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Interactive comment on "Uncertainties and re-analysis of glacier mass balance measurements" *by* M. Zemp et al.

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Final author reply to review comments

We are grateful to Graham Cogley, Mauri Pelto, and Regine Hock for their thorough reviews and constructive comments which greatly improved our paper. The following is a short response to the general issues and selected specific comments provided by the reviewers. A detailed reply to all review comments is provided in the supplement to this comment.

Definition of "re-analysis" and related terms:

Terminology is a challenging field because there is no universally accepted definition of terms; the meaning of a term differs between communities and languages. We ad-

dress this issue by following the 'Glossary of Glacier Mass Balance and Related Terms' of Cogley et al. (2011), providing definitions for additional terms, and illustrating our reanalysing concept in Figure 1. Based on the reviewer comments, we use 'reanalyse' and 'reanalysing' rather than 're-analysis', and add short definitions and references to key terms in order to explain the difference to the use in other communities (e.g., 're-analysis' in Kalnay et al., 1996; 'homogenization' in Aguilar et al., 2003, or in Begert et al., 2005).

Representativeness of observational point network:

Most glacier mass balance programmes start with a large network of stake and pit observations and reduce the number of measurement points once the spatial balance pattern has been determined. Mauri Pelto proposes to increase the observational network every decade or so to reassess the spatial balance pattern, especially in cases of strong changes in glacier area and elevation distribution. We agree and add a corresponding recommendation for investigators of glacier mass balance to Section 5.4 of the paper. Another possibility would be checking point-to-point balance correlations and its stability over time.

Thickness change assessment from profile and point observations:

Ideally, a geodetic survey covers the entire glacier. Mauri Pelto brings up the issue of the utilization of thickness change results from geodetic survey profiles for comparison with (and calibration of) glaciological balances. For ice fields and ice caps, ground-based (e.g. GNSS) and airborne surveys (e.g. laser-altimetry) are often limited to profiles along the centre line of glaciers whereas spaceborne surveys (e.g. ICESat and GcryoSat-2) obtain a more random sample with denser coverage towards high latitudes. A comparison with the glaciological balance can be done along common centre lines or after extrapolation to the entire glacier. The uncertainty and potential bias related to extrapolation to the entire glacier (e.g., Arendt et al., 2002; Berthier et al., 2010) need to be quantified in a similar manner as for the glaciological method.

We extended the corresponding statement in Paragraph 1 of Section 2.3 (Geodetic observation method) and clearly state that this paper is focusing on geodetic estimates that contain full sampling of the glacier.

Reduction of Section 2, providing the theoretical background:

All three reviewers note that the paper is rather long, especially Section 2 providing the theoretical background. However, Mauri Pelto and Graham Cogley also clearly acknowledge that detailed examination of this large topic is required in order to move the practice of mass balance measurement onto a more rigorous footing. And all reviewers bring up several points which they would like to see discussed in more detail. As a consequence, we reduce Section 2 (providing the theoretical background) by deleting the theoretical background which is not of immediate relevance to paper and by moving technical details related to the co-registration and spatial auto-correlation to Appendices A and B. In addition, we delete the summaries at the end of each section of Chapter 3 (describing the reanalysing concept) but add a corresponding but shortened summary to the rewritten conclusions (as proposed by Regine Hock). Chapter 4 is shortened by moving the references related to the selected glaciers with long-term observation programmes to Table 1. The revised paper is shortened but still detailed enough allowing the readers (of different communities!) to understand the measurement principals and the reanalysing procedure without reading further literature; also thanks to a consistent terminology.

Calculation of annual uncertainties of glaciological and geodetic balances (manuscript Eqs. 12 and 15, respectively):

We agree with Graham Cogley in that the mean annual uncertainty of glaciological and geodetic balances need to be calculated differently: For the glaciological balance, the random error cumulates the uncertainties of annual observations according to the law of error propagation. For the geodetic balance, the random error originates from the two DEMs and is independent of the length of the corresponding balance period.

Consequently, the mean annual random error is estimated by dividing the uncertainty over a period of record (a) by the square root of the number of observation years for the glaciological balance (cf. Eq. 12) and (b) by the number of observation years for the geodetic balance (cf. corrected Eq. 15). We, hence, corrected Eq. 15, deleted Eq. 22 and adjusted Eqs. 26 and 27. Note that this difference does not affect any of the cumulative results over balance periods and does not change any of the conclusions.

Calibration of entire or partial glaciological balance series with the geodetic balance:

There were review question about the reason of calibrating the glaciological with the geodetic balance (Regine Hock) and of calibrating partial versus entire balance series (Graham Cogley). Ideally, a bias in the glaciological balance series can be detected through comparison with the geodetic balance. A subsequent calibration allows maintaining the relative annual variability of the glaciological balance and – at the same time – adjusting to the absolute multi-annual value of the geodetic method. In reality, geodetic surveys do not completely cover the full time period of the glaciological observations and are subject to systematic and random errors themselves. A calibration, hence, only makes sense after a careful uncertainty assessment and a significant difference between the two methods over a common period of records. Thereby it is important to test both the entire period of record and the individual (multi-annual) intervals: The differences can be large for individual intervals but compensate over the entire period of record (such as in the case of the old DEMs from Storglaciären, cf. Section 5.1) or may only become significant over the entire period (such as in the case of Kesselwandferner, cf. Section 5.1). Large uncertainties limit the ability to detect a difference at high confidence level. In such cases, further research is required in order to solve the ambiguity in the balance results from the two methods. Note that the generic differences between the two methods are attributed to the geodetic results for the validation. This ensures that even in the case of a partial calibration the entire series remains a surface balance series.

Calibration of seasonal balances:

Graham Cogley and Regine Hock raise concern over the (non-)calibration of the winter balances (cf. Eq. 33) because they do not believe that a bias comes by default from the summer balance. We do fully agree that the summer balance is not necessarily more prone to systematic measurement errors than the winter balance. However, in most cases summer balance is not directly measured but calculated from annual and spring surveys. Hence, in our approach, the bias is attributed by default to the annual observations "unless there is a clear hint that the bias comes from the spring observations". We added an additional comment to clarify this issue.

Calibration of equilibrium line altitude (ELA) and accumulation area ratio (AAR):

Mauri Pelto raises concern over the calibration of ELA and AAR because of changing an observational input to the mass balance calculation by the glaciological method. We do not share this concern since we differentiate between the (annual) ELA, which is calculated by fitting a curve to the surface balance data as a function of altitude, and the (end-of-summer) snowline which can be directly observed on the glacier (cf. Cogley et al., 2011). A calibration of the ELA (and corresponding AAR) does not require changing directly observed snowline which is often used as equilibrium line for mass balance calculations at glaciers where all mass exchange is expected to occur at the glacier surface and with no superimposed ice. In fact, deviations of the calibrated ELA (and corresponding AAR) from the spatially averaged altitude of the observed snowline (and the topographic AAR) might help identifying remaining error sources in the glaciological method. We revised Section 3.6, Calibration, in order to clarify this issue.

Improve the number and richness of geodetic observations available from the WGMS database:

Graham Cogley raises the issue of limited availability of geodetic measurements. Since the publication of the first volume of the Fluctuations of Glaciers series, the World Glacier Monitoring Service (http://www.wgms.ch) and its predecessor service have

been compiling and disseminating standardized information about glacier changes in area, thickness and volume from the geodetic method. Unfortunately, the direct data contributions from principal investigators of geodetic surveys are relatively small, as compared to the glaciological balance data received every year. Compiling geodetic data from the literature is very time-consuming and does not provide the full richness of the results. We agree with Graham Cogley and would like to strongly encourage all observers to share both glaciological and geodetic results in full richness with the scientific community through the WGMS.

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Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/7/C650/2013/tcd-7-C650-2013-supplement.pdf

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Interactive comment on The Cryosphere Discuss., 7, 789, 2013.