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The Cryosphere Discussions

Interactive comment on "Extrapolating glacier mass balance to the mountain range scale: the European Alps 1900–2100" *by* M. Huss

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SUMMARY The discussion paper by Matthias Huss addresses the extrapolation of glacier mass balance series from a few observation series to the entire mountain range. He uses long-term (modelled) mass balance series of 50 Swiss glaciers which are calibrated with (mainly) geodetic measurements and additional measurement series (based on the direct glaciological method) outside Switzerland. These data series are extrapolated to the entire European Alps based on a complete Alpine Inventory of the year 2003 and using (a) arithmetic averaging, (b) glacier hypsometry, and (c) multiple regressions. The extrapolated Alpine mass balances are validated against nine independent long-term mass balance series (outside Switzerland) as well as against geodetic volume change assessments and result in estimates for systematic and stochastic uncertainties. In addition, future mass balance and volume change for the time period from 2011-2100 are calculated by driving a combined model for mass balance and glacier geometry.

GENERAL COMMENTS The paper by Huss is a comprehensive study greatly integrating a large number of published datasets and methods in order to address a highly important issue of global relevance: how representative are a few available observation series for the glacier changes over the entire mountain range. The paper is well written, has a generally clear concept, and leads the reader nicely through the different steps of the analysis to the results. The comprehensive approach based on several other publications comes, however, with the price of being partly superficial and it is sometimes difficult to follow all explicit and implicit assumptions. As such, the paper probably has some conceptual mistakes in the sections about the extrapolation based on the glacier hypsometry (3.3) and in the calculation of stochastic and systematic uncertainties (5), and should elaborate further the sections about the extrapolation based on arithmetic averaging and based on multiple regressions. In view of the global relevance of this Alpine study, it would be great if the paper discussed the effects of a moving mass balance sample on the extrapolated mountain range estimate as well as the representativeness of the observation series for both the variability of the mean specific balance of all glaciers and the total mass change (i.e., contribution to run-off and sea level rise) of the entire mountain range. Also, the sections about the future scenarios could be better linked to the lessons learned from the extrapolation exercises which actually are the main focus of the paper. Furthermore, Figures 5 and 6 show some interesting features at the change from observations to scenario runs which might be illustrative to discuss.

Overall, Matthias Huss addresses with his study about the extrapolation of glacier mass balance series to the entire mountain range an important issue of global relevance. After moderate revisions following the general and detailed comments given here, the paper will make a great scientific contribution to be published in The Cryosphere.

SPECIFIC COMMENTS

Page 1118, Line 2, "extrapolation of single glacier mass balance measurements": In fact it is rather an extrapolation of a small (usually moving) sample of measurement series to the mountain range.

Page 1121, Mass balance datasets: The author uses modelled mass balance series (calibrated mainly with geodetic measurements) from Switzerland and glaciological mass balance measurements outside Switzerland for the extrapolation to the entire Alps. For some of these modelled Swiss series, there are glaciological mass balance measurements available too. It might, hence, be illustrative to show how good do these results compare?!

Page 1122, Line 2: Is it correct that the 16 short-term mass balance series outside Switzerland are used together with the modelled Swiss series for the extrapolation whereas the 9 long-term series outside Switzerland are used for validation only? Please clarify.

Page 1123, Future climate: Please mention if you consider or ignore other parameters in the GCM-scenarios (e.g., radiation budget, cloudiness) and in your glacier model (e.g., albedo, lake formation, debris cover) that might be of importance for the energy and mass balance results. This might help to discuss if the current results are rather optimistic or pessimistic in view of how fast glaciers will melt away.

Page 1125, Lines 1-3: You should check your assumptions about the four climatic different regions against corresponding literature (e.g., Böhm et al. 2001, Auer et al. 2005, 2007).

Page 1125, Lines 16-18: Actually there is a forth Swiss Glacier Inventory available for 1998/99 (Kääb et al. 2002, Paul et al. 2002, Paul 2004). Resulting area change estimates (1850-2000) for the entire Alps are given in Zemp et al. (2008).

Page 1125, Lines 18-23: Interpolating area changes between the available inventories using mass balance variations (cf. Equation 4) is straight forward but ignores the fact that area changes are a delayed, filtered, and enhanced reaction of a glacier to the energy and mass balance forcing at its surface. You should at least discuss the impact of this simplification on your results and might use available length changes measurements for the quantification of a corresponding estimate.

Page 1127, Line 1 & Figure5: Your density assumptions on this page (850 kg m-3) and in Figure 5 (900 kg m-3) are different and should be harmonized.

Page 1127, Arithmetic averaging: I propose to (i) extend this approach of simple averaging with regional averaging, and to (ii) assessing the impact of a moving sample (as used in most other studies) vs. a static sample (of long-term series as used in this approach).

Page 1127, Glacier hypsometry: Consideration of the glacier hypsometry is certainly a promising extension of the approach(es) using arithmetic averaging. And I agree that simple averaging over given elevation bands is a first but not necessarily best approach. Nevertheless, you should show its results and the corresponding improvement of your suggested correction to glacier median elevations. I think your proposed approach, shifting the averaged mass-balance elevation distribution to the glacier's median elevation, might work for years and glaciers with mass balances not too fare from steady-state conditions. However, for stronger mass imbalances (as we have had for the past two decades) the enforced positive balance of half of the glacier area will lead to systematic biases in your results and might explain the low performance of this approach. I, hence, propose to extend this section with testing a third approach: use (regional) ablation and accumulation gradients instead of elevation-band averaging and shift these gradients to the median elevation corrected for ELA-deviations from steady-state conditions (derived from ELA0 or median elevations of your observation sample).

Page 1128, Multiple regression: This approach is nicely complementary to arithmetic and hypsometry-base averaging. In my view it would be worthwhile testing also some parameters a bit more innovative than just area, slope, and aspect. It would be interesting to see if including parameters related to glacier hypsometry (e.g., difference between mean and median elevation or percentage of area above mean elevation) or continentality (e.g., Tmax-Tmin or the index by Gorczynski (1920)) are able to improve the explained variance?!

Page 1128, Line 27; “So far, no study has attempted mass balance extrapolation using multiple regression.”: This is not quite true. There is for example the paper by Schöner and Böhm (2007) using stepwise linear regression models for the reconstruction of LIA ice mass of glaciers in the European Alps.

Page 1129, Line 19: Any explanation for why south-exposed glaciers show less negative balances than north-exposed ones? Maybe, because these glaciers have built at higher elevations?!

Page 1130, Lines 7-14: Paul and Haeberli (2008) attribute glacier thickness changes to the period between 1985 and 1999 (not 2000) in order to account for the effect of C-band radar penetrated into the winter snow pack. Furthermore, a comparison of SRTM-based elevation changes against repeat DEMs based on aerial photogrammetry requires a careful co-registration process (cf. Nuth and Kääb 2011) before deriving glacier elevation changes. Please check your corresponding results in view of these two points and clarify the text in this section accordingly.

Page 1132, Line 2: Why are you now including all 50 glaciers? For reasons of consistency, it would be logical to use the same sample of 38 glaciers as before. Please clarify.

Page 1132, Lines 2-5: Why are you not using one of the extrapolation methods discussed in the sections before? This would much better motivate and link the observation part with the scenario part.

Page 1132, Line 19-24 & Table 3: For completeness and comparison, you should include the measured total glacier area for the 1970s (2,900 km2, WGMS 1989) as well as the thereof derived areas for 1850 (4,470 km2) and 1998/99 (2,270 km2) by Zemp et al. (2008).

Page 1133, Line 1: It would be interesting to compare your estimated Alpine mass loss to the results by Kaser et al. (2006), Radic and Hock (2011) as well as to the GRACE-based estimates by Jacob et al. (2012).

Page 1133, Lines 8-9: Another reason for the comparably lower ice loss of Swiss glaciers is probably the higher elevation of the summits.

Page 1133, Lines 17-19: The negative feedback due to glacier retreat into higher elevations might be at least partly compensated by a positive feedback due to the lowering of the glacier surface.

Page 1133, Lines 24-29: Here you should include a short statement about the significant uncertainty in remaining ice volume (cf. Page 1131) and its impact on the timing of glacier disappearance.

Page 1134, Lines 1-11: In view of effects not considered in your modelling approach (cf. comment on Page 1123), are these results to be seen rather as best or worst case scenarios?

Page 1134, Line 27: where does the value for the stochastic uncertainty σg come from? Please clarify.

Page 1135, Line 4-27: At line 4 you start to mix up systematic and stochastic uncertainties and corresponding treatments! You cannot calculate a systematic uncertainty according to the law of error propagation. Please completely revises this section and also better reference the values used for comparison.

Page 1137, Line 11: What is the reason for using the 80% confidence interval? Confidence intervals are typically reported at the 90, 95, or 99% level.

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P1137, Lines 21-23: ...which confirms the monitoring strategy as proposed by Haeberli (1998) and Haeberli et al. (2000).

P1137, Lines 24-29: This would be a good section for discussing the impacts of major corrections in some of the long-term series or of a moving sample on the Alpine-wide mass balance estimate.

P1138, Lines 5-8: You should specify what the term 'representative' refers to. As such a sample of observed glaciers might be representative for the total glacier run-off contribution (that originates from the few large glaciers) but not for the average specific mass balance of all Alpine glaciers (dominated by the large number of small glaciers).

P1138, Lines 9-17: this might be a good section for at least mentioning issues related to down-scaling techniques and potential changes in climate variability.

P1139, Line 2: ..and represent best estimates given the current state of knowledge and available datasets.

P1140, Line 6: ...at drastically reduced glacier size whereas others show a run-away effect with annual mass losses above 2 m w.e.

P1140, Line 12, Colgey 2011: or Bolch et al. (2012) for the same region or Zemp et al. (2009) globally. However, I would recommend leaving the conclusions without references.

P1150, Fig. 1: the circles as well as the black triangles are hard to see against the dark grey of the hillshaded terrain. Plotting elevations > 1,500 m a.s.l. in light grey (instead of the hillshading) might do a better job.

P1151, Fig. 2: The range of the y-scale in the lower figure should be enlarged in order to cover the full range in precipitation scenarios. Also, the thin grey lines are difficult to attribute to the individual GCM runs.

P1152, Fig. 3: In the left panel, there seems to be a switch of the glacier hypsometry based estimate from over- to under-estimation of the observed balance (from left to right which probably is from larger to smaller glaciers). Can you explain this feature?! According to the figure caption, the glacier area of 2003 is given – where?

P1153, Fig. 4: The example given shows a glacier system where processes not included in the modelling approach (i.e. cold ice temperature, summer accumulation regime) might lead to a different future reaction of Grenzgletscher as compared to Gornergletscher. When showing these two glaciers, it might be worthwhile discussing that issue.

P1154, Fig. 5: I guess the dashed line refers to the year 2011? Having the concept of climate scenarios in mind, I think the scenario mean is irrelevant and should not be shown.

P1154, Fig. 5: Why do the scenarios in plot (a) not start at the same mass balance value? And why do RCP 2.6, 4.5, and 6.0 show a trend towards less negative mass balance until 2020? If this is due to the reference period of the scenarios starting earlier (e.g., mean of 1961-90), it might be illustrative to show the scenario runs from the very beginning and discuss the course of the observations within the scenario ensemble.

P1155, Fig. 6: It looks like the dashed line refers to the year 2009? For reasons of consistency, it should refer to the same year as in Fig. 5.

P1155, Fig. 6: Again, there seems to be this trend towards less negative mass balancess until 2020?! And what is the reason for the enormous spread in reaction between different size classes after 2020 which is not visible in the observations?!

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