4~~	~~10.6~~

~~Säntis~~	~~-~~	~~3.2~~	~~4.5~~
~~sunshine duration~~	~~1850-1969~~	~~1970-1998~~	~~1999-2006~~
~~01.05-30.09.~~	~~-~~	~~hours~~	~~hours~~
~~Innsbruck~~	~~-~~	~~201~~	~~215~~
~~Kremsmünster~~		~~209~~	~~171~~
~~Mariapfarr~~		~~180~~	~~190~~
~~Patscherkofel~~		~~184~~	~~199~~
~~Sonnblick~~		~~147~~	~~159~~
~~Villacher Alpe~~		~~185~~	~~208~~
~~Zugspitze~~	~~-~~	~~162~~	~~171~~

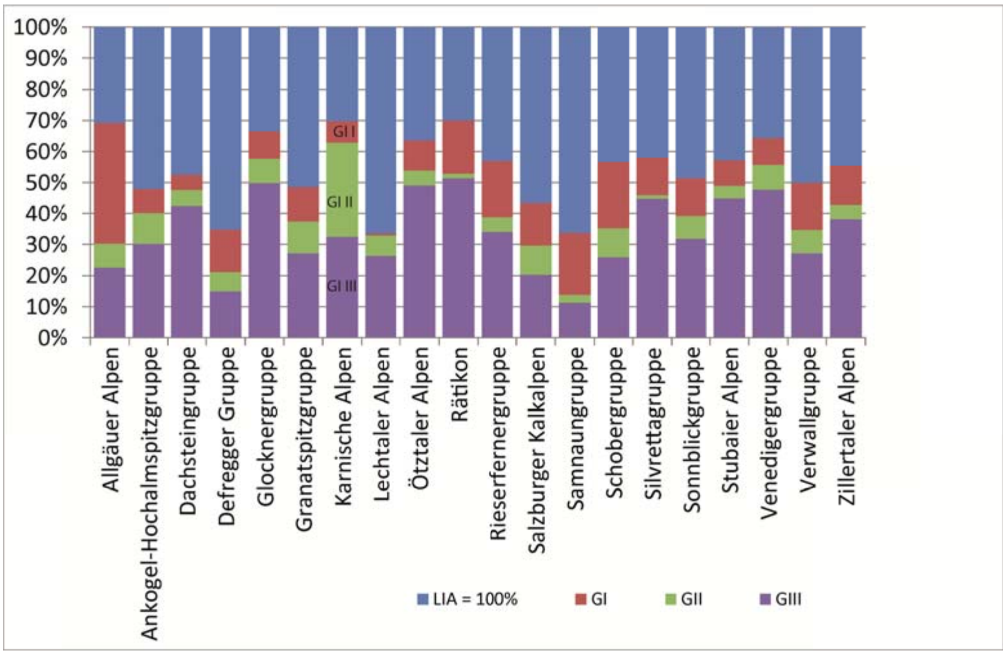
Figures



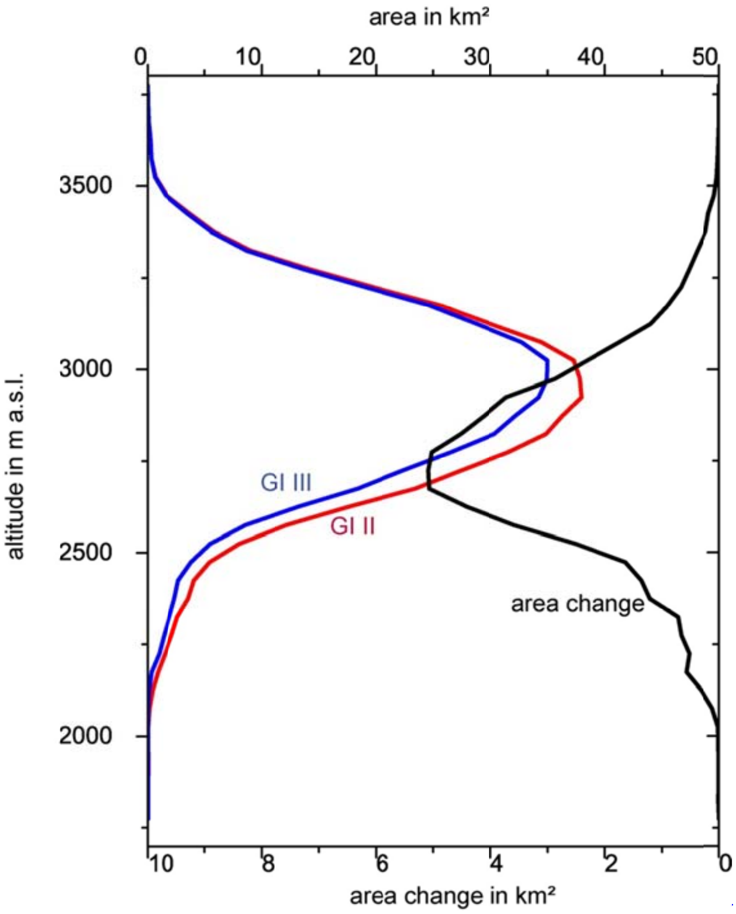
~~Figure 1: Austrian glaciers displayed on an elevation model (Jarvis et al., 2009) with mountain ranges and the acquisition dates of the LiDAR data as well as position of the climate stations. A…Allgäuer Alpen, AH…Ankogel-Hochalmspitzgruppe, Da…Dachsteingruppe, De…Defreggergruppe, G…Glocknergruppe, GS…Granatspitzgruppe, K…Karnische Alpen, L…Lechtaler Alpen, O…Ötztaler Alpen, R…Rätikon, Ri…Rieserfernergruppe, SK…Salzburger Kalkalpen, S…Samnaungruppe, So…Schobergruppe, Si…Silvrettagruppe, Sb…Sonnblickgruppe, St…Stubaier Alpen, V…Venedigergruppe, Vw…Verwallgruppe, Z…Zillertaler Alpen.1… Innsbruck, 2…Koetschach-Mauthen-Kornat, 3…Kremsmünster, 4…Linz-Stadt, 5…Mariapfarr, 6…Marienberg/Montemaria, 7…Patscher Kofel, 8…Rauris, 9…Sonnblick, 10…Villacher Alpe, 11…Zugspitze, 12…Davos, 13…Säntis.~~



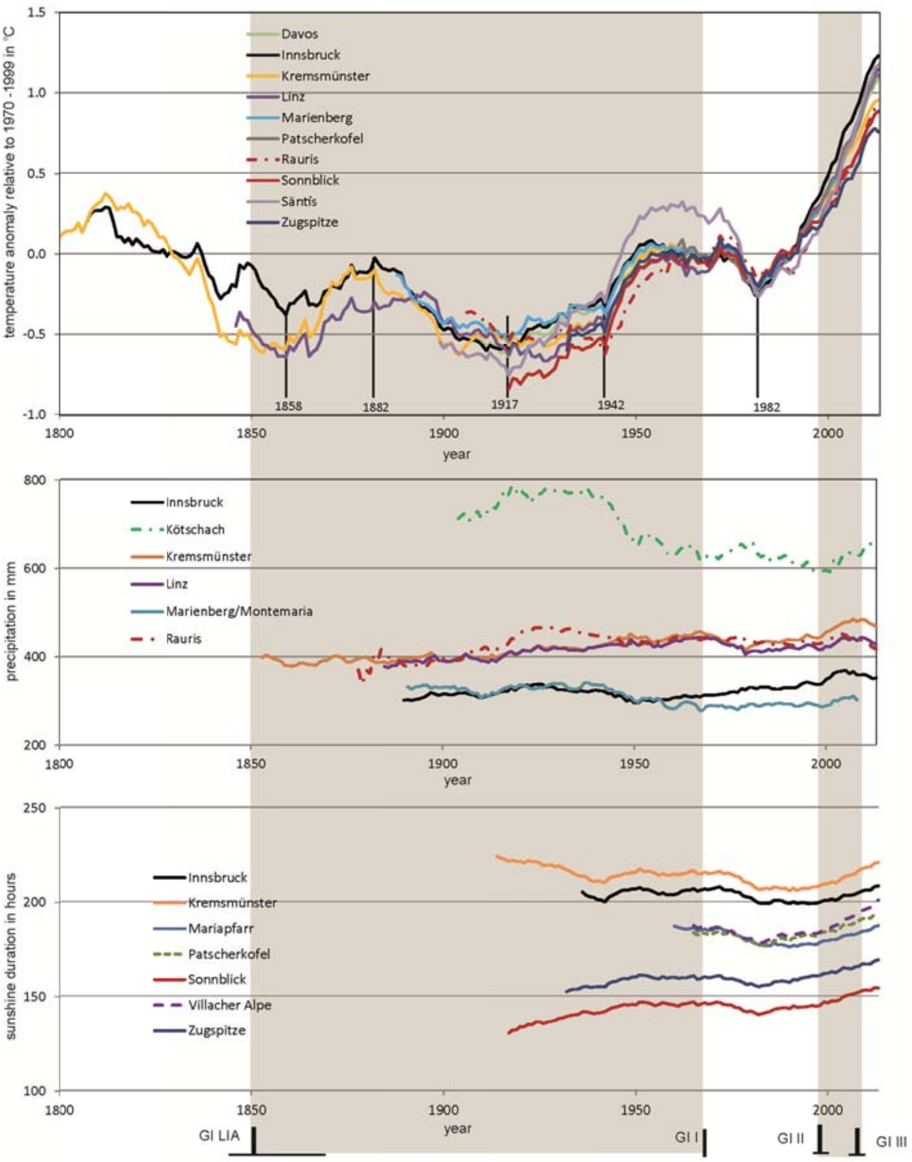
~~Figure 2: Areas in the specific mountain ranges recorded in the glacier inventories.~~



~~Figure 3: Percentage of LIA glacier area for specific mountain ranges.~~



~~Figure 4: Altitudinal distribution of glacier areas and area losses for GI II and GI III by reference to the 1998 DEM.~~



~~Figure 5: 30-year running means of summer air temperatures (mean June to September), winter precipitation (sum October to April) and summer sunshine duration (sum June to September) for the stations listed in Table 2.~~

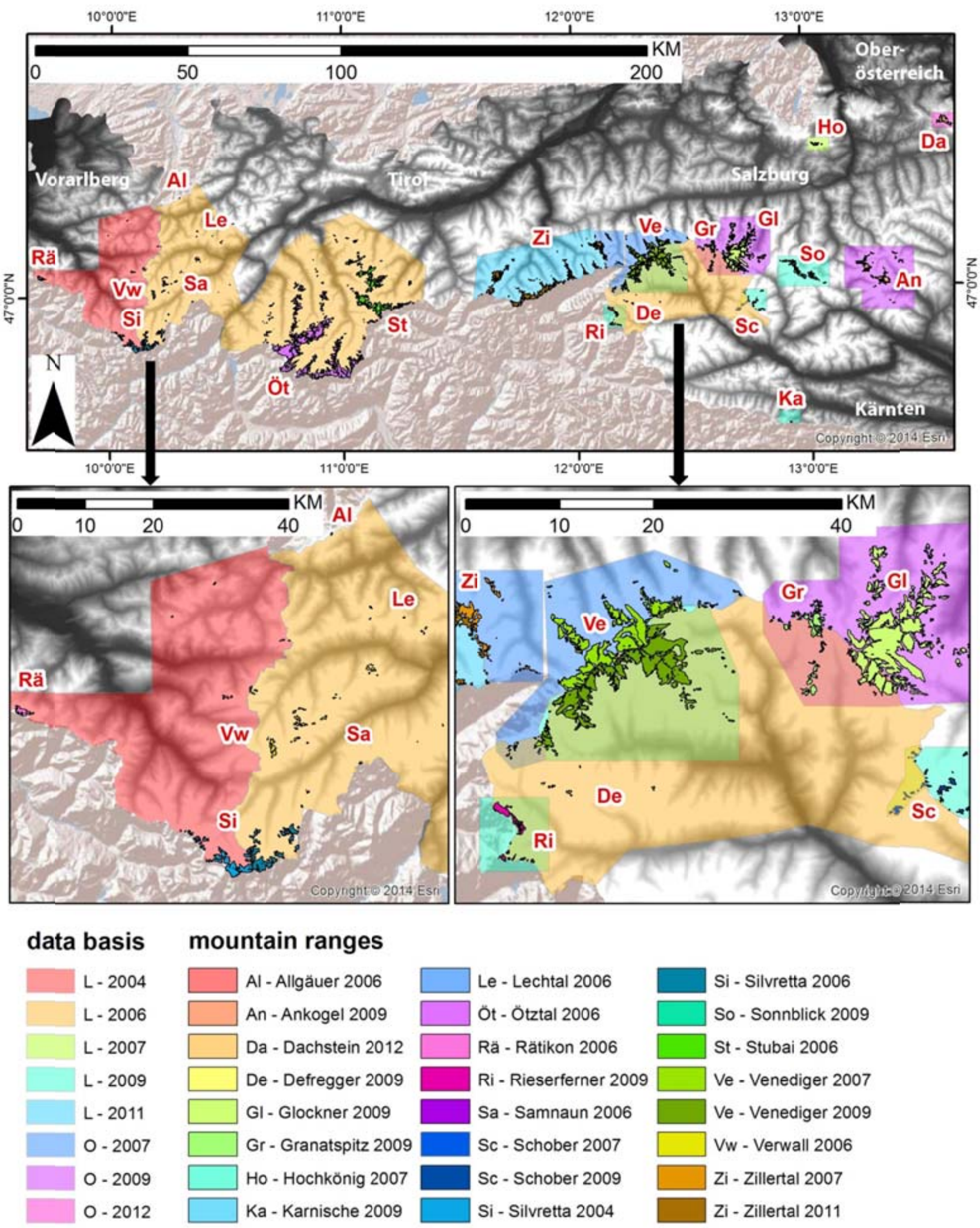


Figure 1: Austrian glaciers displayed on a DEM (Jarvis et al., 2009) color-coded by mountain ranges, with polygons showing data type and date used for deriving GI 3 and GI LIA.

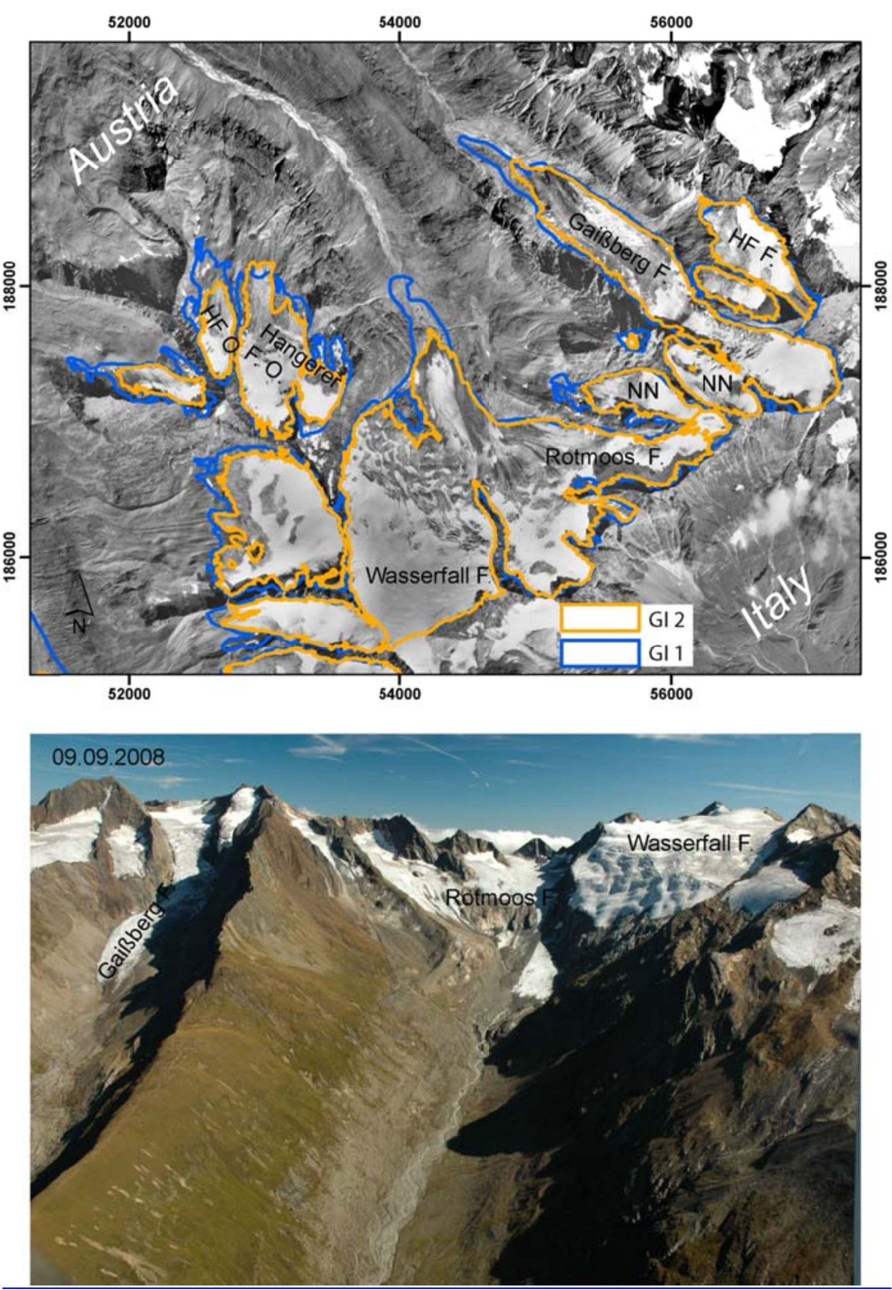


Figure 2: GI 1 and GI 2 glacier margins superimposed on a GI 2 orthophoto with an oblique photograph of the area in Ötztal Alps.

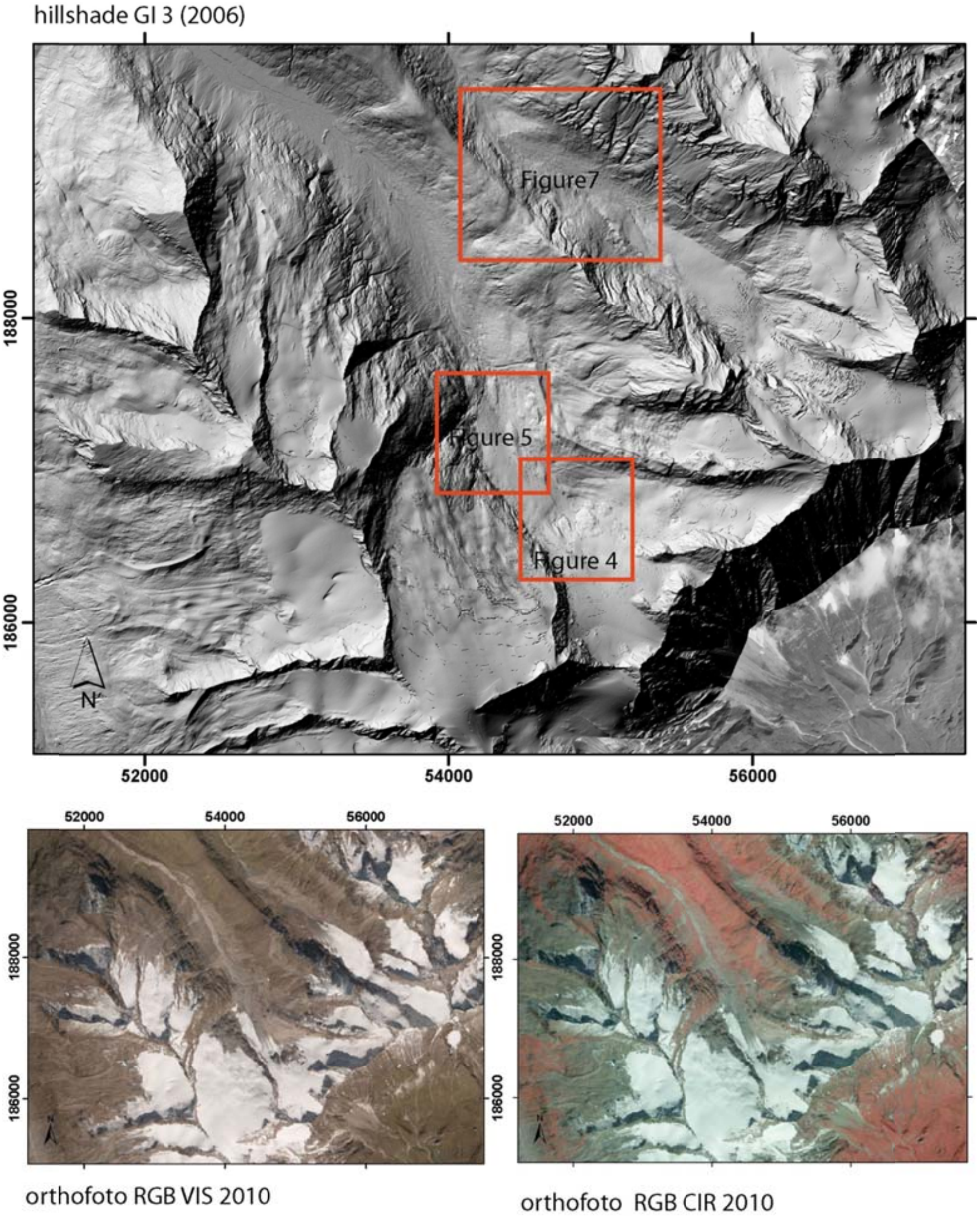


Figure 3: Example of an LiDAR hillshade (2006) of the same area as in Figure 3 with VIS and CIR RGB orthophotos from 2010 for comparison. The inserts show the positionof the subsets shown in Figure 4 (lower right rectangle) and Figure 5 (upper left rectangle).

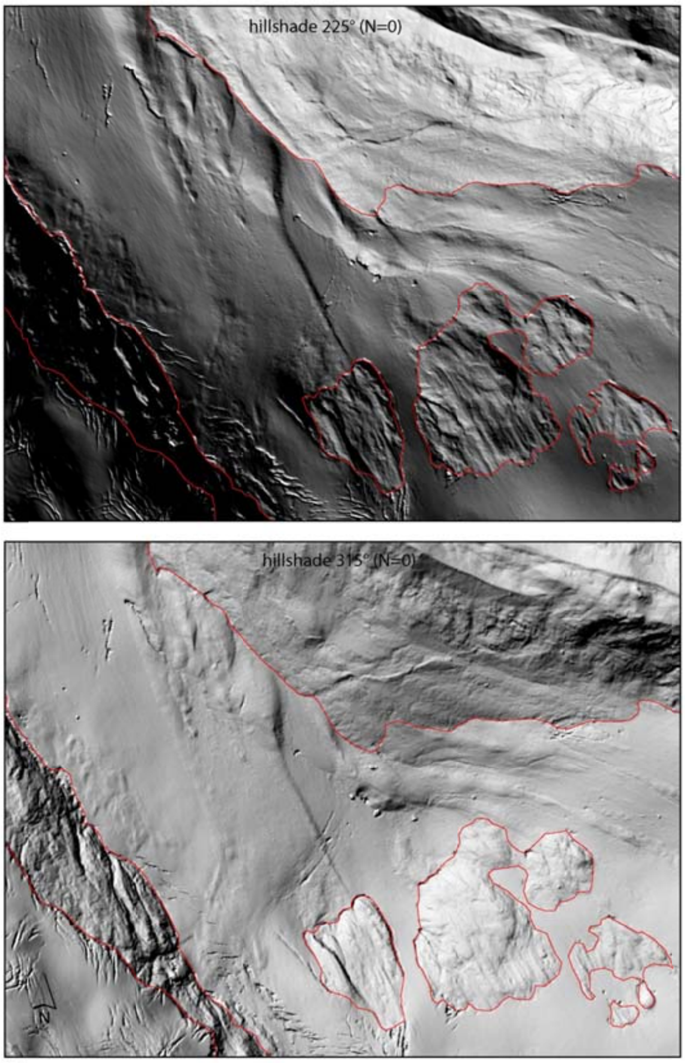


Figure 4: Hillshades from different view angles allow to distinguish smooth glacier surfaces from bedrock (position of the subset shown in Figure 3).

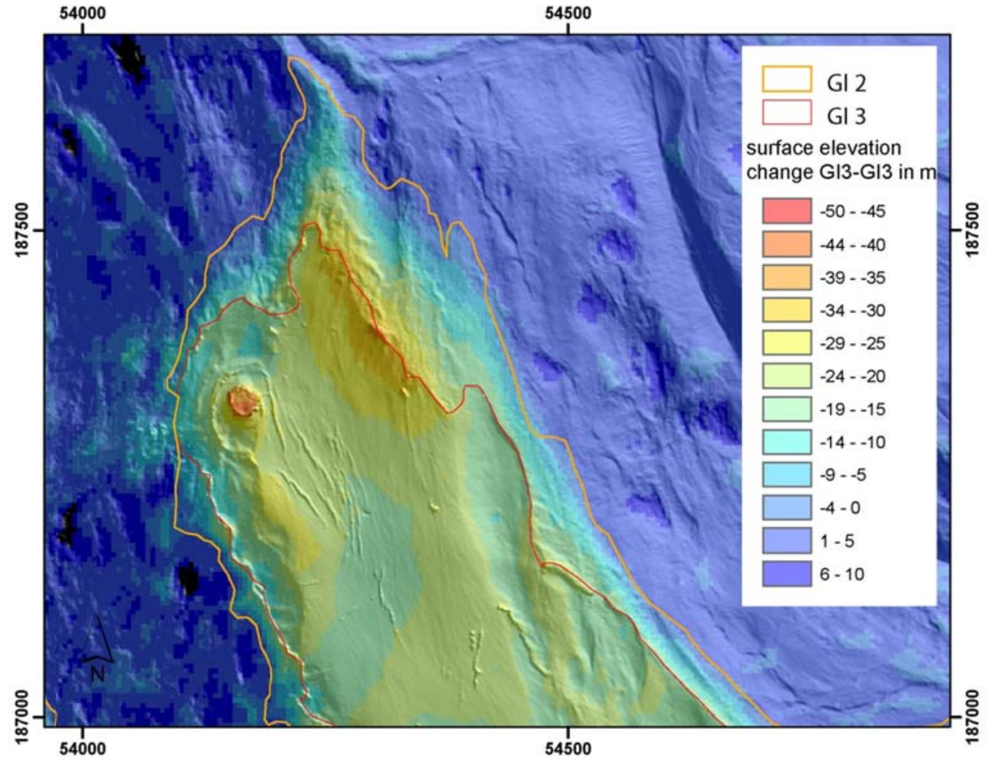


Figure 5: The elevation change between GI 2 and GI 3 superimposed on a hillshade shows that the elevation changes can help to delineate the actual (maximum elevation change) and previous (outer minimum of elevation change) position of the glacier margin (position of the subset shown in Figure 3).

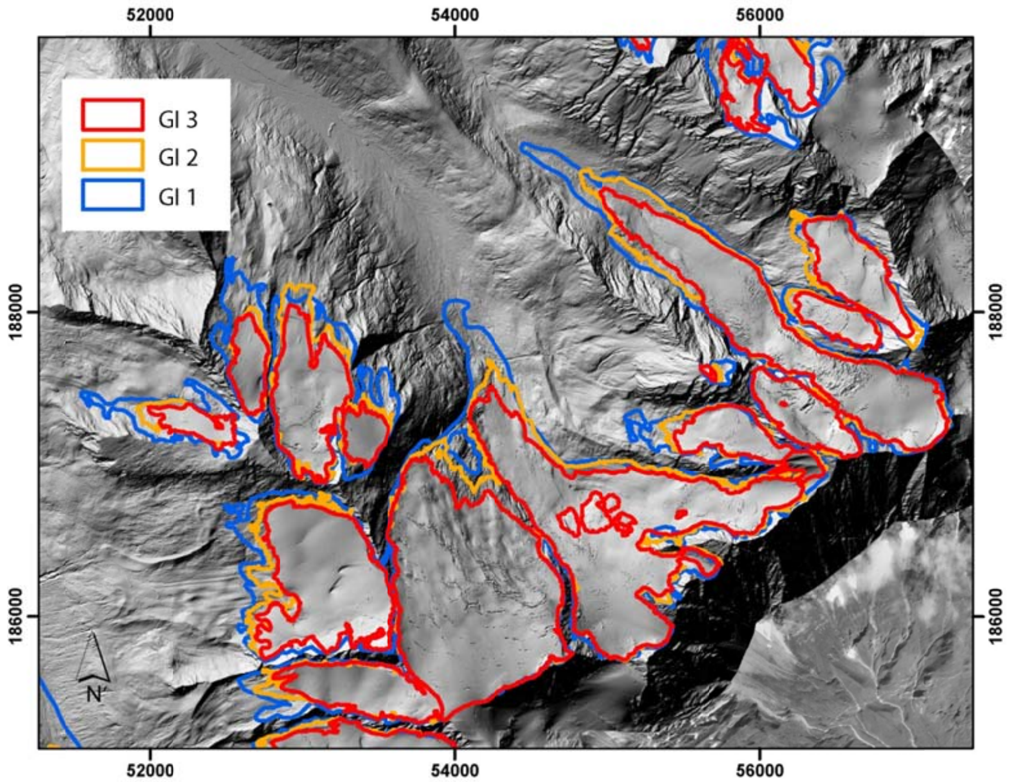


Figure 6: GI 3 glacier boundaries superimposed on LiDAR hillshade with GI 1 and GI 2 boundaries.

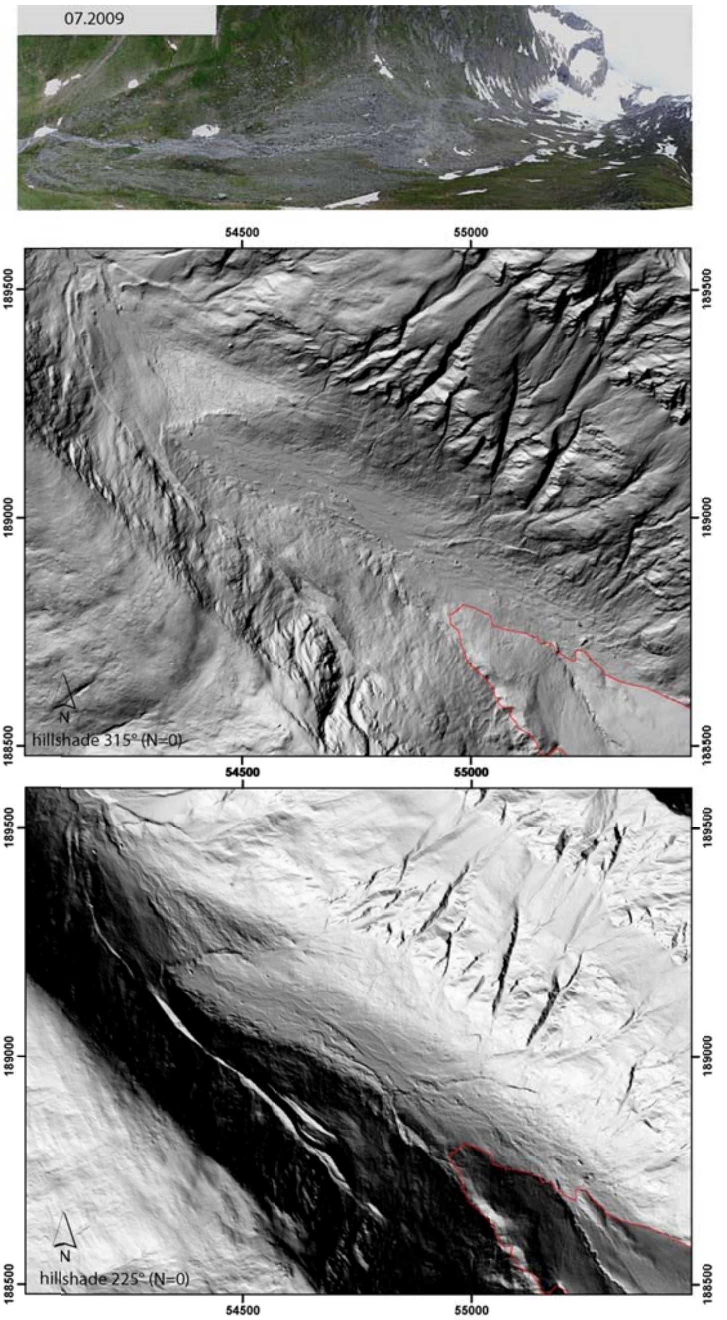


Figure 7: Periglacial area of Gaißbergferner with moraines dating from LIA, 1920 and 1980 (position of the subset: see Figure 3).

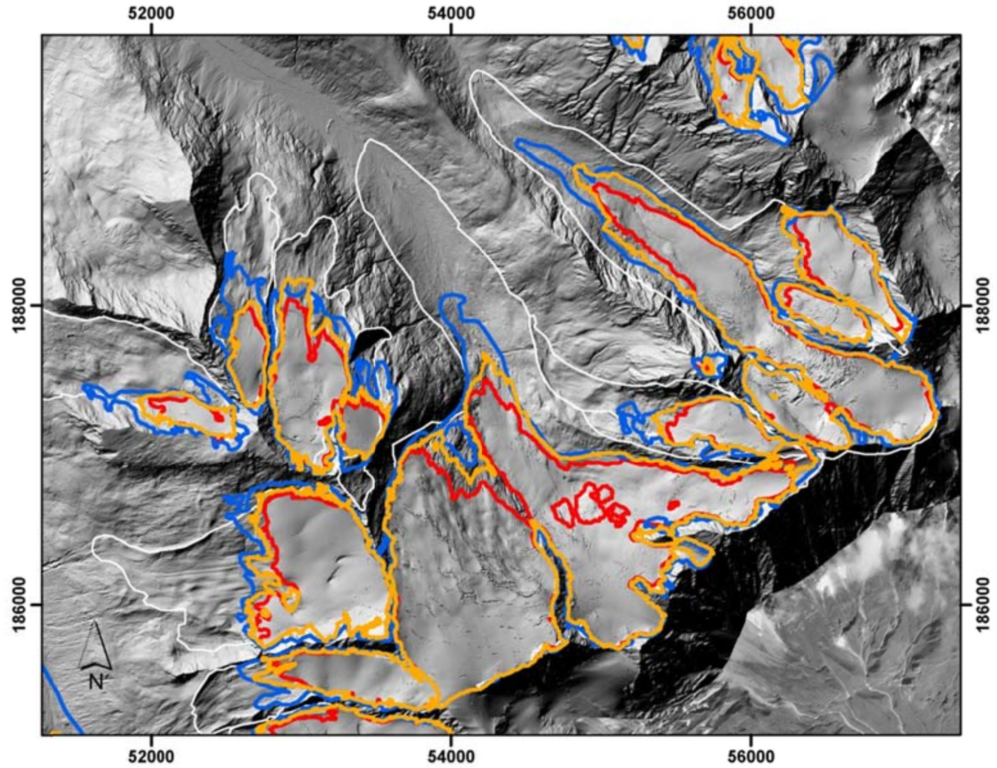


Figure 8: Resulting LIA glacier areas (white) with several modern glaciers contributing to the LIA Rotmoos Ferner and LIA Gaißbergferner.

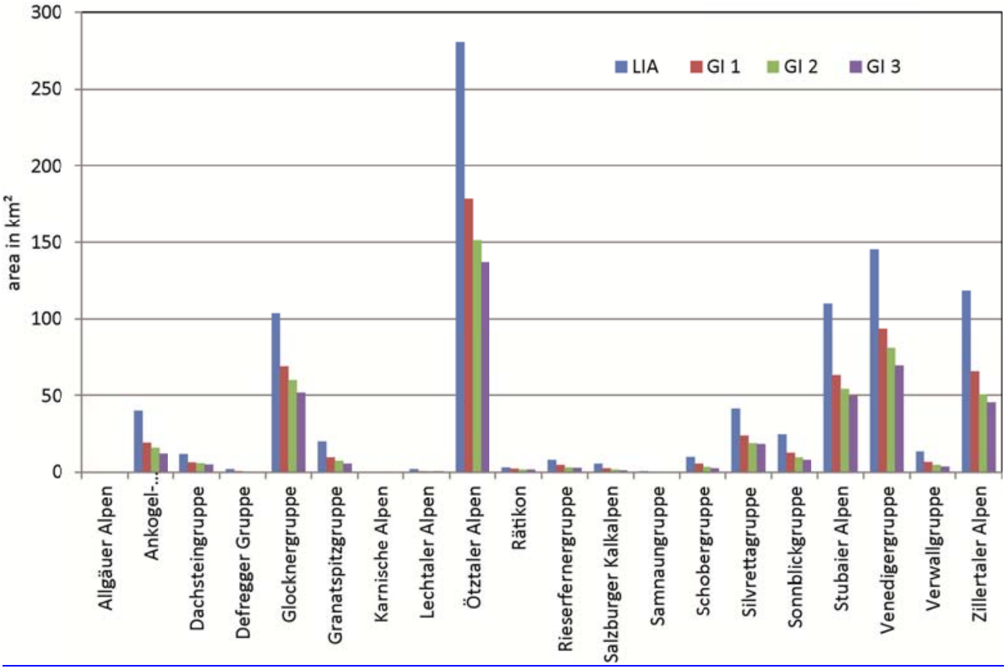


Figure 9: Glacier areas for specific mountain groups in GI LIA to GI 3.

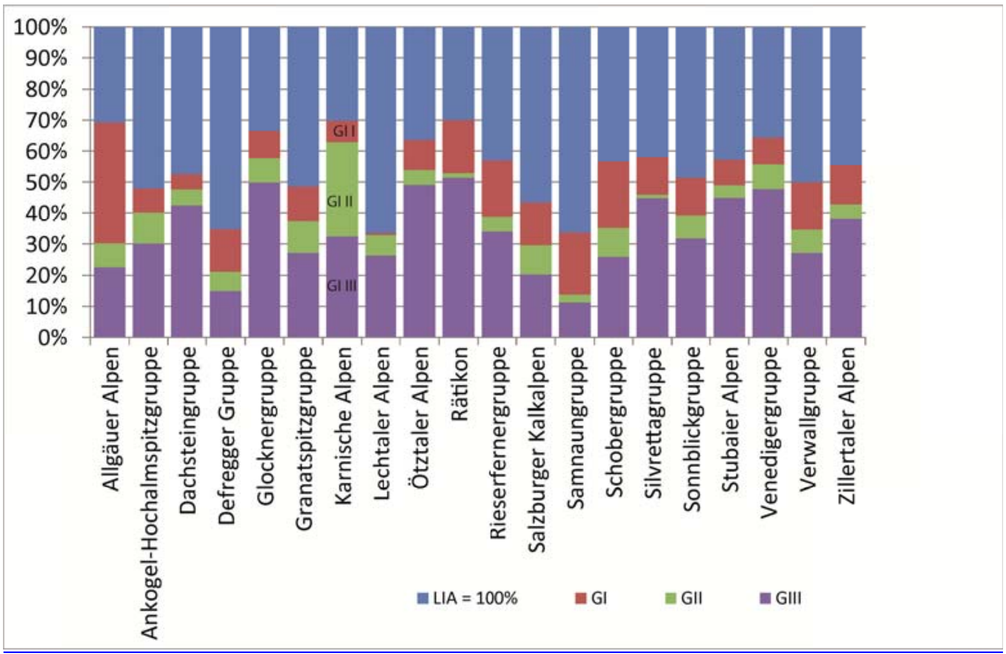


Figure 10: Area changes of specific mountain ranges in percentage of their LIA area.

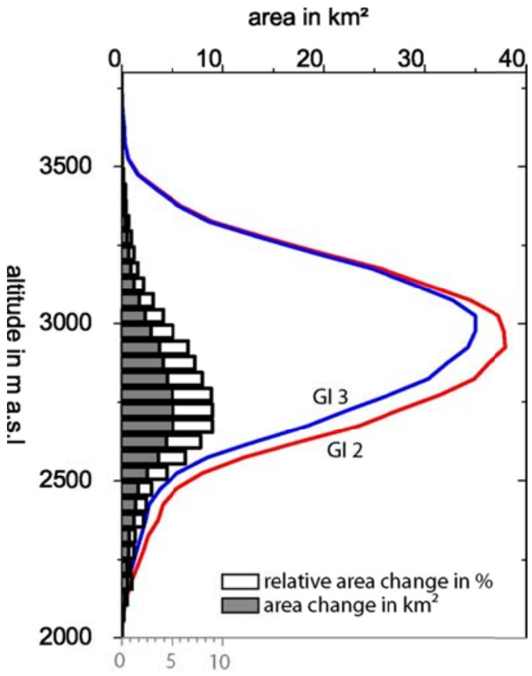


Figure 11: Altitudinal distribution of areas in GI 2 and GI 3 with absolute and relative area changes.

second federal survey (1816-1821) third federal survey (1869-1887)

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.