Versuchsanstalt für Wasserbau,
Hydrologie und Glaziologie

GLAMOS
Glacier Monitoring Switzerland

A Best Practice Guide for Long-term Glacier Monitoring in Switzerland

MEASUREMENT, DOCUMENTATION AND EVALUATION OF GLACIER MONITORING DATA

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January 2021

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SUMMARY

Digitalization and automation are important trends that also extend to glaciology. The century-long practices of glacier monitoring are altered by new technologies and the need for machine-readable data formats changes the way of documentation. Nevertheless, a continuity and consistency of long-term observations are the backbone of monitoring efforts and need to be kept up at a high quality.

Recent and ongoing changes in glacier monitoring require an update of established monitoring manuals and guidelines. With this Best Practice Guide established in the framework of the national programme GLAMOS (Glacier Monitoring Switzerland), we provide an overview on the current practices in data acquisition, documentation and evaluation. The focus of this guideline is on mass balance measurements, length change observations and the compilation of glacier inventories.

The first chapter contains practical recommendations for mass balance data acquisition by direct field observations. First, methods for annual and winter mass balance measurements are described, including the distribution of measurement sites, stake drilling, placement and reading, as well as the measurement of snow depths and determination of snow density, including the estimation of uncertainties. Subsequently, a comparison of glacier length change observation methods, which are currently undergoing a transition from traditional field observations to mapping based on aerial images and landscape models is provided. We also give insights into the strategies for compiling updated glacier inventories based on the processing stream of the Federal Office of Topography (swisstopo).

The second chapter focusses on documentation of glacier monitoring data. We describe a new standardized format for documenting seasonal point mass balance measurements. In addition to previous data formats, the new format allows recording and reconstructing important metadata on accuracy, quality and the source.

The third chapter provides an overview on data evaluation techniques currently applied in GLAMOS. We focus on the determination of glacier-wide mass balance from point mass balance observations and the evaluation and homogenization of length variations. The appendix contains additional information on all observed glaciers and practical suggestions for organizing fieldwork on these sites.

1. INTRODUCTION: GLACIER MONITORING & DOCUMENTATION

In a nutshell: Observation of glacier changes in Switzerland has a long history. Currently, the monitoring is coordinated by the national programme Glacier Monitoring in Switzerland (GLAMOS). This Best Practice Guide provides a written documentation of Swiss glacier monitoring standards.

1.1. GLACIER MONITORING IN SWITZERLAND

Systematic observation and documentation of glacier fluctuations in Switzerland date back to the late 19th century (Figure 1). In 1880, the later founder of the International Glacier Commission, F.A. Forel (1841-1912), initiated annual measurements of glacier length change on about 30 Swiss glaciers (Forel, 1881). The length change was measured with a tape relative to local reference points maintained in the glacier forefield. Thanks to this simple technique, measurements could be carried out by collaborators with only limited experience. In the following years, length change observations were extended to about 160 glaciers in Switzerland and most of them have been continued until today (see Figure 28 in Appendix 7.1) (GLAMOS, 2020c).

The first glacier mass balance measurements (both in Switzerland and worldwide) were conducted in 1884 on Rhonegletscher (Mercanton , 1916). In 1911, members of the Swiss alpine club started to measure ablation and accumulation using mass balance stakes on Glacier d'Orny on an annual basis (Forel et al., 1912). In the following years, similar measurement activities were initiated at Claridenfirn, Silvrettagletscher, Glacier de Tsanfleuron and Grosser Aletschgletscher (Mercanton, 1920). The recordings on Clariden, Aletsch and Silvretta were continued until today almost without interruption (Huss et al., 2009; GLAMOS 2019). These over 100-year long time series of seasonal point mass balance are worldwide unique. In the following decades, new glaciers have been added but also removed from the monitoring network, resulting in many shorter, yet diverse time series (see Figure 29 in Appendix 7.2).

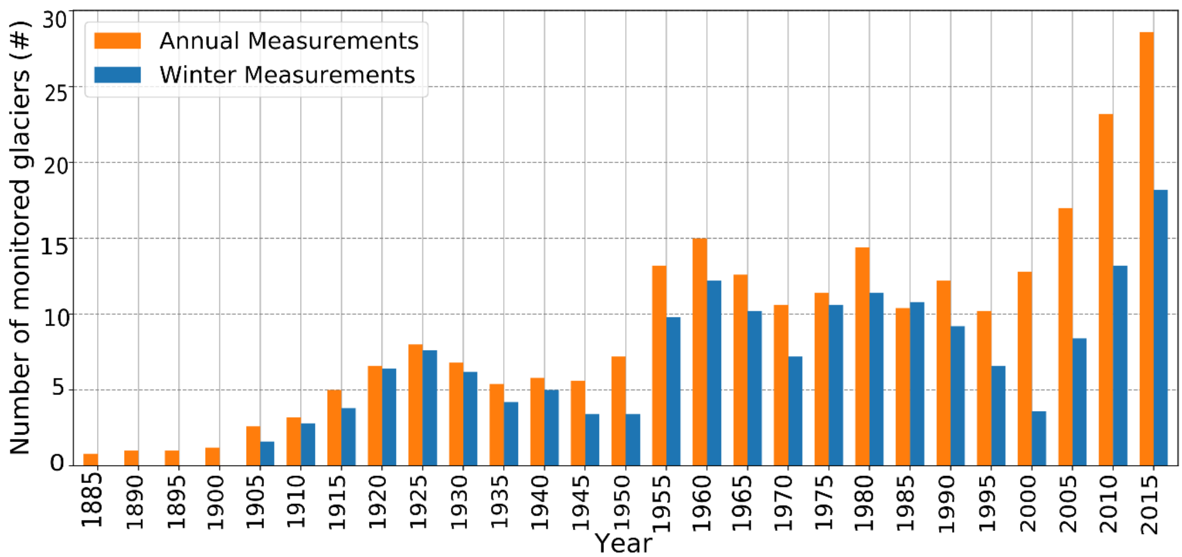

Figure 1: Number of glaciers with direct mass balance observations. Data have been aggregated to 5-year averages.

Since 2016, acquisition of glaciological data in Switzerland is run by the programme Glacier Monitoring in Switzerland (GLAMOS). GLAMOS is currently under the auspices of the Cryospheric Commission of the Swiss Academy of Sciences (CC/SCNAT) and is jointly operated by the Laboratory of Hydraulics, Hydrology and Glaciology at ETH Zürich (VAW/ETHZ), the Department of Geosciences of the University of Fribourg, and the Department of Geography of the University of Zurich. The activities are secured by financial support from the Federal Office for the Environment (FOEN), MeteoSwiss within the framework of GCOS Switzerland and the Swiss Academy of Sciences (SCNAT). It is also supported by the Federal Office of Topography (swissstopo). The main focus of GLAMOS is to collect the following data: length change, mass balance, volume change, surface flow speed, glacier inventories, englacial temperature, as well as to manage a database of special events. GLAMOS is responsible of maintaining the measurement series, evaluating and archiving the data, and making them publicly available (www.glamos.ch).

Measurements of variations in glacier length are carried out every year at around one hundred glacier tongues. In 2019, for example, length variations were recorded at 84 Swiss glaciers (GLAMOS, 2020c). More complex methods are used to measure the mass balance both at the end of winter and in autumn. In 2020, mass balance measurements were conducted on more than 20 glaciers (GLAMOS, 2020b). With the help of data from swisstopo, the change in ice volume for a larger number of glaciers at intervals of 5-10 years is determined, and a new inventory of all glacier areas is compiled at intervals of six years. Currently, a new inventory referring to the years 2013-2018 is in preparation (GLAMOS, 2020a; Linsbauer et al., in prep).

1.2 HISTORY OF DATA DOCUMENTATION

Thanks to the meticulous documentation of glacier observations and subsequent publication by the Swiss Alpine Club, Swiss glacier fluctuations can be reconstructed for over 100 years. The monitoring results have been continuously published in the format of glaciological reports (*Gletscherberichte*) in the yearbooks of the Swiss Alpine Club (SAC) from 1880 to 1970. Starting from that year, publications were split into more detailed scientific data-reports by the Swiss Academy of Sciences (SCNAT) and a summary of general outcomes in the SAC magazine *Die Alpen/Les Alpes/Le Alpi* for the broad public. Also, the Zuercher Gletscher Kommission has published their own monitoring results in the so-called firn reports (*Firnberichte*) from 1914 to 1978. Important sources for more recent glacier data are reports by VAW/ETHZ for hydropower construction sites (Limmern, Silvretta, Gries, Albigna, Mattmark and Mauvoisin). The data have been stored in local archives in different formats; sometimes only as handwritten internal field notes never mentioned in any official publication (Huss et al., 2015).

All documented length variation data of the 100 years of systematic monitoring was compiled and published in GLAMOS (1986). Starting in the 1990s the entire time series of the 120 glaciers with ongoing observations in the network have been transformed and stored in digital format and finally made available for a larger audience through a first website of the Swiss glacier monitoring. A further completion of all documented observations of 160 glaciers was realized by Antoni (2005).

Although some efforts had been made to digitize some of the longest time series of mass balance measurements, it was not until 2015 that previously unpublished and unevaluated observations of point winter and annual mass balance were compiled, consistently evaluated and made available to the scientific community (Huss et al., 2015). In 2016, these time series, together with recent data, were integrated into a digital database, which was set up by GLAMOS. However, an estimate of data quality and an assessment of the sources was missing. Also, some data series were incomplete, shorter time series and intermediate mass balance measurements remained undigitized so far.

To fill this gap, in 2019 the GCOS-funded project “Rescue, documentation and re-analysis of glacier monitoring data” was launched. In the frame of this project, all individual measurements of point mass balance at the seasonal and annual scale were revisited, assessed for their quality and transferred into a new standardized storage format. Yet undigitized sources were identified and directly entered in the new documentation format (GLAMOS, 2021).

The project resulted in an increase of more than 18,000 newly digitized point mass balance measurements and an addition of more than 19 glaciers to the database. The largest part of the increase is due to the intermediate measurements referring to periods of a few days to several months. Currently, the database contains mass balance information for more than 50 glaciers with more than 58,000 single data points:

Table 1: Comparison of GLAMOS database content for point mass balance observations before and after the data rescue project

	Annual		Winter		Intermediate		Total
	No. Glaciers	No. point MB	No. Glaciers	No. point MB	No. Glaciers	No. point MB	No. point MB
Before project	35	9,162	35	9,162	0	0	39,654
After project	54	10,243	44	10,243	46	10,984	58,108
Addition	**19**	**1,081**	**10**	**1,081**	**46**	**10,984**	**18,453**

In Appendix 7.3, a table with all glaciers in the database and all available mass balance data (separated into the type - annual, winter, intermediate) from 1884 to 2020 can be found.

1.3 GLACIER MONITORING IN OTHER ALPINE COUNTRIES AND WORLDWIDE

Glacier monitoring in the neighbouring countries Austria and Germany has a long history as well. In 1891, the German and Austrian alpine associations began with systematic length change measurements and set up the archiving of the data. Results have been published in annual glaciological reports since 1927 (Klebelsberg, 1926). In contrast to Switzerland, length change measurements are still under the auspices of the alpine association.[1] Currently, 94 glaciers are monitored for length change (WGMS, 2020). Mass balance has been recorded since 1948 (WGMS, 2017). Today, mass balance measurements are conducted on 10 glaciers (WGMS, 2020). Glacier inventories are available for 1969, 1997-1998 and 2006-2012.[2]

Also, in Italy monitoring of “movimenti dei ghiacciai” was initiated by the Italian alpine association (Club Alpino Italiano CAI). In 1895, a Commission for the study of glaciers (CGI[3]) was founded. Since 1914, the commission has been publishing its annual scientific activities (CGI & CAI, 1914). Mass balance has been recorded since 1964 (WGMS, 2017). At present, approximately 150 glaciers are monitored for their

[1] https://www.alpenverein.at/portal/museum-archiv/gletschermessdienst/index.php
[2] https://www.glaziologie.at/gletscherinventar.html
[3] https://www.glaciologia.it/en/il-comitato/la-storia-del-comitato/

length change and 20 for mass balance by voluntary surveyors (Baroni et al., 2019).[4] Several partial glacier inventories are available (WGMS, 2017).

In France, long-term amateur observations of glacier length, height and velocity started in 1905. However, these time series were not continuous, and observations did not cover the entire glacier surface. In 1993, the IGE (Institut des Géosciences de l'Environnement, University of Grenoble) extended the mass balance observation network to the entire surface of four glaciers and increased the number of observations over time (bi-annual measurements at least, for the measure of winter and summer balances). In addition, INRAE (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement) is providing bi-annual mass balance observations on another glacier. Those five glaciers are monitored as part of the GLACIOCLIM (Les GLACIers, un Observatoire du CLIMat) Alpes observation service hosted by the University of Grenoble.[5] Multitemporal glacier inventories of the French Alps exist from the 1960s to the late 2000s (Gardent et al., 2014).

In Slovenia, regular monitoring of the two small glaciers has been conducted since 1946. Due to their low altitude, the glaciers have almost disappeared. The last geodetic measurement of the glacier area took place in 2012 (Triglav-Čekada & Zorn, 2013).

Since 1986, the World Glacier Monitoring Service (WGMS) is maintaining and continuing the collection of information on glacier changes worldwide (Haeberli et al., 2007; Zemp et al., 2009, 2015). More than 40 countries are currently contributing to the database. Active mass balance programs are currently (2019) run in 28 countries on more than 150 glaciers (WGMS, 2020). In 2019, length change was recorded in 21 countries at 401 glaciers in total (WGMS, 2020). The measurements are part of an integrated monitoring strategy, the Global Terrestrial Network for Glaciers (Haeberli et al., 2000). The WGMS collects standardized observations on changes in mass, volume, area, and length of glaciers with time (glacier fluctuations), as well as statistical information on the distribution of perennial surface ice in space (glacier inventories). All data and information are freely available for scientific and educational purposes. Summaries are published regularly (WGMS, 2017).

1.4 EXISTING MANUALS AND GUIDELINES

First guidelines documenting variables of glacier monitoring and how to acquire them addressed to mountaineers who visited the glaciers in late 19th century (Gletscherkollegium, 1872).

In the 1960s, Anonymous (1969) published a paper on "Mass-balance terms" with the purpose of "reducing the ambiguity and confusion caused by the use of a large number of alternate schemes and definition". It became the effective standard of glacier mass-balance terminology for the next 40 years until it was revised by Cogley et al. (2010).

In 1969, a booklet on the good practice of mass balance measurements was published by Østrem and Brugman (1969): "Glacier mass-balance measurements: A manual for field and office work". The manual has been an authoritative reference for glacier mass-balance methodology in Canada and Norway. The manual represents a consolidation of Norwegian and Canadian methodologies but was also used in other countries. The publication set the stage for a standardization of glacier mass-balance terminology

[4] https://www.glaciologia.it
[5] https://glacioclim.osug.fr/

and standard data formats, enabling comparison of results from different countries. The manual was revised in 1991 (Østrem & Brugman 1991).

In the early 21st century, Kaser et al. (2003) drafted a manual for glacier mass balance measurements on glaciers in low latitudes, in particular the Hindu Kush-Himalaya region. The manual provides the theoretical background of glacier mass balance and an outline of definitions and common data formats. The second part of the manual provides practical details for fieldwork, data analysis, and data presentation. The manual also contains chapters about mountain safety and high-altitude medicine (Kaser et al., 2003).

With the aim to update and revise Anonymous' mass-balance terminology, a Working Group of the International Association of Cryospheric Sciences (IACS) compiled a "Glossary of Glacier Mass Balance and Related Terms" (Cogley et al., 2011). The new glossary tried to eradicate ambiguities in current usage and reflects changes in practice with conventional measurement tools and replacement by new technologies (Cogley et al., 2011).

The Global Cryosphere Watch under the auspices of the World Meteorological Observation (WMO) is currently preparing to publish a new guide to instruments and methods of glaciological variables (Thorsteinsson et al., in preparation). The guide is scheduled to appear in 2021 or 2022, also with contributions from GLAMOS.

1.5 AIMS OF THIS BEST PRACTICE GUIDE

With the present Best Practice Guide, GLAMOS aims to provide an up-to-date glacier monitoring guideline tailored to Swiss conditions. The main focus of this guide are mass balance and length change measurements. An overview on the compilation glacier inventories is provided as well.

Our Best Practice Guide depicts the whole process of glacier monitoring, ranging from practical information on fieldwork to subsequent data documentation and storage and concludes with the calculation of glacier wide mass balance. The guideline on data documentation also refers to the compilation and documentation of historical glacier mass balance data. A homogenization and quality assessment, including the estimation of uncertainties, of historic data is necessary for a consistent storage in the GLAMOS database and subsequent re-analyses of glacier wide mass balances.

Although there is an unwritten consensus on measurement techniques among the observers in Swiss glacier monitoring, a written guideline has not been existing so far. A documentation of the best practices in glacier monitoring is thus important for ensuring seamless continuation of the efforts by the next generation of glaciologists.

2. DATA ACQUISITION

In a nutshell: GLAMOS is currently collecting observations of the following variables: (1) length change, (2) mass balance, (3) volume change, (4) surface flow speed, (5) glacier inventories, and (6) englacial temperature. This chapter focuses on the acquisition of mass balance data, length change observations and glacier inventories.

2.1 MASS BALANCE

2.1.1 GENERAL CONSIDERATIONS

Mass balance is the change in the mass of a glacier over a stated span of time, usually a year or a season (winter/summer) (Cogley et al., 2011). Mass change of a glacier is arising from two processes: Accumulation and ablation. Glacier ablation comprises all glacier mass, which is removed by melting, calving, evaporation or wind erosion. The most important component on mountain glaciers is melt (Østrem & Brugman, 1991). Ablation usually occurs in the lower part of the glacier (ablation zone), while positive mass balances typically prevail in the upper regions of the glacier (accumulation zone) (Kaser et al., 2003). Accumulation is referred to all processes that add to the mass of a glacier (Cogley et al., 2011). The main process of accumulation is snowfall. Accumulation, however, also includes deposition of hoar, freezing rain, solid precipitation in forms other than snow, gain of windborne snow and avalanching (Østrem & Brugman, 1991). In a given period, a glacier receiving the same amount of accumulation as it loses ablation, is said to be in balance. If accumulation exceeds ablation, mass balance is positive; the glacier thickens and advances. Conversely, if ablation exceeds accumulation, mass balance is negative; the glacier thins and retreats (Østrem & Brugman, 1991). Mass balance measurements based on the direct glaciological method at individual sites are essential for the investigation of glacier changes in the context of climate change. The calculation of the mass balance of an entire glacier (glacier-wide mass balance) is obtained by extrapolation of point observations and possible approaches are described in Chapter 5. In this chapter, we focus on the acquisition of seasonal point measurements.

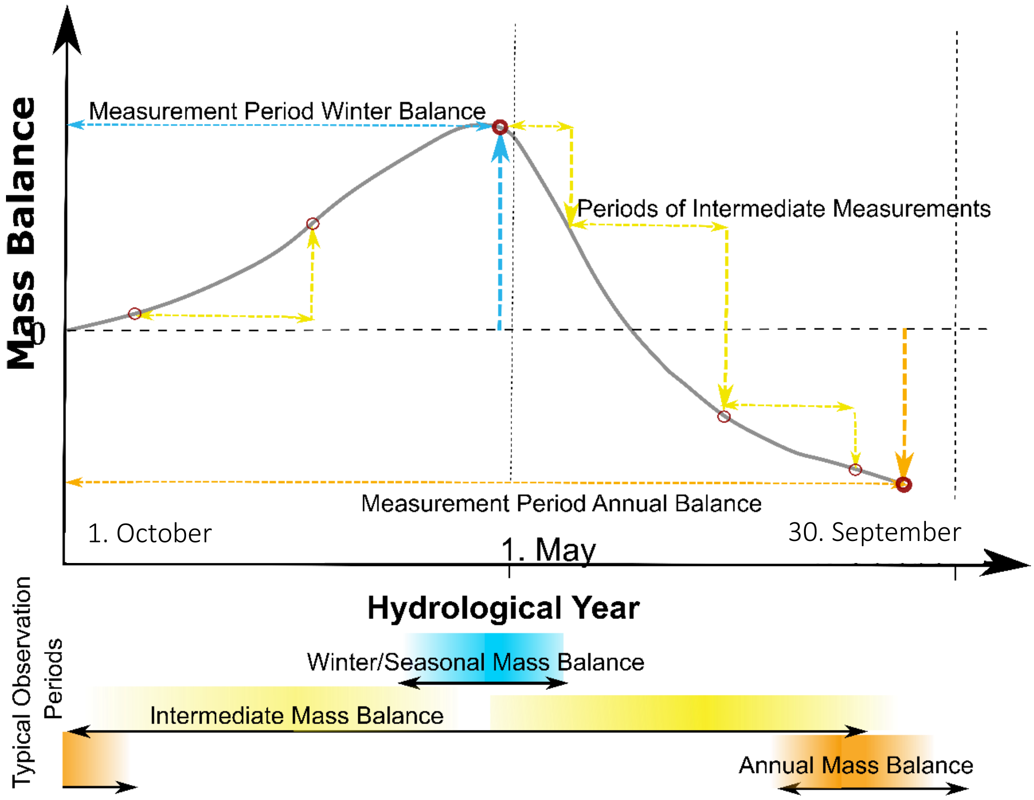

Figure 2: Evolution of mass balance at a given point on the glacier surface during the hydrological year with corresponding measurements.

Direct mass balance measurements acquired in the frame of GLAMOS can be categorized into three types, depending on the periods of the year they are covering (Figure 2):

1. **Annual measurements** cover a period roughly corresponding to an entire hydrological year (1 October to 30 September), but observation dates can vary by up to a month.
2. **Winter measurements** refer to total accumulation over the winter season and are typically acquired in April or May.
3. **Intermediate measurements** are undertaken at irregular intervals throughout the year and result in observations of mass balance at a scale of days to several months.

In 2020, in situ point mass balance measurements were carried out at 22 glaciers in Switzerland. Of these glaciers, seasonal observations have been acquired on 16 glaciers whereas six have only been observed are annually (Figure 3). See Appendix 7.3 for a table of currently observed glaciers with their observational intervals and mean numbers of annual and winter point mass balance samples.

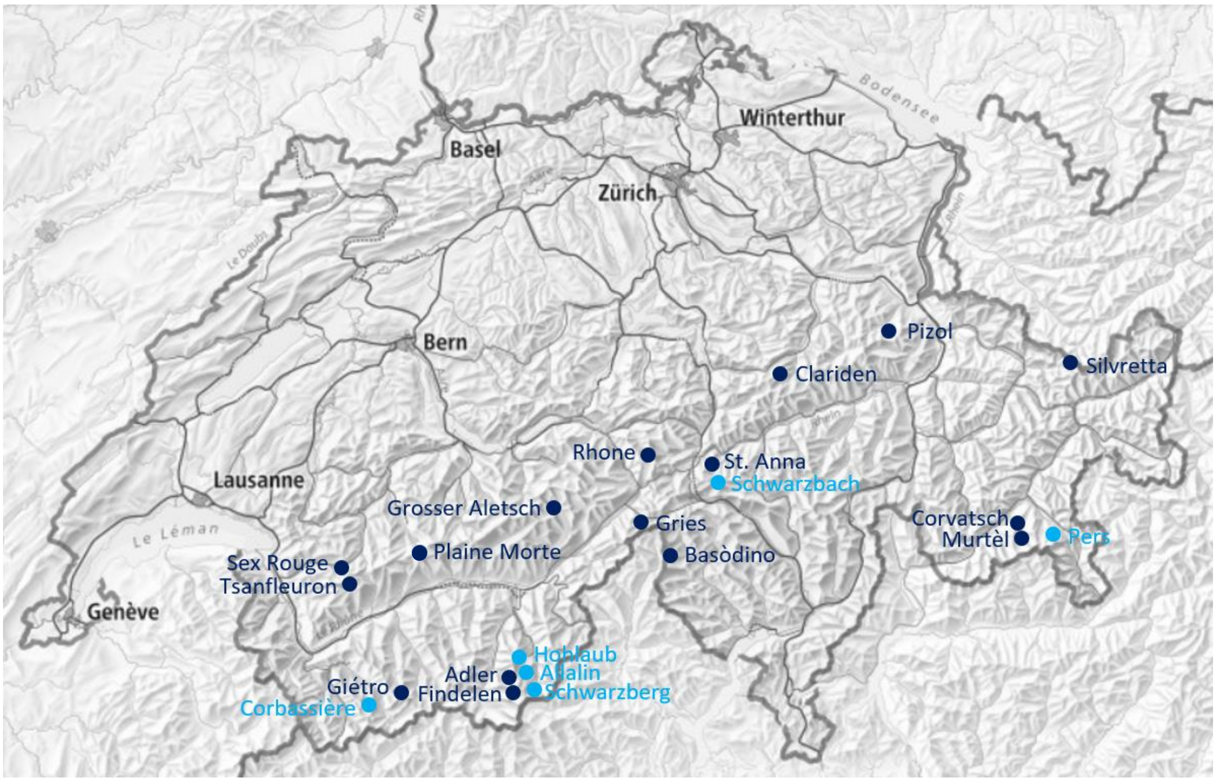

Figure 3: Investigated glaciers for mass balance in 2020 (dark blue = seasonal sampling, light blue = annual sampling)

Appendix 7.4 provides an overview on the accessibility of every glacier, required team size and an assessment of fieldwork difficulty.

2.1.2 ANNUAL POINT MASS BALANCE MEASUREMENTS

The annual mass balance at a given point on the glacier surface is the ice layer lost or the firn layer accumulated during the period between two successive minima. These minima are usually reached at different times in successive years, and the duration of the stratigraphic mass-balance year may therefore vary irregularly and substantially in duration from year to year (Cogley et al., 2011). For practical reasons, mass balance measurements cannot be taken at the dates of the stratigraphic minima (or maxima when referring to winter balance) but are acquired at variable intervals, referring to the *measurement period*. For the determination of annual balance, the measurements are acquired in late September, and for winter balance in late April or early May. In order to compare observations from different glaciers and from different years, the fixed-date period (here defined as the hydrological year, 1 October to 30 September) is often used, and direct observations referring to the measurement period need to be extrapolated (ideally over a minimal time interval) to these fixed dates based on suitable techniques (e.g. Huss and Bauder, 2009; Huss et al., 2015).

SPATIAL DISTRIBUTION OF SITES FOR THE DETERMINATION OF MASS BALANCE

As ablation is a rather uniform process, point measurements can be representative over large areas (Kaser et al., 2003). On valley glaciers, stakes should be distributed centrally along a longitudinal axis along the central flow line of the glacier, ranging from the head to the terminus of the glacier (Figure 4). It is recommended to distribute stakes evenly in elevation, not in distance (Figure 5). Lateral variations occurring from different aspects or shading can be accounted for by cross sections that may be placed at right angles to longitudinal profile (Kaser et al., 2003). Crevassed areas shall not be completely avoided because accumulation tends to be reduced and ablation is typically higher in these regions and hence are to be incorporated in mass balance calculations (Østrem & Brugman, 1991). Stakes shall be placed at the same position every year, i.e. the stakes are set back accounting for ice flow. Thereby, mass balances from different years can be compared directly.

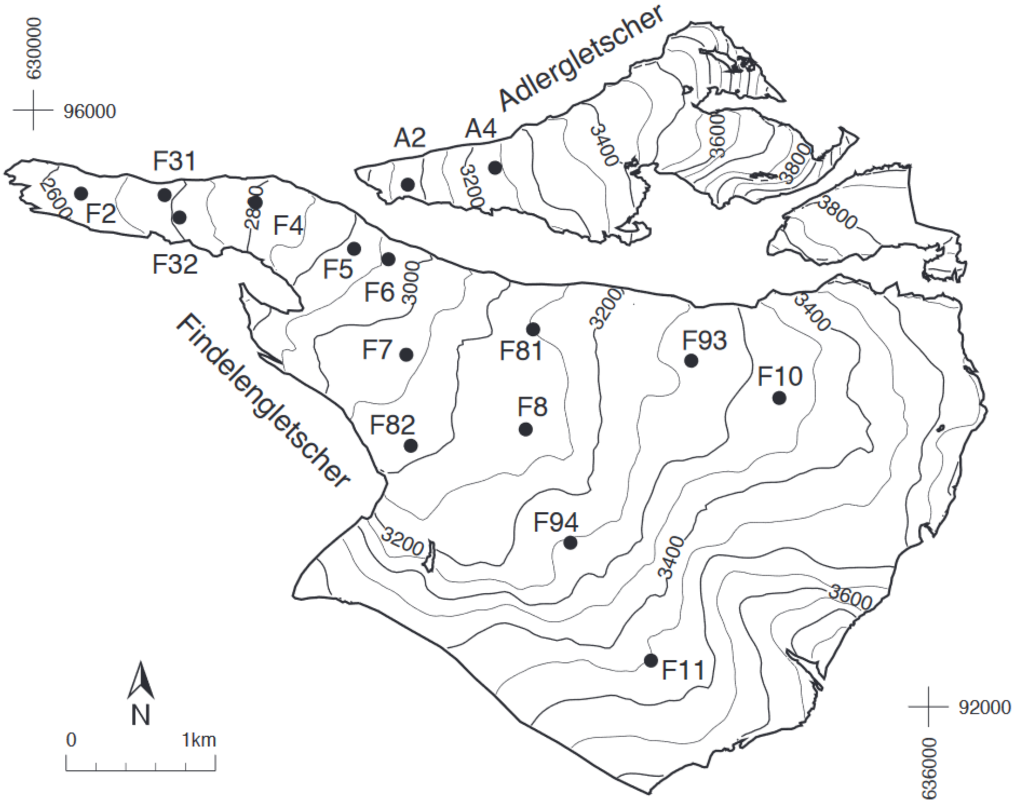

Figure 4: Findelengletscher – example of stake distribution for a valley glacier.

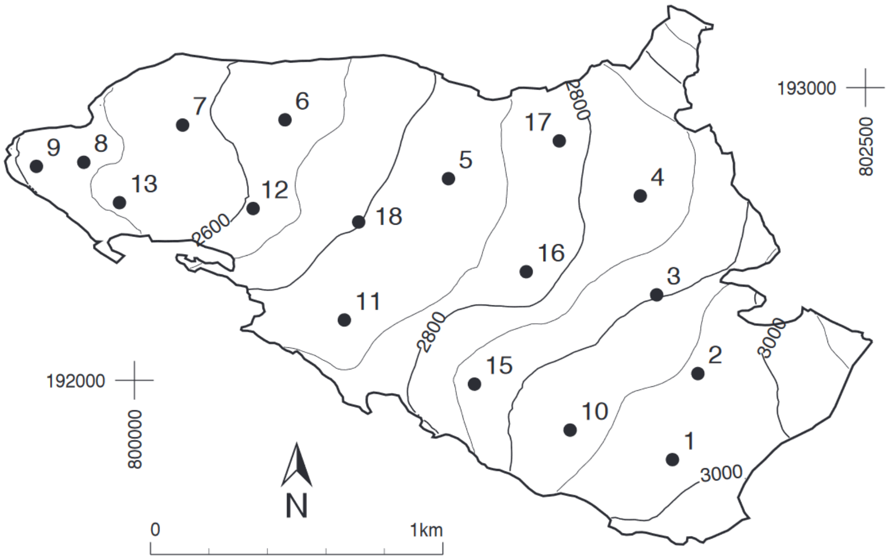

Figure 5: Silvrettagletscher – Example for an evenly distributed stake network.

MASS BALANCE STAKES

The material of choice for stakes in the accumulation zone is aluminium as the stakes need to be retrieved at the end of the year to avoid a loss due to positive local mass balance (Figure 6a). Aluminium stakes are also often used in the ablation area as they are durable (Figure 6b). Either aluminium stakes with connectable two-meter segments, or up to four-meter long stakes are used. Aluminium stakes have a diameter of between 3.5 and 4 cm. In the ablation zone, also plastic stakes (PVC) with a diameter of 2 cm are currently in use in GLAMOS mass balance monitoring programmes (Figure 6c). They are light-weight and are only loosely connected so that they lay down on the ice surface after melt out; there is thus no necessity of re-visiting locations with high melt rates for shortening the stakes during the melting season. Formerly, also wooden stakes were in operation for many decades, but were gradually replaced by PVC stakes as these are considered to be lighter and more stable. Only at the Glacier de Corbassière, wooden stakes are still in use.

The length of the stakes is dependent on expected ablation/accumulation rates and varies between 4 and 10 meters. In the ablation zone, where stakes have to be long due to high ablation rates, stakes are often sectioned to facilitate transport and setup (Figure 6d). Stakes should be repositioned ideally every year to compensate for glacier movement and be drilled into the ice approximately 1 meter deeper than the maximum expectable melt rate at the respective location. At every visit, the position of the stake should be recorded (e.g. using a GPS). Stakes should be labelled to permit unambiguous detection, e.g. in the case of different generations of stakes at the same site. Stakes are often marked with a tape at regular intervals to facilitate the reading of the height and to indicate the number of remaining stakes in the ice in the case of sectioned stakes.

Figure 6: Examples of mass balance stakes. (a) Aluminium stake in the accumulation area with markers at 50 cm intervals (Aletsch), (b) Aluminium stake with 2 cm markers for real-time determination of ablation based on a webcam (Rhone), (c) PVC (left) and aluminium (right) stake in the ablation area (Murtèl), (d) Setting up a sectioned stake (PVC) in the ablation zone (Adler). (Photos: M. Huss, A. Cicoira)

INSERTING STAKES

Both in the accumulation and the ablation area, stakes must be placed in a borehole drilled into the ice. There are several methods how such shallow boreholes can be drilled that have recently been in use in Swiss glacier monitoring: Two mechanical drills, the Kovacs-drill and the Vierzack-drill, as well as the steam drill. In Switzerland, Kovacs-drilling established as the preferred method a few years ago for reasons of efficiency. In the following, a description and comparison of the different drilling methods for setting mass balance stakes is provided.

Kovacs-drill[6]

The Kovacs-drilling rod is typically driven by a battery-powered screwdriver but can also be operated manually (Figure 7). The rod consists of an arbitrary number of single segments of 1 meter each, which can be put together according to the needed drilling depth. During drilling, loose ice should be removed from the borehole by pulling back the drill from time to time. It should be paid attention that the borehole is vertical, so that the stake will not be inclined. The diameter of the borehole is 5 cm.

Figure 7: Drilling with a Kovacs-rod at Grosser Aletschgletscher. (Photo: M. Huss)

Vierzack-drill

The Vierzack-drill (Figure 8) is a relatively light-weight hand drill with a diameter of about 4 cm. An arbitrary number of 1.5 meter elelments can be added to the hollow steel drilling tip that can optimally accommodate more than 1 meter of drilled ice. The drill is operated manually by turning the instrument. At regular intervals - after about 1 meter in the case of good conditions and after a few centimeters in case of wet or cold ice - the entire drill has to be retrieved and be emptied. This process hampers the drilling of holes deeper than about 5 meters by one person and down to 10 meters by two persons. For shallow boreholes, the Vierzack drill can however be a valueable alternative to other approaches as it is easy to carry and does not rely on battery power and/or heating to produce steam.

[6] https://kovacsicedrillingequipment.com/

Figure 8: Operation of a Vierzack-drill on Silvrettagletscher. (Photo: M. Huss)

Steam-drill

A butane (or propane) burner heats water in a boiler and generates steam (Figure 9). When the valve is opened, the steam escapes through the nozzle of a drilling pipe at the end of an insulated hose. The condensing steam transfers energy to the ice causing it to melt. The high degree of latent heat contained in the steam guarantees a very efficient energy flow from the boiler to the ice. The entire drilling device consists of the steam generator, the rubber hose, and the drilling pipe with interchangeable tips. It can be carried on the back like a backpack and can be operated by one person (Kaser et al., 2003). Holes of up to 15 meters depth can be drilled based on this technique, however, drilling is time-consuming and is hampered in the case of very windy or cold conditions. The diameter of the borehole can be varied between about 3 cm and 6 cm depending on the nozzle used. The Heucke steam-drill is the most widely used type but also other individually manufactured types were in use in Swiss glacier monitoring.

Figure 9: Operation of a Heucke steam-drill in Findelengletscher. (Photo: M. Huss)

Table 2: Comparison of advantages and disadvantages of different drilling methods.

Method	Advantages	Disadvantages
Kovacs-drill	Very fast (ca. 5 min/10 m); easily portable (segments)	Relatively heavy for deep boreholes; problems in snow/firn and when water is present
Vierzack-drill	Light; no electricity needed	Time consuming, especially for deep boreholes; problems when water is present, or the ice is not temperate
Steam-drill	Deep drilling possible (up to 15 m); works well in snow and firn	Relatively heavy (ca. 15 kg); slow (ca. 30-45min/10 m), inefficient in windy/very cold conditions

STAKE PLACEMENT

The depth chosen for installing a stake and length of the respective stake depend (i) on the location on the glacier, (ii) the time of set up, and (iii) the type of stake used and the envisaged observations. In the **ablation area** (Figure 10), stakes must be drilled to a sufficient depth to accommodate the maximum expectable ablation at this location over the period of one year, i.e. until the stake can be visited and be re-drilled again. Experience from previous surveys is thus required. If no estimates of local ablation rates are available, it is suggested that a generous margin is included to account for this uncertainty. In almost all cases, stakes are drilled in autumn in order to cover an annual period. If it is intended to locate the stake during the spring survey, only aluminium stakes are practicable as flexible PVC stakes will be buried beneath the winter snow. In that case, the stake should have a length above the late-summer surface of at least the expected winter snow depth at the time of the spring survey. If the stake does not need to be located during the spring survey, the use of shorter stakes is also possible as this reduces the amount of material that needs to be transported. In the ablation area, it is also possible to select stakes shorter than the actual depth of the borehole. This is however only recommended if expected ablation rates are significantly higher than the top of the stake is beneath the surface at the time of installation.

In the **accumulation area** (Figure 11), stakes tend to be buried by snow/firn in the course of the year. They thus need to be retrieved and be replaced in every year, at least in the case of substantial accumulation. Thus, only aluminium (or wooden) stakes are practicable. Stakes should be drilled into the firn by at least 2 meters to anchor them well enough. They should extend above the surface by at least the expectable amount of annual firn accumulation. If measurements are also conducted during the spring survey, the length of the stakes should also be able to accommodate the winter snow accumulation. In the accumulation area, the previous year's surface layer is often not clearly recognizable (unlike in the ablation area where it consists of ice). Hence, the surface close to the stake must be marked with ochre or sawdust on an area of about 10 m^2 (Figure 12). This allows clearly locating the last summer's horizon for measurements in snow pits or using coring when determining snow density and thus accumulated water equivalent. It is not uncommon that aluminium stakes in the accumulation area tend to melt in due to energy uptake or can be pushed out due to firn compaction. This is related to the unconsolidated nature of the firn in comparison to ice. Therefore, it is suggested to seal the bottom of the stake with an isolating material. Also, it is often observed that stakes in the accumulation area are bent (due to creep of the snow with a certain slope angle or due to wind/riming). Direct measurements at a bent stake are imprecise. The stake in the accumulation area will thus, in most cases, only serve to locate the marked layer from the previous late summer surveys at which the measurements of accumulation are performed.

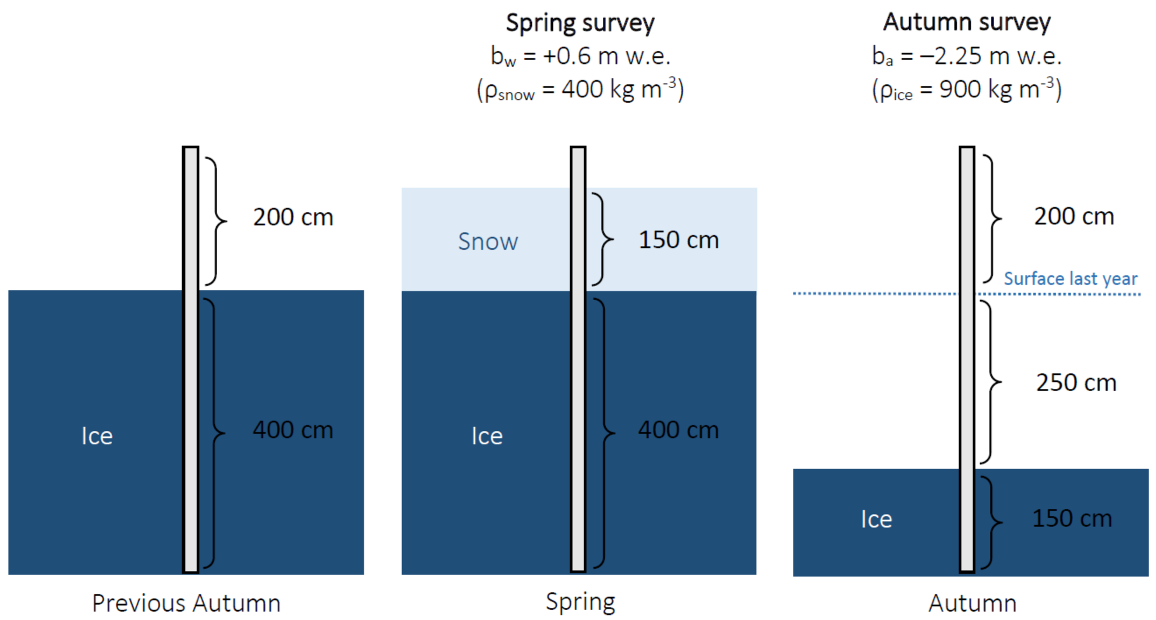

Figure 10: Schematic representation of the placement and reading of stakes in the ablation area. An example for mass balance computation based on the depicted situation is given.

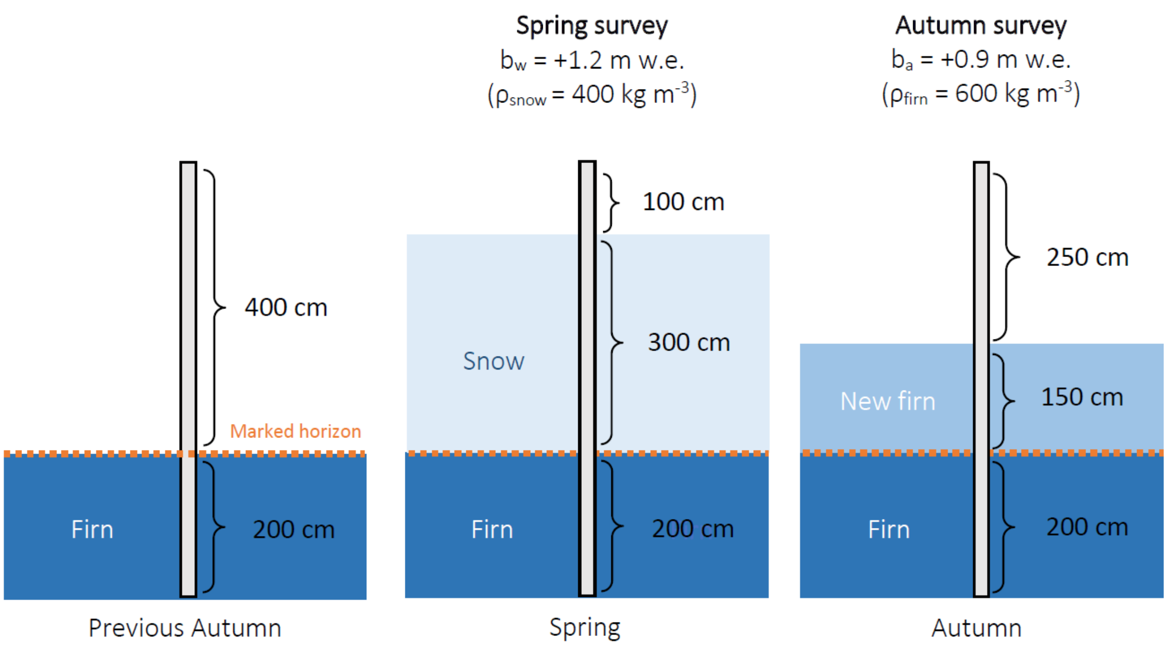

Figure 11: Schematic representation of the placement and reading of stakes in the accumulation area. An example for mass balance computation based on the depicted situation is given.

Figure 12: Marking the firn surface with sawdust close to the stake (Findelengletscher). The sawdust has to be compacted to avoid being blown away by wind. (Photo: M. Huss)

STAKE READINGS

Reading of stakes usually takes place at the end of the ablation season, i.e. in September, but can also deliver intermediate observations at any time throughout the year. In the ablation area, the change in the ice surface relative to the stake is recorded by measuring the distance from the top of the stake down to the surface (Figure 10). By comparing this measurement with the previous observation of stake length above the surface, the change over the respective time period can be determined by accounting for the density of the lost or gained layer. In the accumulation area, the marked surface layer of the last year has to be located based on the stake, and the density of the accumulated layer is measured (Figure 11). Accumulation corresponds to the difference between marked horizon and the current glacier surface.

One may encounter several special situations when reading stakes related to particular densities of the ablated and/or accumulated material. Figure 13 present two typical examples, (a) one being ice ablation after the autumn survey, and (b) another being fresh snow that has fallen during the ablation period and is still present during the survey. In case (a), the loss of ice after the autumn survey has to be recorded separately and substracted from the spring snow depth (snow surface to ice). In case (b), both the visible length of the stake (part above the snow surface) and snow height (snow surface to ice) need to be recorded in order to account for the different densities. This separate consideration is necessary to correctly compute mass balance in water equivalent. The snow depth is typically measured with a snow probe and it is suggested to average several soundings nearby the stake to obtain a representative depth of fresh snow.

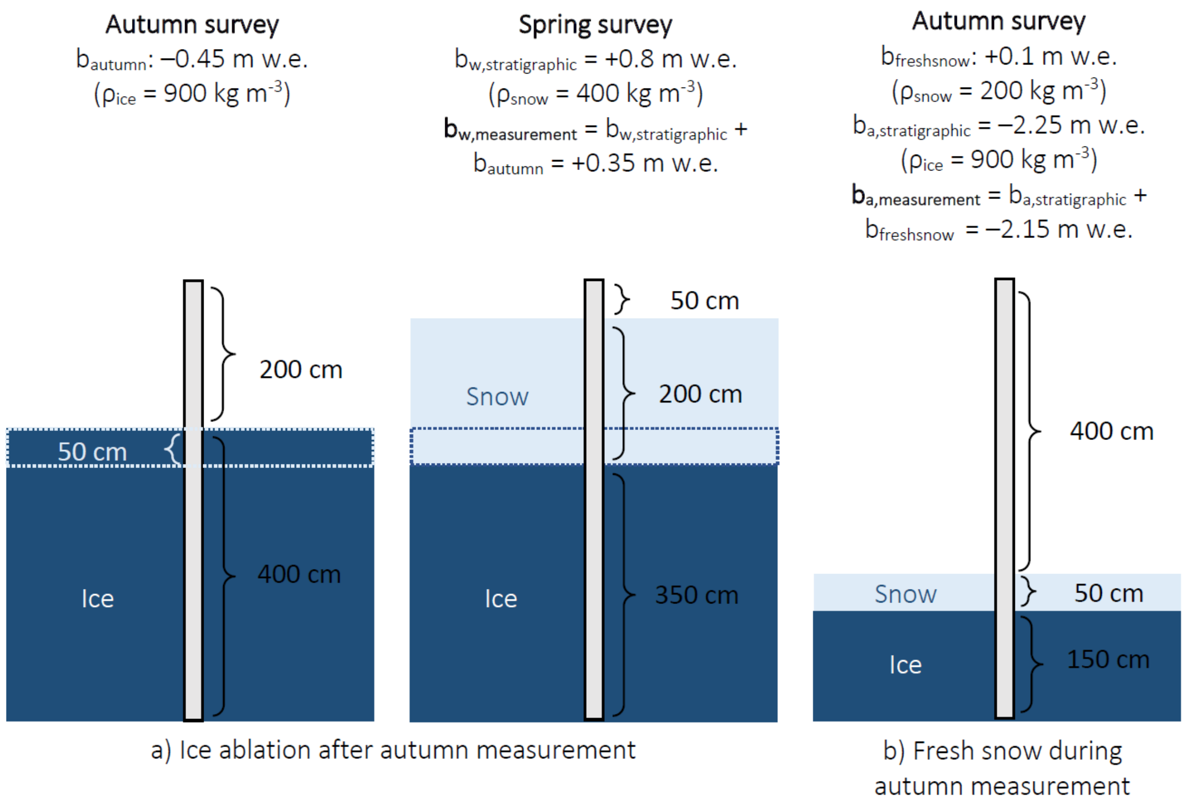

Figure 13: Special cases of ablation stake reading: a) Ice ablation after autumn visit, b) fresh snow in summer before the late-summer visit. An example for mass balance computation based on the depicted situation is given.

2.1.3 WINTER MASS BALANCE MEASUREMENTS

Winter mass balance is clearly dominated by the accumulation term in the climate of the Alps but can also contain limited amounts of ablation during the winter season. Winter accumulation is thus not the same as winter mass balance (Cogley et al., 2011). Accumulation is expressed in snow water equivalent (Østrem & Brugman, 1991) and is calculated from measured snow depth and the respective snow density (measured, or extrapolated/estimated) at each point (Kaser et al., 2003). Therefore, winter mass balance measurements involve the recording of snow depths and density measurements. Snow depth is usually measured with a snow probe (Figure 16) and snow density is determined by coring or in snow pits (Figure 17). In contrast to mass balance measurements at stakes, where the time period of observation is clearly defined by the two stake readings, snow depth observations based on soundings have an unknown starting date. They document the accumulation occuring since the minimum surface of the previous year, thus corresponding to a stratigraphic system, as opposed to the measurement period or the fixed-date system (Huss et al., 2009; Cogley et al., 2011). The date of the last summer's minimum surface is inherently unknown and can vary over different part of the glacier (typically later on the glacier tongue than in the accumulation area). For mass balance interpretating the starting date of the observations needs to be estimated based on appropropriate methods, such as periodic in situ observations, automatic cameras, or mass balance modelling. At the scale of entire glaciers and for long-term monitoring at different sites, only the last option is able to deliver homogenous and consistent results (e.g. Huss et al., 2009, 2015), although in situ observations can provide a valueable verification when they are available. For sites with a marked late-summer horizon and a stake that can be located also during the witer survey, snow coring or observations in snow pits can directly deliver the accumulation occurring since the date of the autumn survey.

MEASUREMENT OF WINTER SNOW DEPTH

Snow probing

Snow depth on glaciers is usually recorded with a snow depth probe while moving on the glacier with skis. Winter snow accumulation can be highly variable even within short distances on a glacier, because snow deposition is greatly affected by topography and wind redistribution. Hence, snow depth measurements at the glacier-scale require a much denser sampling than ablation measurements (e.g. Sold et al., 2013, 2016; Pulwicki et al., 2019). Snow probings should be uniformly distributed over the entire glacier surface. The density of snow sampling points depends on the glacier area and the spatial snow depth variability, which is substantially larger on small glaciers than on valley glaciers (Figure 14 and 15; e.g. Fischer et al., 2016). Because the greatest variations in snow depth are expected in the upper part of the glacier, but the stake network is usually less dense there, it is important to invest particular effort in this region (Østrem & Brugman, 1991). In addition to randomly distributed sampling points, snow depth should be recorded at the position of all ablation stakes with highest priority in order to compute point seasonal mass balance. Per site, two to three snow soundings should be averaged and the location of probings have to be recorded with a GPS. Repeated snow probing at one site (i.e. within a distance of a few meters) allows recognizing erroneous measurements (e.g. due to ice lenses, or crevasses) and also provides an estimate of the small-scale variability in snow depth (e.g. due to surface roughness), and thus uncertainty in the point observation. This local-scale variablity in snow depth should also be reported along with the average value.

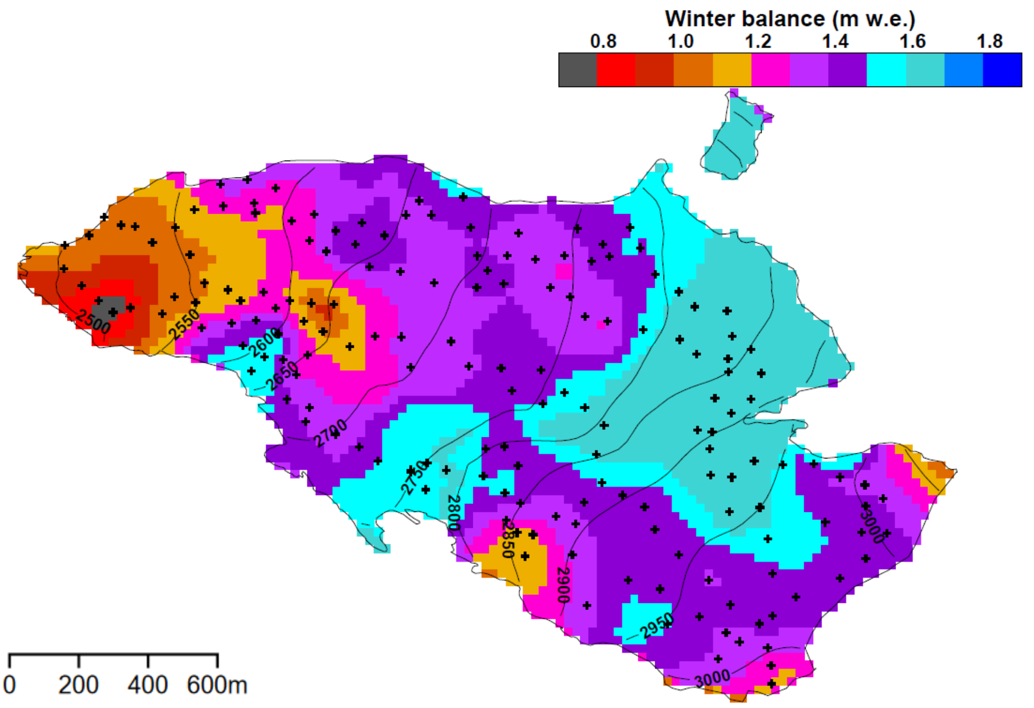

Figure 14: Example for evenly distributed snow probings on Silvrettagletscher (May 2020). Crosses indicate locations of snow depth probings and colours refer to extrapolated winter balance.

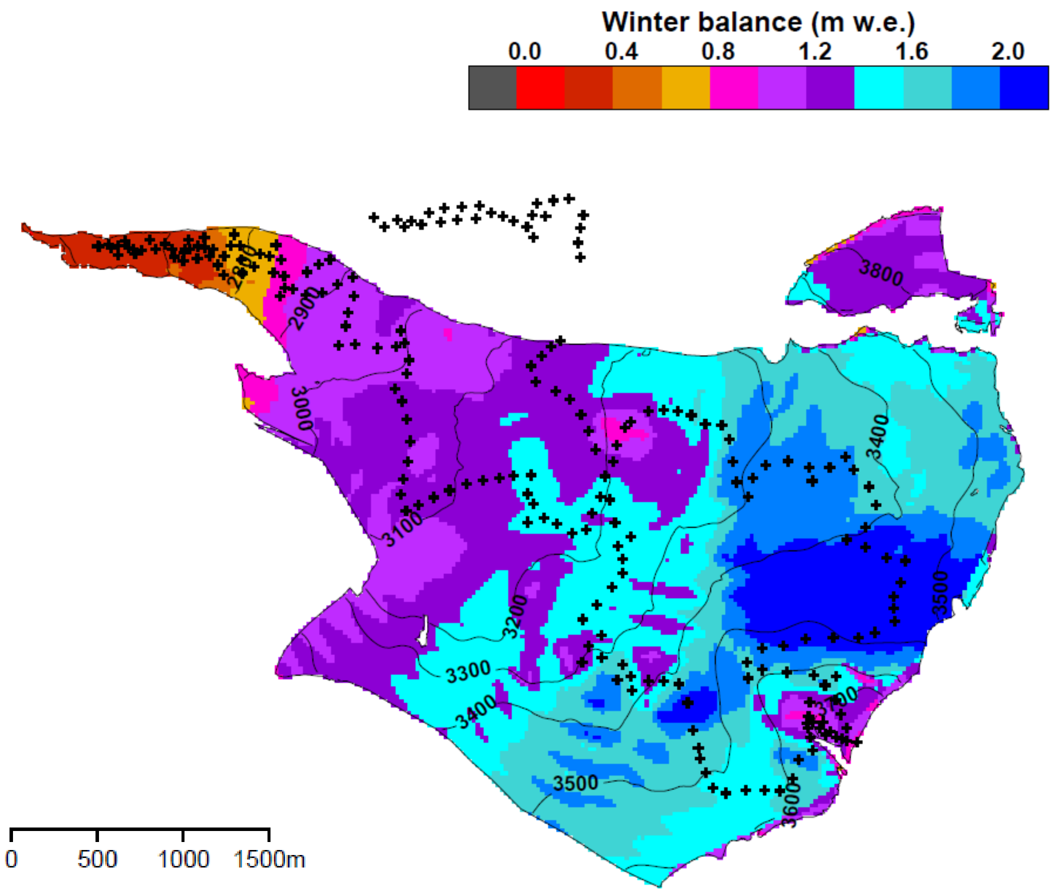

Figure 15: Example for limitations of evenly distributed probings on a large valley glacier (Findelengletscher, May 2020). Crosses indicate locations of snow depth probings and colours refer to extrapolated winter balance.

Snow depth is measured directly with a snow probe (Figure 16) which is pushed vertically through the snowpack until it reaches the ice surface (in the ablation area) or the previous year's hardened summer surface (in the accumulation area). The layer should be easily recoginzable with the probe because it is harder than the overlying snow. However, attention must be paid not hit ice lenses, which might have formed during warm spells or rain events during the winter season (Østrem & Brugman, 1991).

Ground penetrating radar (GPR)

Determination of snow depth based on ground penetrating radar (GPR) is increasingly used in the frame of GLAMOS and delivers continuous profiles with much smaller effort than manual snow probings. Both ground-based and helicopter-borne applications of GPR have been used in recent years (Machguth et al., 2006; Sold et al., 2013, 2016; Bauder et al., 2018). The movement speed of the radar device (both when dragged on ski, and operated from a helicopter) depends on the sampling frequency. Ideally, it allows at least one measurement per two meter. Radar frequencies used are between 500 Mhz and 1.2 GHz, depending on the snow depth and the desired level of detail regarding internal snow structures. However, interpretation of GPR signals can be ambiguous (different internal reflectors) and radar-wave velocity can vary with snow depth, density and liquid water content. Thus, a simultaneous determination of wave velocity should be envisaged and independent manual snow probings should be acquired in any case to verify and, if necessary, to calibrate snow depth inferred by GPR.

Figure 16: Snow depth measurements using a snow probe (St. Annafirn, Silvrettagletscher) and Radar (Rhonegletscher). (Photos: M. Huss)

DETERMINATION OF SNOW DENSITY

Snow density can be determined either via snow coring or in snow pits. As snow coring is significantly less time consuming, it is now often preferred over digging snow pits. In comparison to snow depth, density is relatively homogenous in space. Hence, depending on the altitudinal range of the glacier, only one up to five sites are typically selected for density measurements.

Snow pits

Snow pits (Figure 17) are excavated by hand using shovels and are hence time consuming. The time required exponentially grows with snow depth and can amount to several hours for more than 4 meters of snow. However, snow pits provide direct insights into snow stratigraphy and thus allow detecting ice lenses that might cause erroneous results for snow probing. Furthermore, the snow can be directly sampled, and the measurements of density are considered to be more accurate in comparison to coring. Before digging a snow pit, it is suggested to perform some soundings to determine the overall depth and to ensure that no crevasses are present. If a pit is dug near a stake, it should be dug at a distance of at least 3 meters.

Snow pits should be dug down to the marked horizon or to the ice surface. Normally, the pit will have a square or a rectangular cross section (Østrem & Brugman, 1991). The size of a snow pit depends on the expected depth. The deepest point of the pit should be a square approximately 0.5 x 0.5 meters to provide sufficient room for making density measurements (Kaser et al., 2003). At least one wall must be vertical and stay untouched to allow unbiased sampling. To avoid changes in snow conditions due to direct sunlight, the southern pit wall should be selected for sampling (Østrem & Brugman, 1991).

Snow samples are taken vertically in the pit wall from the untouched snow surface downwards (Figure 18). The samples must be taken continuously, but the length of each sample is arbitrary, normally being determined by the physical condition of the snow, presence of ice layers, etc. (Østrem & Brugman, 1991). A snow sample is obtained as follows: A steel plate is horizontally inserted into the undisturbed pit wall about 20 to 40 cm below the surface. Then, a sampling tube with known diameter is pushed vertically downwards onto the steel plate and the distance between the surface and plate is measured.

This is the length of the first sample. Subsequently, the sampling tube is removed, and the contents are transferred into a suitable bag. Bag and contents are weighed. The weight of the empty bag must be subtracted to obtain the net weight of the snow sample. The length and weight of the sample are noted. From these data, the snow density can be calculated by dividing the mass by the volume of the sample. Afterwards, the steel plate is moved another step downwards and the steel cylinder pressed into its second sampling position (Østrem & Brugman, 1991).

Figure 17: Snow pit for density measurements (Photo: M. Huss) and Figure 18: Weighing of a snow sampling tube. (Photo: M. Werder)

Snow coring

The principle of snow coring is to retrieve a continuous column of snow directly from the surface, i.e. avoiding the labourious excavation of a snow pit. Especially in the case of large snow depths (> 2 meters) this has a considerable potential to limit the effort required to acquire density measurements. Different types of coring devices are operated. All have in common that a cylindrical metal tube with a length of 0.5-1.5 meters and a diameter of around 10 cm is equipped with a drilling bit (Figure 19). With an arbitrary number of prolongations, snow cores to a depth of up to 6 meters (and potentially more) can be acquired. After the metal tube has been filled with snow from the bottom of the borehole, the device is retrieved and the snow is weighed. Afterwards, the depth of the borehole must be carefully measured to determine the length of the retrieved core. The snow density can then be determined by dividing the snow weight by the snow sample volume. Care must be taken to not enlarge the diameter of the borehole while lowering the device repeatedly to retrieve new cores. In the case of wet or cohesionless snow, it can be difficult to retrieve the snow. It is recommended to perform at least three profiles at the same site to detect outliers and to be able to average the measurements for reducing the uncertainty. The densities of the individual measurements should also be reported as they provide important information on uncertainty when re-analysing the observations.

Figure 19: Snow density measurements using a core drill. (Photo: M. Huss, C. Kurzböck)

SnowFox™

SnowFoxTM by Hydroinnova[7] is a portable cosmic ray sensor capable of measuring the water equivalent depth of snow (SWE) over a small area. The sensor is placed on or just beneath the ground where it is allowed to be buried by falling snow. The sensor records the intensity of downward-directed secondary cosmic-rays that penetrate the snow pack. This intensity is proportional to the mass of snow traversed by cosmic-rays, and is related to SWE through a calibration function. Measurements are typically averaged over one hour. This technology is relatively new and currently installed at Findelen and Plaine Morte glacier (Gugerli et al., 2020). Direct comparison of density measurements in snow pits and with coring to the autonomous measurements indicate that all methods yield the same densities within a range of ±6% throughout the accumulation season (Gugerli et al., 2019). However, some outliers have been detected that call for attention when analyzing and interpreting snow density measurements.

Table 3: Comparison of approaches to measure the density of winter snow or firn.

Method	Advantages	Disadvantages
Snow coring	No need to dig snow pits (very fast); many cores are possible (reduction of uncertainty)	Coring may compress the snow leading to over-estimating the actual snow density; device relatively heavy
Snow pits	Reliable; direct observation of snow stratigraphy	Very time consuming, especially for high snow depth
SnowFox™	Automated, continuous observation of snow water equivalent	Set-up and maintenance of station expensive and laborious; no information about variations of density with depth; only possible at very few locations

[7] http://hydroinnova.com/snow_water.html

2.1.4 INTERMEDIATE MASS BALANCE MEASUREMENTS

Measurements not acquired during the late-summer (September/October) or spring (April/May) field campaign are referred to as *intermediate* measurements. These observations can cover arbitrary intervals ranging from a day to several months and are often not taken at all measurement sites but only at selected stakes in combination with other activities. In former times, intermediate mass balance observations were often performed by Alpinists passing the stakes and were reported to the Swiss Alpine Club, e.g. on Claridenfirn or Glacier d'Orny since the 1910s. Nowadays, intermediate mass balance measurements are often recorded in the framework of other research projects. Since 2019, one to four automatic cameras[8] are set up on the glaciers Aletsch, Findelen, Plaine Morte and Rhone, enabling remote and real-time daily recording of intermediate mass balance (Landmann et al., 2020). Intermediate measurements give information about the current state of the glacier and the temporal dynamics of mass balance throughout the year (Figure 20).

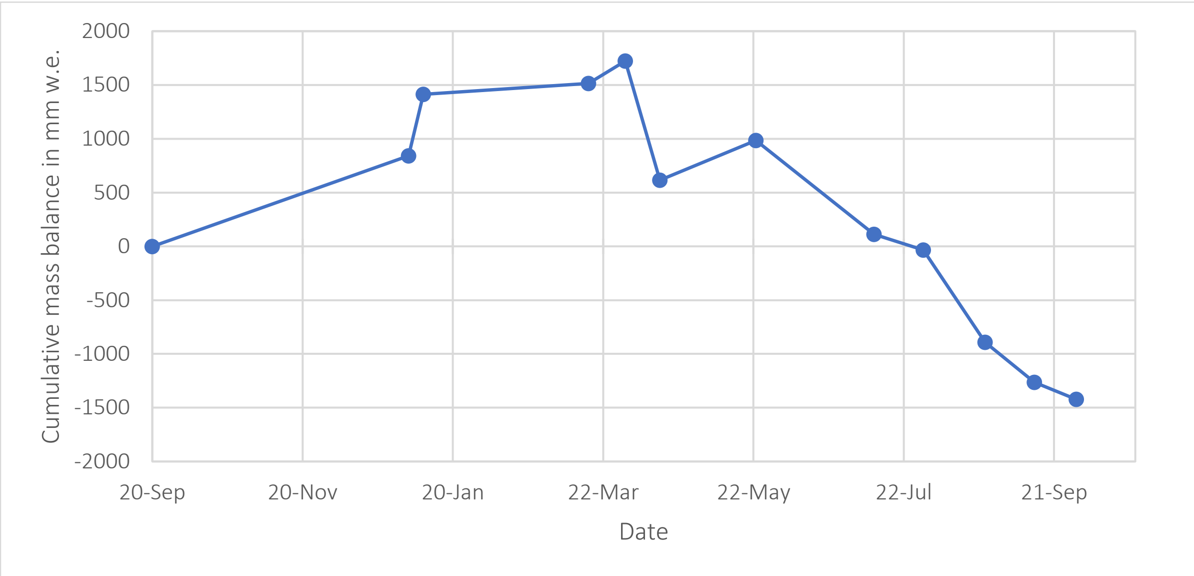

Figure 20: Example for intermediate mass balance measurements at the lower stake on Claridenfirn in the year 2009. Cumulative observations since 20 September 2008 are shown.

[8] https://holfuy.com/en

2.2 GLACIER LENGTH CHANGE

Glacier length variations are key indicators of glacier evolution as they represent the results of the complex and interlinked processes of climate, mass balance, ice-flow dynamics and the response of glacier geometry. Glacier length variations typically show a filtered and delayed response and are often difficult to be interpreted in relation to individual climatological parameters. Time series of glacier length variation are relevant for both the scientific community, as well as the broader public, as they are a very clear and easily understandable signal of climatic change (Hoelzle et al., 2003; GLAMOS, 2020c).

2.2.1 OBSERVATIONAL NETWORK

Length change measurements are presently conducted on about 100 Swiss glaciers (Figure 21). A few glaciers are observed only sporadically and at irregular intervals. Since the beginning of coordinated and systematic glacier monitoring in Switzerland, the surveys are carried out by a collaborative network of observers of the cantonal forestry departments, universities and from the private sector. At present, GLAMOS uses annual aerial photographs acquired by swisstopo or private companies to determine length variations for about 20 glaciers, while for all other glaciers in situ field surveys are carried out. The present network for measuring glacier length variations aims at covering all regions of Switzerland and different glacier types (GLAMOS, 2020c). See Table 9 in Appendix 7.5 for a comprehensive list of all glaciers in the monitoring network and their priority rating in the upcoming monitoring period.

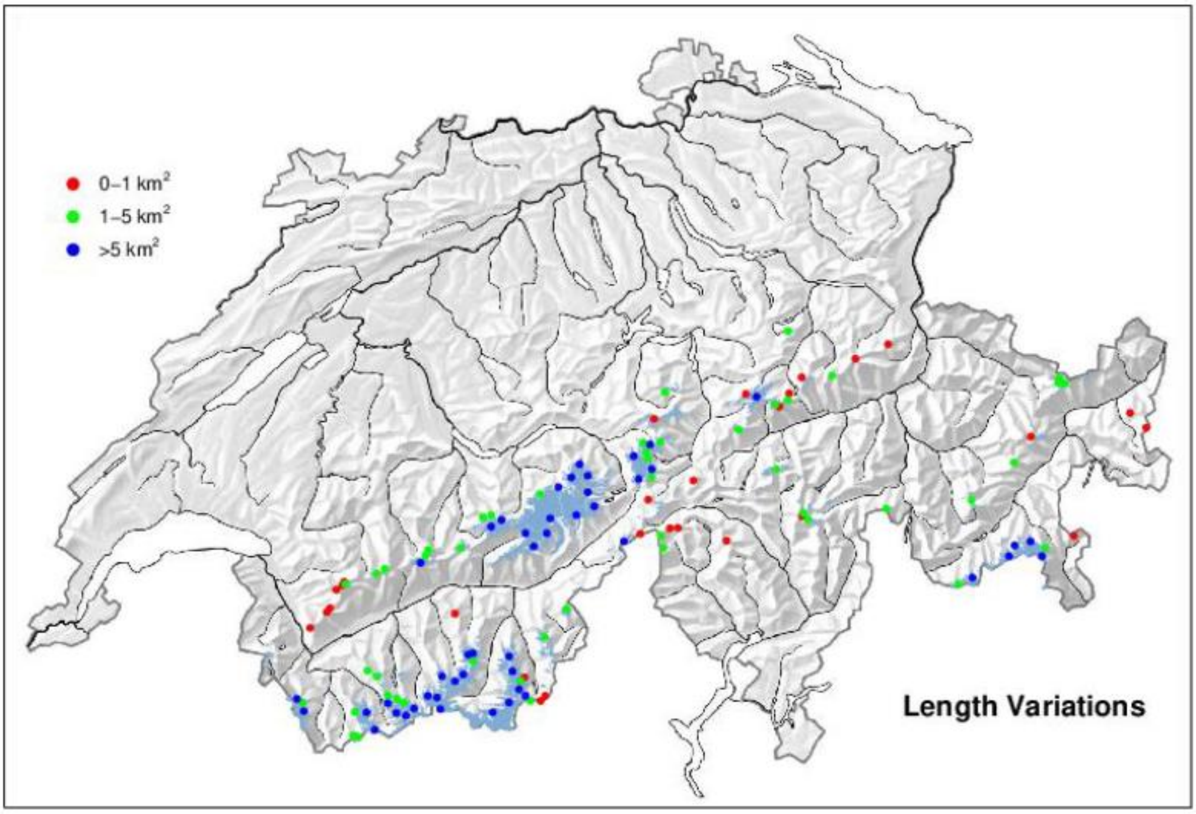

Figure 21: Glaciers presently investigated for length variations by GLAMOS. Glaciers are classified in terms of their surface area (GLAMOS, 2020c).

2.2.2. DATA ACQUISITION METHODS

At present, the length change monitoring program is in a state of upheaval. Traditional field observations at small glaciers or glacier snouts with difficult accessibility are gradually replaced by 3D topographical landscape models (swissTLM^{3D}) based on current aerial images. Also, according to a new measurement concept, the time interval of observation will shift from mainly annual to 2-year, 3-year or 6-year measurement intervals with more detailed geo-referenced observations for about half of the monitored glaciers in order to increase the quality of the monitoring and to adapt to the challenges posed by climate change. Due to the large variety of situations at the glacier termini, there is no homogeneous data acquisition strategy. Glacier lengths are recorded by five different methods:

1) FIELD: Annual direct field observations of glacier tongue (traditional approach)
2) AIR: Annual evaluation of aerial photographs (for selected glaciers with annual acquisition of aerial photographs)
3) MIX: Bi-annual field surveys at glacier tongues, complemented at 6-year intervals with swisstopo data (aerial images, TLM-outlines)
4) TLM: Evaluation based on swisstopo data (aerial images, TLM-outlines) in 6-year intervals
5) TLM+: Evaluation based on swisstopo data (aerial images, TLM-outlines) in 6-year intervals, and swisstopo aerial images evaluated by GLAMOS at 3-year intervals

All considered approaches have their advantages and disadvantages and strongly differ regarding annual workload and cost:

Table 4: Comparison of the different length change observation methods.

Method	Advantages	Disadvantages
FIELD	Traditional method, optimal continuity, high accuracy (no remote interpretation), acquisition of meta-information (e.g. image documentation, natural hazards), only minimal post-processing and timely availability of results	Relatively expensive, inhomogeneous data acquisition (different observers and instrumentation), and thus partly large effort in data evaluation and training, inaccessibility of glacier tongues due to climate change
AIR	Annual resolution, complete spatial coverage, high accuracy, homogeneous data evaluation glaciers with difficult field-site access can be covered	GLAMOS relies on the acquisition and photogrammetrical processing of the images (financed by BAFU or third party), additional effort for data evaluation to be covered by GLAMOS, no field validation, delayed availability of results, relatively high costs, no meta-information (images, observations of potential hazard processes)
MIX	Reduced costs per glacier by 40 %, ground-truth of FIELD-type complemented with homogeneous photogrammetrical data acquisition	Reduced time resolution from one to two years.

TLM	Strongly reduced annual costs in comparison to FIELD (90 %), AIR (90 %) and MIX (85 %), homogeneous data evaluation, glaciers with difficult accessibility can be covered, robust as it relies on fully operational data (swisstopo aerial images)	Very low temporal resolution (6 years), photogrammetrical interpretation difficult for debris-covered glacier tongues, no ground-truthing (problematic if the glacier boundary is difficult to be identified), no meta-information (images, observations of potential hazard processes), required intensive data processing outside of GLAMOS results in delayed availability of results
TLM+	Strongly reduced annual costs in comparison to FIELD (–75 %), AIR (–75 %) and MIX (–55 %), see TLM for additional advantages	Low temporal resolution (3 years), see TLM for additional disadvantages

Table 4 shows the targeted number of glaciers per observational method for the period 2020-2023 according to GLAMOS (2020c). Still, traditional field measurements will account for almost half of the monitoring program and are important to maintain continuity for the longest and most valuable time series, as well as for regular in situ surveys of the general hazard situation at the glacier snout.

Table 5: Target number of glaciers per observation type according to the new length change measurement concept implemented during the period 2020-2023 (GLAMOS, 2020c).

Observation Type	Number of glaciers	Percentage
FIELD	43	36
AIR	19	16
MIX	22	18
TLM	9	7
TLM+	28	23

2.3 GLACIER INVENTORIES

A glacier inventory describes the extent of all glaciers in a country at a given point in time. It provides "*a detailed record of attributes of the glaciers in a region*" (Cogley et al., 2011), such as glacier name, location, area, length, mean elevation and other data (Paul, 2017). Glacier inventories are crucial to understand observed glacier changes and project their future evolution (Hoelzle et al., 2007). Furthermore, inventories are essential for assessing climate change impacts on future runoff in glacierized catchments (e.g. Huss, 2011).

Since 2005, global glacier outlines have been collected and published in the Global Land Ice Measurements from Space (GLIMS) database (Raup et al., 2000). A complete global coverage of a glacier inventory was achieved with the Randolph Glacier Inventory (RGI) in 2012 for the first time (RGI Consortium, 2017). In Switzerland, three complete Swiss Glacier Inventories (SGIs), SGI1850 (Maisch et al., 2000), SGI1973 (Müller et al., 1976) and SGI2010 (Fischer et al., 2014) were generated. Additional inventories based on coarser baseline data and incomplete attribution to previous inventories are available for 1999, 2003 and 2015 (Paul et al., 2002, 2011, 2020). The compilation of Swiss Glacier Inventories was not an institutionalized task, but was based on research projects and individual initiatives (Müller et al., 1976; Maisch et al., 2000; Paul, 2004; Fischer et al., 2014).

Glaciers in the Swiss Alps reached their maximum extent around 1850 (Ivy-Ochs et al., 2009). For this time, the reconstructed total glacierized area is 1,788 km^2 (Maisch et al., 2000). In the following, glaciers showed general retreat. In 1973, 1,311 km^2 of Switzerland were still covered by glaciers, which corresponds to a total area loss of 477 km^2 (–25 %, or –0.2 % a^{-1}) between the maximum and 1973. After a stagnant phase during the 1970s to the mid-1980s with only minor area changes, glaciers in the Swiss Alps rapidly retreated again to an area of 944 km^2 (Fischer et al., 2014), leading to an area change of 367 km^2 for the time period 1973-2010. According to the newest glacier inventory, the SGI2016, a glaciated area of 961 km^2 is found. However, this apparent positive change is not due to an increase in ice area but due to a higher accuracy of the baseline data and higher level of detail, as well as the mapping of more debris-covered glacier parts (Linsbauer et al., in prep.). Figure 22 shows a compilation of glacier outlines for the SGIs 1850, 1973, 2010 and 2016.

2.3.1 SWISS GLACIER INVENTORIES OVER TIME

Due to the great effort involved in compiling a glacier inventory, the generally relatively low rates of change and the data requirements, complete inventories cannot be compiled every year. Datasets can be divided into two classes: Swiss glacier inventories based on (a) maps, aerial images and manual digitizing (SGI1850, SGI1973, SGI 2010, SGI2016), and (b) satellite images and semi-automatic mapping, published by Frank Paul in 2000 (Paul et al., 2002), 2003 (Paul et al., 2011) and 2015 (Paul et al., 2020).

SGI 1850 (Müller et al., 1976) (a)
The inventory depicting the maximum of glaciation in the Swiss Alps was based on the digitalization of historical maps and geomorphological evidence.

SGI 1973 (Maisch et al., 2000) (a)
The first Swiss Glacier Inventory was derived from stereo-photogrammetry-based interpretation of aerial photography data collected in early September 1973. The glacier outlines were transferred to topographic maps of the scale 1:25 000.

SGI 2000 (Paul et al., 2002) (b)

The inventory was compiled with a semi-automatic method (applying a band rationing and manual correction, automated generation of glacier parameter). Landsat Thematic Mapper (TM) satellite imagery acquired mainly in 1998/1999 was used.

Alps-2003 (Paul et al., 2011) (b)

Using the same methodology as in 2000, Paul et al. (2011) compiled a new glacier inventory for the entire Alps (Alps-2003) using Landsat images acquired within a two month period in the late summer of 2003. The large coverage was to the detriment of resolution of the satellite data (30 meter).

SGI 2010 (Fischer et al., 2014) (a)

The third Swiss Glacier Inventory was compiled by manual digitization from high-resolution (25 cm) aerial orthophotographs acquired between 2008 and 2011. The reference year for the inventory is 2010 as most entities are mapped from source data acquired in autumn 2010.

Alps-2015 (Paul et al., 2019) (b)

Based on Sentinel-2 satellite imagery with a spatial resolution of 10 meter, Paul et al. (2019) compiled an alpine wide glacier inventory for 2015. Clean glacier ice was mapped automatically as in the previous inventories, whereas debris-covered glaciers were edited manually, leading to a higher accuracy as previous inventories based on the semiautomatic approach.

SGI 2016 (Linsbauer et al., in preparation) (b)

The most recent inventory referring to 2013-2018 was derived from different high-resolution datasets produced by swisstopo, including:

- SWISSIMAGE - aerial photographs
- swissALTI^{3D} - digital elevation model
- swissTLM^{3D} - topographic Landscape Model (TLM).

The new inventory additionally provides information on supraglacial debris cover and ice divides.

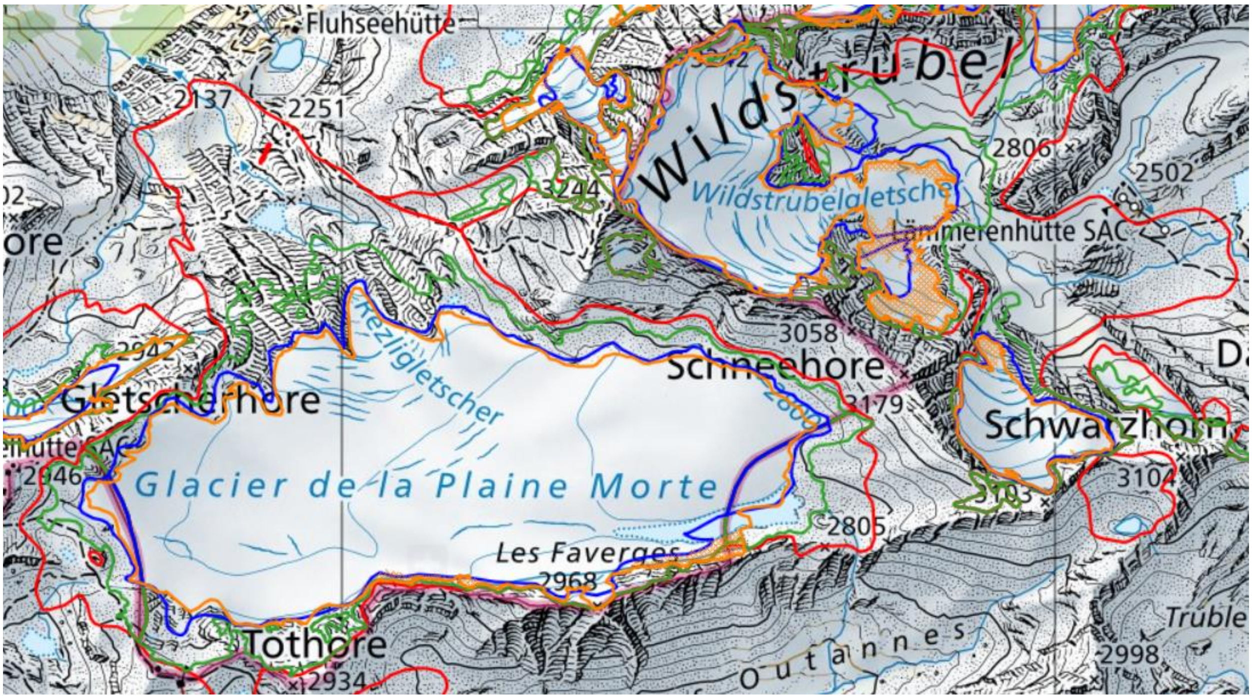

Figure 22: Compilation of glacier outlines around Glacier de la Plaine Morte for 1850 (red), 1973 (green), 2010 (blue) and 2016 (orange). Debris cover in 2016 is depicted as orange cross pattern.

2.3.2 METHODS FOR THE UPCOMING GLACIER INVENTORIES

The swissTLM^{3D} object class "glacier" is the central basis dataset for the compilation of the new SGI2016. This dataset has been digitized by swisstopo cartographers based on glaciological guidelines from GLAMOS to delineate glaciers but is produced under the framework of swissTLM^{3D} and is primarily a topological land cover dataset (Weidmann et al., 2019). Nevertheless, the swissTLM^{3D} object class "glacier" does still not fully meet the general glaciological requirements to directly serve as the new glacier inventory and has to be edited by GLAMOS experts (Linsbauer et al., in prep.). Future inventories will be derived from TLMs in a six-year rhythm. Currently, swisstopo and GLAMOS are optimizing the process and aligning the products TLM and SGI.

WHAT TO REGISTER

All entities meeting the definition of a glacier according to Cogley et al. 2011 " *a perennial mass of ice, and possibly firn and snow […] showing evidence of past or present flow"* should be compiled for a glacier inventory, irrespective of size, debris cover, type or other factors. This implies that imagery acquired at the end of the ablation period or dry season is preferred, i.e. without seasonal snow outside the glaciers. To achieve this, every effort should be made to screen the available images and select only the best scenes for glacier mapping, even when parts of them are cloud-covered. When possible, multitemporal analysis is recommended to separate seasonal snow from perennial snow or glaciers (Paul et al., 2009).

The lower limit of glacier size in the SGI2016 is defined at 0.01 km^2 for already inventoried glaciers, new entities for the glacier inventory have to be larger than 0.025 km^2 to be included into the SGI2016 (Linsbauer et al., in prep.).

DETERMINING GLACIER OUTLINES

The workflow of shaping glacier inventory from the TLM data set consists of the following steps (Linsbauer et al., in prep.):

1. *Application of minimal area size threshold*

According to the definition of the minimal glacier size all polygons < 0.01 km^2 are removed, if they have an SGI-ID and all polygons < 0.025 km^2, if they don't have an SGI-ID. This step is done a second time after generalization.

2. *Creating clipping masks by experts/glaciologists*

All classified features in the swissTLM^{3D} layer have to be controlled by glaciologists. Features classified erroneously as glaciers, mainly due to confusion with snow, or debris-covered ice bodies, have to be removed. Outlines have to be simplified by cutting of bulges.

3. *Harmonization and generalization*

The clipping masks are merged and homogenized to one single clipping mask that is applied to the swissTLM^{3D} layer. The resulting file id harmonized and generalized. Finally, the minimal area size threshold is applied a second time.

4. *Clipping with ice divides and debris cover layers*

The ice divides are used to split the glaciers into individual entities in the same way as in the previous SGI's. The swissTLM^{3D} layer also contains a layer with debris information. The harmonized and generalized glacier outlines are used to clip the debris information to the glacier outlines.

GLACIER INVENTORY PARAMETERS

The compilation of glacier inventory parameter follows the recommendation of the World Glacier Monitoring Service and GLIMS (Paul et al., 2010). The following attributes are compiled for the Swiss glacier inventory:

- geometry-ID
- UUID for internal use
- Swiss Glacier Inventory ID
- name of the glacier
- riverlevel_0-3: Subdivision of the inventory area on the basis of catchment areas of major rivers
- inventory code
- year of acquisition of the aerial image
- year of release of Swiss Glacier Inventory
- area in square kilometres
- glacier length according to automated mapping of the central flowline (Machguth & Huss, 2014)
- minimum of meter above sea level based on the newest swissALTI^{3D} release
- mean of meter above sea level based on the newest swissALTI^{3D} release
- median of meter above sea level based on the newest swissALTI^{3D} release
- maximum of meter above sea level based on the newest swissALTI^{3D} release
- average of slope in degree based on the newest swissALTI^{3D} release
- average of aspect in degree based on the newest swissALTI^{3D} release

ADDITIONAL DATA LAYERS

In the course of the preparation of the SGI2016, additional important data layers have been produced that belong to the package of the SGI2016 (Linsbauer et al., in prep).

- Location layer: a point layer with SGI-ID, glacier name and x and y coordinates. These points have been chosen manually, mainly for labelling purposes
- Debris cover layer: a polygon layer with SGI-ID and glacier name of the underlying glacier, giving the spatial extent of debris cover as well as the area in km^2 and the year of acquisition
- Ice divide layer: a polyline layer, separating glacier entities along ice divides and giving SGI-ID's and name for each side
- Surface type raster: a 10 meters resolution raster layer, aligned with swissALTI3D raster cells (2 meters), providing the surface types 0: no ice; 1: glacier/ice; 2: debris-covered ice/glacier

3. DATA DOCUMENTATION & STORAGE

In a nutshell: The long history of glacier monitoring resulted in a variety of documentation formats. In the course of a data rescue project, GLAMOS developed a consistent format for data documentation. Both historical and recent data were quality-checked and converted into the new format.

3.1 STANDARDIZED DOCUMENTATION FORMAT FOR MASS BALANCE MEASUREMENTS

The documentation format combines essential basic information for every raw point mass balance measurement with a quality-indicator allowing an estimate of the accuracy. To our knowledge, the addition of such indicators is not yet general practice in the global mass balance monitoring community. However, the addition of such metadata is highly valuable for further mass balance analyses and to ensure the traceability of all direct observations.

Basic information belonging to each observation of each seasonal point mass balance record is: Glacier name, glacier number, start and end date and start and end time of the observation, period, sampling position (x, y, z) and observer or source. Where available, the density of the point mass balance sample and calculated water equivalent can be added. Additionally, the accuracy of observation date, position, density and calculated mass balance are specified with indicators (see below). Also, the overall measurement quality and the type of observation are specified with indicators.

All data, manually digitized from historical sources or imported from more recent digital files, should be archived in the standardized format. If the respective data is available, three separate files will be generated for each glacier:

- annual (approximately encompassing a hydrological year)
- winter (encompassing the winter season)
- intermediate (shorter periods or arbitrary length)

Each file contains 19 columns for measurement data and corresponding metadata. Each line represents a single point measurement. In the next sections, a step-by-step instruction of the file structure with examples is provided:

Header

Mass Balance	Albigna	No. 116	annual
Stake	date0	time0	date1
(-)	(yyyymmdd)	(hhmm)	(yyyymmdd)
GLAMOS / VAW-ETHZ	production-date 20201216	reference	http://www.glamos.ch
Q2	19541020	1200	19551014

first line:	data type, glacier name, glacier number, measurement type (annual/ winter/intermediate)
second line:	column headers
third line:	units: yyyymmdd, hhmm, d, m, m, m a.s.l., cm, kg m^{-3}, mm w.e.
fourth line:	analysis/copyright: source institution, revision year(date), bibliographic ref, url
fifth line - xth line:	measurement data and metadata

Date and time

Mass Balance	Albigna	No. 116	annual		
Stake	date0	time0	date1	time1	period
(-)	(yyyymmdd)	(hhmm)	(yyyymmdd)	(hhmm)	(d)
GLAMOS / VAW-ETHZ	production-date 20201216	reference	http://www.glamos.ch		
Q2	19541020	1200	19551014	1200	359

name: name / number of measurement (stake, sounding, probing, etc.)

date0: date of begin of period in the format YYYYMMDD
if day is not known: YYYYMM00
if month is not known YYYY0000
if date is not known at all: 00000000

time0: time of begin of period in hhmm
by default 1200. If known, add in format hhmm

date1: date of end of period in the format YYYYMMDD
if day is not known: YYYYMM00
if month is not known YYYY0000
if date is not known at all: 0000000

time1: time of end of period in hhmm
by default 1200. If known, add in format hhmm

period: difference between date1 and date0 in days.

date_quality: quality identifier for date
0: start and end dates estimated/unknown
1: start and end dates exactly known
2: start date exactly known, end date estimated/unknown
3: start date estimated/unknown, end date exactly known

Position

x_pos	y_pos	z_pos	position_quality
(m)	(m)	(m a.s.l.)	(#)
770011.6	131666.9	2298.0	3

x-pos: x-position of point measurement (CH1903)

y-pos: y-position of point measurement (CH1903)

z-pos: elevation of point measurement in meter above sea level

position_quality: quality identifier for position (position refers to end of period)
0: undefined/unknown
1: measured by dGPS
2: measured by handheld GPS

3: measured using an alternative method (e.g. theodolite, triangulation)
4: estimated from previous measurements
5: estimated based on altitude information

Measurement

mb_raw (cm)	density (kg m-3)	density_quality (#)	mb_we (mm w.e.)	measurement_quality (#)	measurement_type (#)	mb_error (mm w.e.)	source (-)
-282	900	1	-2538	1	1	67	vaw

mb_raw: raw mass balance measurement in cm

density: snow/firn/ice density in kg m^{-3}
typical values: 900 kg m^{-3} for bare ice, 550 kg m^{-3} for firn, 400 kg m^{-3} for snow

density_quality: quality identifier for density
0: quality/source unknown
1: Ice density
2: Measured snow/firn/ice density
3: Density of snow/firn estimated from nearby measurements
4: Density of snow/firn estimated without nearby measurements
5: water equivalent based on combination of fresh snow density and ice density (no separate information available)
6: estimated based on linear regression and elevation in post-processing

mb_we: point mass balance in mm w.e. / kg m^{-2}

measurement_quality: quality identifier for reading (definitions see below)
0: quality/source unknown
1: typical reading uncertainty
2: high reading uncertainty
3: reconstructed/exceeds min. measurement range (e.g. stake melted out)
4: reconstructed/exceeds max. measurement range (e.g. stake snow buried)
5: reconstructed value (other reason)

measurement_type: type of mass balance observation
0: unknown
1: stake
2: depth probing / snowpit / coring
3: marked horizon (e.g. in snowpit or coring)
4: ground penetrating radar (GPR)
5: snowline
6: nivometer (painted marks on rock face)
8: other

mb_error: uncertainty of point mass balance as square root of the sum of squares of the fractional uncertainties of *density* and *raw balance* in mm w.e.

The estimation of point mass balance uncertainty is highly relevant when evaluating the data series, but benchmarking an estimate is difficult as the relevant information is often lacking. In the absence of detailed studies on the uncertainty of individual measurements, we estimate the uncertainty based on assigned generic values for the relevant IDs that determine overall uncertainty. These generic average values are motivated by previous studies. We suggest, however, that all available information on known uncertainties (e.g. from repeated snow probings, or multiple snow density measurements) are reported along with the data.

source: NN: unknown
glrep: Glaciological Reports
...
ab: Andreas Bauder
mh: Matthias Huss
...

File-name convention

All files are saved in a homogenous format:

<glaciername>_annual.dat: annual point mass balance
<glaciername>_winter.dat: winter point mass balance
<glaciername>_intermediate.dat: intermediate values of point mass balance

<glaciername>: short working name (no special characters)

Example: silvretta_annual.dat

The complete data package, including all point mass balance observations and metadata are available in GLAMOS (2021).

4. DATA EVALUATION

In a nutshell: Glacier wide mass balance is derived from direct glaciological point observations with a distributed accumulation and temperature-index melt model and validated against geodetic ice volume changes.

4.1 DETERMINATION OF GLACIER-WIDE MASS BALANCE

Time series of glacier-wide mass balance are indispensable for many glaciological applications, for example for the assessment of water storage changes or comparing rates of mass change between different glaciers and mountain ranges (e.g., Harrison et al., 2005; Zemp et al., 2009; Gardner et al., 2013). Various approaches are currently used to calculate glacier-wide mass balance from point measurements and are the basis of evaluated results on glacier-wide mass balance submitted to the WGMS (Zemp et al., 2009):

1. Profile method (e.g., Østrem & Stanley, 1969),
2. Contour line method (e.g., Østrem & Brugman, 1991; Escher-Vetter et al., 2009),
3. Application of kriging (e.g., Hock & Jensen, 1999),
4. Statistical approaches based on the linear mass balance model (e.g., Thibert et al., 2008),
5. Extrapolation based on a mass balance model constrained by seasonal field observations (e.g. Huss et al., 2015).

All approaches have in common that a periodic validation of glacier-wide mass balance series derived from direct glaciological point observations against independent geodetic ice volume changes is required at regular intervals to avoid a bias in the long-term observations (e.g. Thibert et al., 2008; Huss et al., 2009; Zemp et al., 2013; Andreassen et al., 2016). In general, point mass balance measurements at stakes or in snow pits provide a high temporal resolution (annual, seasonal, potentially daily) and allow inferring the spatial distribution mass balance, including the equilibrium line altitude (ELA) or mass balance gradients. However, stake measurements are inherently local observations and mass balances need to be interpolated into unmeasured/inaccessible regions leading to partly considerable uncertainties that are estimated to be roughly ± 0.2 m w.e. a^{-1} for many mass balance monitoring programmes (e.g. Dyurgerov, 2002; Zemp et al., 2013). Geodetic ice volume changes cover the entire glacier, but do not yield information on year-to-year variability. Also, they only reveal local surface elevation changes but not mass balance due to the influence of ice flow dynamics. Extracting seasonal/annual mass balance variations and local mass balance, including elevation dependencies and ELAs is thus not possible. Furthermore, the conversion of observed geodetic ice volume change to mass change has a potential for inducing considerable uncertainty (Huss, 2013). Geodetic mass changes are assumed to be most appropriate for detecting long-term biases in the direct glaciological method and are an indispensable prerequisite for a thorough homogenization of long-term mass-balance time series. A complete framework for this procedure has been presented by Zemp et al. (2013).

In this report, focussing on data evaluation in the context of GLAMOS, we only provide a detailed description of the technique to evaluate glacier-wide mass balance that is in use in Switzerland (5). The re-analysis of all previous data series (see e.g. Huss et al., 2015), as well as the current evaluation of point mass balance data is based on this approach. Here, we thus do not further describe other approaches (1-4) that are in use in monitoring programmes in other countries. This should not imply, however, that these techniques cannot also be considered as “best practice” for the observational conditions of those programmes. We refer to previous publications that compare the results of different approaches to evaluate glacier-wide mass balance and the describe the respective techniques in more detail (e.g., Østrem & Stanley, 1969; Østrem & Brugman, 1991; Thibert et al., 2008; Zemp et al., 2013; Sold et al., 2016; GLAMOS, 2020b).

4.1.1 MODEL-BASED EXTRAPOLATION OF MASS BALANCE

The framework to infer glacier-wide mass balance from seasonal point measurements based on a spatially distributed mass-balance model that is tightly constrained with all available in situ observations has been presented in various studies (e.g., Huss et al., 2009, 2015; Huss, 2010; Barandun et al., 2015; Fischer et al., 2016; Kronenberg et al., 2016; Naegeli and Huss, 2017). The approach is in use within GLAMOS activities since more than a decade and has also been transferred to other climatic regions (e.g. Central Asia, Southern Andes, Greenland) and was found to yield good results by other researchers. The basic approach is to use a distributed accumulation and temperature-index melt model (Figure 23) (Hock, 1999; Huss et al., 2008) to infer mass balances in unmeasured regions and to optimize it to agree with all seasonal point measurements that are available. The mass balance model is not regarded as a physical model, but as a statistical tool for obtaining a daily temporal resolution based on seasonal field data and spatial interpolation of point measurements supported by a model (Huss, 2010; GLAMOS, 2020d).

The main advantages are:

1. Consistent and reproducible approach that can be applied (semi-)automatically to all glaciers in the monitoring programme thus providing a homogenous data evaluation.
2. Simultaneous incorporation of both winter and annual point data into the evaluation scheme.
3. High robustness regarding changes in the stake network.
4. Model-based separation of mass balance components (accumulation and ablation).
5. Model-based determination of daily mass balances confined by the seasonal measurements. This allows extracting mass balance over arbitrary time periods (e.g. the hydrological year), which is highly important for intercomparing the signals of different glaciers.
6. Consistent approach for estimating mass balance in years with completely missing measurements.

Required input data for the model-based evaluation of glacier-wide mass balance are:

1. Point mass balance at an arbitrary number of stakes over a period of about one year.
2. If available, winter snow probings and an estimate of snow density before the onset of the melting season.
3. An up-to-date digital elevation model and glacier outlines.
4. Daily air temperature and precipitation measured at a weather station. The weather station is optimally close to the glacier and it should cover the entire period to be analysed. For air temperature, it is recommended to use a station at an elevation similar to the glacier, whereas for precipitation spatial proximity is more important. Sensitivity experiments have however shown that the choice of the weather data (and their quality) have a small impact on the results (GLAMOS; 2018b), i.e. also remote weather stations or re-analysis data can be used in the approach.

The required data input is thus the same as for the other techniques to evaluate glacier-wide mass balance, except for (4).

Daily surface melt rates $M = M(x,y,t)$ at day t and for grid cell (x,y) of the DEM are computed by

$$M(x,y,t) = \begin{cases} (f_M + r_{snow/ice} I_{pot}) T & : \quad T > 0°C \\ 0 & : \quad T \leq 0°C, \end{cases}$$

where f_M is a melt factor, $r_{ice/snow}$ are radiation factors for ice and snow surfaces, $T = T(x,y,t)$ is air temperature, and $I = I(x,y,t)$ is the potential solar radiation. All factors are assumed to be constant over one year. Air temperature is extrapolated to the median glacier elevation using monthly lapse rates derived from weather stations surrounding the study site and is then distributed to every grid cell using an annually constant local lapse rate, dT/dz (Huss et al., 2008).

Snow accumulation, $C = C(x,y,t)$, is calculated based on measured precipitation, $P(t)$, occurring at T lower than a threshold temperature T_{thr} = 1.5°C that distinguishes snow from rainfall with a linear transition range of ± 1°C as

$$C(x,y,t) = P(t) \cdot c_{prec} \cdot D_{snow}(x,y).$$

A correction factor C_{prec} allows the adjustment of precipitation sums. The spatial variation in accumulation over the glacier is taken into account by using a spatial snow distribution multiplier $D_{snow}(x,y)$ derived for each glacier individually from snow probings in winter and terrain characteristics (Huss et al., 2008, 2009; Farinotti et al., 2010). D_{snow} is derived for each year based on spatially interpolating all point observations of snow depth in spring (large-scale accumulation variability) and by intersecting this field with local-scale corrections accounting for high surface slopes (linearly decreasing snow deposition due to avalanches between 40° and 60° slope angle) and curvature as an indicator for increased or reduced snow accumulation due to preferential wind deposition or redistribution of snow (e.g., Sold et al., 2016). The spatial snow accumulation grid is then normalized to an average of 1.0 over the entire glacier surface. Values smaller than 1 indicate less snow accumulation than in the glacier-wide average and vice versa. Values of D_{snow} typically are in the range of 0 to 2.

4.1.2 CONSTRAINING THE MODEL WITH FIELD DATA

The procedure to derive long-term series of glacier-wide mass balance is separated into two steps (Figure 23): (1) optimizing the model to match seasonal point mass-balance data, and (2) correcting the results obtained in (1) using independent geodetic mass changes, if necessary. Basically, step (1) represents the direct glaciological method with a model used for temporal downscaling and for determining the spatial distribution of mass balance. In step (2), the mean specific mass balance is fitted to the geodetic mass change, which is assumed to represent long-term changes more accurately in glacier volume. The concept of this approach is very similar to simplified statistical methods for evaluating mass balance derived from the linear mass balance model (see e.g. Thibert & Vincent, 2009), and the same concept has also been applied at much larger scales for estimating global glacier mass changes (Zemp et al., 2019).

First, the accumulation parameter of the mass-balance model is calibrated using the measurements of winter balance. C_{prec} is tuned so that the calculated snow water equivalent at the winter survey date matches the measured value. If no winter balance data are available, C_{prec} has the average value of all years with winter measurements and dP/dz is estimated from regional meteorological conditions.

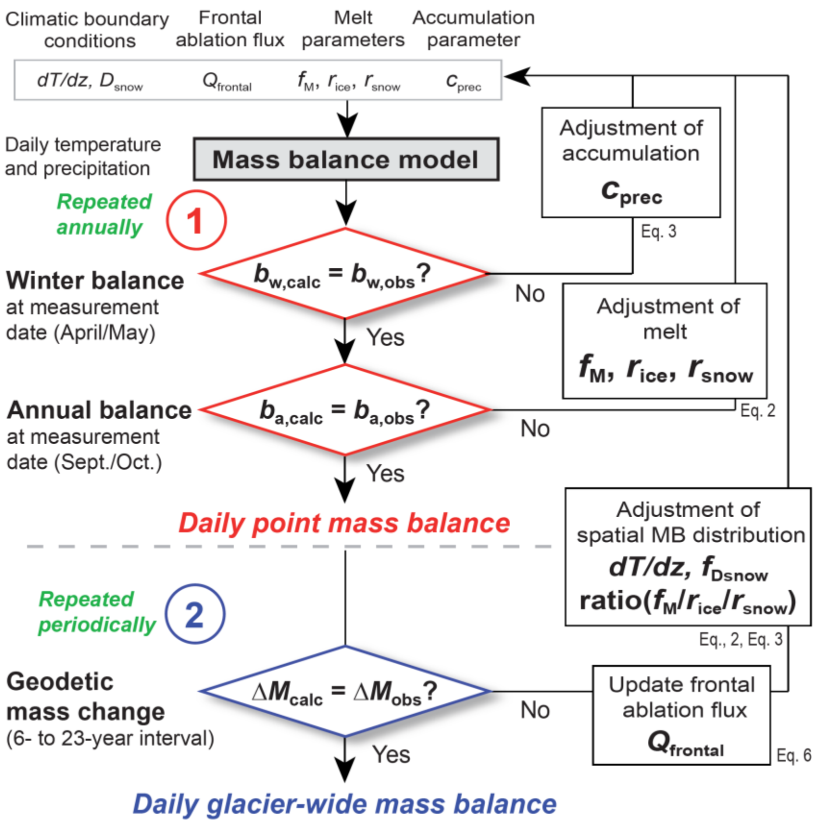

Figure 23: Schematic overview of the approach to derive long-term series of glacier-wide mass balance from seasonal point observations and geodetic ice volume changes. The variable of frontal ablation is only relevant for a few glaciers experiencing mass loss by processes other than surface melting (Huss et al., 2015).

The calibration of the melt parameter f_M and $r_{ice/snow}$ is performed annually using the measurements of point balance. Mass balance calculated between the exact dates of the late-summer field surveys in two successive years is tuned to the field data. The parameter are varied systematically in order to obtain (i) an average difference of field data and calculation equal to zero, and (ii) a minimization of the root-mean-square error of point measurements and model results at these locations.

Before comparison of the resulting cumulative annual mass balances to geodetic ice volume changes, differences in the date of these independent acquisitions need to be corrected. This can be achieved by adding total mass change given by the constrained model for the respective year, occurring between the acquisition date of the aerial photograph and the field survey. Geodetic ice volume change is often converted to mass change using a density of volume change of 850 ± 60 kg m^{-3}. This estimate represents a value that is valid in a wide range of constellations and accounts for changes in firn density and volume in the case of both positive and negative mass balance (Huss, 2013). For short time intervals (< 4 years) and small mass changes, however, the volume-to-mass conversion factor is significantly more uncertain.

In the second homogenization step, the resulting time series are compared to the density- and date-corrected ice-volume changes. In the ideal case, the cumulative direct mass balance coincides with the geodetic mass change (Figure 24). Zemp et al. (2013) provide a detailed framework for deciding when a misfit between cumulative glaciological mass balance and geodetic mass changes is significant and should be corrected. This mainly depends on the estimated uncertainties in direct point observations and the mass balance extrapolated to the glacier-wide scale, and the uncertainty in geodetic ice volume change. If there is a significant bias between glaciological and geodetic series, it is suggested that the parameter obtained in step (1) are updated in order to yield the corrected cumulative mass balance better matching the geodetic mass changes (Figure 23). Long-term geodetic surveys of ice volume change can thus be used to optimize parameters of the extrapolation scheme that are poorly constrained but are relevant for correctly estimating mass balance in unmeasured regions of the glacier. The result of the complete procedure is the spatial distribution of mass balance in the measurement period (see Fig. 25 for two examples), where the mass balance in unmeasured regions is given by physical relations directly constrained by the seasonal measurements. In addition, a model-based daily series of glacier mass change is available permitting the evaluation of mass balance quantities over arbitrary time periods.

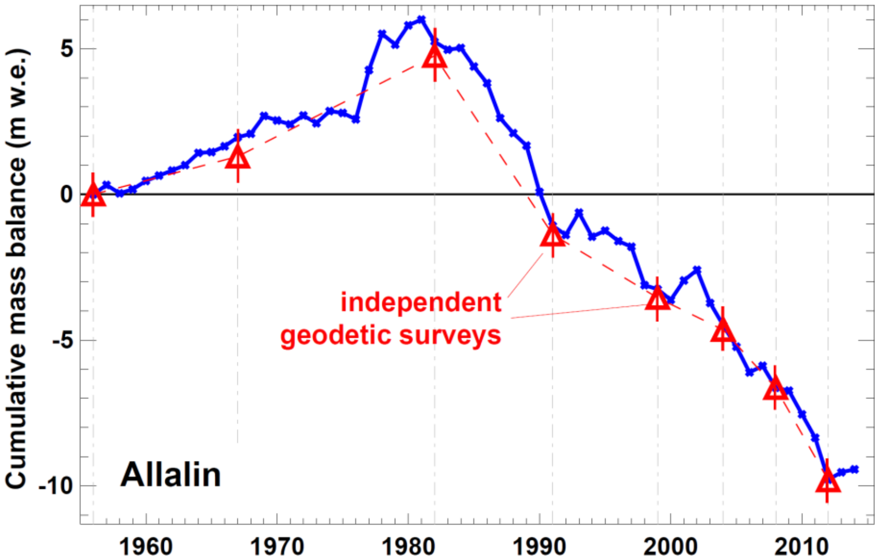

Figure 24: Comparison of annual mass balance series derived based on the glaciological method (blue) with independent ice volume changes (red) based on periodic geodetic surveys (Huss et al., 2015).

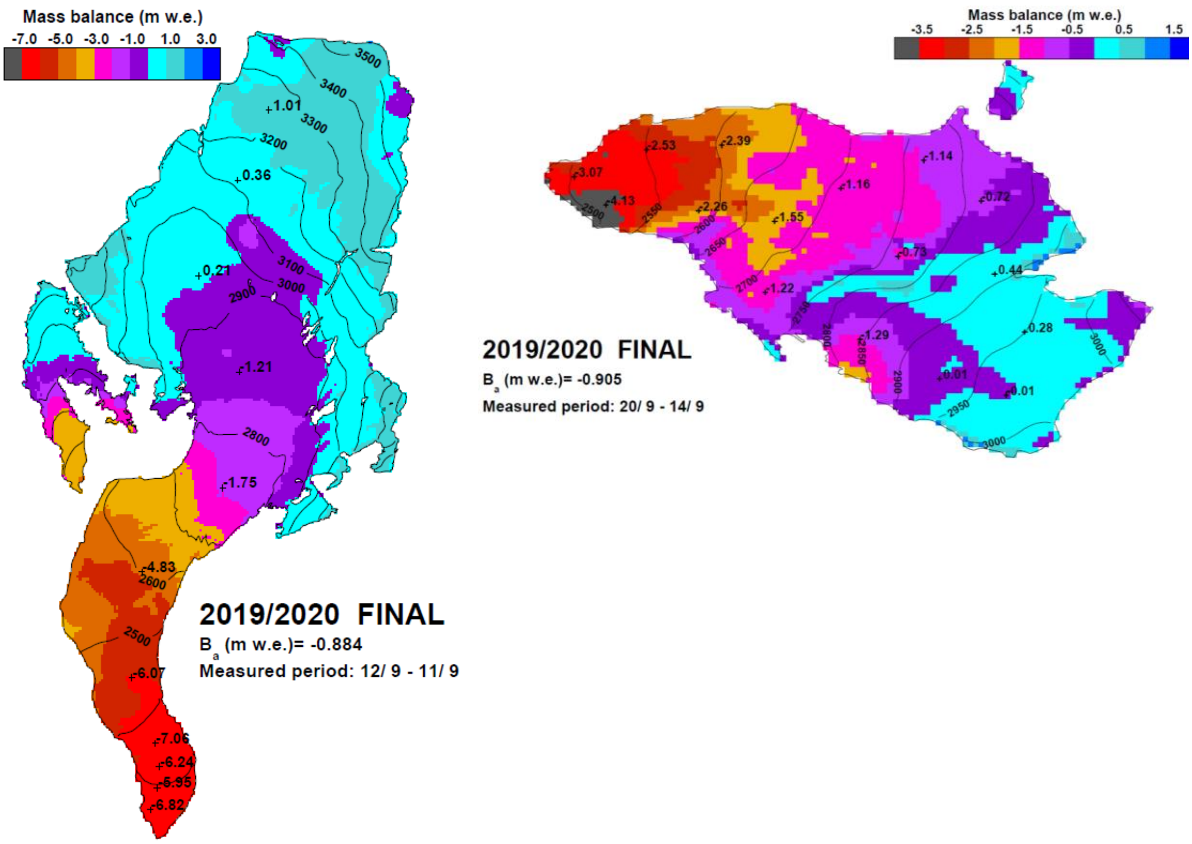

Figure 25: Result of the model-based extrapolation of glacier-wide mass balance for Rhonegletscher and Silvrettagletscher (2019/2020). Measurements of point annual mass balance are shown by crosses and values indicate measured mass balance in m w.e. for the measurement period. The significant spatial variability in mass balance, only partly consistent with surface elevation gradients, is clearly visible and can be resolved by the utilized approach.

4.2EVALUATION AND HOMOGENIZATION OF GLACIER LENGTH CHANGE OBSERVATIONS

Length change observations have been acquired over more than a century mainly based on relative distance measurements from marked reference points to the glacier snout. The traditional evaluation procedure averages a few individual measurements distributed along the central section of the snout (Kasser, 1976). Only the resulting length variation was stored without the number or position of individual measurements. For a few exceptions the outline of the snout has been mapped (e.g. Rhonegletscher, see Figure 26 for the states 1874-1900, Mercanton, 1916). Since the 1960s the elevation of the lowest point has also been collected as additional meta-information. Only more recently, the acquisition of geo-referenced glacier outlines based on orthorectified aerial images have become available (Figure 26, states 1970-2010). Comparison of re-evaluated glacier length changes based on these geo-referenced data might result in a bias in comparison to annually cumulated length change observations from the traditional method. This is mainly explained by inconsistencies in the annual difference measurements relative to fixed reference points, and to an incomplete consideration of the entire width of the glacier snout for the assessment of length change.

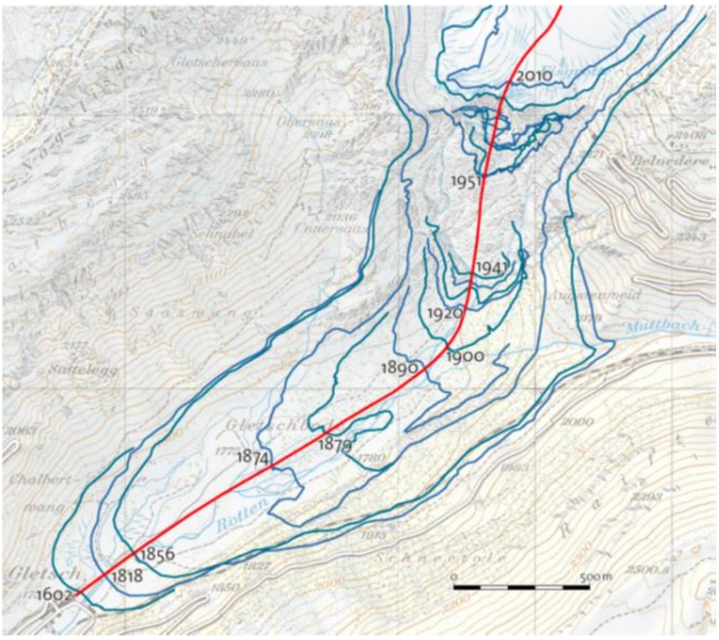

Figure 26: Geo-referenced glacier outlines for Rhonegletscher. The red line corresponds to a central flowline.

To overcome this problem, it is suggested to perform a periodic re-analysis and homogenization of the annual length change measurements using geo-referenced glacier states. In the frame of GLAMOS this has been performed for the majority of the long-term series relying on almost 3000 newly digitized glacier termini covering a time period from the early 20th century until today. Cumulative length changes originating from the traditional method are compared to independently evaluated, periodic length changes (time intervals of one year to several decades) along a central flowline (Figure 26). Potential periodic biases are then computed at the annual scale and are evenly distributed over the considered time period resulting in a match of the annual series of the traditional method with geo-referenced glacier states. Figure 27 provides an example for this procedure and shows that this correction can be relevant for some series and in certain periods.

The advantage of this homogenization is that long-term glacier length changes can be computed according to a consistent and reproducible methodology, strongly enhancing traceability of the data set. However, the availability of geo-referenced outlines of the terminus region is a prerequisite. The acquisition of such data in the field (e.g. by GPS or drone-surveys), or by direct evaluation on aerial imagery is enforced in the new concept for length change observations (GLAMOS, 2020c).

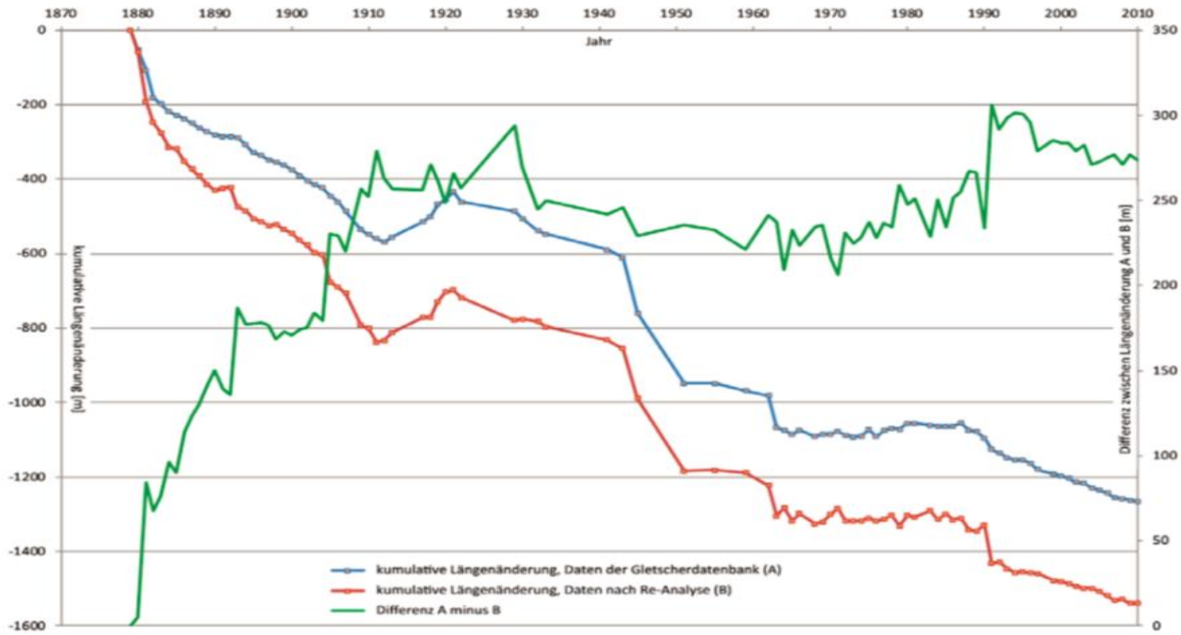

Figure 27: Cumulative length change of Rhonegletscher according to the traditional method (blue) and the re-analyzed series (red). The cumulative bias is shown in green and can mainly be attributed to the period between 1880 and 1910, whereas differences are small afterwards.

5. CONCLUDING REMARKS AND RELEVANCE OF THE BEST PRACTICE GUIDE

This Best Practice Guide provides an up-to date overview on the current practices in data acquisition, documentation and evaluation in Swiss glacier monitoring. The aim of this document is to ensure continuity and consistency of long-term term observations.

Point mass balance observations are currently acquired at about 20 glaciers in the Swiss Alps, usually twice a year. At the end of the ablation season (i.e. in late September), mass balance is recorded at ablation stakes. These stakes are drilled in the glacier ice the autumn before and are distributed in a way that they allow extrapolation of mass balance to the whole glacier surface. The Kovacs-drill has become the established tool for fieldwork and sectioned aluminium and/or PVC stakes were found most practical. Autumn fieldwork also includes the marking of the surface layer in the accumulation area at sites where firn accumulation is determined in snow pits or by coring. During the end-of-winter survey (typically in April or May), snow depth is recorded with a snow probe while skiing over the glacier. Also ground penetrating radar (GPR) for measuring snow depth is increasingly used due to a high efficiency. Winter fieldwork also includes snow density measurements. Density is mostly determined using snow coring. Snow pits may provide more reliable values but are extremely laborious, limiting the number of potential observations. Length change of the glacier terminus is observed annually at around 100 glaciers in Switzerland. Currently, the observation method is in transition from annual field surveys at the glacier snout to data based on aerial imagery for small glaciers or glaciers with limited accessibility. The compilation of glacier inventories involves a great effort and inventories are therefore only released periodically. A new Swiss glacier inventory (SGI2016) is soon to be released. According to this new and consistent methodology, based on regular high-resolution aerial images and digitization in the frame of the terrestrial landscape model through swisstopo, 6-yearly updates are expected in the future.

In this guide, we also present a new standardized data documentation format for point mass balance measurements. The documentation format combines essential basic information for every observation with quality-indicators allowing an estimate of the data accuracy. The addition of such metadata has been neglected so far but is indispensable for further mass balance analyses and to ensure traceability of all direct observations.

For the determination of glacier-wide mass balance from point mass balance observations, a consistent and reproducible data extrapolation scheme based on a distributed mass balance model closely constrained by all available field observations for each year is used in Swiss glacier monitoring. This methodology infers mass balances in unmeasured regions and optimizes it to agree with all seasonal point measurements that are available. To homogenize long-term series of the glacier wide mass balance, the mean specific mass balance is calibrated with independent geodetic mass changes.

This Best Practice Guide reflects the state of glacier monitoring in Switzerland as of the year 2020 and documents the techniques used in GLAMOS, including their background, pros and cons. Technical progress, novel approaches and data sets may require periodic supplements and updates of this document in the coming years or decades. This Best Practice Guide may be an inspiration for other national monitoring programmes but not all suggestions may be transferable as they are tailored to Swiss conditions.

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7. APPENDIX

7.1 DOCUMENTED LENGTH VARIATION

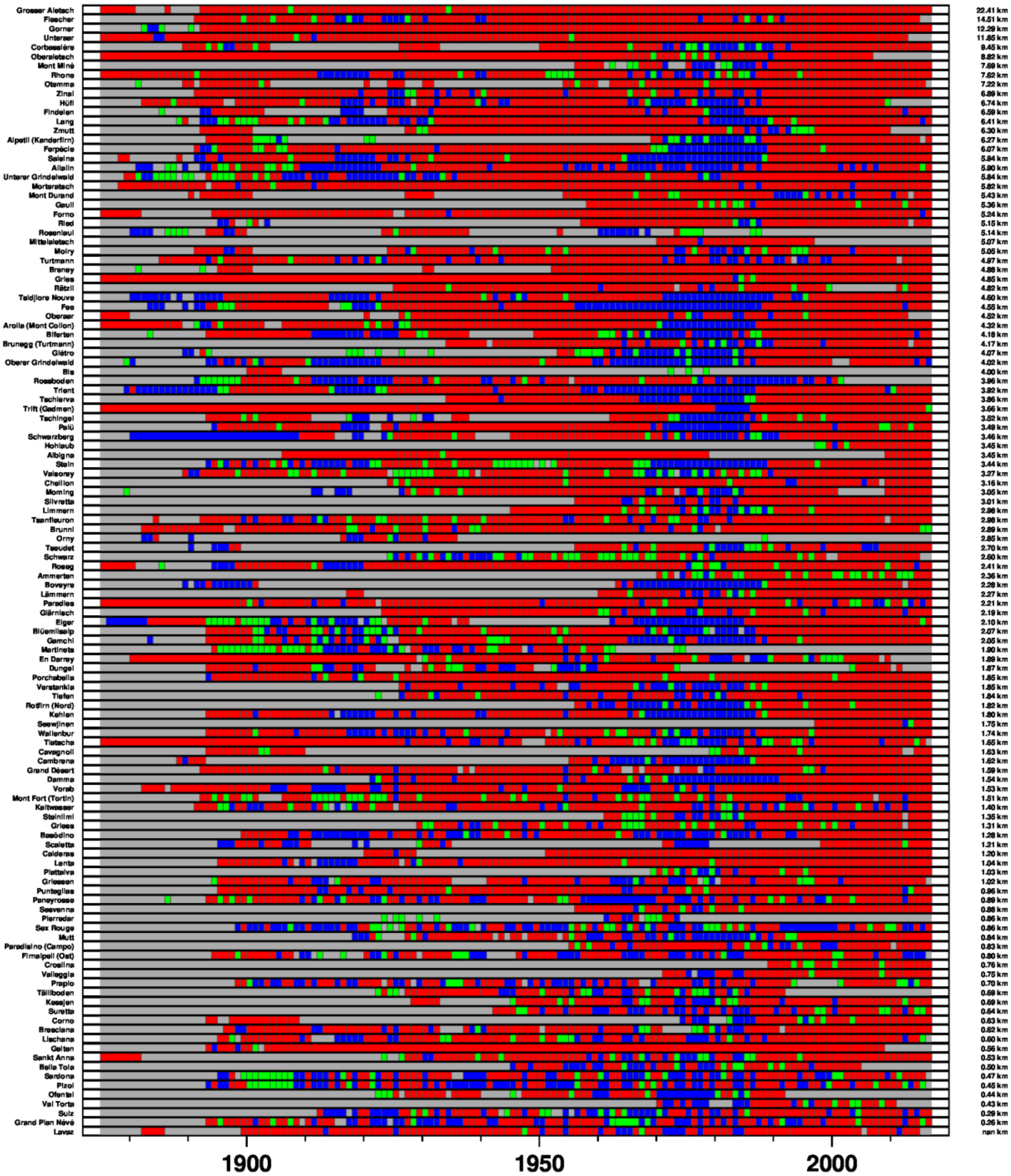

Figure 28: Temporal coverage of selected series of the length change data set. Individual glaciers are arranged in descending order regarding their present total length. Red colours indicate retreat, blue advance, and green stationary conditions. Time-transient coverage of annual or multi-annual measurement periods, as well as data gaps are visible (GLAMOS, 2020c).

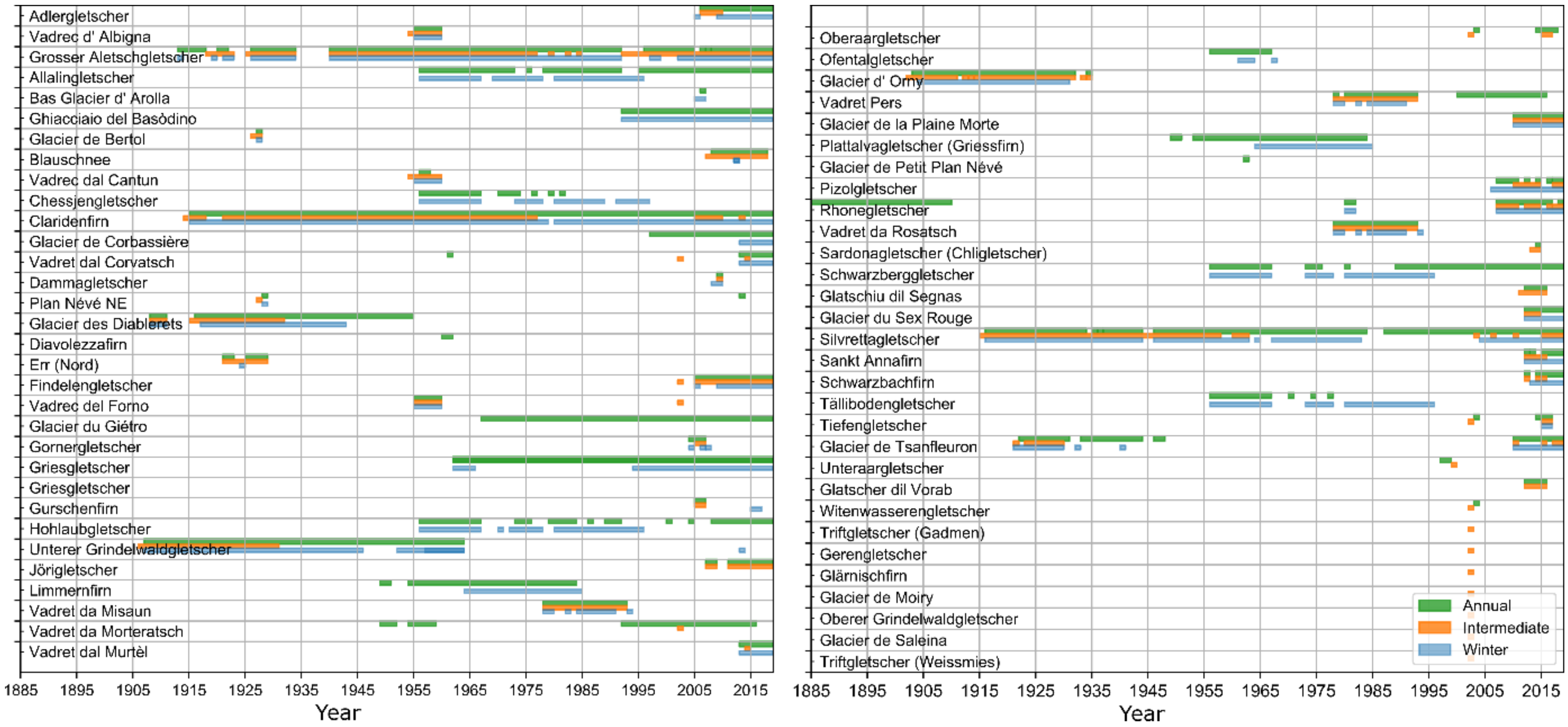

Figure 29: Observation periods of annual (green), intermediate (orange) and winter (blue) mass balance on Swiss glaciers between 1884-2020.

7.3 LIST OF GLACIERS IN THE MASS BALANCE MONITORING NETWORK

Table 6: Basic information on glaciers in the mass balance monitoring network.

Glacier name	Glacier area (km^2)	Sampling interval	Average no. of point annual obs. (2010-2020)	Average no. of point winter obs. (2010-2020)
Aletsch	78.52	seasonal	2.2	1.0
Allalin	9.55	annual	9.0	-
Basòdino	1.76	seasonal	9.5	38.3
Clariden	4.55	seasonal	2.0	2.0
Corbassière	15.08	annual	6.9	-
Corvatsch	0.22	seasonal	3.2	15.5
Findelen	12.67	seasonal	16.6	860.4
Giétro	5.28	annual	7.6	0.0
Gries	4.35	seasonal	18.3	38.9
Hohlaub	2.13	annual	1.4	-
Murtèl	0.29	seasonal	4.7	112.7
Pers	6.66	seasonal	5.3	-
Pizol	0.03	seasonal	7.9	77.6
Plaine Morte	7.11	seasonal	4.3	98.6
Rhone	15.31	seasonal	12.6	335.5
Sankt Anna	0.15	seasonal	7.4	71.0
Schwarzbach	0.03	seasonal	2.4	35.9
Schwarzberg	4.89	annual	2.8	-
Sex Rouge	0.26	seasonal	3.4	127.7
Silvretta	2.58	seasonal	17.2	177.7
Tsanfleuron	2.45	seasonal	5.2	559.0

7.4 PRACTICAL INFORMATION FOR FIELDWORK

Table 7: Information on site access, team size and technical/physical requirements for fieldwork in summer and winter

Glacier	Typical access in the frame of GLAMOS	Team size	Technical difficulty		Requirements to physical condition		Strength and carrying capacity	
			summer	winter	summer	winter	summer	winter
Aletsch Jungfraujoch	Railway/ Hike from Fiescheralp	2-4	easy	none (snow-shoes)	medium	basic	medium	light
Aletsch tongue	Railway/ Hike from Fiescheralp	2-4	medium	medium	strong	basic	light	light
Allalin	Helicopter	2-3	easy	-	basic	-	light	-
Basòdino	Hike from	2-3	easy	medium	medium	medium	medium	light
Clariden	Hike from	2-3	easy	medium	medium	medium	medium	light
Corbassière	Helicopter	2-3	difficult	-	medium	-	medium	-
Corvatsch	Cable Car	2-3	difficult	good	medium	basic	light	light
Findelen	Helicopter	4-8	medium	medium	medium	medium	medium	medium
Giétro	Helicopter	3	difficult	-	medium	-	medium	-
Gries	Hike from Nufenenpass	2-4	medium	little	strong	-	medium	light
Hohlaub	Helicopter	2-3	easy	-	basic	-	light	-
Murtèl	Cable Car	2-3	difficult	good	medium	basic	light	light
Pers	Hike from Diavolezza		difficult	good	strong	medium	medium	medium
Pizol	Hike from Pizol hut	2	medium	medium	medium	medium	light	light
Plaine Morte	Cable Car	2-3	none	little	basic	medium	none	light
Rhone	Helicopter	3-8	medium	medium	medium	medium	medium	light
Sankt Anna	Cable Car	2	difficult	good	medium	basic	medium	light
Schwarzberg	Helicopter	2-3	easy	-	basic	-	light	-
Schwarzwasser	Cable Car	2	difficult	good	medium	basic	medium	light
Sex Rouge	Cable Car	2	easy	little	medium	basic	light	light
Silvretta	Hike from Sardasca	2	medium	medium	medium	medium	medium	medium
Tsanfleuron	Cable Car	2	easy	little	medium	basic	light	light

Table 8: Explanation of the fieldwork requirements rating

Technical/alpinistic difficulty	
Easy	Minimal danger of crevasse fall, minimal danger of sliding off, no danger of falling; flat firn slopes, few and well visible crevasses, easy walking terrain (scree, blocks), simple and clear orientation. → little surefootedness required; team leader: basic rope handling skills
Medium	Danger of crevasse fall, minimal danger of sliding off, no danger of falling; moderately steep firn slopes (< 30°), few crevasses, easy walking terrain (scree, blocks), simple to medium orientation. → surefootedness required; team leader: good rope handling skills
Difficult	Danger of crevasse fall, danger of sliding off, danger of falling; steep firn slopes (> 30°) possible, few to many crevasses, possibly easy climbing sections, medium orientation difficulty → surefootedness both with and without crampons required; team leader: very good rope handling
Skiing technique and avalanche awareness	
None	Use of snowshoes possible
Little	Flat terrain (< 25°), little experience on ski tours, safe and controlled ski descent (safe skiing on black slopes), basic knowledge in avalanche assessment & rescue
Medium	Little steep terrain (< 30°), experienced on ski tours, safe and controlled ski descent (safe off-piste skiing in all conditions), solid knowledge and application of avalanche assessment & rescue
Good	Steep terrain (> 30°), very experienced on ski tours, safe and controlled ski descent in all conditions (including when roped-up), very good knowledge and application of avalanche assessment & rescue
Requirements to physical condition	
Little	Short fieldtrip (< 4h), effective walking time: very short (<1h), ascent/descent: negligible, distance: <4 km
Basic	Day trip, effective walking time: short (1-4 h), ascent/descent: < 400hm, distance: 4-8 km speed: 400 hm/h, 4 km/h
Medium	Day or multi-day trip, effective walking time: medium (4-8h), ascent/descent: 400-1000 hm, distance: > 8 km speed: 400 hm/h, 4 km/h
Strong	Day or multi-day trip, effective walking time: long (>8h), ascent/descent: > 1000 hm, distance: > 12 km speed: 500 hm/h, 5 km/h
Strength and carrying capacity	
None	No relevant material in addition to the personal equipment
Light	Transport of light additional material (tools, measuring equipment, light batteries, …), moving of light boxes or other equipment, little effort required (shoveling snow, …)
Medium	Transport of medium-heavy material incl. backpack (SUVA: < 25kg men, < 15kg women), moving of heavy material or equipment, increased and enduring use of force necessary
Heavy	Transport of medium-heavy material incl. backpack (SUVA: < 25kg men, < 15kg women), moving of very heavy material and equipment, large and enduring use of force necessary

7.5 LIST OF GLACIERS IN THE LENGTH CHANGE MONITORING NETWORK

Table 9: Detailed list with the period and number of available observations of all glaciers in the network as well as the priority rating (1-4) of individual series.

Glacier	Period	Observations	Priority
Allalin	1881-2019	123	1
Arolla	1856-2019	124	1
Basòdino	1899-2019	92	1
Biferten	1893-2019	79	1
Blüemlisalp	1893-2019	110	1
Bresciana	1896-2019	87	1
Brunni	1882-2019	97	1
Cheillon	1924-2019	88	1
Chelen	1893-2019	116	1
Damma	1921-2019	87	1
En Darrey	1880-2019	67	1
Fee	1883-2019	108	1
Ferpècle	1891-2019	120	1
Fiescher	1891-2015	119	1
Findelen	1885-2019	90	1
Firnalpeli	1894-2019	78	1
Forno	1857-2019	108	1
Gamchi	1883-2019	112	1
Glärnisch	1923-2019	69	1
Gorner	1882-2019	121	1
Grand Désert	1892-2019	117	1
Grand Plan Névé	1893-2019	101	1
Gries	1847-2019	60	1
Griess	1929-2019	79	1
Griessen	1894-2019	82	1
Grosser Aletsch	1870-2019	127	1
Hüfi	1882-2010	117	1
Kaltwasser	1891-2019	111	1
Lang	1888-2017	117	1
Lavaz	1882-2019	88	1
Lenta	1895-2019	102	1
Lischana	1895-2016	89	1
Moiry	1891-2019	101	1
Moming	1911-2017	79	1
Mont Fort	1892-2019	112	1
Morteratsch	1878-2019	131	1
Mutt	1918-2019	74	1
Oberaar	1926-2013	79	1
Oberaletsch	1870-2007	39	1
Oberer Grindelwald	1893-2019	103	1
Palü	1894-2019	84	1
Paneyrosse	1886-2019	95	1
Paradies	1873-2019	108	1
Pizol	1893-2019	103	1
Porchabella	1893-2019	109	1
Punteglias	1895-2019	108	1
Rätzli (Plaine Morte)	1925-2019	69	1
Rhone	1879-2019	137	1

Roseg	1855-2019	112	1
Rossboden	1891-2002	109	1
Saleina	1878-2019	125	1
Sankt Anna	1926-2019	82	1
Sardona	1895-2019	102	1
Schwarz	1924-2015	83	1
Schwarzberg	1880-2019	86	1
Sex Rouge	1898-2019	93	1
Stein	1893-2019	122	1
Sulz	1912-2019	83	1
Tiatscha	1926-2016	78	1
Tiefen	1926-2019	88	1
Trient	1879-2019	137	1
Trift	1861-2019	26	1
Tsanfleuron	1892-2019	118	1
Tsijiore Nouve	1880-2019	125	1
Turtmann	1885-2019	120	1
Unteraar	1876-2013	117	1
Unterer Grindelwald	1879-2019	105	1
Valsorey	1889-2019	119	1
Verstankla	1926-2019	80	1
Vorab	1882-2019	89	1
Wallenbur	1893-2019	110	1
Zinal	1891-2019	123	1
Zmutt	1892-2010	62	1
Alpetli (Kander)	1969-2019	48	2
Ammerten	1970-2019	47	2
Bella Tola	1945-2005	56	2
Boveyre	1963-2019	46	2
Brunegg	1934-2019	71	2
Calderas	1920-2019	70	2
Cambrena	1953-2019	54	2
Cavagnoli	1979-2019	36	2
Chessjen	1945-2019	60	2
Croslina	1989-2019	26	2
Gauli	1958-2019	55	2
Hohlaub	1997-2019	20	2
Lämmern	1960-2019	58	2
Limmern	1945-2019	53	2
Mittelaletsch	1970-1997	19	2
Mont Miné	1956-2019	53	2
Paradisino	1955-2019	47	2
Plattalva	1969-2019	41	2
Ried	1957-2019	56	2
Rotfirn	1956-2017	58	2
Seewjinen	1997-2019	19	2
Sesvenna	1956-2019	58	2
Silvretta	1956-2019	58	2
Steinlimmi	1961-2019	55	2
Suretta	1942-2019	70	2
Tschierva	1934-2019	72	2
Tseudet	1956-2019	56	2
Valleggia	1971-2019	37	2
Albigna	1906-2019	20	3

Breney	1895-2019	69	3
Corbassière	1889-2017	79	3
Corno	1893-2019	43	3
Dungel	1893-2012	51	3
Eiger	1876-2019	93	3
Gelten	1893-2009	19	3
Gietro	1889-2017	66	3
Mont Durand	1890-2019	69	3
Otemma	1889-2016	73	3
Prapio	1898-2019	94	3
Scaletta	1895-2019	36	3
Tschingel	1893-2019	69	3
Val Torta	1970-2011	30	3
Bis	1900-1979	7	4
Martinets	1894-1975	59	4
Ofental	1922-1992	45	4
Orny	1882-1989	21	4
Rosenlaui	1880-1988	41	4
Tälliboden	1922-1992	55	4