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GLAMOS Glacier Monitoring Switzerland

VAW Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie

WSL

GCOS Switzerland Project

"Rescue, documentation and re-analysis of glacier monitoring data"

Final Report

Project period: 01 November 2019 – 31 December 2020
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Funding: MeteoSwiss in the framework of GCOS Switzerland

1. Summary

The direct observations of glacier mass balance in Switzerland date back until the late 19th century at some sites and have resulted in some of the longest and most complete data series globally. The programme Glacier Monitoring Switzerland (GLAMOS) is responsible of maintaining the measurement series, evaluating and archiving the data, and making them publicly available. Point mass balance observations are the backbone of the monitoring. They represent the original data directly demonstrating the response of surface accumulation and melt to changes in climate forcing. However, comparably little attention had so far been devoted to a careful documentation of the raw point mass balance measurements, including a complete assessment of their sources, an estimate of their uncertainty and the consistent long-term storage in a database.

The present project aimed at compiling a comprehensive data set of carefully documented and quality-checked mass balance observations based on original sources such as published or internal reports, field books or existing digital data. We consistently revisited all individual measurements of point mass balance at the seasonal and annual scale, as well as at shorter time intervals, in Switzerland, acquired since 1884. All individual measurements were traced to their original sources and indicators were assigned documenting the quality, the methods used and the uncertainty in the observations. As about 60'000 single observations have been performed over the last century in Switzerland, the task is colossal and will also keep GLAMOS busy beyond the present project. Data for more than 50 individual glaciers in Switzerland were compiled. Some data series cover more than 100 years continuously which is unequalled at a global scale.

The rescue and documentation of historical mass balance data has resulted in a massive strengthening of the data coverage available in the GLAMOS data base. Most importantly, the traceability of the individual observations and an estimate of their uncertainty greatly supports the evaluation and interpretation of the data, for example in the context of deriving time series of glacier-wide mass balance that are of interest in international glacier monitoring. A consistent re-analysis of some of the most important glacier-wide mass balance time series with the biggest change in the point data basis has been achieved, but future work is needed for a complete re-assessment of all series.

A detailed Best Practice Guide has been compiled, documenting past and present techniques of glacier observation in the Swiss Alps (mass balance, length change, glacier inventory). We expect this document to represent a benchmark in Switzerland for future glaciologists.

All results of the present project are available for download and further use by the scientific community (see details below). Digestible results will be submitted to World Glacier Monitoring Service for the next call-for-data.

2. Scientific Report

2.1. Introduction

Long-term glacier monitoring in Switzerland has resulted in some of the longest and most complete data series globally (Forel, 1881; Mercanton, 1916; Haeberli et al., 2007; Zemp et al., 2009, 2015, 2019; GLAMOS, 1881-2020). The direct observations of glacier mass balance date back until the late 19th century and, at some sites, have been continued until today. GLAMOS (Glacier Monitoring Switzerland) is responsible of maintaining the measurement series, evaluating and archiving the data, and making them publicly available.

The completed project *"Rescue, documentation and re-analysis of glacier monitoring data"* addressed Pillar 1 ("enhance and strengthen the Swiss climate observing system") of the GCOS Switzerland strategy 2017-2026. We focused on Priority 1.4 to "extend time series in the past through promoting data rescue". This emphasis excellently fits the strategic interests of the GLAMOS programme, partly financed by MeteoSwiss in the frame of GCOS Switzerland. The activities of the project targeted the variable *glacier mass balance* (mostly focusing on seasonal/annual point measurements).

Point mass balance observations are the backbone of the monitoring as they represent the raw and original data directly demonstrating the response of surface accumulation and melt to changes in climate forcing (e.g., Cogley et al., 2011; Vincent et al., 2017). However, regarding data archiving and interpretation with respect to trends in climate forcing, the focus of international glacier monitoring has mostly been on evaluated quantities such as the glacier-wide mass balance which is easier to compare among sites (e.g. Zemp et al., 2009). Comparably little attention has so far been devoted to a careful documentation of the raw point mass balance measurements, including an assessment of the observational methodologies, an estimate of their uncertainty and the consistent long-term storage in a database. As source data in original field books, old published reports or meta-knowledge from people working in the field are becoming more and more difficult to be accessed, this task is of utmost relevance for securing the quality of long-term glacier monitoring data and their usability for further studies (e.g., Huss et al., 2015).

The GCOS Switzerland-funded project tried to rectify this by a consistent revisit of all individual measurements of point mass balance at the seasonal and annual scale, as well as at shorter time intervals, in Switzerland acquired since 1884. As ten thousands of single observations have been performed over the last century, the task is colossal and will also keep GLAMOS busy beyond the present project. However, a compilation and complete documentation of almost all known series has been achieved. The project was organized in five work packages (WPs) and was conducted jointly at ETH Zürich and WSL Birmensdorf. Two assistants (L. Geibel, C. Kurzböck) worked full-time on the project for 9 and 12 months, respectively, and were closely supervised by M. Huss and A. Bauder. The main goal of the project was to establish a comprehensive digital compilation of all point glacier mass balance measurements acquired in Switzerland over the last 140 years, including all available metadata, thus allowing full traceability of the observations. In addition, a Best Practice Guide for glacier monitoring with respect to the conditions in Switzerland was established. In this final report we summarize the activities of the entire project duration and give an overview of the results.

2.2. Methods and activities

For compiling and documenting raw point mass balance data acquired in Switzerland, a complete re-assessment of all individual measurements from pre-existing digital sources, published reports, unpublished documents, field notes, as well as meta-knowledge of the observers has been performed. Figure 1 provides an example of one of the investigated documents. A newly developed system of indicators allows attributing quality measures and further information on data acquisition, sources and observers for single measurements and permits consistent documentation within the GLAMOS database. Data series for more than 50 individual glaciers have been re-assessed or newly compiled. A complete list of additional data sources of lower relevance (e.g. short / incomplete series) makes them accessible for further digitization efforts.

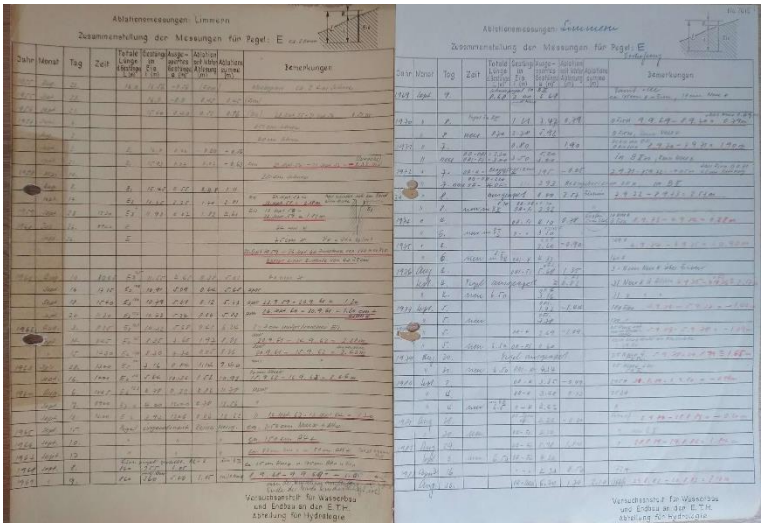

Figure 1: Example of an investigated document with original notes on observed glacier mass balance allowing the tracing of individual mass balance observations (Limmernfirn, source: archive of VAW-ETHZ).

The documented traceability and quality assessment of ten thousands of individual point mass balance observations requires a powerful yet simple system to assign the relevant information to all entries. The system also has been included and will be further maintained in the GLAMOS database. Therefore, we developed a set of variables and indicators that need to be specified for all individual entries. Indicators define

- the *type* (e.g. stake measurement, snow probing, etc.),
- the quality of the observations' *time stamp*,
- the accuracy of their *positioning*,
- the way the *snow/firn/ice density* has been measured/estimated,
- the overall *quality* of the point measurement.

Furthermore, the source and, if known, the observer are specified. This system is a major progress in comparison to the present storage of point mass balance data in the GLAMOS database, which just focused on the measurement values without any options to document their origin and their quality.

For each glacier, three types of data were distinguished and assembled (Fig. 2):

(1) observations spanning an approximately **annual** time period,
(2) observations covering the **winter** season (e.g. Oct. to May),
(3) **intermediate** point observations spanning any time interval from a day up to several months.

Whereas (1) and (2) have been partly available and were used in GLAMOS before for the evaluation of glacier-wide mass balance, no consistent compilations of (3) were available to date, although partly vast amounts of intermediate measurements had been performed since more than 100 years and were archived in various formats.

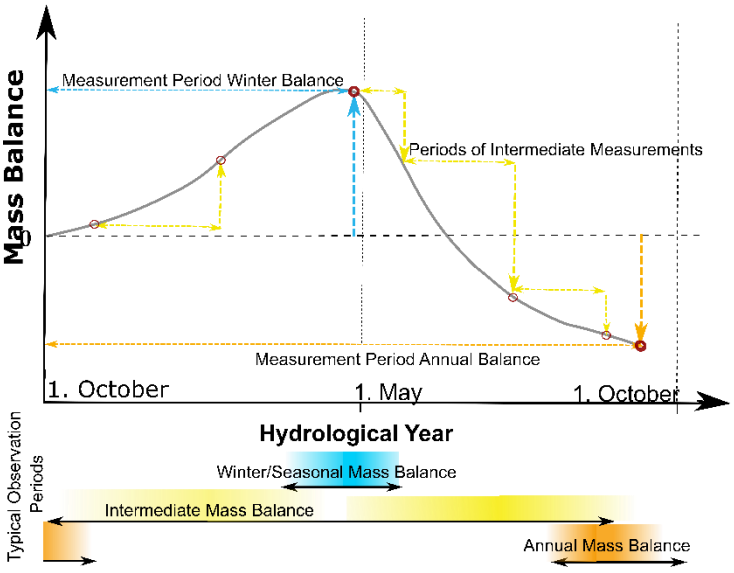

Figure 2: Schematic overview of the time systems archived (annual, winter, intermediate).

Within **Work Packages 1 and 2**, a careful and complete screening of all known and potential data sources on mass balance measurements in Switzerland has been performed: published historical records, original files and folders, field books, and digital data sources available from previous work. By contacting various glaciologists directly, we gained access to additional data. Although it was known that observations on many glaciers were performed, we were surprised how much more information came together that we were not, or only vaguely, aware of. For example, thousands of so far unknown point measurements on Grosser Aletschgletscher were found in the written archives of VAW-ETHZ, or contacts to a retired amateur glaciologist established by chance delivered fully unknown and highly detailed observational series for five glaciers in Eastern Switzerland.

Whereas WP 1 and 2 were the core of the project, accounting for more than 80% of the overall effort dedicated, the other work packages focused on further evaluating these results and documenting the related approaches for future generations of glaciologists. **Work Package 3** aimed at translating seasonal point mass balance measurements into time series of glacier-wide mass balance, relevant for international glacier monitoring, and as collected by the World Glacier Monitoring Service (WGMS; Zemp et al., 2015). Depending on the spatial density of the acquired point mass balance measurements this is a highly challenging task as the extrapolation of point observations to the entire glacier surface may result in significant uncertainties (e.g., Zemp et al., 2013; Sold et al., 2016). Here, we relied on approaches that have been established in Swiss glacier monitoring since more than a decade and are continuously further developed (Huss et al., 2009; 2015). The extrapolation from point observations to the glacier-scale is achieved by a spatially distributed mass balance model that is annually optimized to match all individual measurements. At the long-term, results are constrained to agree with independent geodetic ice volume changes based on repeated digital elevation models. The strategy of extracting long-term glacier mass changes from remote sensing and to rely on in situ point observations for inferring seasonal/annual mass balance variability is consistent with the strategy proposed by the WGMS (see also, Zemp et al., 2013, 2019; Thibert and Vincent, 2009; Andreassen et al., 2016).

Following the recommendation of the GCOS Steering Committee, we have not focused on the homogenization of glacier length change measurements (**WP4**, a minor part of the overall project). No results are presented for this aspect. This task will be further pursued in the frame of the normal GLAMOS activities.

2.3. Results

Overall, data series were compiled for 55 glaciers for the annual time period, 46 for the winter period, and 46 for intermediate observations, containing almost 60’000 point observations in total (Fig. 3). In comparison to data previously available within GLAMOS,

entries for 11 to 37 additional glaciers (depending on data type) and 20'000 new point data have been included (Table 1). The temporal coverage per glacier ranges from one year to more than 100 years. Earliest observations start in 1884 (Fig. 4). A significant amount of new information could also be extracted for the period before 1950 when almost no direct observations are available worldwide. The procedure to document and quality-check the individual mass balance data was extremely laborious and meticulous but also varied strongly between the individual sources. Most existing entries of the GLAMOS database were verified using the original sources, and the individual quality indicators were assigned. For the more recent data series, where also direct field experience from the GLAMOS staff was accessible, the effort was more limited than for older series with hand-written files, incomplete information and no direct contact persons. We realized the importance of performing this work on our monitoring data – various inconsistencies in the previously available series were detected and the data rescue endeavor would become more and more difficult as time goes on.

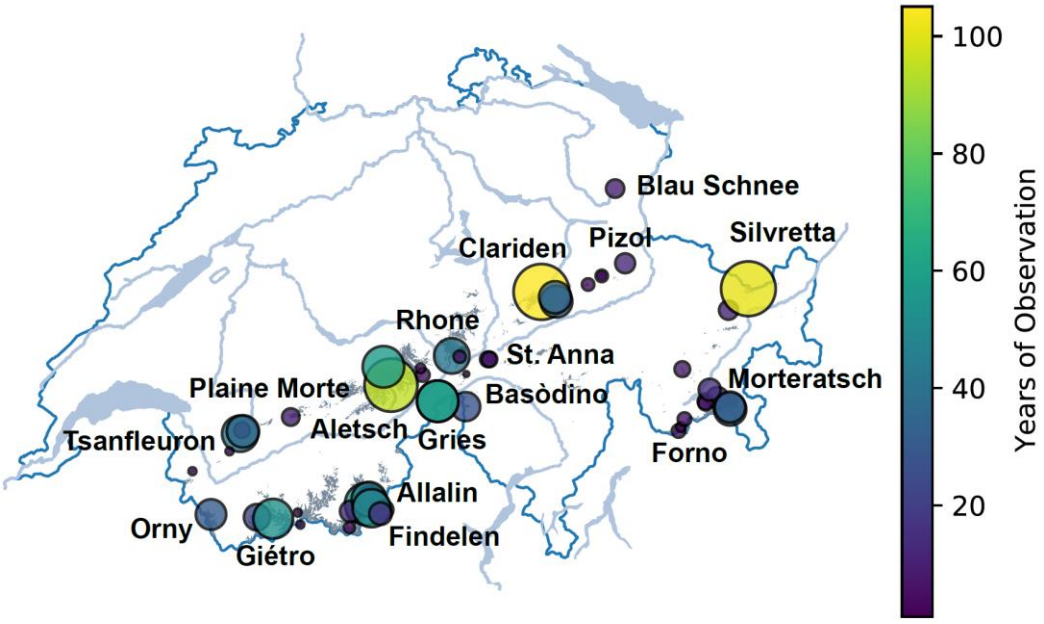

Figure 3: Coverage of annual point mass balance data series. The size of the dots and their colour indicate the length of the observational period. Important sites are labelled.

	Annual	**Intermediate:**	**Winter:**	**Total:**
Previously available:	35	9	35	79
# point entries	9,162	275	30,217	39,654
Current Version:	55	46	46	147
# point entries	11,777	10,992	36,952	59,721
Addition:	**20**	**37**	**11**	**68**
# point entries	**2,615**	**10,716**	**6,738**	**20,069**

Table 1: Statistics on the number of glaciers with previously available and newly integrated point mass balance data specified according to the three types (annual, intermediate, winter)

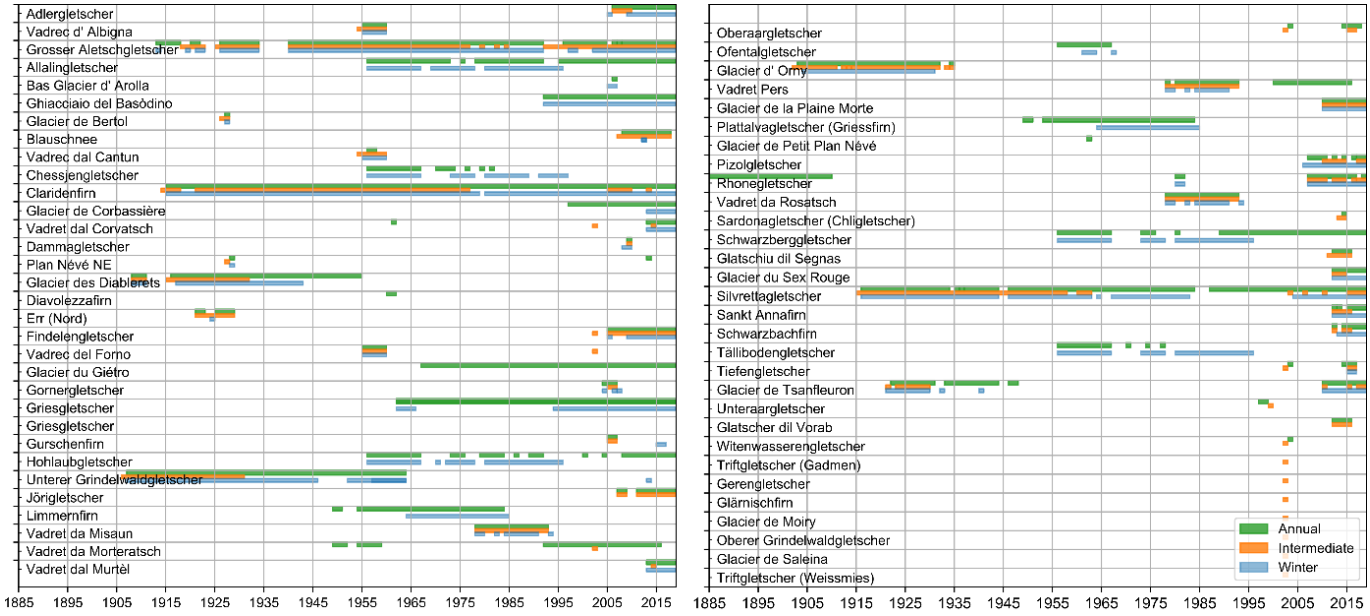

Figure 4: Detailed overview of available data types (annual, intermediate, winter) and time periods covered for individual Swiss glaciers. Glaciers are alphabetically ordered.

Point mass balance observations are highly valuable to investigate the effect of climate forcing on glaciers, and they represent the raw measurements, unaffected by further data evaluation carrying potential uncertainty (e.g. Zemp et al., 2013; Vincent et al., 2017). However, their interpretation is not trivial as time series refer to individual points and are not directly comparable between different sites. We extracted anomalies of the longest and most homogenous sites from a common reference period (Fig. 5). Our long-term data set clearly reveals a trend towards substantially more negative annual mass balance, whereas point winter balances show decadal variations but no consistent changes.

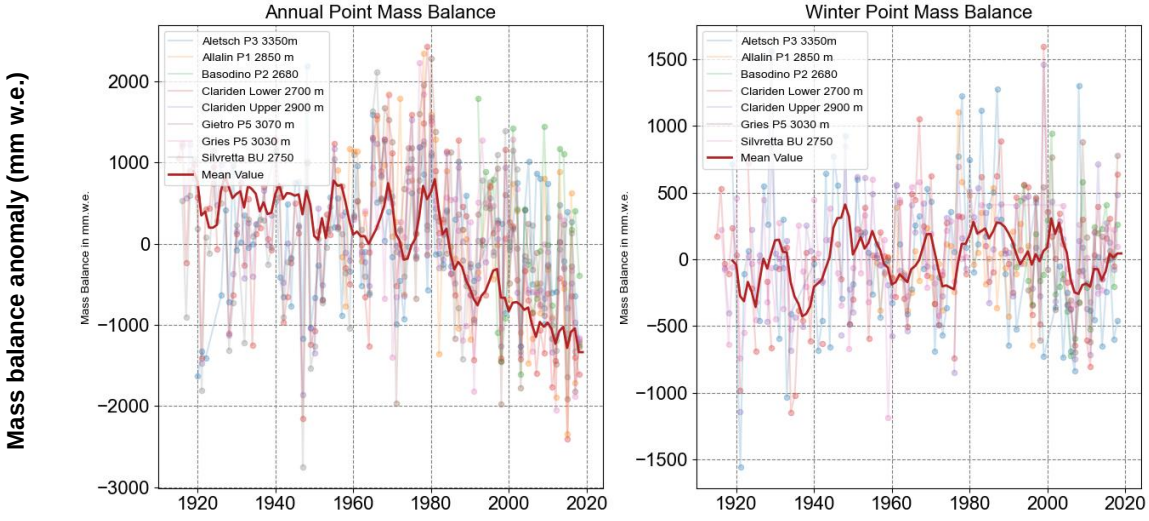

Figure 5: Anomalies in (left) annual and (right) winter point mass balance from a common reference period for the longest point mass balance series in the Swiss Alps (Aletsch, Allalin, Basòdino, Clariden, Giétro, Gries, Silvretta), including observations on the four global reference glaciers of the WGMS.

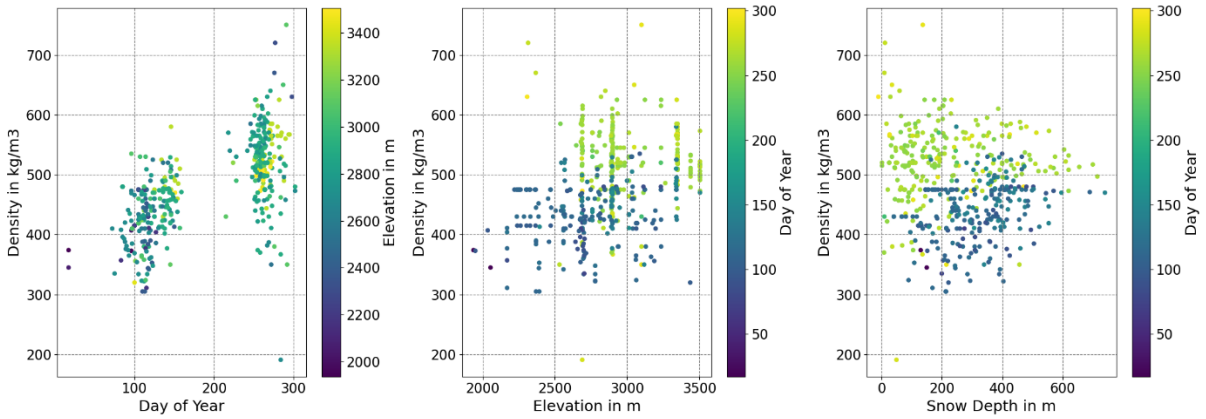

Figure 6: Analysis of measured snow and firn densities depending on the day of year (left), the elevation (center), and the snow/firn depth (right).

Our new documented data set of seasonal point mass balances allows unequalled insights into the observations of snow and firn densities over a centennial time period and several dozen sites. Information on snow and firn density often represents a bottleneck for the determination of mass balance (e.g., Sold et al., 2013; Gugerli et al., 2019). Whereas winter snow depth, and/or raw firn accumulation is relatively easy to be measured from the surface, acquiring data on density is laborious. Our complete compilation of density observations throughout Switzerland allows us to investigate dependencies from various explanatory variables (Fig. 6), and thus to establish approaches to extrapolate density values to sites, for which no observations were performed due to logistical constraints.

Furthermore, due to the documented quality indicators of all point observations, a consistent quantification of the uncertainty in individual measurements is possible for the first time. This is considered as a major progress and allows much better constraints on data evaluation and interpretation. We find that average uncertainty in annual mass balance measurements over all sites is ±0.14 m w.e. a^{-1}, whereof roughly half of the uncertainty is explained by the reading error or incompletely known metadata, and half is due to the uncertainty in the snow/firn/ice density estimate. The absolute uncertainty is found to be similar for ablation and accumulation measurements, although relative uncertainty is bigger for accumulation data.

Based on the new quality-checked and consistently documented seasonal point data series, a re-analysis of all time series of glacier-wide mass balance in Switzerland has been started (**WP3**), updating and replacing previous assessments (GLAMOS, 1881-2020; Huss et al., 2009, 2015). This task relies on established methodologies that are able to account for all observational data, their uncertainties, as well as additional independent variables such as long-term ice volume change from geodetic surveys. Our new data set thus provides a significantly larger and better constrained coverage for the Swiss Alps. However, the amount of work for a careful and complete re-analysis of several dozens of mass balance series is large and unfortunately could only be completed for 13 of the most important series with relevant changes in the data set of point mass balance observations (e.g. Aletsch, Clariden, Gries, Silvretta), or series with substantial new information on mass balance (e.g. Blau Schnee, Joeri, Oberaar, Orny). Figure 7 demonstrates the impressive data set of additional point mass balance observations acquired on Aletschgletscher between the 1950s and 1980s, and Figure 8 shows an example of the re-analysis of the glacier-wide mass balance series for Griesgletscher, updating the previous data set (Huss et al., 2009). Consistency of cumulative annual mass balances with independent geodetic mass changes has been ensured for all series (Fig. 8). The re-analysis and homogenization of long-term mass

balance series is also part of the annual GLAMOS programme and receives funding. Consequently, this task can be completed also after the termination of the present project.

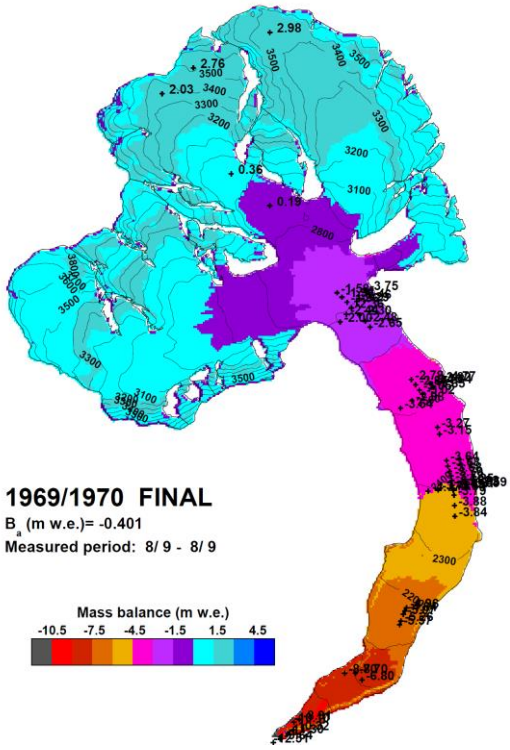

Figure 7: Mass balance of Grosser Aletschgletscher in 1969/1970 as given by the point observations (symbols, values indicate measured mass balance in m w.e.) and the model-based extrapolation to the entire glacier (colours).

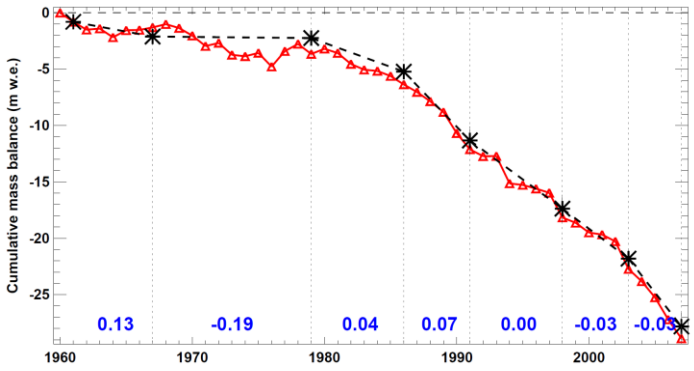

Figure 8: Time series of annual glacier-wide mass balance of Griesgletscher (red), validated with independent geodetic mass changes (black symbols). Blue colours indicate the periodical average bias of the annual series in m w.e. a^{-1}.

Figure 9: Selected images from the GLAMOS techniactice Guide (GLAMOS, 2021b).

We have compiled a detailed Best Practice Guide (**WP 5**) documenting techniques and procedures related to Swiss glacier monitoring on 60 pages. The Best Practice Guide mainly focusses on the variable *glacier mass balance*, but also includes the variables *length change*

and *glacier inventory*. We partly relied on previous similar documents compiled in an international context (Østrem and Brugman, 1991; Kaser et al., 2003). Our Best Practice Guide does not intend to represent an international reference for techniques in glacier monitoring as a corresponding effort currently led by the World Meteorological Organization with contributions from GLAMOS staff (Thorsteinsson, in prep.), but is tailored to Swiss conditions in order to provide a benchmark of past and present approaches used in Swiss glacier monitoring. The Best Practice Guide is publicly available (GLAMOS, 2021b). Figure 9 gives a graphical insight into some aspects of the GLAMOS Best Practice Guide.

2.4. Conclusion and limitations

The GCOS-funded project *"Rescue, documentation and re-analysis of glacier monitoring data"* has indicated that tapping into the raw observations of mass balance in Switzerland is a tremendous task. Although many observations have been previously available, they were not traceable, and their quality was mostly unknown. A surprising number of additional data sets for the monitored glaciers and completely new observational series for some glaciers were discovered. Furthermore, we consider the new data format with complete metadata and specified uncertainties as another main achievement of the project.

The rescue and documentation of historical mass balance data has resulted in a massive strengthening of the data coverage and its documentation available in the GLAMOS data base. In the course of the project, it became clear that this task was more laborious than originally thought as many more data sources than expected could be located in the archives. The enhanced and extended basis of seasonal point mass balance data for more than 50 Swiss glaciers, covering a period of significantly more than a century, represents a globally unequalled data set for the direct observation of glacier surface mass balance. The compilation of a detailed Best Practice Guide for Swiss glacier monitoring will be highly useful for documenting past and present techniques of glacier observation in the Swiss Alps and represents a benchmark for future glaciologists.

We note that the most important goals set in the proposal were fully achieved: (1) A complete rescue, documentation and archiving of almost all historical point mass balance observations in Switzerland in digital form, and (2) the compilation of a detailed Best Practice Guide for glacier monitoring in Switzerland. The re-analysis of long-term series of glacier-wide mass balance based on the new point data set has not yet been completed but the most important additions have been taken into account and updated series are available to the scientific community. As suggested by the GCOS Steering committee, we have not focused on the re-analysis of glacier length change records in this project (WP4).

The limitations to this project have clearly been set by the immense breath of available observations and the diversity of their formats (various digital formats, old printed reports, hand-written field books etc.). The measurements over 140 years came with a variety of observational techniques and reporting systems that were partly very difficult, if not impossible, to be reconstructed. It is challenging to manually assess every single one of the 60'000 data point, and in some cases full information was not available anymore. In those cases, the quality indicators were used to flag missing or estimated values to the best of our knowledge.

2.5. Outreach work, publication of data and results

We note that the work conducted in the present project only has a limited potential for public outreach. Pursuing the sources of the individual measurements and documenting their

quality is meticulous detective work, occurs in the background, and does not pay back with large public attention. Therefore, we cannot report major outreach activities directly related to the project. However, the general work of GLAMOS related to the acquisition of point mass balance data and their evaluation receives abundant coverage (e.g. >100 individual media reports and dozens of interviews in TV and radio in 2019 and 2020), as well as substantial attention via Social media (Twitter).

We have presented the approaches, the data sets, and the results of the project at two national/international conferences:

- **Swiss Geoscience Meeting (Nov. 2020)**
  Link to Abstract
- **American Geophysical Union (Dec. 2020, virtual)**
  Abstract only available with AGU login

A preparation of an article on the documentation of point mass balance measurements in Switzerland and the results is underway in “Earth System Science Data”, an international, interdisciplinary, peer-reviewed journal.

> **Geibel, L., Huss, M., Kurzböck, C., and Bauder, A. (in prep.). Mass Balance Data Rescue and Homogenization. Earth System Science Data.**

The quality-checked and documented point mass balance series (**WP 1/2**), representing the main outcome of the project, have been ingested into the GLAMOS database and are available through the regular GLAMOS data releases:

> **GLAMOS (2020). Swiss Glacier Point Mass Balance Observations, release 2020, Glacier Monitoring Switzerland. doi:10.18750/massbalance_point.r2020.2020**

We intend to also publish the re-analyzed glacier-wide mass balance series (**WP 3**) in a peer-reviewed journal in due time. At the moment all completed results are available via the GLAMOS data portal (**www.glamos.ch**), and directly as a data set:

> **GLAMOS (2021a). Swiss Glacier Mass Balance, release 2021, Glacier Monitoring Switzerland, doi:10.18750/massbalance.2020.r2021**

The Best Practice Guide (**WP 5**) has been published as a GLAMOS internal report.

> **GLAMOS (2021b). A Best Practice Guide for long-term glacier monitoring in Switzerland. Internal Report No 5, doi:10.18752/intrep_5**

For the next call-for-data (**November 2021**), all digestible data (seasonal point mass balance observations, re-analyzed glacier-wide mass balance series) will be submitted to the World Glacier Monitoring Service (WGMS).

2.6. Outlook

The completed project has indicated the pressing need for documenting data acquired in the field in detail and storing the metadata in a consistent format. Only if this information is available, a re-analysis of the observational time series at a later stage is possible and data can be interpreted by future generations of glaciologists. Luckily, many of the glacier mass balance measurements acquired in the Swiss Alps over the last century permitted the reconstruction of the necessary meta-information based on publications, internal reports and

notes, and the relevant information is available for the more recent series. The system for storing the metadata in a consistent and durable format, and to archive the information in the GLAMOS data base, established thanks to the present project, will be a reference for Swiss glacier monitoring for the decades to come. It is expected to have a great value for allowing the tracing of the data acquired in the field. The project has thus brought a substantial progress for the documentation of point mass balance data, the backbone of GLAMOS glacier observations, and the elaborated concepts will be pursued in the future.

We also note that the quality assessment and documentation of historical glacier mass balance observations is never finalized, also after the tremendous efforts of the present project. More information might become available, allowing a more accurate tracing of the source of the individual measurement values, or even more time could be invested for investigating the basis of single data points. We have tried to find an optimum between accuracy and efficiency in order to establish a complete data basis of all observations.

Also the re-analysis of glacier-wide mass balance series on the basis of the compiled and documented point observations will be a continuously ongoing task within GLAMOS. The funding received within the present project has allowed to invest additional effort into this task. Regular updates of the time series evaluated to optimally honour all available observations will be released by GLAMOS, and be subsequently submitted to the WGMS. The publication of the Best Practice Guide established in the frame of this project will be advertised via our Twitter-channel (@glamos_ch, @VAW_glaciology) and via the GLAMOS Website. We also aim at updating the Best Practice Guide in due time to account for evolutions in glacier monitoring in Switzerland. The document is currently also feeding into the larger international effort by the WMO to establish a global Best Practice Guide, an activity with strong involvement of GLAMOS.

2.7. Acknowledgements

We first would like to acknowledge Meteoswiss in the framework of GCOS Switzerland for providing funding to our proposal. Without this support, this important work resulting in a massive strengthening of our observational data basis would not have been possible. We also thank the innumerous glaciologists acquiring mass balance measurements on Swiss glaciers over the past century. To name just a few with whom we were in direct contact in the frame of this project: A. Linsbauer, O. Langenegger, M. Funk, G. Kappenberger, U. Steinegger, J. Landmann, M. Fischer, H. Machguth, M. Zemp, N. Salzmann, etc.. Without the effort of many scientists acquiring mass balance data, often on a voluntary basis and beyond funded projects, the observational basis in Switzerland would not be as unique (both in time and space) at the global scale.

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