Computation of glacier-wide mass balance: evaluating the potential of the *linear mass balance model*

Summary

Glacier mass change is an element of the Essential Climate Variable *Glacier* as defined by the Global Climate Observing System. Time series of glacier mass balance also represent one of the most important variables of national and international glacier monitoring. However, the annual mass change of a glacier cannot be directly measured and relies on the spatial extrapolation of a discrete number of point observations to the entire glacier area. According to the GCOS Implementation Plan, *"documented traceability"* is a crucial asset of long-term monitoring series. The feedback of the GCOS CH Steering Committee on the GLAMOS Evaluation on 12 March 2019 indicated that the use of most simple approaches for evaluating glacier-wide mass balance should be considered. The present report provides an in-depth evaluation of the so-called *linear mass balance model* using GLAMOS data. The aim is to shed light on the potential of this approach to process mass balance observations but also to emphasize the related drawbacks and problems.

By applying the linear mass balance model to 15 Swiss glaciers with long-term data, it could be shown that the strongly simplified approach to evaluate glacier-wide mass balance delivers results that are within the uncertainty of the standard evaluations by GLAMOS using a further developed methodology for about two thirds of the sites. It therefore qualifies as a simple and easily understandable alternative approach providing processed time series of glacier-wide mass balance that might be valuable as an independent quality check of the reference evaluations. However, the linear mass balance model has a number of limitations which, according to the judgement of the GLAMOS Office, preclude its application in annually updated data series on the Essential Climate Variable *Glacier*, as well as data products and further analysis:

(1) The linear mass balance model is only applicable retrospectively.
(2) The linear mass balance model does not deliver spatial mass balance distribution.
(3) The linear mass balance model is unable to evaluate seasonal mass balance components.
(4) The linear mass balance model is highly sensitive to data gaps and the accuracy of geodetic mass balance surveys.
(5) The basic concept of the linear mass balance model does only partly hold (see details in report).

Our assessment of the potential of the linear mass balance model for evaluating annual glacier mass change has indicated that it serves as an easy-to-understand tool for *retrospectively analysing long-term series*. We thus provide supplementary data series of "processed measurements" (following the GCOS Implementation Plan) based on the linear mass balance model along with this report. Nevertheless, the various limitations outlined above are unfavourable for an application in the frame of the GLAMOS strategy that aims at meeting both the needs of the international glaciological community and the broader public.

1. Introduction

Glacier mass change is an element of the Essential Climate Variable (ECV) *Glaciers* as defined by the Global Climate Observing System (GCOS). Time series of glacier mass balance also represent one of the most important variables of national (in the frame of Glacier Monitoring Switzerland, GLAMOS) and international (in the frame of the World Glacier Monitoring Service, WGMS) glacier monitoring. However, the seasonal/annual mass change of a glacier cannot be directly measured and relies on the spatial extrapolation of a discrete number of point observations to the entire glacier area (Cogley et al., 2011). Glacier-wide mass balance as reported in international glacier monitoring is thus never a direct observation, but a quantity inferred by extrapolation tools of varying complexity. As the spatial distribution of the point measurements is rarely comprehensive nor fully representative, extrapolation introduces uncertainties in the variable of glacier mass change that are often difficult to be estimated (Zemp et al., 2013).

According to the GCOS Implementation Plan (GCOS, 2016, p. 45/46) “raw measurements” (direct point observations at stakes), need to be transformed to “processed measurements” (e.g. glacier-wide mass balance), serving as ECV variables. Further studies (“data analysis”) can then provide data products that are temporally or spatially more complete (e.g. mass change at the mountain-range scale for the hydrological year). The evaluation of glacier-wide mass balance (“processed measurements”) from point observations does not yet follow an internationally standardized procedure and many different approaches are used by the observers contributing data to the WGMS (Zemp et al., 2015). This is related to strongly varying observational approaches (both in space and time), the site-specific conditions, and the available knowledge and experience for data evaluation. Methods span from very simple approaches (linear mass balance model, profile line method) and manual techniques (contour line method) to more complex methods (kriging, model-based extrapolation) attempting to include all available information in an optimal way (e.g. Kaser et al., 2003; Cogley et al., 2011; Sold et al., 2016). Within GLAMOS, mass balance evaluation has been standardized and current measurements, but also all past observations have been (re-)evaluated using the same approach which has been repeatedly described and documented (Huss, 2010; Huss et al., 2009, 2015; GLAMOS, 2018a,b). The methodology relies on a distributed mass balance model used as an extrapolation tool that is optimized to match all seasonal observations in each year. The mass balance variations are thus given by the direct point measurements, whereas the extrapolation to the unmeasured regions is made by the model relying on physically based, individually adjusted relations with other explanatory variables. Frequent re-analysis of mass balance series with independent geodetic ice volume changes obtained from differencing of digital elevation models is an important element of the strategy implemented in GLAMOS and is consistent with international standards (Haeberli et al., 2007; Zemp et al., 2013).

The GCOS Implementation Plan (GCOS, 2016) identifies *“documented traceability”* as a crucial asset of long-term monitoring series. The feedback of the GCOS CH Steering Committee on the GLAMOS Evaluation on 12 March 2019 indicated that the use of most simple approaches for evaluating glacier-wide mass balance should be considered. They carry the advantage of being fully reproducible also by non-experts and provide results on glacier-wide mass balance (i.e. “processed measurements”) in a less complex and thus easily understandable way. The present report provides an in-depth evaluation of the so-called *linear mass balance model* (Lliboutry, 1974; Reynauld, 1980; Funk et al., 1997; Thibert &Vincent, 2009) using GLAMOS data. The aim is to shed light on the potential of this simple approach but also to emphasize the related drawbacks and problems. This report provides the basis for a supplementary data product of glacier-wide mass balance based on a strongly simplified but easy-to-understand methodology.

2. Methods

2.1. The linear mass balance model

The linear mass balance model was proposed several decades ago by Lliboutry (1974) and is, for example, still in use by French glaciologists to evaluate their point mass balance data (e.g. Thibert & Vincent, 2009). The linear mass balance model relies on the assumption that the mass balance at each location of a glacier can be described by a site-specific factor and a parameter describing temporal variations and is formulated as follows:

$$b_{jt} = \alpha_j + \beta_t + \varepsilon_{jt} \quad (1)$$

where b_{jt} is the mass balance at position j and year t, α_j is a parameter specific to the site j, β_t is a parameter depending on the climate in year t, and ε_{jt} is an error term containing the unexplained variance (Lliboutry, 1974). As such, Lliboutry's model is not applicable to compute glacier-wide mass balance from point observations. Reynauld (1980) proposed an extension and generalization of the model of the form

$$B_t = B_0 + \Delta B_t + \varepsilon_t \quad (2)$$

where B_t is the annual glacier-wide mass balance in year t, B_0 is the average mass balance over an arbitrary period of several years, ΔB_t is the centered mass balance anomaly of year t relative to B_0, and ε_t is the residual in year t (Reynauld, 1980).

Equation (2) is applicable in the context of mass balance evaluation as the long-term average over a time period (B_0) is available from the differencing of repeated digital elevation models and the subsequent conversion to mass change. Since 2018, GLAMOS is relying on the swissALTI^{3D} product of swisstopo with 6-year repeat cycles. Results on B_0, documenting the average mass change of the entire glacier, is thus provided by remote sensing, whereas the annual variability in mass balance ΔB_t is given by the mean deviation of an arbitrary number of point mass balance measurements on the glacier with annual readings.

The concept introduced above has several advantages: (1) Application is very simple, robust and easily traceable. (2) No actual extrapolation to unmeasured regions of the glacier is required – the mass change signal is taken from remote sensing. (3) The approach can also be applied using a strongly reduced set of point mass balance measurements which could potentially limit the effort in conducting field measurements. Conceptually, the approach is very similar to the one chosen in the study by Zemp et al. (2019) for glacier mass balance estimates at the global scale.

2.2. Evaluating the performance of the linear mass balance model

In order to evaluate the performance of the linear mass balance model, 15 glaciers with detailed and ongoing mass balance observations in the frame of GLAMOS were chosen. In the context of the present assessment we consider the evaluation of glacier-wide mass balance by GLAMOS as the reference, although uncertainties in an estimated range of ±0.10-0.25 m w.e. a^{-1} apply to these series (Huss et al., 2009, 2015; GLAMOS, 2018a,b).

In a first step, the average mass balance B_0 is computed over time periods of between 4 and 20 years, given by the actual availability of digital elevation models. However, for full comparability of the linear mass balance model results with the reference series we here extract B_0 from the annual GLAMOS time series, instead of directly from geodetic surveys. This is supported by the re-analysis of all series that has guaranteed an agreement of the annual series with the independent long-term geodetic mass changes with their uncertainties (Huss et al., 2015).

Second, mass balance point measurements positioned at the same location during the period for evaluating B_0 were compiled, and for each position their average mass balance, as well as the deviation Δb_t from this average in year t was computed. This was performed for between n=2 to n=19 point measurements per glacier, resulting in n series of Δb_t for each time period considered and each glacier. The glacier-wide deviation of mass balance from the long-term mean was then obtained by arithmetically averaging the site-specific series of Δb_t to obtain a signal representative at the glacier-scale.

For the evaluation of the performance of the linear mass balance model three options were tested:

(1) All point observations were used to compute ΔB_t. Subsequently, B_t was estimated using Eq. 2.
(2) One single point measurement was selected from all available ones to compute ΔB_t. This mimics that only one point observation per glacier was made (which would reduce field work efforts). The procedure was repeated 50 times randomly selecting a different point, thus resulting in 50 independent estimates of B_t (Eq. 2).
(3) Four point observations were randomly selected from the available set. For most cases this corresponds to a reduction of the sample size by around 50%. Figure 1 illustrates the distribution of available observations on Rhonegletscher and two randomly selected sets of four point measurements, either biased to the accumulation or the ablation area.

Option (1) refers to the optimal situation that can practically be applied. Options (2) and (3) shed light on the feasibility of the approach when using slightly or strongly reduced stake networks (see also Fountain & Vecchia, 1999), as well as the spread of the solutions with randomly changing sets of selected points.

To evaluate the performance, the difference in computed B_t using the linear model in comparison to the reference GLAMOS mass balance series was evaluated, resulting in a standard deviation for the entire series that can be interpreted as an uncertainty. When the standard deviation is smaller than the assumed uncertainty in the reference series (between ±0.10-0.25 m w.e. a^{-1}, depending on the site), the two approaches can be considered equally well suited for inferring annual mass balance.

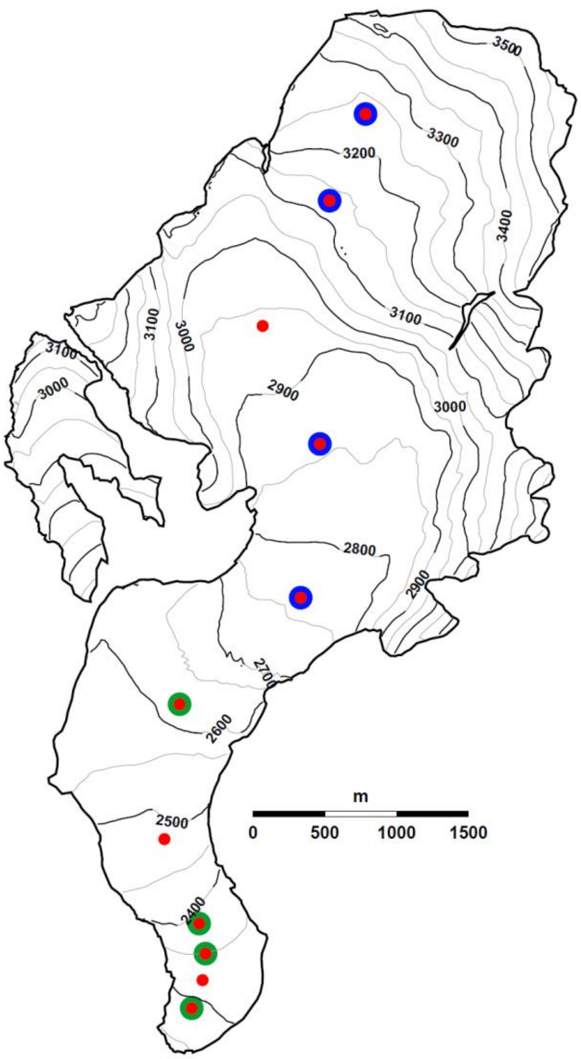


Figure 1: Mass balance stake network of Rhonegletscher. 11 stakes are currently positioned along a central flowline. In our approach we randomly sample either one, or four of all available point measurements for determining the skill of the linear mass balance model in the case of a reduced network. Blue colours show an example of randomly selected observations biased towards the accumulation area, green colours show an example that is biased towards the accumulation area.

3. Results

The linear mass balance model was applied using the three options described above to 15 Swiss glaciers, the years spanning from 1915 to 2019 at maximum. First, the results of individual glaciers are presented and summarized for all glaciers at the end of this chapter.

Figure 2 shows annual glacier-wide mass balance series of Rhonegletscher (see also Fig. 1), which is well-suited for illustration due to a stable mass balance stake network and its rather short time interval covered. In general, the mass balance variability as given by the reference GLAMOS series is well reproduced by the linear mass balance model. By design, both series have exactly the same average over the considered period. However, differences are remarkable in individual years, e.g. in 2018, when the linear model predicts a mass balance 0.7 m w.e. a^{-1} more negative than the reference series although all point measurements have been used. This can likely be attributed to a skewed distribution of measurements with elevation – more point observations per elevation band are available close to the glacier terminus than in the accumulation area (Fig. 1). This is rather typical for many mass balance monitoring programmes on large glaciers. In the case that deviations from the long-term average differ for stakes in the accumulation area from those in the ablation area, the linear mass balance model will give a too high weight to the better-represented regions which is an inherent limitation of the linear model. The approach utilized by GLAMOS is able to better take into account this spatial variability, on the one hand by appropriately weighting the annual point observations, but also by including many additional data of winter snow distribution directly into the procedure, providing crucial information on spatial mass balance variability.

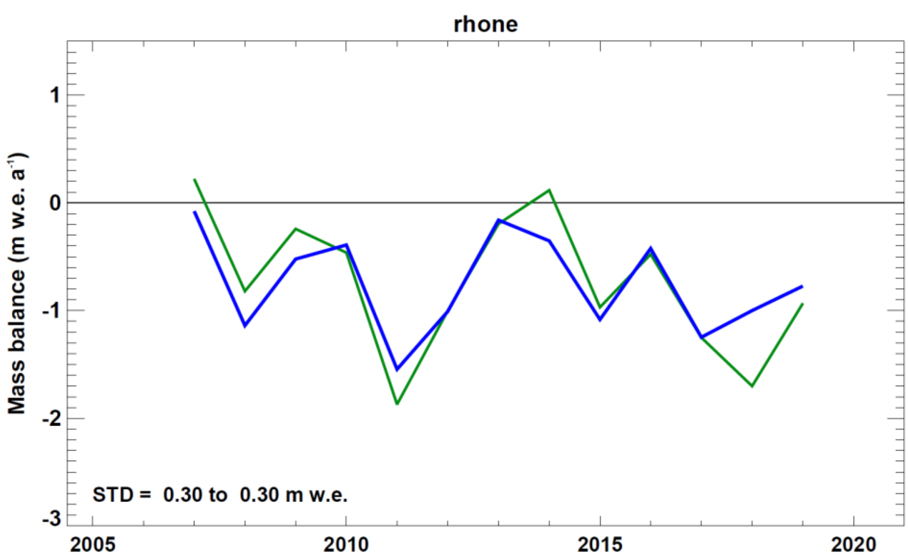
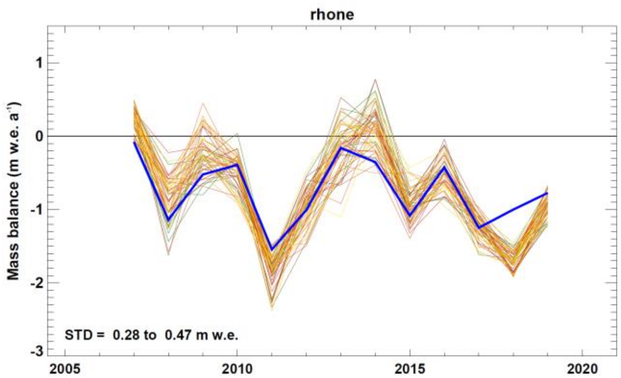


Figure 2: Mass balance time series of Rhonegletscher (2007-2019). The blue line refers to the reference evaluation by GLAMOS. The green line shows the result of the linear mass balance model using all available point measurements.

When randomly selecting four and one point, respectively, out of the available point measurements, the deviation of linear mass balance model results from the reference becomes larger (Fig. 3). Although the general pattern of temporal variability is even resolved when only considering a single observation, the spread of the individual solution drastically increases, for example also resulting in substantially positive mass balances in 2013 and 2014, and values significantly more negative than –2 m w.e. a^{-1} in 2011.



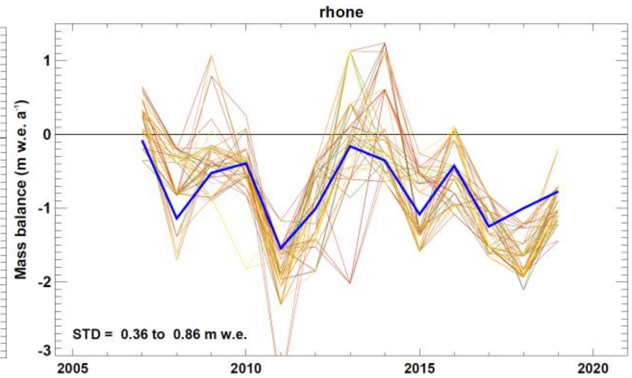


Figure 3: Mass balance time series of Rhonegletscher (2007-2019). The blue line refers to the reference evaluation by GLAMOS. The thin lines represent 50 independent realizations of randomly chosen (left panel) four point mass balance observations in each year, and (right panel) one point observation. The range in standard deviation of the 50 independent realizations in comparison to the reference series is given and can be considered as the uncertainty of the linear mass balance model.

The best performance of the linear mass balance model is found for Ghiacciaio del Basòdino (Fig. 4). This might be attributed to the relatively homogenous glacier surface and the regular distribution of mass balance stakes that is possible on this glacier. Even when randomly selecting only four out of the 11 stakes the standard deviation in comparison to the reference remains between ±0.13 and 0.29 m w.e. a^{-1}, i.e. similar as the uncertainty estimated for the GLAMOS series (Fig. 4).

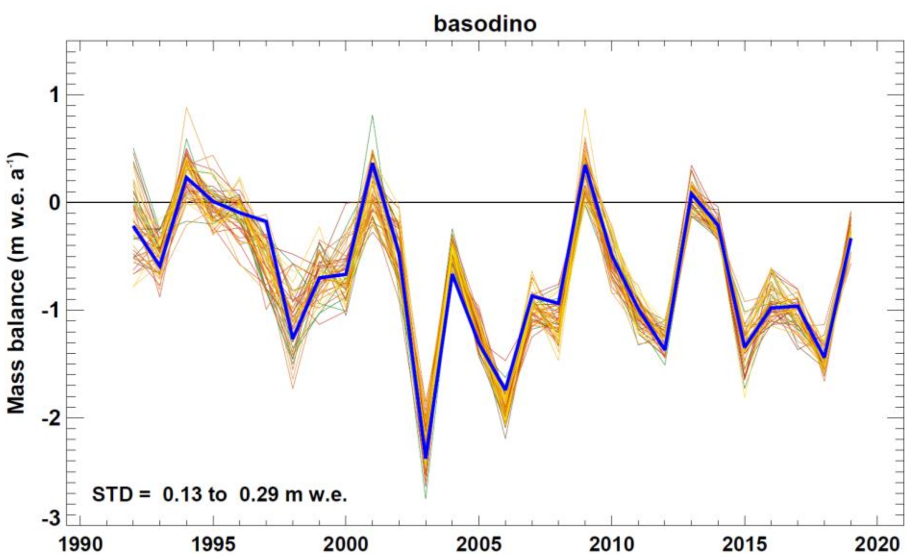


Figure 4: Mass balance time series of Ghiacciaio del Basòdino (1992-2019). The blue line shows the reference series and thin lines represent 50 independent realizations of randomly chosen four point observations in each year.

An overview of all analysed glaciers indicates that the performance of the linear mass balance model when using all observations is within or slightly above the uncertainty of the GLAMOS mass balance series for most glaciers (Fig. 5). For four glaciers (Giétro, Rhone, Allalin, Schwarzberg) standard deviations are clearly higher. This can be attributed to (1) the spatial distribution of point observations concentrated in the ablation area, and (2) some data gaps in the series (only Allalin, Schwarzberg) strongly impacting on the applicability of the linear mass balance model (see Discussion). Sites with standard deviations of the difference to the reference of <±0.15 m w.e. a^{-1} are typically small to medium-sized glaciers with a spatially representative stake network and a relatively simple mass balance regime.

As expected, errors are significantly higher when only a single point observation is chosen (grey bars) but might still deliver results with a reasonable accuracy in some cases. Selecting four point measurements generally results in a performance somewhat lower than when all observations are used, but in some cases (e.g. Murtèl, St. Anna, Plaine Morte) it can even be beneficial to not use all observations (Fig. 5).

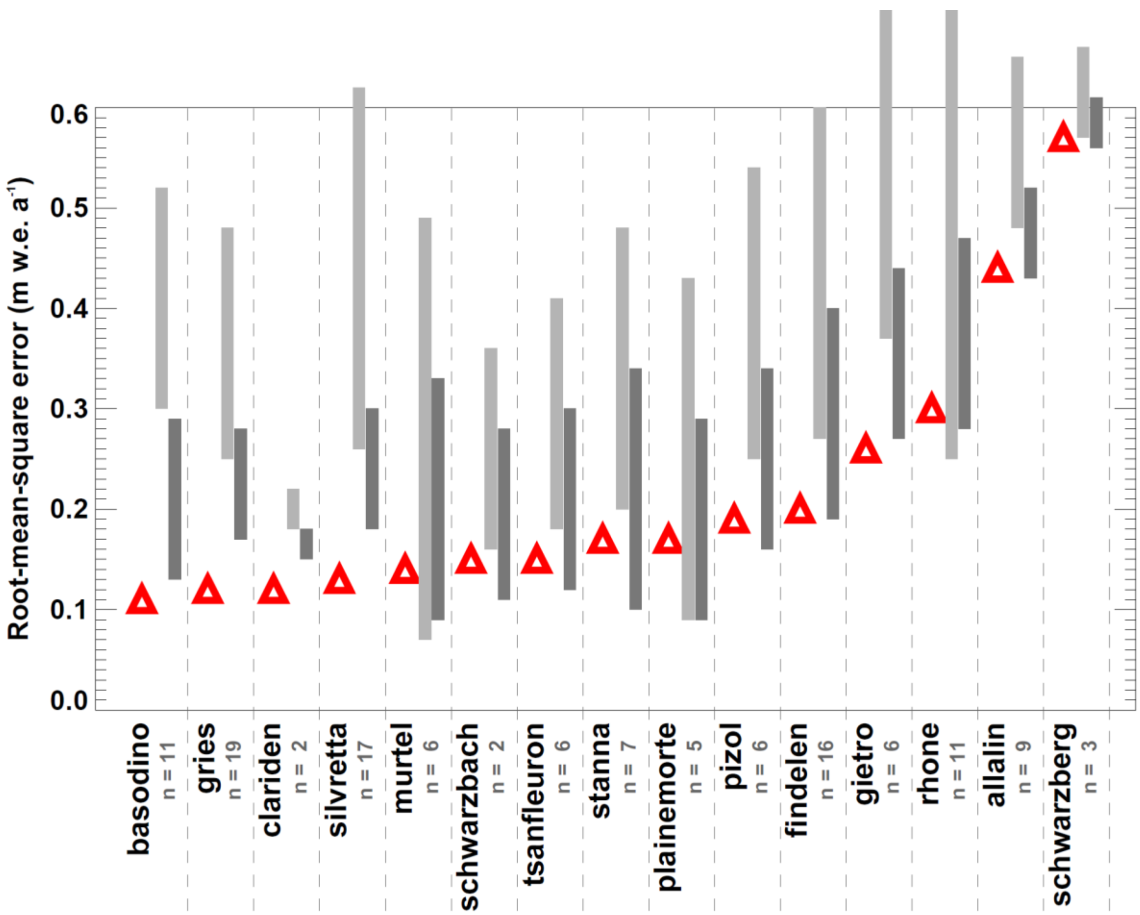


Figure 5: Overview of the performance of the linear mass balance model for 15 glaciers with detailed mass balance observations. The red triangles show the standard deviation of annual mass balances from the GLAMOS reference series when all available stake observations are used for the linear mass balance; the number of point measurements (n) is given for all sites. The grey bars indicate the range of standard deviations for 50 realizations of randomly selecting one point observation (light grey) and four measurements (dark grey), see Figures 2-4 for comparison. The glaciers are ordered according to the standard deviation found when using all point observations.

4. Discussion and Conclusion

The above analysis has indicated that application of the linear mass balance model in the described framework is possible and delivers time series of glacier-wide mass balance that lie within the estimated uncertainty of the GLAMOS evaluations for about two thirds of the investigated sites. Uncertainties with artificially reduced stake networks are substantially larger for most glaciers investigated. The linear mass balance model using all available point measurements qualifies for a strongly simplified and easily understandable approach for evaluating glacier-wide mass balance for these glaciers. The results could, for example, serve as an independent quality-check of mass balances inferred based on the complete standard scheme for deriving “processed measurements” used within GLAMOS. Time series based on this alternative approach could also be of interest for scientific questions related to the uncertainty in mass balance series or for investigating the climate-glacier linkage (e.g. Vincent et al., 2017).

However, the linear mass balance model has a number of limitations which, according to the judgement of the GLAMOS Office, preclude its application in annually updated GLAMOS results and data products:

(1) **The linear mass balance model is only applicable retrospectively**. When a new geodetic mass change has been derived from digital elevation models, B_0 (Eq. 2) can be computed and the linear model be applied. Results on glacier-wide mass balance would, thus, only become available **one to seven years** after the acquisition of the measurements. This is neither acceptable for scientific applications (e.g. transfer to the WGMS database), nor for information of the broad public.

(2) **The linear mass balance model does not deliver spatial mass balance distribution**, but just one value per glacier. This is inconsistent with the data collected in international glacier monitoring (elevation bands, mass balance gradients, equilibrium line altitude, accumulation area ratio, WGMS, 2017), and would strongly limit the value of GLAMOS results for further scientific studies (e.g. model calibration).

(3) **The linear mass balance model is unable to evaluate seasonal mass balance components.** Besides the annual glacier-wide mass balance, the seasonal mass balance components are an important result of modern glacier monitoring (see e.g. Machguth et al., 2006; WGMS, 2017). The linear model is unable to deliver results on this variable. Regarding traceability of the data products originating from monitoring, we consider it highly beneficial to be able to perform all evaluations in a single processing chain, however.

(4) **The linear mass balance model is highly sensitive to data gaps and the accuracy of geodetic mass balance surveys.** Data gaps, i.e. missing measurements at a single location in one year, or completely missing in situ observations in an entire year, substantially hamper the applicability of the linear mass balance model to infer “processed measurement” (according to GCOS, 2016). Losses of point measurements in a single year (e.g. likely in the case of extreme years) have the potential to substantially bias the results, whereas other techniques to evaluate glacier-wide balances are able to account for such data gaps. Furthermore, the linear mass balance model inherently assumes the geodetic mass balance (obtained from remote sensing) to be correct. Although current imagery is constantly improving, uncertainties remain considerable (e.g. Joerg et al., 2012; Rastner et al., 2016; Zemp et al., 2013, 2019).

(5) **The basic concept of the linear mass balance model does only partly hold.** As demonstrated by long-term measurements on various glaciers, mass balance is not always a strictly “linear” variable, as implicitly assumed by the linear model. Although the concept holds in theory, many exceptions exist (see Fig. 1) where the assumption of linearity leads to erroneous results. This is

common e.g. in the case of valley glaciers (e.g. Findelen, Rhone, Allalin) with an overrepresentation of observations in the ablation area.

(6) **The linear mass balance model does not allow correcting for differences in the timing of observations.** In practice, mass balance observations are performed over time periods different from the hydrological year. When comparing mass balances among glaciers, or for hydrological applications, an approach that is able to internally and consistently correct for these offsets is required. GLAMOS thus provides a data product for the hydrological year, involving temporal extrapolation using modelling (considered as "data analysis" following GCOS, 2016), as well as "processed measurements" referring to the observation dates. The latter data set is submitted to the WGMS and is independent of any meteorological data input (GLAMOS, 2018b).

Our assessment of the potential of the linear mass balance model for evaluating glacier mass change has indicated that it could serve as a simple and easy-to-understand tool for *retrospectively analysing long-term series*. However, according to the judgement by the GLAMOS Office, the various limitations outlined above offset the benefit, mainly consisting in the simplicity of the method. Our analysis thus indicates that results provided by the linear mass balance model are unlikely to meet the needs of both international glacier monitoring and the broader public, as only an incomplete set of processed glaciological variables with a considerable time delay can be derived.

Along with the present report we provide a data set (see Annex) of glacier-wide mass balances evaluated from all point observations using the linear mass balance model according to the approach described above being completely independent from the present GLAMOS evaluations. These results might be useful to, for example, detect years with particularly high uncertainties. Nevertheless, the GLAMOS Office considers the results of the linear mass balance as less suitable than the reference results as various important aspects cannot be taken into account (see above), and it is difficult to link the result to real-world processes as it is purely statistical. Analysing in situ point mass balance measurements to infer glacier-wide mass balance is complex, especially due to temporal variations in the observational network and large unmeasured regions of the glacier. The GLAMOS Office thus recommends applying techniques that are robust to data gaps and outliers and permit an objective extrapolation into regions not covered by direct observations to infer "processed measurements" from "raw observations".

GLAMOS Office, March 2020

(Responsibility: M. Huss)

Annex

Two .zip repositories contain evaluated mass balance results for the 15 glaciers analysed both for the linear mass balance model and the standard GLAMOS processing. All data refer to the measurement period. Variables that cannot be computed with the linear mass balance model are marked with *NaN*.

- Mass balance evaluation based on linear mass balance model:
  GLAMOS_linear_mass_balance_model.zip
- Mass balance evaluation based on standard GLAMOS processing chain:
  GLAMOS_measurement_period.zip

References

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., ... & Zemp, M. (2011). Glossary of glacier mass balance and related terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2. International Hydrological Program, UNESCO, Paris.

Fountain, A. G., & Vecchia, A. (1999). How many stakes are required to measure the mass balance of a glacier?. Geografiska Annaler: Series A, Physical Geography, 81(4), 563-573.

Funk, M., Morelli, R., & Stahel, W. (1997). Mass balance of Griesgletscher 1961-1994: different methods of determination. With 10 figures. Zeitschrift fur Gletscherkunde und Glazialgeologie, 33(1), 41-56.

GCOS (2016). THE GLOBAL OBSERVING SYSTEM FOR CLIMATE: IMPLEMENTATION NEEDS. World Meteorological Organization, 341 pp.

GLAMOS (2018a). The Swiss Glaciers 2015/16 and 2016/17, Bauder, A. (ed.), Glaciological Report No. 137/138 of the Cryospheric Commission (EKK) of the Swiss Academy of Sciences (SCNAT) published by VAW / ETH Zürich, doi: 10.18752/glrep_137-138.

GLAMOS (2018b). Mass balance evaluation and uncertainty: Claridenfirn 1914-2017, Glacier Monitoring Switzerland, internal report, doi: 10.18752/intrep_1.

Haeberli, W., Hoelzle, M., Paul, F., & Zemp, M. (2007). Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. Annals of glaciology, 46, 150-160.

Huss, M. (2010). Mass balance of Pizolgletscher. Geographica Helvetica, 65(2), 80-91.

Huss, M., Bauder, A., & Funk, M. (2009). Homogenization of long-term mass-balance time series. Annals of Glaciology, 50(50), 198-206.

Huss, M., Dhulst, L., & Bauder, A. (2015). New long-term mass-balance series for the Swiss Alps. Journal of Glaciology, 61(227), 551-562.

Joerg, P. C., Morsdorf, F., & Zemp, M. (2012). Uncertainty assessment of multi-temporal airborne laser scanning data: A case study on an Alpine glacier. Remote Sensing of Environment, 127, 118-129.

Kaser, G., Fountain, A., & Jansson, P. (2003). A manual for monitoring the mass balance of mountain glaciers (p. 137). Paris: Unesco.

Lliboutry, L. (1974). Multivariate statistical analysis of glacier annual balances. Journal of Glaciology, 13(69), 371-392.

Machguth, H., Eisen, O., Paul, F., & Hoelzle, M. (2006). Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent Alpine glaciers. Geophysical research letters, 33(13).

Rastner, P., Joerg, P. C., Huss, M., & Zemp, M. (2016). Historical analysis and visualization of the retreat of Findelengletscher, Switzerland, 1859–2010. Global and planetary change, 145, 67-77.

Reynaud, L. (1980). Can the linear balance model be extended to the whole Alps. IAHS AISH, 126, 273-284.

Sold, L., Huss, M., Machguth, H., Joerg, P. C., Leysinger Vieli, G., Linsbauer, A., ... & Hoelzle, M. (2016). Mass balance re-analysis of Findelengletscher, Switzerland; benefits of extensive snow accumulation measurements. Frontiers in Earth Science, 4, 18.

Thibert, E., & Vincent, C. (2009). Best possible estimation of mass balance combining glaciological and geodetic methods. Annals of Glaciology, 50(50), 112-118.

Vincent, C., Fischer, A., Mayer, C., Bauder, A., Galos, S. P., Funk, M., ... & Huss, M. (2017). Common climatic signal from glaciers in the European Alps over the last 50 years. Geophysical Research Letters, 44(3), 1376-1383.

WGMS 2017. Global Glacier Change Bulletin No. 2 (2014-2015). Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Huber, J., Machguth, H., Paul, F., and Hoelzle, M. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 244 pp.

Zemp, M., Thibert, E., Huss, M., Stumm, D., Denby, C. R., Nuth, C., ... & Joerg, P. C. (2013). Reanalysing glacier mass balance measurement series. The Cryosphere, 7(4), p-1227.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., ... & Bajracharya, S. (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61(228), 745-762.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., ... & Thomson, L. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature, 568(7752), 382-386.