Review of the study by Fischer et al.

General comments

The study by Fischer et al. presents results of an area change analysis from four Austrian glacier inventories covering the period 1850 to 2011 and demonstrating the regional variability of the changes. Although I think such an analysis is worth publishing, I struggle somewhat with the contents that is presented here. In essence, I would have liked to see a much more in-depth analysis and extended illustration of the results and a removal of the climate data presentation. Just as an example: there is not a single image showing how glacier extents have changed through time (e.g. illustrating the disintegration problem), but I find a table listing the availability of climate station data from various locations. I also think that the authors should get aware of the current state-of-the-art in either a methodological (e.g. the parent glacier ID concept is long established in the GLIMS database) or a scientific sense (e.g. comparing relative area changes instead of absolute ones). They also downplay the shortcomings of their dataset (e.g. by only listing the benefits) and avoid discussing the really problematic issues in detail (e.g. the mapping of seasonal snow in GI II). The list of general points given below is further explained in the specific comments section along with other, partly minor issues. Although I have listed a lot of points, I think they can all be addressed by the authors using the already existing datasets. I thus recommend major revisions.

(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.

(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.

(3) 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).

(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.

(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.

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

Specific comments

P5196

L5 / 9: I 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.

L8: Have orthophotos not been used to identify anything?

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.

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 km^2 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.

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

L20: Better use 'glacier mass budgets'.

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.

P5197

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

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

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.

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

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

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

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).

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)

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

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.

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,

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.

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'.

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.

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?

P5199

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

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.

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

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.

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

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)?

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.

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.

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.

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?

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.

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).

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

P5201

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

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

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.

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).

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.

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.

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?

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?

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?).

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 decreas-

ing elevations can also be selected automatically)? It would be helpful to illustrate how the combination of datasets finally results in correct outlines for debris-covered glaciers.

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).

L20: On the other hand it might result in an underestimation of the real loss if all the pieces below 0.01 km^2 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.

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

P5203

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

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)?

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.

P5204

L1: I suggest removing this entire section.

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 km^2 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).

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

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.

P5205

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

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

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.

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

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 km^2) for better comparability of the different datasets and thus a more sound evaluation of trends.

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.

P5207

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

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).

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.

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?

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.

P5208

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

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.

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.

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

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

L22: Please report what the impact of this is is (in km^2 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).

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%.

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

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 begin-

ning. Assuming that a glacier has to flow by definition, the 'units' smaller than 0.01 km^2 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).

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

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

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

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.

L18: Please do not care about the different number of glaciers in different inventories, and maybe reduce the number of digits somewhat (384 km^2 should be ok).

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 km^2) in the RGI and too large glaciers in the AGI-1998 / AGI-2009 due to inclusion of perennial (and seasonal) snow.

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).

P5210

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

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

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?)

L9: If comparable periods are compared the loss rates are likely equal (about -1.2%/year).
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.
L17-20: I recommend having a look at the GLIMS database design. The parent glacier ID concept is there since about a decade.
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 2. How does an ID help for this?
L23-27: Please remove. There is no 'proposed relation' in this study.

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.
T2/T6: Please remove; this study is about area changes of glaciers.
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.
T4/5: Please merge and use either totals or percentages for better comparability.

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).
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.
F3: I think this one is ok, but it requires a more detailed description in the main text.
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 km^2 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.
F5: Please remove.

Cited references

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

Radić, V., A. Bliss, A.C. Beedlow, R. Hock, E. Miles and J.G. Cogley (2014): Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Climate Dynamics, 42, 37–58.

Raup, B.H., A. Racoviteanu, S.J.S. Khalsa, C. Helm, R. Armstrong, and Y. Arnaud (2007): The GLIMS Geospatial Glacier Database: a new tool for studying glacier change. Global and Planetary Change, 56, 101-110.

Schmid, M.O., P. Baral, S. Gruber, S. Shahi, T. Shrestha, D. Stumm and P. Wester (2014): Assessment of permafrost distribution maps in the Hindu Kush–Himalayan region using rock glaciers mapped in Google Earth. The Cryosphere Discussions, 8, 5293–5319.