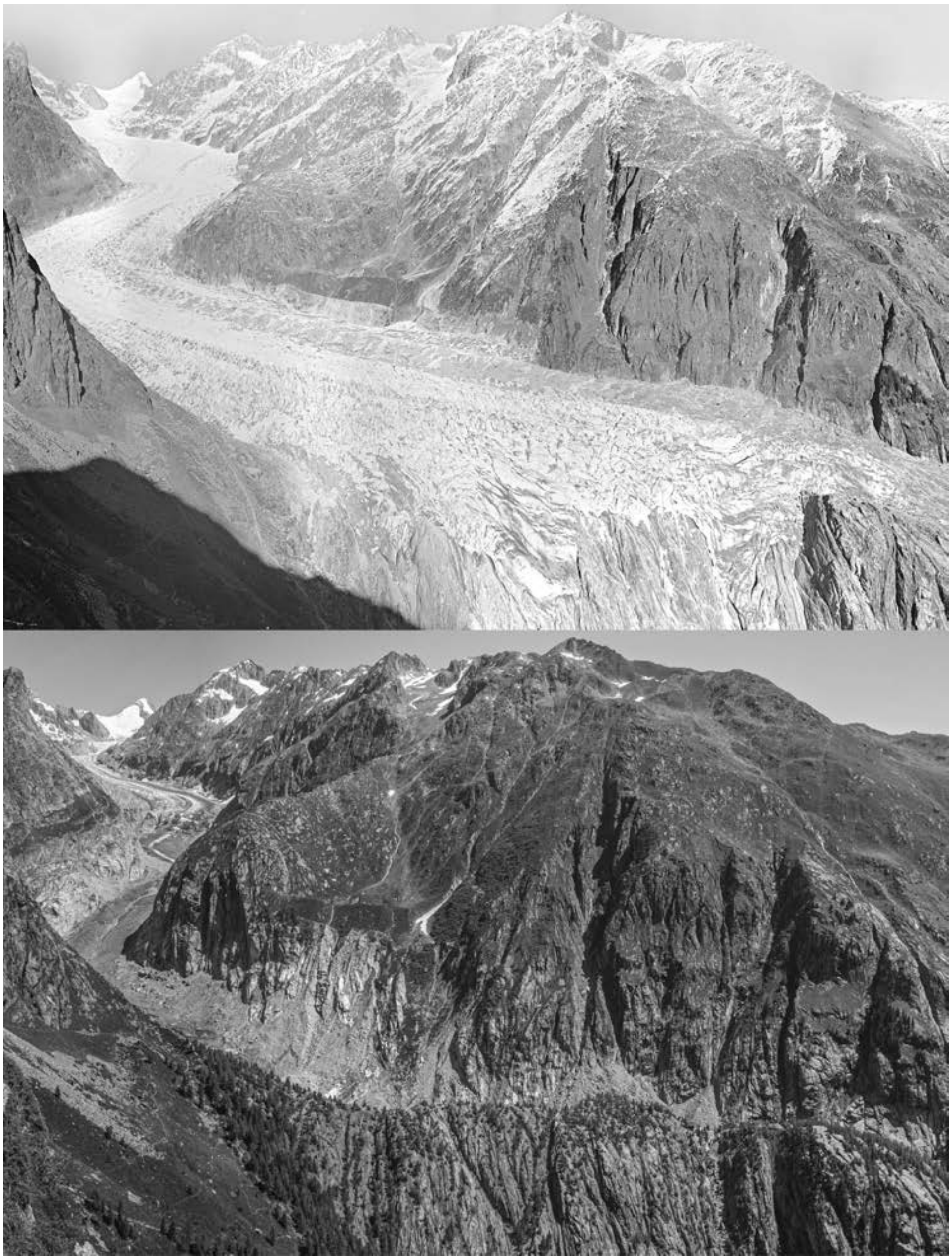
The Swiss Glaciers

2021/22 and 2022/23

Glaciological Report (Glacier) No. 143/144



2024

The Swiss Glaciers

2021/22 and 2022/23

Glaciological Report No. 143/144

Edited by

Andreas Bauder[1,2], Matthias Huss[1,2,3], Andreas Linsbauer[4,3]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich

[2] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)

[3] Department of Geosciences, University of Fribourg

[4] Department of Geography, University of Zurich

GLAMOS Glacier Monitoring Switzerland

2024

Publication of the Swiss Commission for Cryosphere observation (SKK) of the Swiss Academy of Sciences (SCNAT)

c/o Laboratory of Hydraulics, Hydrology and Glaciology (VAW)
at the Swiss Federal Institute of Technology Zurich (ETH Zurich)
Hönggerbergring 26, CH-8093 Zürich, Switzerland
http://www.glamos.ch

DOI: http://doi.org/10.18752/glrep_143-144

ISSN 1424-2222

Imprint of author contributions:

Andreas Bauder	:	Chapt. 1, 2, 3, 4, 5, App. A, B, C
Marcus Gastaldello	:	Chapt. 6
Elias Hodel	:	Chapt. 3, 4, 5, 7, App. A
Matthias Huss	:	Chapt. 1, 2, 4, 7

Citation:
GLAMOS (2024). The Swiss Glaciers 2021/22 and 2022/23. Bauder, A., Huss, M., Linsbauer, A. (eds), Glaciological Report No. 143/144 of the Swiss Commission for Cryosphere observation of the Swiss Academy of Sciences (SCNAT), 155p, doi:10.18752/glrep_143-144.

Printed by:
Staffel Medien AG, CH-8045 Zürich, Switzerland

Cover Page:
Fieschergletscher 27.10.1927 (top, swisstopo) and 19.07.2021 (bottom, VAW/ETHZ)

Summary

Glaciers in the Swiss Alps have seen unprecedented losses of ice in the last years due to record-breaking meteorological forcing. During the 143st and 144nd year under review by the Swiss Commission for Cryosphere observation (SKK), they continued to lose both in length and mass. The two periods were characterized by extremely low winter snow cover and very high summer air temperatures, thus resulting in a highly unfavourable situation for Swiss glaciers. Previous record melt rates from the summer 2003 were shattered in both years, bringing Swiss glacier mass loss to a new level. This led to the disintegration of glacier tongues and the need to abandon several long-term observational series on small glaciers. Monitoring activities were challenged by the extreme conditions, with a substantial additional effort required to maintain the measurement network. Nevertheless, data could be acquired at high standards to document glacier change in these highly unusual years.

For late summer 2022, a change in glacier length was determined for 71 of the 115 glaciers currently under active observation, while for autumn 2023 95 glaciers were measured with both in-situ observations and based on aerial imagery. In the two observation periods, 2021/22 and 2022/23, Swiss glaciers experienced significant losses in length. Several glaciers displayed remarkably high retreat rates in a single year. These can be attributed to the detachment of a mass of dead ice from the glacier snout, or to the melting of sections of the glacier that had been thinning constantly for many years.

Mass balance observations at seasonal to annual resolution were acquired on more than 20 glaciers using direct glaciological measurements, among others, Allalin, Basòdino, Clariden, Findelen, Giétro, Gries, Grosser Aletsch, Pers, Plaine Morte, Rhone, Silvretta and Tsanfleuron. In the first period (2021/22) under consideration in this report, glaciers in all regions of Switzerland showed record-breaking mass loss with thinning rates of partly beyond 4 metres and an estimated total reduction in Swiss glacier volume of 6% in just one year. In the second period under observation (2022/23), again a very dry winter resulted in a thin protective layer for the glacier ice and a hot summer season removed another 4% of the remaining ice volume, in some regions resulting in the second-most negative mass balance since the beginning of the systematic observations.

Measurements of surface ice velocity were performed at eight glaciers throughout the Swiss Alps. The trend continued toward diminishing velocities reflecting the reduction in ice thickness. Englacial temperatures were measured at the high-elevation saddle of Colle Gnifetti indicating massive shifts in firn temperature in the upper layers due to substantial melting occurring at almost 4500 m a.s.l.

Published Reports

Annual reports on measurements on Swiss glaciers started in the year of 1880 by F.A. Forel (1841-1912). While the first two reports appeared in "Echo des Alps", reports 3 to 90 were published in the yearbooks of the Swiss Alpine Club (SAC). Starting from report 91, they appeared as separate publication of the the Swiss Academy of Sciences (SCNAT) and a summary was published in the magazine of the Swiss Alpine Club (SAC).

Authors of the annual reports:	No.	Year
F.A. Forel	1 - 15	1880 - 1894
F.A. Forel et L. Du Pasquier	16 - 17	1895 - 1896
F.A. Forel, M. Lugeon et E. Muret	18 - 27	1897 - 1906
F.A. Forel, E. Muret, P.L. Mercanton et E. Argand	28	1907
F.A. Forel, E. Muret et P.L. Mercanton	29 - 32	1908 - 1911
E. Muret et P.L. Mercanton	33 - 34	1912 - 1913
P.L. Mercanton	35 - 70	1914 - 1949
P.L. Mercanton et A. Renaud	71 - 75	1950 - 1954
A. Renaud	76 - 83	1955 - 1961/62
P. Kasser	84 - 91	1962/63 - 1969/70
P. Kasser und M. Aellen	92	1970/71

Authors and editors of the glaciological two year reports:		
P. Kasser und M. Aellen	93/94	1971/72 - 1972/73
P. Kasser, M. Aellen und H. Siegenthaler	95/96 - 99/100	1973/74 - 1978/79
M. Aellen	101/102	1979/80 - 1980/81
M. Aellen und E. Herren	103/104 - 111/112	1981/82 - 1990/91
E. Herren und M. Hoelzle	113/114	1991/92 - 1992/93
E. Herren, M. Hoelzle and M. Maisch	115/116 - 119/120	1993/94 - 1998/99
E. Herren, A. Bauder, M. Hoelzle and M. Maisch	121/122	1999/00 - 2000/01
E. Herren and A. Bauder	123/124	2001/02 - 2002/03
A. Bauder and R. Rüegg	125/126	2003/04 - 2004/05
A. Bauder and C. Ryser	127/128	2005/06 - 2006/07
A. Bauder, S. Steffen and S. Usselmann	129/130	2007/08 - 2008/09
A. Bauder	131/132 - 137/138	2009/10 - 2016/17
A. Bauder, M. Huss and A. Linsbauer	139/140 - 143/144	2017/18 - 2022/23

Contents

1 Introduction

Systematic and long-term records of glacier changes in Switzerland started in 1880 with annual length change measurements of selected glaciers. At that time, these measurements were motivated by the interest to gain insights into past and future ice ages. In the meantime, the goals of worldwide glacier monitoring have evolved and multiplied. Glacier change data are necessary for investigations of the glacier-climate interaction, but the data are also important for the assessment of water resources, sea-level rise and natural hazards. Finally, the broad public manifests an increasing interest in glacier retreat as an element of the Alpine environment excellently illustrating climate change.

The main focus of the Swiss glacier monitoring network is to collect the following data: (1) length variation, (2) mass balance, (3) volume change, (4) ice surface flow velocity, (5) glacier inventories, (6) englacial temperature, as well as (7) to document special events related to glaciers. The programme for GLAcier MOnitoring in Switzerland (GLAMOS) has been adopted by the Swiss Commission for Cryosphere observation (formerly Cryospheric Commission) in March 2007 and receives long-term funding and support by the Federal Office for Environment (BAFU), MeteoSwiss within the Global Climate Observing System (GCOS) Switzerland, the Swiss Academy of Sciences (SCNAT), and the Federal Office of Topography (swisstopo) since 1.1.2016. A detailed description of the aims, the current status and perspectives of the monitoring programme was presented in Chapter 1.1 of "The Swiss Glaciers" volume 125/126.

As part of GLAMOS ongoing effort to improve the monitoring programme the strategy for the evaluation of length variation has recently revised (GLAMOS, 2020b). An evaluation of the available dataset acquired in past offered crucial deficiencies. In order to ensure optimal data quality and the use of available resources and measurement techniques an adaptation of the monitoring strategy was needed. Details are introduced in the corresponding chapter 3.

The results of Swiss glacier monitoring contribute to the international efforts to document glacier fluctuations worldwide as part of global environmental monitoring initiatives of the Global Terrestrial Network for Glaciers (GTN-G) within the Global Terrestrial and Climate Observing System (GTOS/GCOS). All results are annually reported to the World Glacier Monitoring Service (WGMS).

This report is the new volume No. 143/144 in the series "The Swiss Glaciers" and presents the results of the two observational periods 2021/22 and 2022/23. It carries on the long tradition of yearbooks documenting monitored fluctuations of Swiss glaciers since 1880 (see page iv). Data and digital versions of the present and earlier volumes are available at www.glamos.ch.

Thanks to the continuous efforts of many people, public and private organisations in Switzerland, long time-series of data related to glacier changes have been acquired and are highly valuable for scientific research, applied questions and outreach.

2 Weather and Climate

In this section the weather and climate conditions for the two periods 2021/22 and 2022/23 are described. We focus on the variables that are most relevant for glacier mass balance – temperature and precipitation. In general, glacier mass balance is largely determined by the amount of winter snow fall and air temperature during summer. High temperatures in April, May or June can reduce the winter snow pack rapidly and expose the much darker ice surface already in July. During July and August solar radiation receipts are high and melting of the unprotected ice is enhanced. When these two factors are combined, very negative mass balances as during the heat waves of summer 2003, 2022 and 2023 are expected. On the other hand, summer snow down to the glacier termini protects the ice surface from melting and will lead to less negative mass balances.

We have selected the four high-elevation meteorological stations at Grand St-Bernard (2472 m a.s.l.), Jungfraujoch (3580 m a.s.l.), Säntis (2502 m a.s.l.) and Weissfluhjoch (2690 m a.s.l.) to illustrate the monthly anomalies in air temperature (Figure 2.1), and 14 stations (Airolo, Chateau-d'Oex, Disentis, Engelberg, Elm, Grand St-Bernard, Grimsel Hospiz, Montana, Lauterbrunnen, Säntis, Scuol, Sils-Maria, Weissfluhjoch, Zermatt) throughout all regions of the Swiss Alps to document monthly anomalies in precipitation (Figure 2.2) for the two reporting periods. For annual precipitation and mean summer temperature (May-September), the long-term record since 1880 is shown in Figures 2.3 and 2.4 as a mean of 12 homogenized stations (Begert and Frei, 2018). The description of the weather conditions in the two reporting periods refer to the annual and monthly reports of the meteorological conditions by MeteoSwiss. Data are provided by the observational networks maintained by MeteoSwiss.

2.1 Weather and Climate in 2021/22

Glaciers in the Swiss Alps started to be partly snow-covered from early October 2021 onwards and a relevant snow layer was observed in late November at the latest depending on the region. Frequent snowfalls in December then contributed to average or somewhat below-average snow depths on glaciers until early March in the North and West of Switzerland, while the snow deficit at high elevation was more pronounced in the South. At the same time there was very little snow in the Swiss Plateau, and at the two MeteoSwiss stations in Basel and Lucerne it was only the second time that no snow was observed at all. Due to almost absent precipitation in March 2022 and only few snowfall events in April, snow depth on glaciers was significantly lower than normal at the beginning of the melting season.

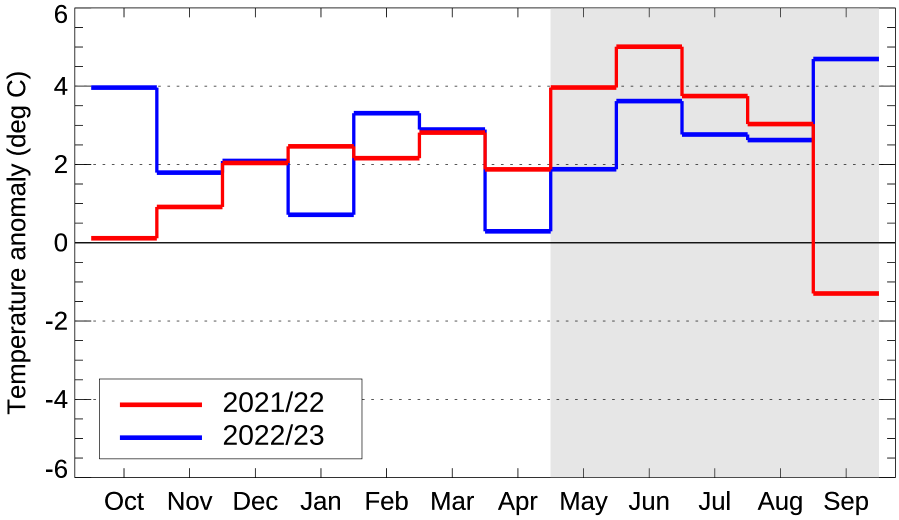


Figure 2.1: Mean monthly anomaly of temperature from the long-term climatic mean (period 1961-1990) for four selected stations at high elevation of the MeteoSwiss network. Anomalies in the two reporting periods 2021/22 and 2022/23 are shown. The grey shaded area indicates the months that are relevant for glacier melting.

Due to strongly above-average air temperatures in May and June, the snowpack disappeared at all altitudes about one month earlier than normal. The more than 80-year-old series of snow measurements at Weissfluhjoch (2540 m a.s.l.) showed the second earliest snow depletion date (6 June), just three days later than in the year 1947. In addition, several strong Saharan dust events occurred between March and May 2022, leading a substantial darkening of the snow surface and, hence, accelerated the melting of the snowpack. The summer months were record-breaking hot and sunny. For example, at the MeteoSwiss station Jungfraujoch (3571 m a.s.l.), the daily minimum temperature did not drop below 0°C on 41% of all days between June and August. But the summer was also extremely dry. Until mid-September, there was only a few centimetres of fresh snow even beyond an elevation of 3000 m a.s.l., which only lasted for one or two days.

Although snow depletion was already advanced also at the high elevations of the Alps in June, some snowfall events delayed the final disappearance of the snow cover. The months of July to September were once again characterized by above-average temperatures but average precipitation totals (Figure 2.1, Figure 2.2). In contrast to the last years, however, two events with fresh snow down to 2000 m a.s.l. occurred in August. At the end of September, there was snow to partly below 1000 m a.s.l. on the northern side of the Alps, which is exceptional for this time of year, and abruptly ended the ablation season for most glaciers.

Compared to the reference period 1961-1990, summer air temperatures (May-September) were 3.3°C higher than the long-term mean evaluated for homogenized measurement series throughout Switzerland, resulting in the second-highest value since 1864 after the summer 2003. Precipitation amounts were below the average both in the winter (October to April, -23%), and throughout the summer season (May to September, -12%, Figure 2.4). In summary, the weather conditions during the period 2021/22 resulted in maximally unfavourable conditions for the glaciers both at the end of winter with a very early snowcover depletion and especially during the summer season with persistently hot and sunny weather.

2.2 Weather and Climate in 2022/23

The winter of 2022/23 was characterized by very low precipitation and excessively high temperatures on both sides of the Alps. This caused severely below-average snow depths at both high and low elevation. While glaciers were partly snow-covered already from late September onwards, persistent warm and dry conditions delayed the build-up of a consistent snowpack on the glacier ice until early December 2022 but precipitation amounts remained limited also until the end of January with the exception of the very West of Switzerland. Above 1000 m a.s.l., the conditions in February and early March stand out: In the first half of February, the snow depths at measurement stations were still somewhat higher than in the dry winters of 1964, 1990 or 2007. In the second half of February, on the other hand, the relative snow depth dropped to a new record minimum at most stations. Also the more than 80-year-old snow monitoring series of Weissfluhjoch (2540 m a.s.l.) showed record-low snow depths of only about 1 m compared to the usual 2 m at the beginning of March, even though there have also been winters with less precipitation in the past (e.g. 1964). Now, however, the higher temperatures caused by climate change mean that, firstly, some of the precipitation falls as rain instead of snow, and secondly, some of the snow melts away again.

Major snowfalls followed only between mid-March and May, so that snow depths on glaciers ap-

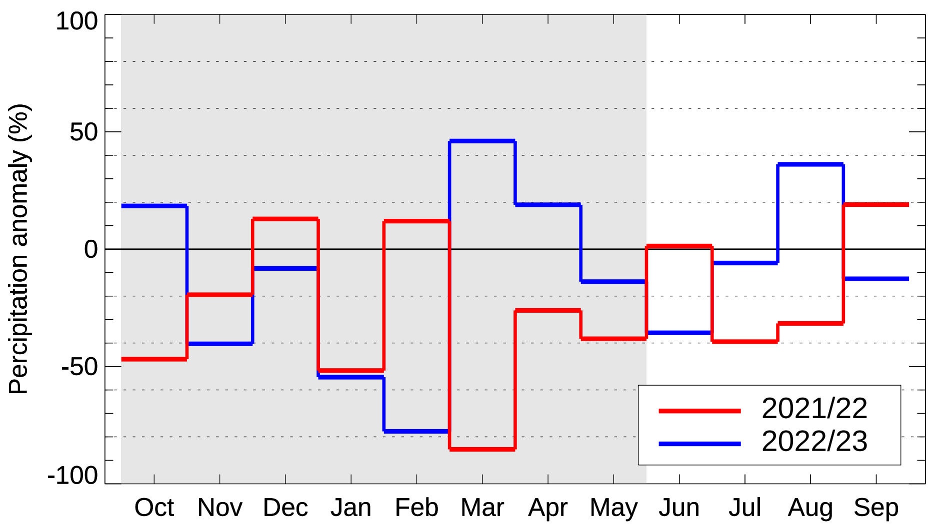


Figure 2.2: Mean monthly anomaly of precipitation from the long-term climatic mean (period 1961-1990) for 14 selected stations of the MeteoSwiss network. Anomalies in the two reporting periods 2021/22 and 2022/23 are shown. The grey shaded area indicates the months that are relevant for winter snow accumulation.

proached the average in the second half of May for glaciers in the North and West of Switzerland, while staying significantly below normal conditions in the South and East. Due to the dry and very warm June, the snow at elevations of around 2000 m a.s.l. disappeared 2-4 weeks earlier than normal. The third warmest summer since measurements began and a record-high zero degree line of partly almost 5200 m a.s.l. in late August and early September were responsible for the fact that summer snowfall events were restricted to the highest regions, and melted away quickly. Furthermore, melting during heat waves extended to the very highest summits of the Swiss Alps. During the summer months, only 25 cm instead of the usual 66 cm of fresh snow accumulated at the snow measurement station of Weissfluchjoch. However, this is still more than in the summer of 2022, when no snow fell at all before mid-September.
Summer air temperatures (May to September) were again 3.3°C higher than the 1961-1990 mean, and thus rank second after 2003 and and reached the same value as in the previous summer 2022 (Figure 2.3). Over the entire hydrological year from October 2022 to September 2023, even the highest air temperature since the beginning of the measurements in 1864 was recorded. Precipitation (Figure 2.4) was below the long-term average both during the winter from October to April (-5%) and during the summer season (May to September -9%, Figure 2.2). The massive deficit in snow precipitation until mid-March in almost all regions of Switzerland led to a very precarious situation on Swiss glaciers at the end of winter, even though additional snowfalls in April and May were able to somewhat relax the pressure. The summer season, however, again was far too warm and only interrupted with a few snowfall events resulting in a second year with extreme glacier mass loss.

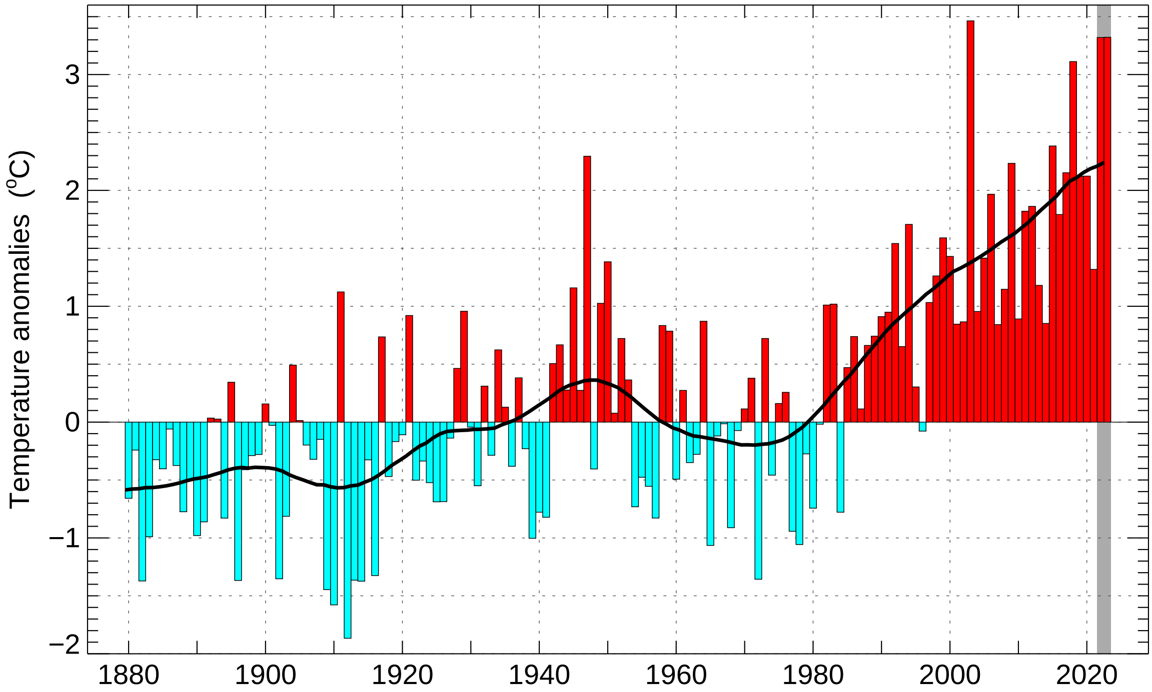


Figure 2.3: Anomalies of mean summer air temperature (May-September) from the mean value 1961-1990 in degrees Celsius for the period 1864-2023 based on 12 homogenized long-term stations of MeteoSwiss. The gray-shaded area highlights the years of the current report.

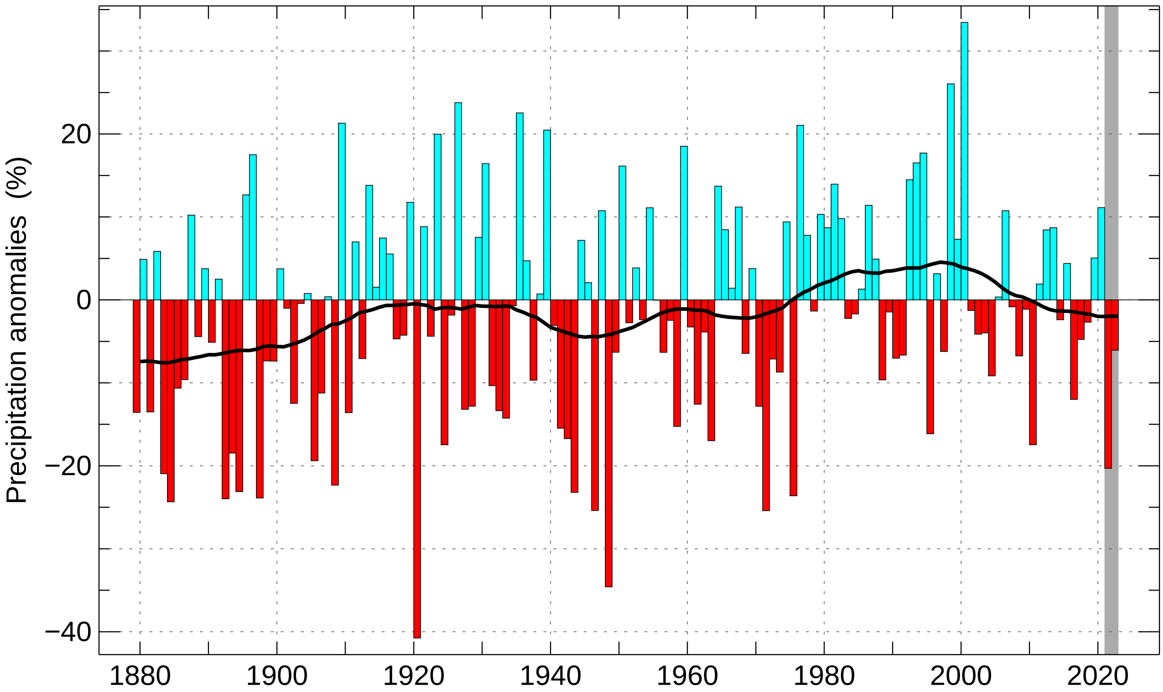


Figure 2.4: Anomalies of annual precipitation (hydrological year) from the mean value 1961-1990 in percentage for the period 1864-2023 based on 12 homogenized long-term stations of MeteoSwiss. The gray-shaded area highlights the years of the current report.

Glaciers investigated for length variations that experienced a large retreat during the periods of the report: Glacier de Moiry in September 2022 (top, Photo: F. Fellay, DN/VS) and Glacier du Brenay in August 2022 (bottom, Photo: C. Chabloz)

3 Length Variation

3.1 Introduction

Systematic observations of length variations started in 1880. Due to ongoing and coordinated efforts long and continuous time-series documenting glacier length variations for a large number of glaciers have been collected. Since the beginning the annual surveys have been carried out by a collaborative network of people on different types of glaciers covering all regions of the Swiss Alps. Measurements based on simple techniques carried out by collaborators without any special training and measurement equipment available turned out to be a key factor for the success of the extensive monitoring.

An evaluation of the existing dataset of length variations identified two major deficiencies: (1) Only the change in length has been evaluated and reported so far but the location of the underlying measurement is often not precisely known. (2) The summation of incremental differences, hence may show large systematic errors and biases when compared to actual distances of dated glacier extent as derived from aerial imagery or features in the terrain. In addition, several of the long-term series are affected by data gaps of some years up to several decades. The strategy has been revised recently with the aim of: (1) continuation of existing long-term series, (2) a consistent and reproducible evaluation methodology, (3) improved data quality of only geo-localized measurements. The goals are accompanied by the requirement of the optimal use of available resources and integration of new measurement techniques. A considerable potential for higher data quality is attributed to the products of the Federal Office of Topography swisstopo due to more frequent periodical aerial surveys and operational photogrammetrical processing. A conceptual change of the observation principle with a reduction from annual to multi-annual observations is expected to make data acquisition more efficient, while providing geo-localized data with high quality and reduced costs (GLAMOS, 2020b). The major update to the previous concept is a multi-level data acquisition with a combination of four different observation types:

(1) FIELD: Annual field observations, periodically complemented with glacier outlines ensure continuity and high accuracy

(2) AIR: High spatial coverage at annual resolution with accurate and homogeneous data

(3) MIX: Combination of bi-annual field measurements and outlines from the swisstopo's operational products, large coverage, homogeneous data and still high temporal resolution

(4) TLM: Homogeneous data with strongly reduced effort and costs at 3-year intervals

Based on the various needs and requirements such as the quality of existing time series, well-balanced distribution over all regions and glacier types (size or shape), expected further evolution and accessibility, and also individual needs of local collaborators, the 121 glaciers with available length variation time-series and recent observations have been assigned to the four new observation types. This resulted in a selection of 43 glaciers (35%) to be continued with annual field observations (FIELD). 19 (16%) glaciers were selected for the AIR observation type, while another 22 (18%) glaciers were allocated to the MIX observation type. The 37 (31%) remaining glaciers eventually are evaluated based on the operational swisstopo SWISSIMAGE and TLM products (3-year intervals). The modifications in the observation strategy have been implemented gradually starting in 2020.

In the two periods covered by this report, 102 of 157 glaciers with documented length fluctuations have been actively observed (Figures 3.1, 3.2 and Table 3.1). The other glaciers have melted back drastically or are heavily debris-covered, with the result of only being observed at irregular intervals. As a result of the modified observation strategy, evaluated length change information for glaciers observed periodically based on the operational swisstopo products will be appended to the database also after the corresponding reporting period.

During the two years under review, 2021/22 and 2022/23, Swiss glaciers suffered further losses in length. As in previous periods, most of the measurements were within the range of 0 to −30 metres. This overall trend was once again overshadowed in both years by a few very high retreat values, which could be traced to local influences, and in some cases also pertain to a period of several years. They are usually the result of a process extending over a longer period of time and thus are not unexpected.

3.2 Length Variations in 2021/22

After a summer with warm weather conditions resulting in intense melt, optimal measurement conditions were present for the survey in autumn 2022. Changes in the terminus position as compared to the previous years were determined at 71 glaciers (Figure 3.1). Of these, 68 were found to be in recession, for one no change was observed, and two glaciers showed a positive value. With the exception of eight glaciers, the values ranged from a retreat of −54 meters at Glatscher da Lavaz to a slight advance of both about +4 meters at Bisgletscher and Sulzgletscher, respectively. Nearly three quarters of the measurements lay between −1 and −30 meters.

The eight exceptions refer to the larger recession observed at the snout and cover also some multi-year periods. The large retreat values are a result of the evolution of the glaciers over the last decade and were therefore expected. Due to the continued absence of ice flow from the accumulation area or the increasingly thick debris cover, the tongues of these glaciers were thinned out or were melting irregularly without any major reduction in length over the previous years. Eventually, in one summer a large section splits apart or melts completely and the dynamic terminus shifts back abruptly.

The positive value at Sulzgletscher is the result of local changes at the terminus and do not stem from abundant ice flow from the accumulation area. Due to a thick and continuous debris coverage the glacier experiences hardly no melt at the surface. The steep and incised ice cliff at the portal migrated also lateraly. The combination of these effects resulted in a positive change of the position of the snout. Under such conditions the ice margin is difficult to detect and may further cause erroneous interpretations. However, the cumulative length change is not affected by such uncertain individual results as they will cancel out in successive measurements. On the steep and still dynamicaly active tongue of Bisgletscher the ice flow movement compensated for the ice melt at the snout.

3.3 Length Variations in 2022/23

In autumn 2023 results for length variations are available for 95 glaciers (Figure 3.2). Of these, 92 became shorter, one did not change the position, and another one slightly increased in length. With the exception of ten glaciers, the values ranged from a recession of −53 meters at Glatscher dil Vorab to an advance of +2 meters at Ammertengletscher. Almost two thirds of the measurement values lay between −1 and −30 meters. The survey at the glacier terminus benefited from optimal measurement conditions as a result of intensive melting during the summer and the widespread observations of retreat values are expected.

Paradiesgletscher and Vadret Calderas were the exceptions featuring a very large reduction in length. As in the previous period, the high retreat values of several hundred meters for each is linked to a process that has been underway for many years. The tongue of the two glaciers successively thinned out over last years due to high melt rates and the absence of ice supply from the accumulation area. Eventually a larger part lost connection at a steep section of Calderas or the remaining thin flat surface disintegrated along an ice-divide and the dynamic terminus shifted back abruptly.

3.4 Length Variations in 2021/22 and in 2022/23, Summary

No. [a]	Glacier	Ct. [b]	Length variation [c] (m) 2021/22	2022/23	Altitude [d] (m a.s.l.) 2023	Date of measurements (Day, Month) 2021	2022	2023
Catchment area of the river Rhone (II)								
1 [e,f]	Rhone	VS	−44.8	−95.5	2210.9 [16]	20.08.	16.07.	20.08.
2 [f]	Mutt	VS	n	−40.4 [2a]	2696.5 [21]	28.08.	n	05.09.
3 [e,f]	Gries	VS	−70.7	−26.8	2430.4 [16]	24.09.	12.09.	20.08.
4 [f]	Fiescher	VS	n	−102.7 [3a]	1682 [15]	n	n	06.09.
5 [e,f]	Grosser Aletsch	VS	−17.1	−36.5	1602.0 [16]	29.07.	13.07.	10.08.
106	Mittelaletsch	VS	n	−69.2 [3a]	2365	n	n	06.09.
6 [f]	Oberaletsch	VS	n	−28.6 [3a]	2150	n	n	06.09.
7 [e,f]	Kaltwasser	VS	−28.8	−14.4	2660 [12]	14.09.	09.09.	24.08.
173 [e]	Seewjinen	VS	n	−25.7 [3a]	2735.5 [16]	n	n	07.09.
10 [e,f]	Schwarzberg	VS	n	−96.1 [3a]	2663.2 [16]	n	n	07.09.
11 [e,f]	Allalin	VS	−35.6 [2a]	−8.7	2676.7 [16]	n	06.09.	06.09.
174 [e]	Hohlaub	VS	n	−26.0 [3a]	2841.0 [16]	n	n	06.09.
12 [e]	Chessjen	VS	n	−120 [3a]	2920	n	n	06.09.
13 [f]	Fee	VS	n	−475 [3a]	2300	n	n	06.09.
14 [e,f]	Gorner	VS	−33.1	−29.8	2211 [15]	14.08.	15.07.	23.08.
15 [f]	Zmutt	VS	n	−104.1 [3a]	2250	n	n	07.09.
16 [e,f]	Findelen	VS	−49.7	−75.9	2555.8 [16]	14.08.	15.07.	21.08.
107	Bis	VS	+4.4	−13.9	2440	14.08.	15.07.	23.08.
17	Ried	VS	−6.0	−38.6	2400 [20]	14.08.	15.07.	06.09.
18 [e,f]	Lang	VS	n	−67.4 [2a]	2045 [17]	03.09.	n	11.09.
19 [e,f]	Turtmann	VS	x	n	2625	08.09.	28.07.	n
20 [e]	Brunegg (Turtmann)	VS	n	−85.3 [2a]	2710	08.09.	n	06.09.
22 [f]	Zinal	VS	n	−51 [3a]	2085	n	n	01.09.
23 [f]	Moming	VS	n	−66.4 [3a]	2580 [13]	n	n	06.09.
24 [f]	Moiry	VS	−550	−14.5	2505	01.09.	01.09.	24.08.
25 [f]	Ferpècle	VS	−34.1	−13.3	2324	01.10.	05.10.	26.09.
26	Mont Miné	VS	n	−31.9 [3a]	2090 [12]	n	n	07.09.
27 [e,f]	Arolla (Mont Collon)	VS	−635	−24.6	2520	17.09.	12.10.	19.09.
28 [e,f]	Tsidjiore Nouve	VS	−10.1	−24.2	2304	17.09.	13.09.	19.09.
29 [f]	Cheillon	VS	−16.1	−32.9	2685	23.09.	09.09.	29.09.
30 [f]	En Darrey	VS	n	−32.7 [3a]	2702	n	n	29.09.
31 [f]	Grand Désert	VS	−25.6	−10.5	2810 [17]	16.09.	01.09.	23.08.
32 [f]	Mont Fort (Tortin)	VS	−71.5	−28.8	2785 [18]	27.08.	22.09.	23.08.
33 [e,f]	Tsanfleuron	VS	−46.7	−26.8	2510	14.09.	04.09.	25.09.
34	Otemma	VS	x	−141.2 [3a]	2480 [18]	n	23.08.	07.09.

No. [a]	Glacier	Ct. [b]	Length variation [c] (m) 2021/22	2022/23	Altitude [d] (m a.s.l.) 2023	Date of measurements (Day, Month) 2021	2022	2023
35	Mont Durand	VS	x	−61.5 [3a]	2380 [19]	n	23.08.	07.09.
36	Breney	VS	x	−134.4 [3a]	2575 [19]	n	23.08.	07.09.
37	Giétro	VS	n	−117.9 [3a]	2718.6 [16]	n	n	07.09.
38	Corbassière	VS	n	−134 [3a]	2309.5 [16]	n	n	07.09.
39 [f]	Valsorey	VS	−32	−28.1	2466	30.09.	07.10.	06.09.
40 [e]	Tseudet	VS	−7.3	−6.7	2622	30.09.	07.10.	06.09.
41 [e]	Boveyre	VS	n	−33.4 [3a]	2692	n	n	06.09.
42 [f]	Saleina	VS	−26.6	−21.1	1875.7	24.09.	23.09.	06.09.
108	Orny	VS	n	−34.7 [2a]	2660	16.07.	n	07.09.
43 [e,f]	Trient	VS	−61	−20	2205	25.09.	02.10.	01.10.
44 [e,f]	Paneyrosse	VD	−12.8	−6.3	2420	20.10.	05.10.	15.08.
45 [f]	Grand Plan Névé	VD	−6.1	−4.9	2416	20.10.	18.10.	29.09.
47 [f]	Sex Rouge	VD	n	−8 [3a]	2747 [20]	n	n	10.08.
48	Prapio	VD	n	−138 [3a]	2555 [19]	n	n	10.08.
Catchment area of the river Aare (Ia)								
50 [f]	Oberaar	BE	−20.8	−7.2	2345 [21]	23.09.	23.08.	23.08.
51 [f]	Unteraar	BE	−35.1	−15.6	1970 [21]	26.08.	23.08.	20.08.
52	Gauli	BE	n	n	2140 [21]	25.09.	n	n
53 [e,f]	Stein	BE	−23	−23	2120	05.09.	28.08.	03.09.
54	Steinlimi	BE	n	n	2530 [19]	12.08.	n	n
55 [e,f]	Trift (Gadmen)	BE	−0.1	−7.5	2111.5 [16]	20.08.	16.07.	20.08.
57 [e,f]	Oberer Grindelwald	BE	−3.3	−11.3	2178.6 [16]	20.08.	13.07.	20.08.
58 [e,f]	Unterer Grindelwald	BE	−11.1	−52.6	1587.1 [16]	20.08.	13.07.	20.08.
59 [e]	Eiger	BE	n	n	2413.3 [20]	23.09.	n	n
60 [e]	Tschingel	BE	n	−54.3 [2a]	2310	31.08.	n	06.09.
61 [e,f]	Gamchi	BE	−8.5	−9	2135	14.10.	03.10.	13.09.
109 [e]	Alpetli (Kanderfirn)	BE	−26.8	−26.5	2410	01.10.	20.09.	28.09.
63 [e]	Lämmern	VS	n	−66 [2a]	2820	01.10.	n	26.09.
64 [e,f]	Blüemlisalp	BE	n	n	2394 [18]	23.09.	n	n
65 [e,f]	Rätzli	BE	−35.2	−2.7	2467.6 [16]	21.08.	12.09.	20.08.
111 [e]	Ammerten	BE	−2.2	2.4	2360	12.09.	22.09.	01.10.
112	Dungel	BE	n	n	2620 [21]	30.09.	n	n
113	Gelten	BE	n	n	2595 [21]	30.09.	n	n
Catchment area of the river Reuss (Ib)								
66 [e,f]	Tiefen	UR	−16.5	−37.5	2670	02.09.	23.09.	08.09.
67 [e,f]	Sankt Anna	UR	−22	−5	2635	24.09.	21.09.	26.09.
68 [e,f]	Kehlen	UR	−22.8	−5.7	2400	25.08.	04.10.	05.10.

No. [a]	Glacier	Ct. [b]	Length variation [c] (m) 2021/22	2022/23	Altitude [d] (m a.s.l.) 2023	Date of measurements (Day, Month) 2021	2022	2023
69	Rotfirn (Nord)	UR	x	n	2070 [17]	12.08.	04.10.	n
70 [e,f]	Damma	UR	x	−159.3 [2a]	2500	25.08.	04.10.	05.10.
71 [e,f]	Wallenbur	UR	−300	−39	2320	19.10.	05.10.	11.10.
72 [e,f]	Brunni	UR	−17.0	−9.7	2570	24.09.	22.09.	28.09.
73 [f]	Hüfi	UR	n	n	1920 [21]	01.10.	n	n
74 [e,f]	Griess	UR	n	−31.3 [2a]	2232	01.10.	n	21.09.
75 [f]	Firnalpeli (Ost)	OW	n	n	2210 [19]	01.10.	n	n
76 [f]	Griessen	OW	−34.8 [3a]	−5.5	2530 [19]	n	29.08.	03.09.
Catchment area of the river Linth / Limmat (Ic)								
77 [e,f]	Biferten	GL	−6.9	n	1964.3 [22]	25.09.	30.10.	n
78 [e]	Limmern	GL	−11.5 [2a]	n	2290 [22]	n	06.10.	n
114 [e]	Plattalva	GL	−31.9 [2a]	n	2635 [22]	n	07.10.	n
79 [f]	Sulz	GL	+3.9	−7.4	1810 [19]	30.09.	06.10.	25.09.
80 [f]	Glärnisch	GL	−20.9	n	2368.1 [22]	30.09.	27.10.	n
81 [e,f]	Pizol	SG	−8.1	−5.2	2600	11.10.	06.10.	09.10.
Catchment area of the river Rhine / Lake Constance (Id)								
82 [e,f]	Lavaz	GR	−54.3	−48.7	2448	31.08.	29.08.	10.10.
83 [e,f]	Punteglias	GR	−950 [4a]	−3.5	2655	n	23.09.	11.09.
84 [e,f]	Lenta	GR	x	−70 [5a]	2740	n	12.09.	05.10.
85 [e,f]	Vorab	GR	−37.1	−53.3	2624	25.08.	26.08.	12.09.
86 [e,f]	Paradies	GR	x	−550	2793	10.09.	16.09.	20.09.
87	Suretta	GR	−21.1	−17.7	2595	14.09.	09.09.	27.09.
88 [e,f]	Porchabella	GR	−41.8	−26.2	2703	10.09.	07.09.	08.09.
115 [e]	Scaletta	GR	−11.4 [2a]	n	2721 [20]	n	18.07.	n
89 [e,f]	Verstankla	GR	−44.3	−97.7 [2a]	2438	22.09.	12.09.	20.09.
90 [e]	Silvretta	GR	−30.7	−12.3	2471.8 [16]	01.09.	12.09.	24.08.
91 [e,f]	Sardona	SG	−11.2	−31.4	2490	03.10.	20.09.	02.10.
Catchment area of the river Inn (V)								
92 [f]	Roseg	GR	−12.3 [3a]	n	2595 [22]	n	08.07.	n
93 [e]	Tschierva	GR	−50.5 [2a]	−31.4	2324	n	07.10.	12.09.
94 [f]	Morteratsch	GR	−22.6	−37.4	2142 [22]	16.09.	23.08.	03.10.
95 [e]	Calderas	GR	−19.9	−270	2880	27.08.	31.08.	18.10.
96 [e,f]	Tiatscha	GR	−15.6	−5.7	2671.5 [17]	01.09.	12.09.	24.08.
97 [e]	Sesvenna	GR	−10.8	−8.7	2817	24.08.	25.08.	01.09.
98 [e,f]	Lischana	GR	x	n	2819 [22]	01.09.	24.08.	n

No. [a]	Glacier	Ct. [b]	Length variation [c] (m) 2021/22	2022/23	Altitude [d] (m a.s.l.) 2023	Date of measurements (Day, Month) 2021	2022	2023
Catchment area of the river Adda (IV)								
99 [e]	Cambrena	GR	−49.0	−22.4	2690	01.10.	29.08.	06.09.
100 [e,f]	Palü	GR	−42.9	−33.8	2595	18.08.	13.10.	09.10.
101 [e]	Paradisino (Campo)	GR	−15.6	−8.3	2848	22.09.	20.09.	24.08.
102 [e,f]	Forno	GR	−33.2	−49.6	2228	07.09.	19.09.	07.09.
116 [e]	Albigna	GR	−20.6	−22.9	2188	09.09.	06.09.	05.09.
Catchment area of the river Ticino (III)								
103 [e,f]	Bresciana	TI	−18.5	−23.2	2998	03.09.	31.08.	27.09.
352 [e]	Croslina	TI	−15 [3a]	n	2779 [22]	n	09.09.	n
118	Val Torta	TI	n	n	2500 [21]	24.09.	n	n
117 [e]	Valleggia	TI	−29.3	−28.9	2428	08.09.	26.08.	12.09.
119 [e]	Cavagnoli	TI	−295	n	2763 [22]	13.09.	26.08.	n
104 [e,f]	Basòdino	TI	−29.3	−14.8	2685	07.09.	25.08.	05.09.
120 [e]	Corno	TI	−15.8	−7.4	2667	13.09.	22.09.	11.09.
105 [f]	Rossboden	VS	n	−0.3 [3a]	2705	n	n	20.08.

Legend

+	advancing	x	value not determined
st	stationary, ±1 m	n	not observed
−	retreating	sn	snow covered

a Identification number of the glacier in the observational network (see Figures 3.1 and 3.2).

b If a specific glacier is situated in more than one canton, the canton indicated in the table is the one where the observed glacier tongue lies.

c If the value given relates to more than one year, the number of years is indicated as follows: −40 [2a] = Decrease of 40 meters within 2 years.

d If the altitude of the glacier tongue is not measured in 2023, the year of the last measurement is indicated: 2210.9 [16] = 2210.9 m a.s.l., measured in the year 2016.

e Compare Appendix B: Remarks on individual glaciers.

f Glacier with nearly complete data series since the beginning of the measurements at the end of the 19^{th} century and one of the 73 glaciers selected in Figure 3.4.

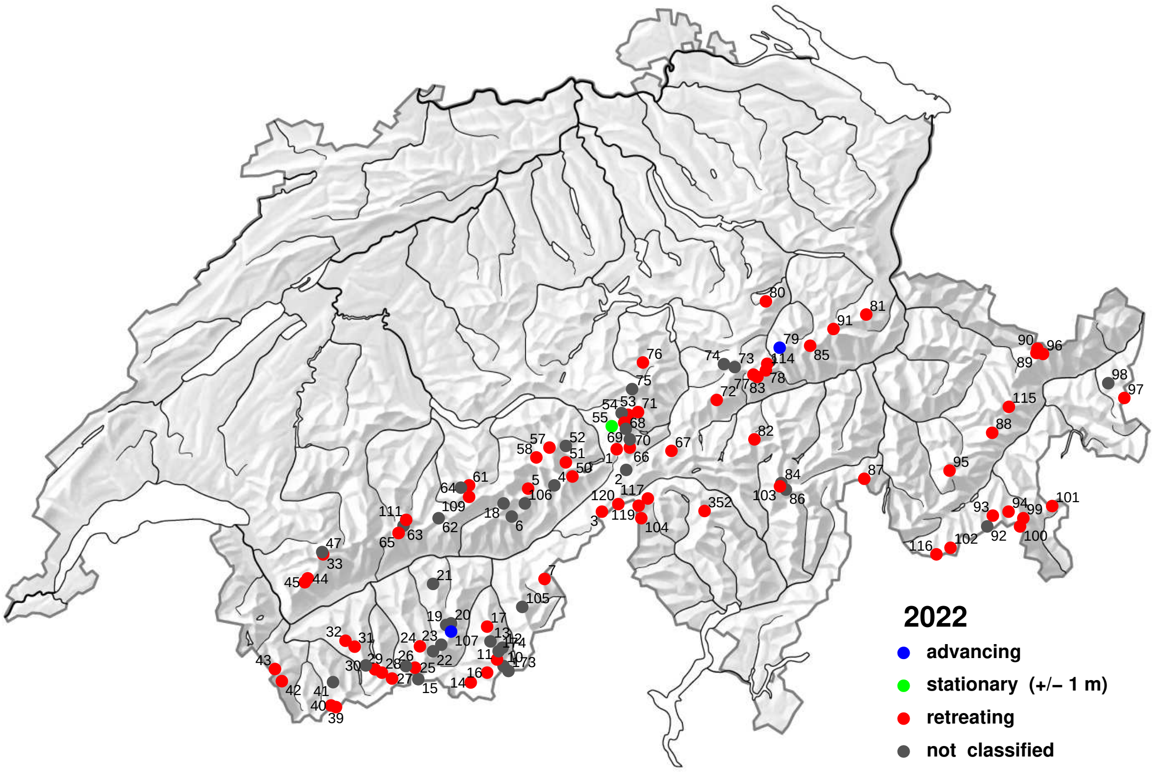


Figure 3.1: Investigated glaciers for length variations in fall 2022.

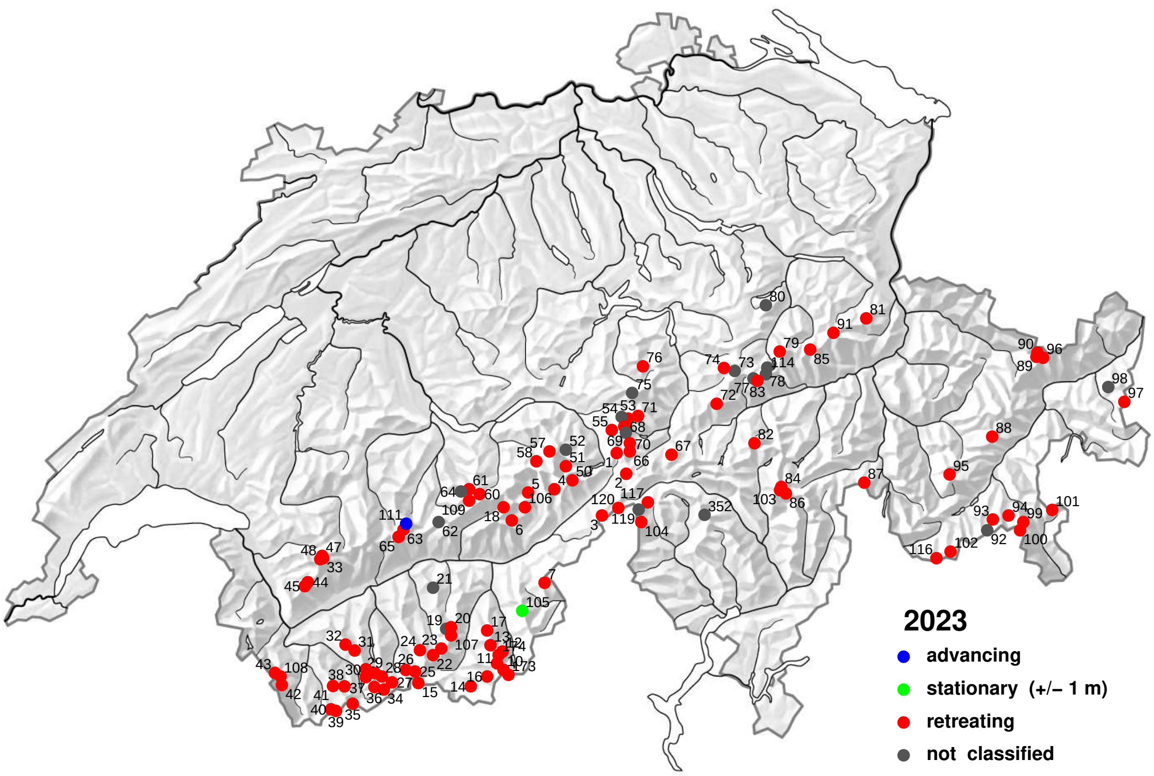


Figure 3.2: Investigated glaciers in fall 2023.

3.5 Length Variations - Statistics for 1880-2023

The long-term development of glaciers in Switzerland is illustrated by using a selected sample of 73 glaciers (Figures 3.3 and 3.4), and the cumulative glacier length variations which have been classified according to length (Figures 3.5 - 3.8).
The dynamic response to climatic forcing of glaciers with variable geometry involves striking differences in the recorded cumulative length changes (Figures 3.4 and 3.5 - 3.8) (Hoelzle et al., 2003). Such differences reflect the considerable effects of size and slope-dependent reaction of the delayed response of the glacier terminus with respect to the undelayed input (mass balance) signal (Zekollari et al., 2020).
In order to avoid a glacier sample whose scope changes annually, not all glaciers were considered for the analysis of the long-term evolution. Only continuous and long series are included. From the entire dataset, 73 glaciers were selected as a sample with nearly complete series since the beginning of the measurements at the end of the 19th century. In Chapter 3.4, these 73 glaciers are indicated by a footnote f. Figure 3.3 presents absolute numbers of yearly measurements available in the database, as well as for the selected glaciers. While in 2022 for 67 glaciers out of the reference sample a length variation was determined, in the following year only 65 glaciers were measured. In both years 64 of the reference glaciers were retreating, only in 2022 one glacier was advancing and two and one glaciers showed no change, respectively.

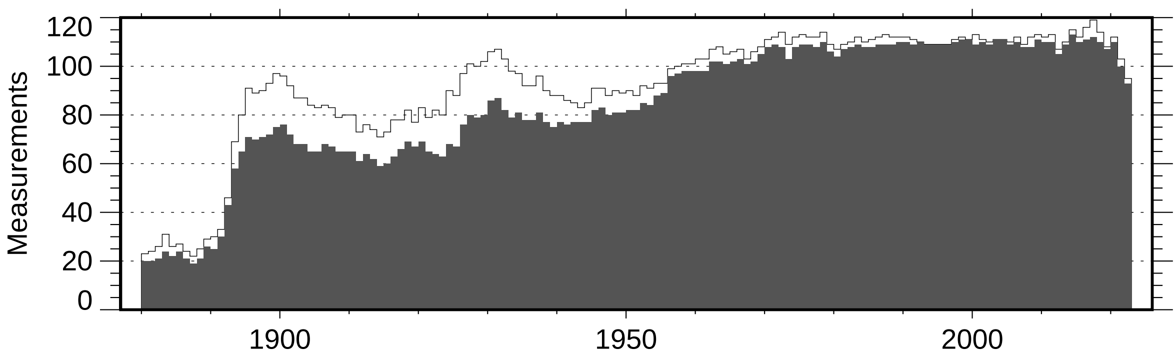


Figure 3.3: Annual number observed length variations in total (line) and number out of the set of the 73 reference glaciers (grey area) classified in the data base.

The sample is dominated by medium-sized glaciers (length between 1 to 5 km) with a typical response time in the order of decades. The periods of advance, such as those in the 1910s to 1920s and the 1970s to 1980s, can be seen clearly. Figure 3.4 shows the annual and individual length change of all 73 selected glaciers sorted according to length. For the purpose of intercomparison, values of cumulative length change are presented with respect to size categories chosen in a way to optimally reflect common characteristics of the response signal at the glacier terminus. It is well recognized that large glaciers, such as Grosser Aletschgletscher, show continuous retreat since 1880, in contrast to the smaller glaciers, such as Pizolgletscher, that have highly variable behavior.

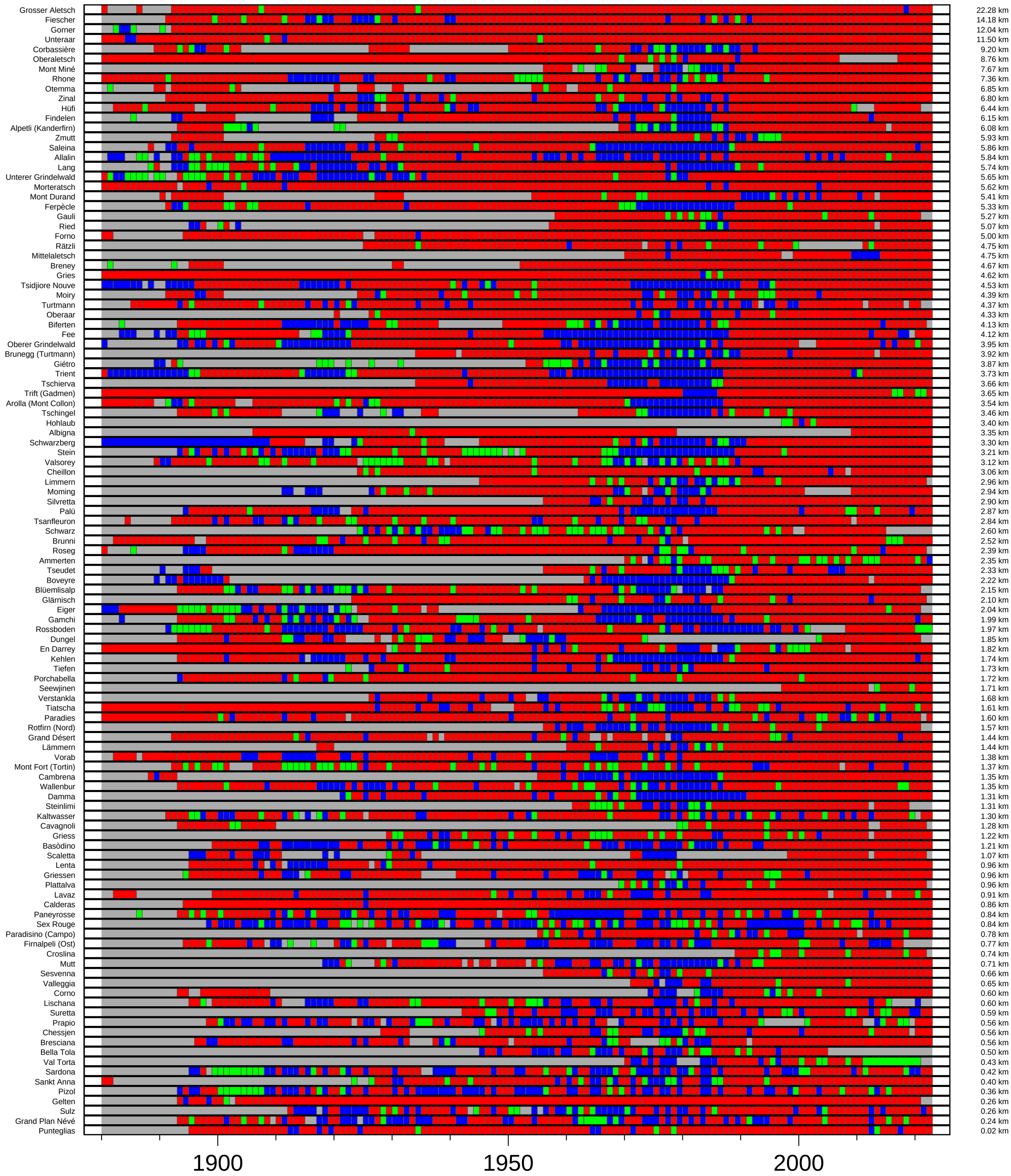


Figure 3.4: Individual pattern of advancing (blue), stationary (±1 m, green) and retreating (red) length variation of the same 73 selected glaciers (displayed in the descending order of current glacier length).

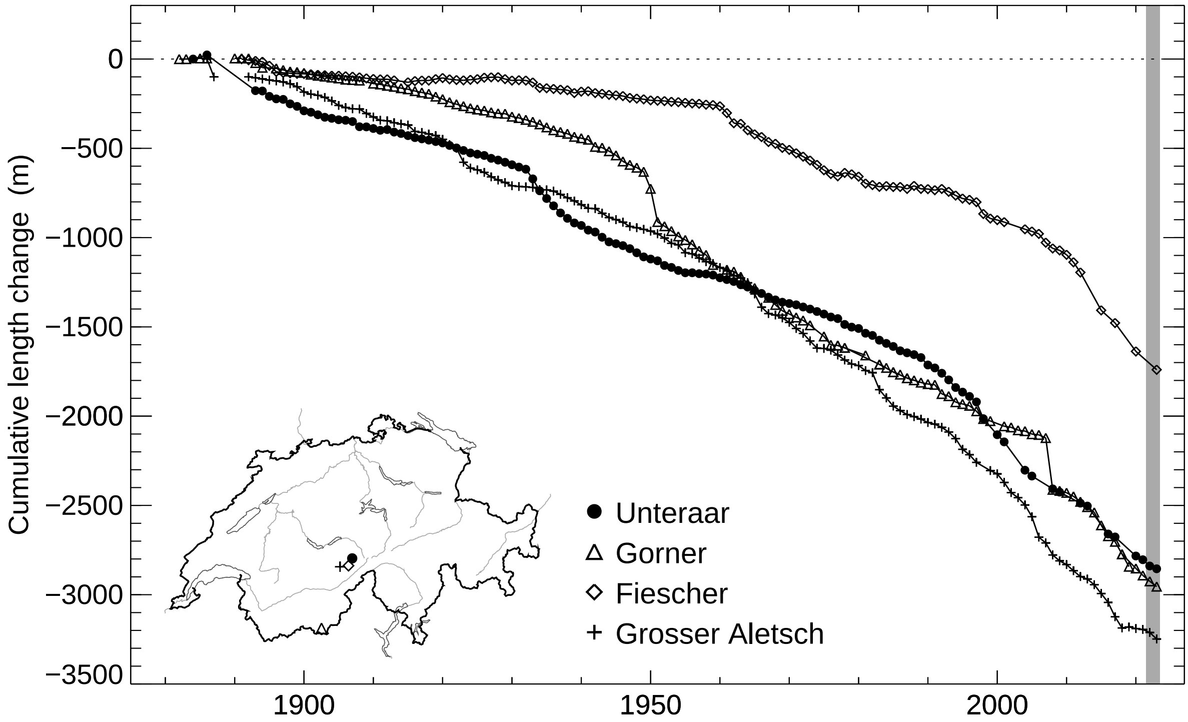


Figure 3.5: Large valley glaciers with a length of more than 10 km displaying a more or less continuous retreat over the entire time period. The gray-shaded area highlights the years of the current report.

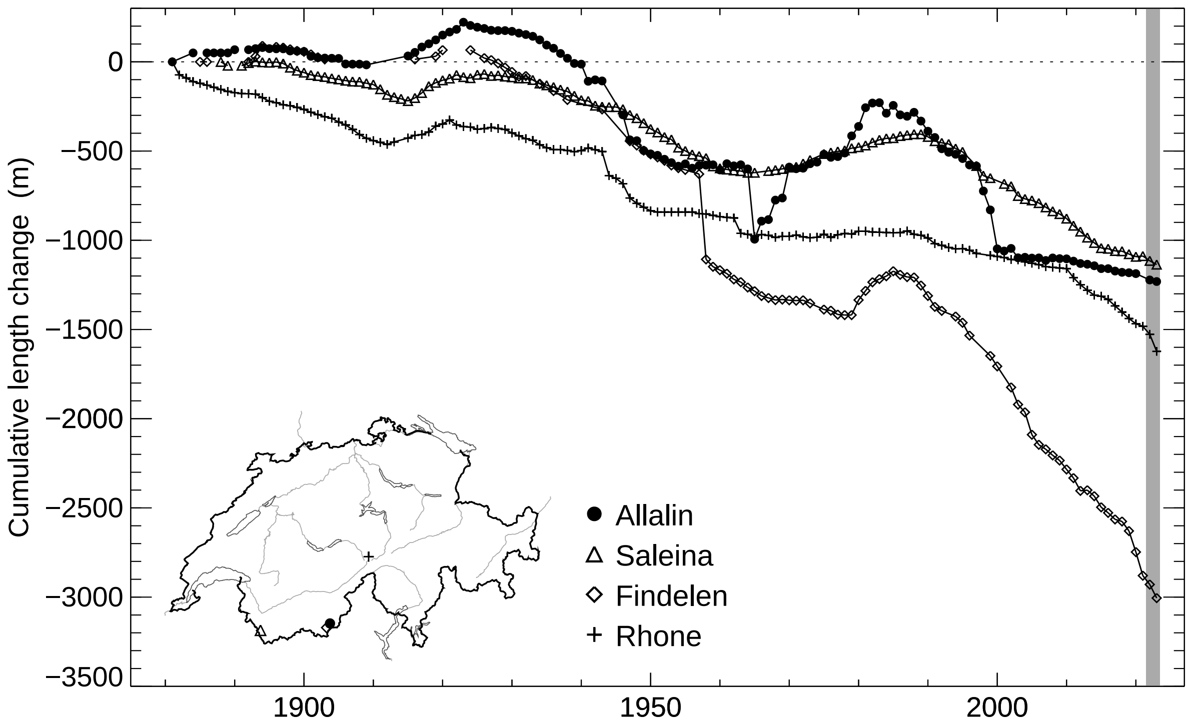


Figure 3.6: Mountain glaciers with a length of 5 to 10 km showing advance and retreat phases in two periods (around 1920 and 1980). The gray-shaded area highlights the years of the current report.

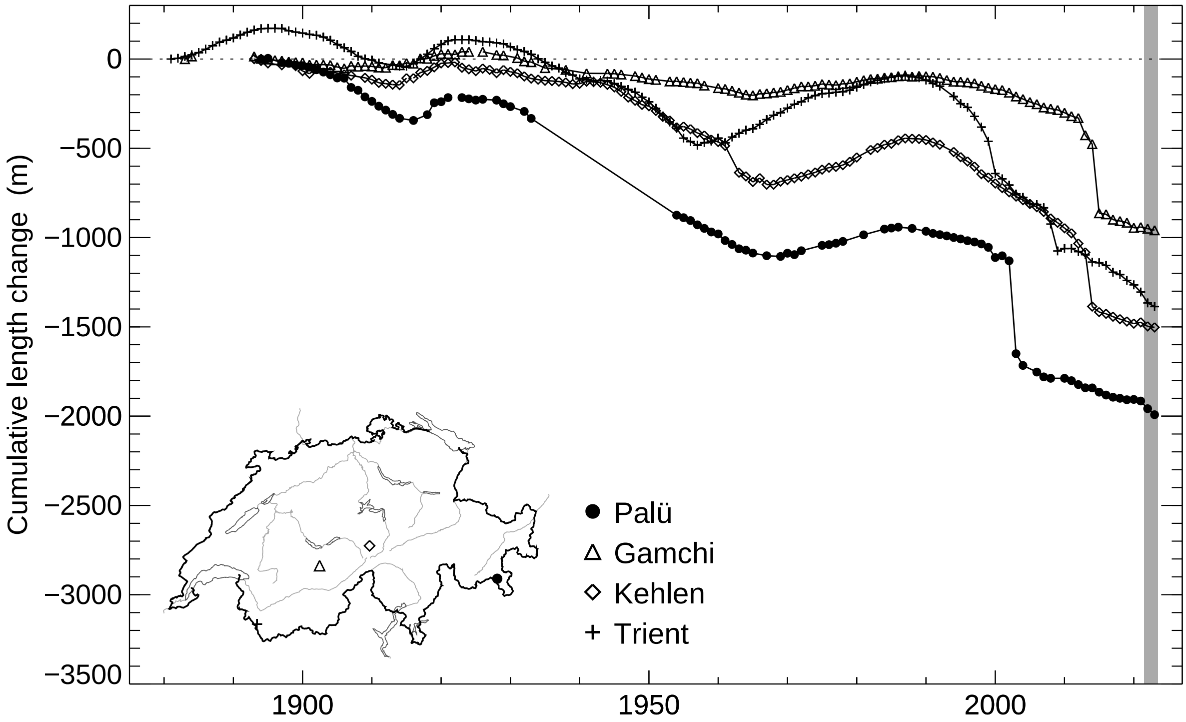


Figure 3.7: Medium-sized mountain glaciers with a length of 1 to 5 km showing two distinct advance and retreat phases. The gray-shaded area highlights the years of the current report.

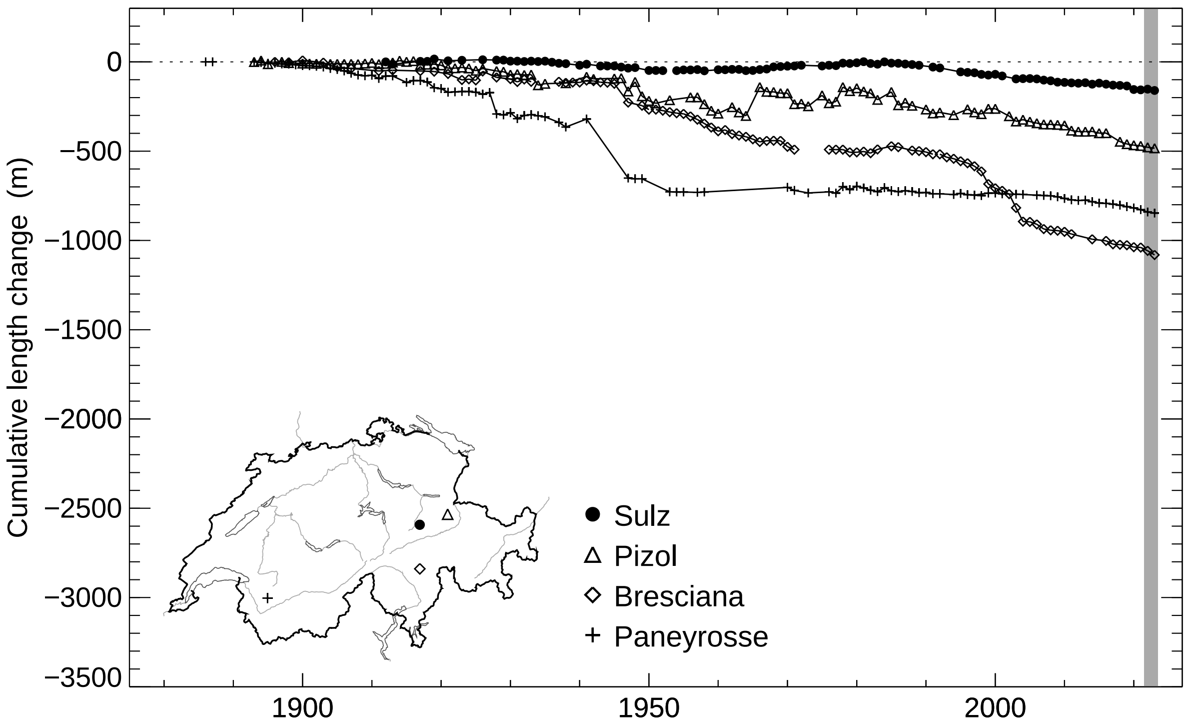


Figure 3.8: Very small cirque glaciers with a length of less than 1 km displaying generally small changes and a more irregular length change signal. The gray-shaded area highlights the years of the current report.

4 Mass Balance

4.1 Introduction, cumulative mean specific mass balances

Seasonal mass balance observations were collected using the glaciological method for Allalingletscher, Ghiacciaio del Basòdino, Claridenfirn, Findelengletscher, Griesgletscher, Grosser Aletschgletscher, Vadret dal Murtèl, Vadret Pers, Glacier de la Plaine Morte, Rhonegletscher, Sankt Annafirn, Silvrettagletscher and Glacier de Tsanfleuron as well as some additional smaller glaciers. Mass balance surveys at annual resolution at a network of mass balance stakes were conducted at Glacier de Corbassière, Glacier du Giétro, Hohlaubgletscher and Schwarzberggletscher. In Figure 4.1 the distribution of these monitoring sites throughout Switzerland is shown.

The mass balance measurements at stakes, as well as extensive snow probing in spring including snow density observations by coring were used to calculate the mean specific components of

Figure 4.1: Investigated glaciers for mass balance with local point measurements and glacier-wide analysis.

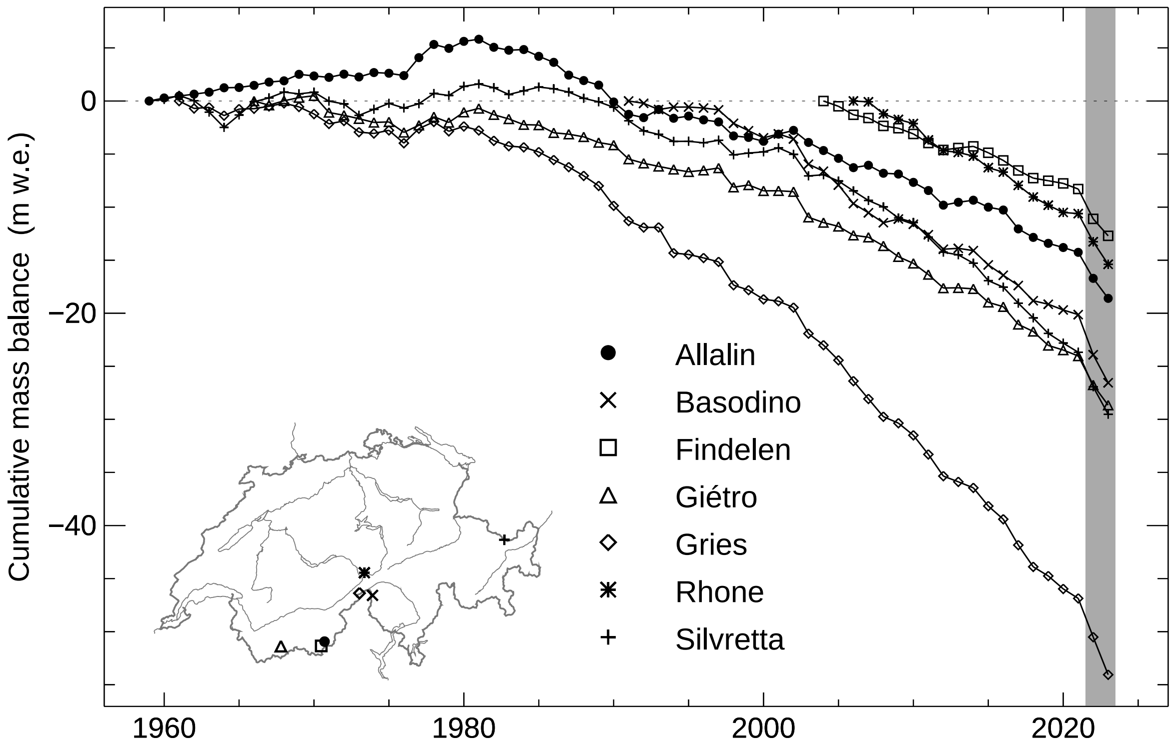


Figure 4.2: Cumulative mean specific mass balance over the whole observation period for the glaciers Allalin, Basòdino, Findelen, Giétro, Gries, Rhone and Silvretta. The gray-shaded area highlights the years of the current report.

mass balance following the methods described in Huss et al. (2021). Extrapolation from individual measurement points to the entire glacier surface was performed using a distributed mass balance model constrained with all seasonal observations. It includes the most important processes governing spatial mass balance distribution. This approach is regarded as an advanced extrapolation tool to infer glacier-wide quantities from point measurements rather than a mass balance model in the conventional sense: the signal of seasonal and annual mass balance variability is purely given by the field measurements. The procedure is thus fully in line with more traditional techniques to extrapolate local observations of glacier mass balance, such as the profile or the contourline method (e.g. Østrem and Brugman, 1991) but takes into account more sophisticated methods to infer mass balance in unmeasured regions of the glacier. The procedure is divided into two steps:

(1) The model is tuned such that both the measurements of winter accumulation and summer ablation are matched optimally over the periods defined by the exact dates of the in-situ measurements. This allows extrapolation of mass balance based on a physical representation of the spatial variability, as well as the calculation of mass balance over fixed-date periods (e.g. the hydrological year).

(2) A periodical, final reanalysis and homogenisation with independent ice volume changes derived from digital elevation models is performed in five- to ten-year intervals, and potential updates of the series are reported subsequently.

Table 4.1: Summary table with area, mean specific winter ($B_{w,meas}$) and annual ($B_{a,meas}$) balance, equilibrium line altitude (ELA) and accumulation area ratio (AAR) for the measurement periods (defined by the exact dates of field surveys) in 2021/22 and 2022/23.

Glacier	Period	Area (km^2)	$B_{w,meas}$ (mm w.e.)	$B_{a,meas}$ (mm w.e.)	ELA (m a.s.l.)	AAR (%)
Allalin	2021/22	9.553	454 [a]	−2455	4185	0
	2022/23	9.517	679	−1882	4115	0
Basòdino	2021/22	1.640	718	−3778	3185	0
	2022/23	1.544	784	−2639	3185	0
Clariden	2021/22	4.321	1451	−3090	3125	0
	2022/23	4.144	1405	−1950	2995	5
Corbassière	2021/22	15.082	610 [a]	−2310	4245	0
	2022/23	15.082	771 [a]	−1614	3955	6
Findelen	2021/22	12.511	486	−2815	3945	0
	2022/23	12.383	660	−1594	3505	21
Adler	2021/22	1.979	344	−2814	4105	0
	2022/23	1.979	460	−2150	3925	2
Giétro	2021/22	5.175	845 [a]	−2729	3685	2
	2022/23	5.061	1092 [a]	−1904	3615	2
Gries	2021/22	4.102	907	−3645	3335	0
	2022/23	3.809	830	−3545	3315	0
Grosser Aletsch	2021/22	77.983	911	−2982	3585	11
	2022/23	77.983	1211	−1576	3225	44
Hohlaub	2021/22	2.072	538 [a]	−2933	3825	3
	2022/23	2.072	669	−2052	3565	13
Murtèl	2021/22	0.261	647	−3250	3297	0
	2022/23	0.252	535	−2160	3282	1
Pers	2021/22	6.661	811	−3024	3485	12
	2022/23	6.537	732	−1963	3175	28
Plaine Morte	2021/22	6.889	1178	−4678	2825	0
	2022/23	6.682	1237	−2567	2815	0
Rhone	2021/22	15.174	1309	−2653	3365	10
	2022/23	15.011	1328	−2129	3215	23
St. Anna	2021/22	0.125	1137	−2847	2887	0
	2022/23	0.123	829	−1798	2887	0
Schwarzberg	2021/22	4.891	708 [a]	−3386	3555	0
	2022/23	4.891	1110 [a]	−2332	3465	2
Silvretta	2021/22	2.389	939	−3253	3065	0
	2022/23	2.325	1356	−2589	3025	0
Tsanfleuron	2021/22	2.324	1578	−3966	2975	0
	2022/23	2.315	2262	−2541	2975	0
Sex Rouge	2021/22	0.257	1532	−4011	2882	0
	2022/23	0.257	2075	−1975	2882	0
Otemma	2021/22	10.805	749	−3613	3675	0
	2022/23	10.805	885	−2670	3435	5

Tortin	2021/22	0.576	878 [a]	−4070	3257	0
	2022/23	0.576	1061 [a]	−2203	3197	2

a only measurements of annual balance available, the winter balance is determined by meteorological data using model-based relations

Table 4.2: Summary table with area, mean specific winter ($B_{w,fix}$) and annual ($B_{a,fix}$) balance, equilibrium line altitude (ELA) and accumulation area ratio (AAR) for fixed-date periods (1 October - 30 April - 30 September) in 2021/22 and 2022/23.

Glacier	Period	Area (km^2)	$B_{w,fix}$ (mm w.e.)	$B_{a,fix}$ (mm w.e.)	ELA (m a.s.l.)	AAR (%)
Allalin	2021/22	9.553	452 [a]	−2384	4195	0
	2022/23	9.517	706	−2342	4165	0
Basòdino	2021/22	1.640	887	−3512	3185	0
	2022/23	1.544	892	−2562	3185	0
Clariden	2021/22	4.321	1314	−2930	3125	0
	2022/23	4.144	1344	−2297	3035	2
Corbassière	2021/22	15.082	605 [a]	−2695	4245	0
	2022/23	15.082	707 [a]	−1650	3935	6
Findelen	2021/22	12.511	514	−3021	3945	0
	2022/23	12.383	703	−1459	3535	15
Adler	2021/22	1.979	360	−3020	4095	0
	2022/23	1.979	492	−2012	3925	2
Giétro	2021/22	5.175	821 [a]	−2955	3735	1
	2022/23	5.061	1004 [a]	−1841	3555	3
Gries	2021/22	4.102	1090	−3859	3335	0
	2022/23	3.809	936	−3130	3315	0
Grosser Aletsch	2021/22	77.983	1058	−2810	3545	15
	2022/23	77.983	1018	−1783	3215	45
Hohlaub	2021/22	2.072	537 [a]	−2832	3835	3
	2022/23	2.072	700	−2588	3755	7
Murtèl	2021/22	0.261	700	−3071	3302	0
	2022/23	0.252	725	−2475	3282	1
Pers	2021/22	6.661	859	−3023	3515	10
	2022/23	6.537	929	−1914	3155	29
Plaine Morte	2021/22	6.889	1256	−4032	2825	0
	2022/23	6.682	1334	−2481	2815	0
Rhone	2021/22	15.174	1326	−2416	3335	12
	2022/23	15.011	1433	−1864	3205	23
St. Anna	2021/22	0.125	1141	−2753	2887	0
	2022/23	0.123	970	−2663	2892	0
Schwarzberg	2021/22	4.891	704 [a]	−3239	3565	0
	2022/23	4.891	1069 [a]	−2896	3515	0
Silvretta	2021/22	2.389	859	−3339	3065	0
	2022/23	2.325	1271	−2309	3025	0
Tsanfleuron	2021/22	2.324	1478	−4001	2975	0

	2022/23	2.315	2350	−2349	2975	0
Sex Rouge	2021/22	0.257	1429	−3760	2882	0
	2022/23	0.257	2172	−2267	2882	0
Otemma	2021/22	10.805	611	−3488	3495	2
	2022/23	10.805	605	−2816	3465	4
Tortin	2021/22	0.576	871 [a]	−4082	3257	0
	2022/23	0.576	993 [a]	−2251	3192	2

a only measurements of annual balnce available, the winter balance is determined by meteorological data using model-based relations

Field measurements were collected on 23 individual glaciers in total during the two reporting periods 2021/22 and 2022/23. Point mass balance was inferred by snow probings and snow density measurements during April/May, and at a network of mass balance stakes in September/October. Distributed measurements permitted inferring glacier-wide mass balance and the corresponding elevation distribution. At most sites intermediate surveys of a part or the entire stake network during the summer season provided valuable insights into temporal dynamics of the mass loss or the present state of the glacier. In addition, real-time observations of mass balance on up to six glaciers are acquired since 2019 to remotely determine the amount of melting and infer overall glacier mass loss up to the respective date by combining the measurements with modeling approaches.

As a result of accelerated atmospheric warming and the two extreme years, several mass balance monitoring sites at small glaciers needed to be abandoned during the reporting period, and measurement series thus were discontinued. In 2022, no further measurements were possible at Pizolgletscher, Vadret dal Corvatsch and Schwarzbachfirn, either due to complete disappearance of the glacier, or too strong shrinkage for extracting relevant information on glacier mass balance. To compensate for the loss of these series, mass balance monitoring programmes at the two large glaciers, Grosser Aletschgletscher and Vadret Pers, were consolidated. These efforts have the aim to establish stable and strong long-term series far into the second half of the 21st century.

The mean specific winter and annual balances are presented in Table 4.1 for the periods defined by the individual measurement dates and in Table 4.2 for comparable fied-date periods corresponding to the hydrological year. The mass balance for Adlergletscher, a former tributary of Findelengletscher, has been evaluated separately but detailed figures are presented together with Findelengletscher. A similar situation exists at Glacier du Sex Rouge (close to Tsanfleuron). For these smaller monitoring sites, as well as for additional glaciers with shorter series acquired beyond the core mandate of GLAMOS by external institutions (Glacier d'Otemma, Glacier du Tortin) only glacier-wide specific values are presented in the summary Tables 4.1 and 4.2 for these glaciers but no detailed figures.

The long-term trends are clearly recognizable for Allalingletscher, Glacier du Giétro, Griesgletscher and Silvrettagletscher with very long and continuous time series (Figure 4.2). Notably, the accelerated mass loss since the mid-1980s is remarkable, as are the balanced mass budgets recorded in the 1960s and 70s. The point measurements of the mass balance are of particular significance with regard to answering questions related to climate change (Ohmura et al., 2007; Huss and Bauder, 2009; Gabbi et al., 2015; GLAMOS, 2020a). The four existing long-term time series at seasonal resolution (Claridenfirn, Grosser Aletschgletscher, Silvrettagletscher) start in the 1910s and cover almost the entire 20th century. Mass balance data of the present report has also been submitted to the World Glacier Monitoring Service (WGMS) as a contribution to the efforts of international glacier monitoring (WGMS, 2023). Allalingletscher, Ghiacciaio del Basòdino, Glacier du Giétro, Griesgletscher and Silvrettagletscher have been selected by WGMS as their reference glaciers, a global list of glaciers that stand out for the length of their data series and the completeness of mass balance observations.

4.2 Mass Balance in 2021/22

Winter snow depth at the end of winter (30 April) was below the average across all of Switzerland (Figure 4.3). In particular, snow cover was very limited from the Southern Valais, over Ticino to Eastern Switzerland with a deficit of 30% up to 60% relative to the period 2010-2020. The deficit was less prominent in the North and West of Switzerland though. The limited snow layer allowed the high summer temperatures prevailing from the end of May onwards to melt the ice much earlier than in other years. In addition, the substantial concentration of Saharan dust on the spring snow surface accelerated the melting. Taken together, these factors unfolded to become the "perfect storm" for Swiss glaciers, and the record mass losses for the hydrological year 2021/22 were already looming on the horizon since early summer.

Unprecedented melt rates were observed in September. The records from the hot summer of 2003 were pulverized. The loss was particularly drastic for small glaciers that sometimes completely disintegrated, or the dead ice was buried by rock debris. Overall, the glacier ice volume decreased by 3.1 cubic kilometers in 2022. This corresponds to roughly 6% of the remaining ice. The figure is particularly impressive considering that years in which more than 2% volume loss have so far been described as "extreme".

In the Engadine and southern Valais, an ice layer of 4-6 meters in thickness disappeared at an elevation of 3000 m. In some cases, this is more than twice as much as the previous maximum. At the very highest measurement sites, where even in previous heat years some snow was able to survive the summer, significant ablation was measured for the first time. For example, at Jungfraujoch it was the first negative mass balance since observations started in 1920. It was thus the first time since systematic mass balance measurements started in Switzerland that no snow accumulation could be detected at any place, and glaciers were thus almost completely snow-free up to their highest elevations. The average loss in ice thickness is around 3 meters in all regions, sometimes even reaching values of over 4 meters (e.g. Ghiacciaio del Basòdino, Griesgletscher). Even glaciers that have shown rather moderate melting in the past (e.g. Findelengletscher) now have melt rates that are completely outside the range of historical fluctuations. Throughout the entire Swiss Alps, summer melting was between 50% and 120% beyond the 2010-2020 average (Figure 4.3).

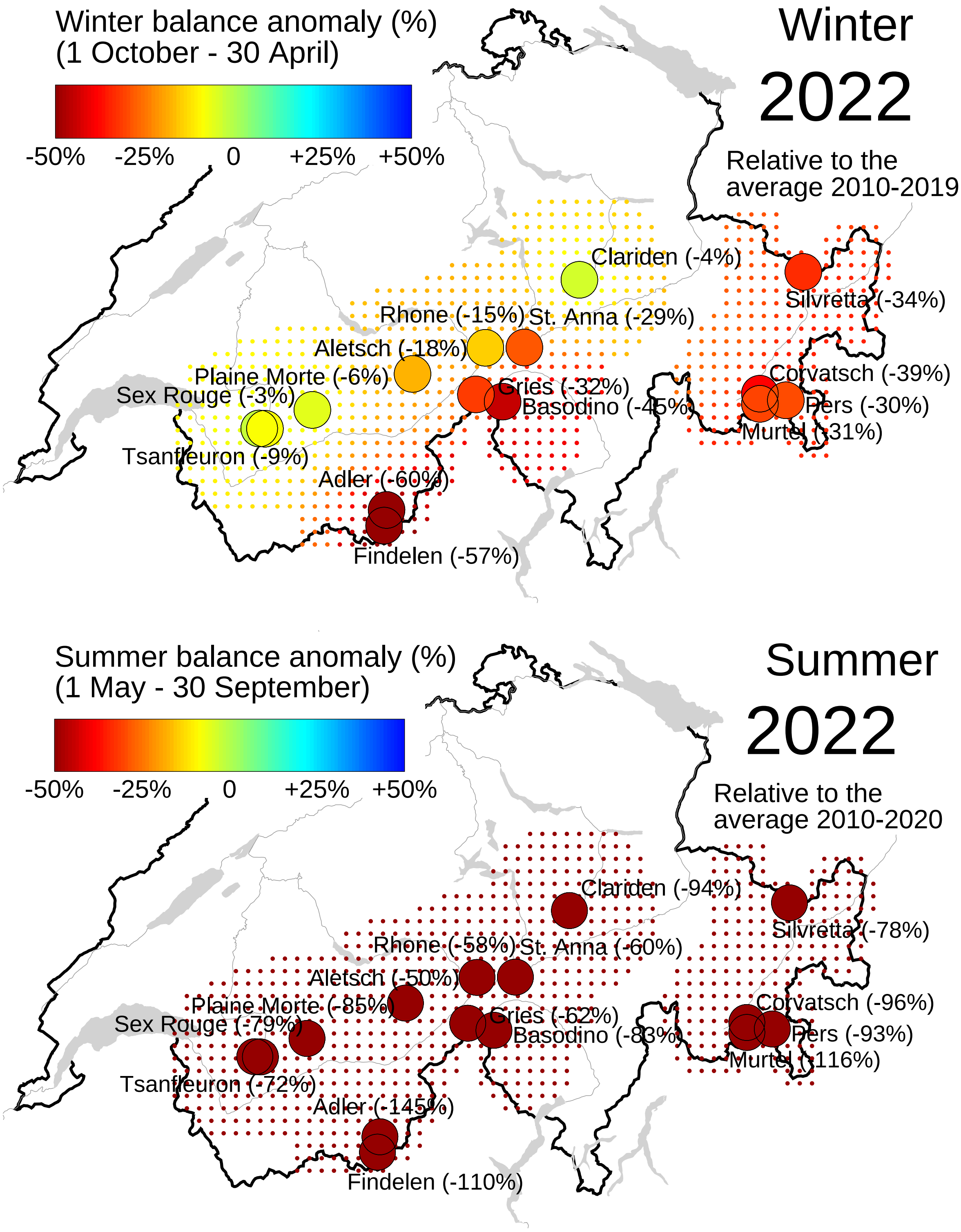
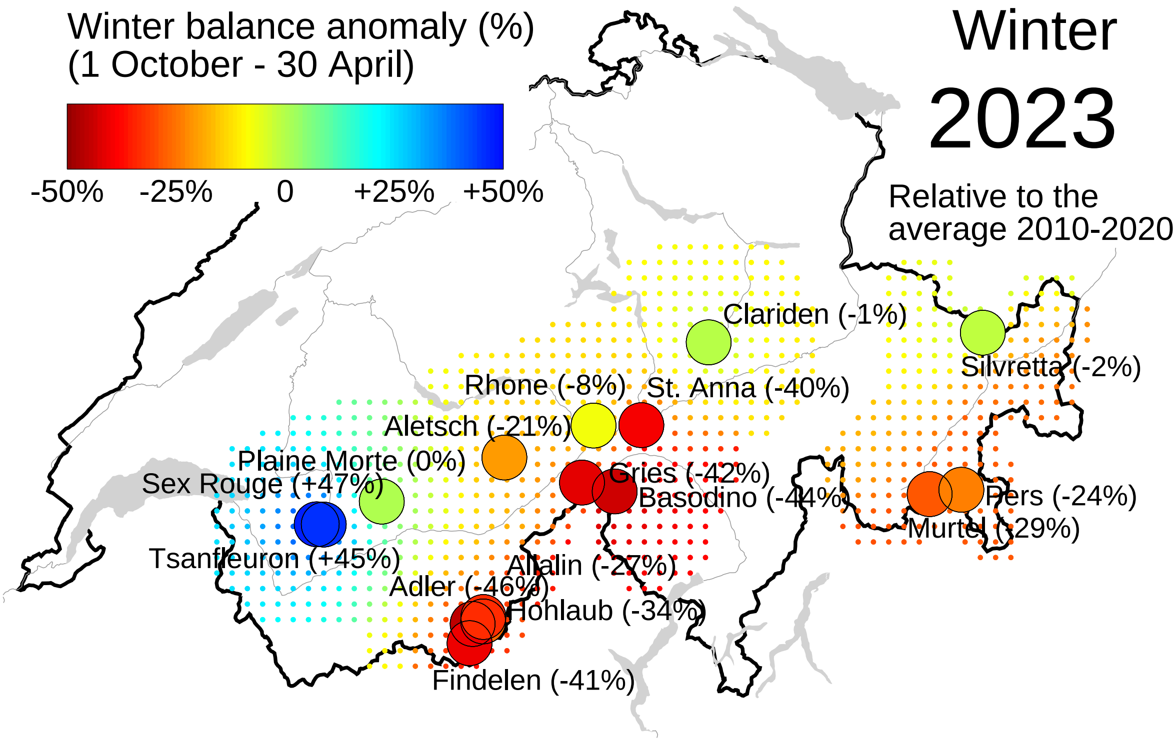


Figure 4.3: Anomaly of winter (top) and summer (bottom) mass balance in 2021/22 relative to the average 2009/10 to 2018/19 of all observed glaciers and extrapolated to the entire Swiss Alps.

4.3 Mass Balance in 2022/23

While during the winter mass balance surveys in April, record-low values of snow water equivalent were found on some glaciers, some snowfalls slightly relaxed the situation afterwards. Snow on



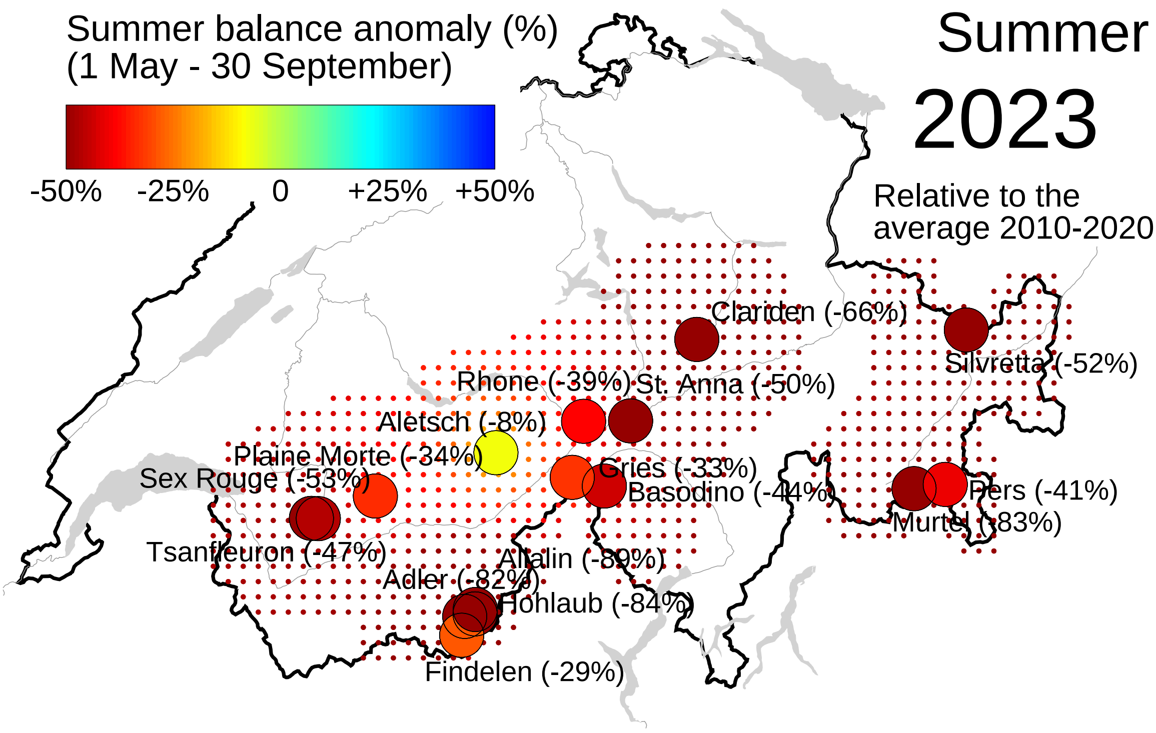


Figure 4.4: Anomaly of winter (top) and summer (bottom) mass balance in 2022/23 relative to the average 2009/10 to 2018/19 of all observed glaciers and extrapolated to the entire Swiss Alps.

glaciers however remained 30-40% below the 2010-2020 average in the South of Switzerland (including Southern Valais and Engadine), but almost reached normal values in the North and even a surplus in the very West of the Swiss Alps (Figure 4.4).

Even though over the annual period the record mass losses of 2022 were not reached, the melt in the South and East of Switzerland is only slightly lower. Especially in the southern Valais, the Ticino and the Engadine melting was particularly impressive with several meters of ice ablation at an elevation at which glaciers were able to maintain their balance until very recently. The average loss of ice thickness in this region was up to 3 meters (e.g. Ghiacciaio del Basòdino, Griesgletscher, Vadret Pers) and is thus significantly higher than in the hot summer of 2003. The situation between the Bernese Oberland and Valais is less dramatic (e.g. Grosser Aletschgletscher, Glacier de la Plaine Morte), as there was more snow at the end of winter. Nevertheless, the loss of more than 2 meters of mean ice thickness is considerable. Overall, summer melting was ca. 30% to 70% higher than the 2010-2020 average (Figure 4.4). Although these values are exceptional, they fade in comparison to those of the summer 2022 which is explained the somewhat later snow depletion (no Saharan dust and more moderate temperature in May), and the few occasional summer snow events. It is remarkable, however, that melting continued exceptionally far into the fall season in 2023 with very high air temperatures until mid-October.
After the unprecedented melting of 2022, the year 2023 was the next blow for Swiss glaciers. With a loss of around 4% of the remaining ice volume, a tenth of the total glacier volume disappeared in just two years. Behind the record year 2022, 2023 year ranked second regarding specific glacier mass balance. However, the rapid reduction of glacier area over the last decades has contributed to a smaller absolute ice volume loss in 2023, e.g. compared to 2003, even though melt rates were higher. This indicates that a peak in absolute glacier mass loss has likely been reached during this reporting period. Even if future heat waves will lead to higher melt rates, it is unlikely that such levels of absolute glacier volume loss, and thus meltwater contribution to the hydrological system, will ever occur again.

The glacier retreat over the past decades affects also the topmost areas as illustrated by the evolution of Vadret dal Corvatsch. (Photos: M. Huss)

4.4 Allalingletscher

Introduction

Allalingletscher is a temperate large mountain glacier located in the Southern Valais Alps. It currently covers an area of 9.6 km^2 flowing in north-eastern direction from 4180 m a.s.l. down to 2700 m a.s.l. Mass balance measurements started in 1955 as a part of investigations for the construction of the Mattmark reservoir for hydro-power production (VAW, 1999, 2024). Initially, the measurement network was set up to cover the entire surface area. Following an ice avalanche on 30th August 1965, when the construction site of the Mattmark reservoir was destroyed and 88 people died in the accident, the observation network was re-arranged in 1967 with a main focus on ice flow investigations at the glacier tongue (see Chapter 5). However, also the readings of local annual mass balance were continued. In April 2023, measurements of winter snow accumulation have been resumed after discontinuation since 1996 and adding the seasonal component to this long-term series again. Data of point mass balance and geodetic ice volume changes since the

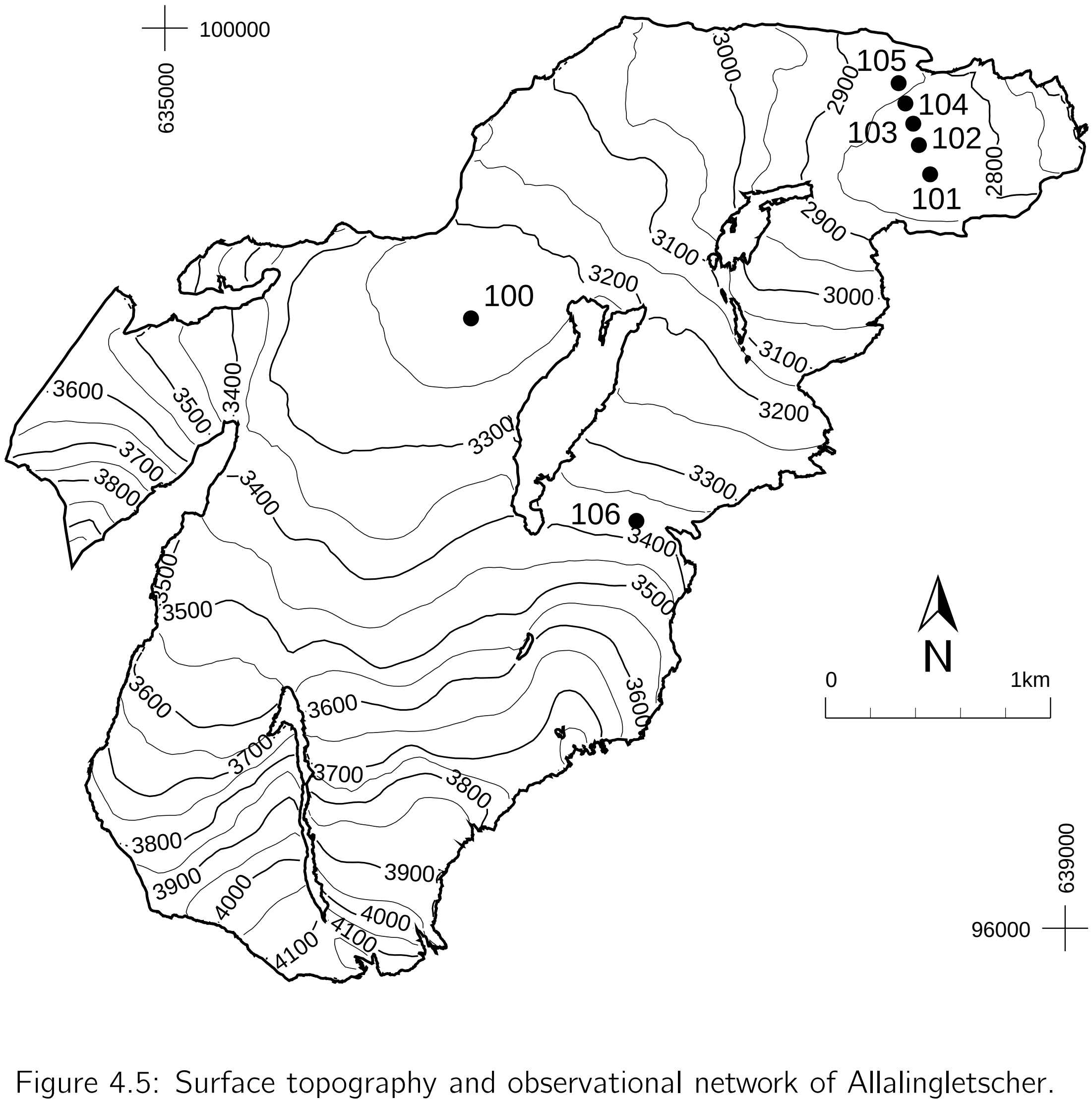


Figure 4.5: Surface topography and observational network of Allalingletscher.

beginning of the measurements in 1955 were re-analyzed and homogenized (Huss et al., 2015). The results of the glacier-wide mean specific annual balance for comparable fixed-date periods were presented in Section 4.17 of Volume 135/136. Further details on long-term observations of ice flow velocities are shown in Section 5.2.

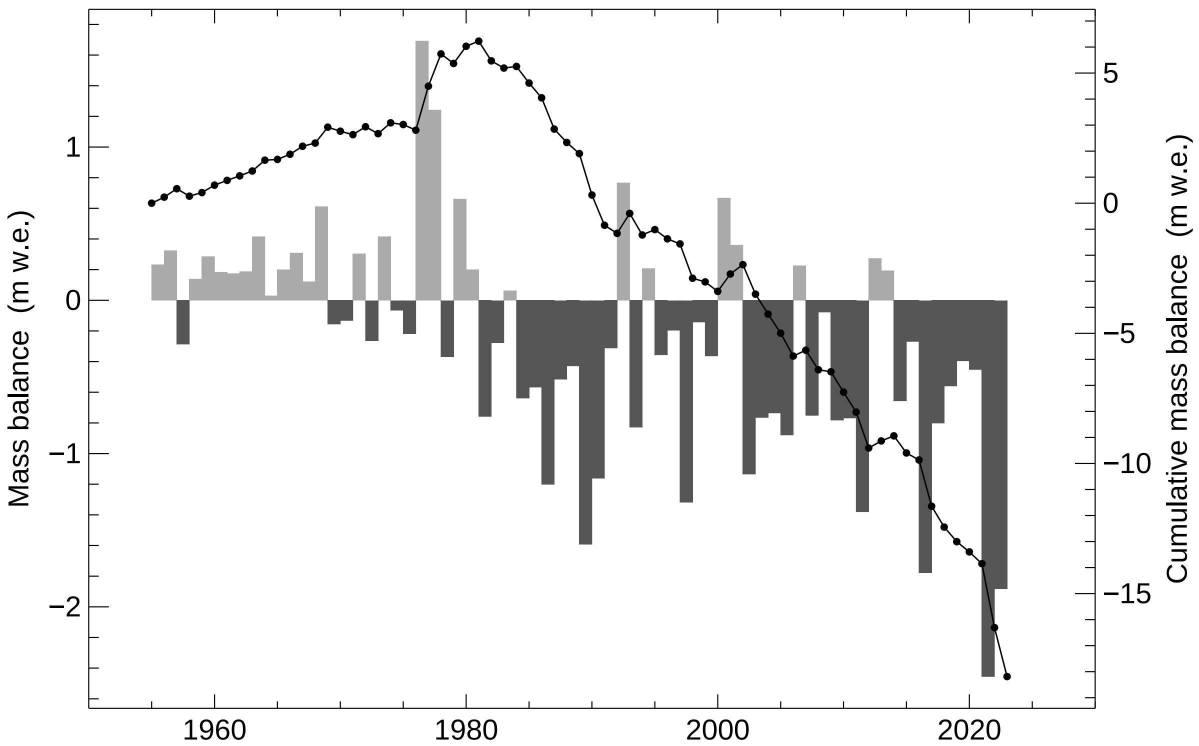


Figure 4.6: Allalingletscher - Mean specific annual balance (bars) and cumulative mass balance for the period 1955-2023. Values refer to the measurement period.

Investigations in 2021/22

Annual observations of mass balance with maintenance of the stake network were carried out on 6th September 2022. All seven stakes were located and set back to the initial position. Highly negative local mass balances have been registered for all stakes including the highest stake on 3370 m a.s.l. where the most negative value since the beginning in 1955 of the investigations at this location has been measured. The transient snowline reached the highest elevations of the glacier which has never been observed before. Two intermediate visits during summer in mid-July and mid-August have been carried out for readings and to avoid losing the measurements by complete melt-out of the stakes.

Investigations in 2022/23

Winter mass balance observations were conducted on 17th April 2023. Snow depth probings were collected at more than 100 locations distributed over the entire elevation range of the glacier.

The bulk density of the snow pack was measured by coring at the two locations 100 and 103 with values of 321 kg m^{-3} and 331 kg m^{-3}, respectively. Annual observations of mass balance with maintenance of the stake network were carried out on 5th September 2023. All stakes were located and set back to the initial position. As in the previous period, negative local mass balances were measured for all stakes.

Table 4.3: Allalingletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2600 - 2700	0.001	438	−4156	0.000		
2700 - 2800	0.134	455	−4880	0.100	660	−4451
2800 - 2900	0.528	469	−4711	0.527	705	−4071
2900 - 3000	0.463	494	−4059	0.463	804	−3168
3000 - 3100	0.713	508	−3743	0.713	853	−2708
3100 - 3200	0.739	502	−3531	0.739	803	−2498
3200 - 3300	1.592	492	−3343	1.592	783	−2485
3300 - 3400	1.005	483	−2420	1.005	844	−1803
3400 - 3500	1.063	470	−1918	1.063	662	−1498
3500 - 3600	0.949	448	−1474	0.949	595	−1122
3600 - 3700	0.838	420	−1180	0.838	619	−782
3700 - 3800	0.517	385	−827	0.517	570	−509
3800 - 3900	0.449	351	−694	0.449	357	−748
3900 - 4000	0.291	323	−504	0.291	230	−787
4000 - 4100	0.181	286	−352	0.181	229	−611
4100 - 4200	0.091	249	−298	0.091	137	−728
2600 - 4200	9.553	454	−2455	9.517	679	−1882

Table 4.4: Allalingletscher - Individual stake measurements of winter and annual balance.

Stake	Period Start	Spring	End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	b_a
100	02.09.2021		06.09.2022	636516 / 98810 / 3217		−3897
101	02.09.2021		06.09.2022	638404 / 99360 / 2812		−5310
102	02.09.2021		06.09.2022	638355 / 99480 / 2816		−4410
103	02.09.2021		06.09.2022	638329 / 99574 / 2814		−4995
104	02.09.2021		06.09.2022	638295 / 99664 / 2828		−4959
105	02.09.2021		06.09.2022	638265 / 99753 / 2844		−4950
106	02.09.2021		06.09.2022	637096 / 97803 / 3367		−2173
100	06.09.2022	17.04.2023	05.09.2023	636515 / 98807 / 3214	667	−3042
101	06.09.2022		05.09.2023	638403 / 99360 / 2807		−5031
102	06.09.2022		05.09.2023	638353 / 99480 / 2812		−3240
103	06.09.2022	17.04.2023	05.09.2023	638329 / 99574 / 2810	743	−4068
104	06.09.2022	17.04.2023	05.09.2023	638293 / 99664 / 2824	676	−3798
105	06.09.2022	17.04.2023	05.09.2023	638263 / 99754 / 2839	625	−5058
106	06.09.2022		05.09.2023	637094 / 97802 / 3365		−1723

Vadret da Palü in October 2023: the glacier retreated out of the lake and was partly separated from the firn area. (Photo: R. Nyfeler, AWN/GR)

4.5 Ghiacciaio del Basòdino

Introduction

Ghiacciaio del Basòdino is a small north-east facing mountain glacier in the southern Swiss Alps. The main body of the glacier presently covers an area of 1.6 km^2 and extends from 2600 to 3186 m a.s.l. Detailed mass balance investigations have been carried out since 1991. Determination of volumetric changes in decadal resolution extend further back to 1929 (Bauder et al., 2007). Topographic maps or photogrammetrical surveys exist for 1929, 1949, 1971, 1985, 1991, 2002, 2008, 2013, 2014, 2018 and 2021. (Huss et al., 2015) re-analyzed and homogenized the seasonal point mass balance data and ice volume changes for the period 1961-2007, and annual updates using a consistent methodology are performed since then (GLAMOS, 2023a). The mass balance time-series of this glacier has recently been included by WGMS among their selection of global reference glaciers with continuous measurement series for more than 30 years.

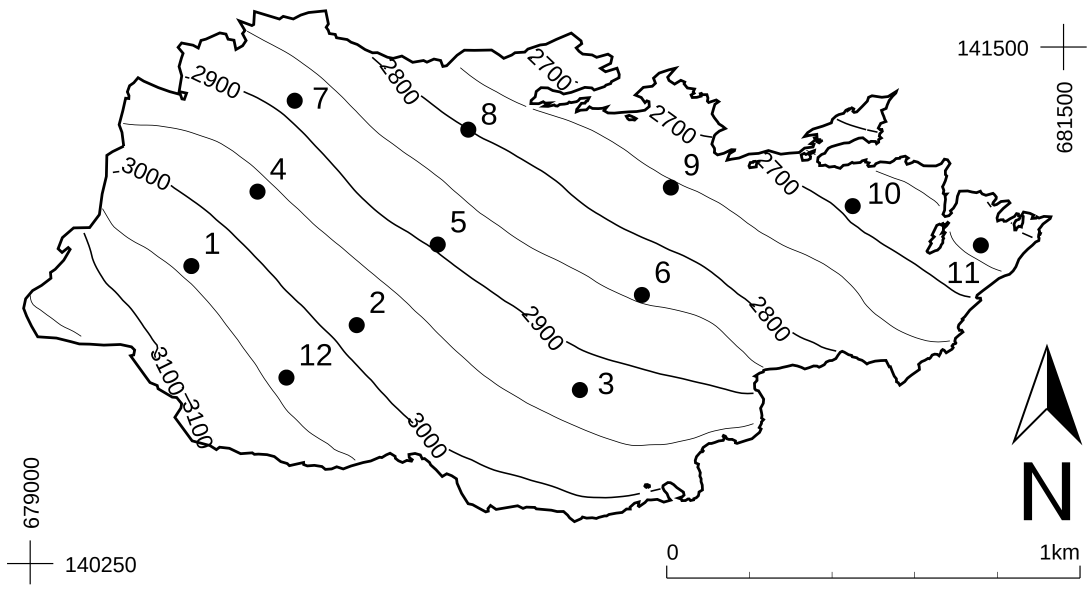


Figure 4.7: Surface topography and observational network of Ghiacciaio del Basòdino.

Investigations in 2021/22

The measurement period extended from 10th September 2021 to 16th September 2022 with a field visit in spring on 20th April 2022 to collect measurements of the snow accumulation in winter. The spring survey included snow depth probing at 110 locations and the determination of mean density of the snow pack using a core drill in the center of the glacier at stake 5. The annual mass balance was observed at 10 stakes. Four additional field visits during the melting season were performed for intermediate stake readings and redrilling of stakes on 7th and 13th July, 9th an 20th August 2022.

Investigations in 2022/23

The measurement period was from 16th September 2022 to 5th October 2023. Winter balance was determined on 19th April 2023. Snow depth probing at 126 locations were carried out. A bulk density of 341 kg m^{-3} was measured at site 5 using a core drill. Three additional field visits during the melting season were conducted on 18th July, 20th August and 5th September 2023. The annual mass balance was determined at all 10 remaining stakes.

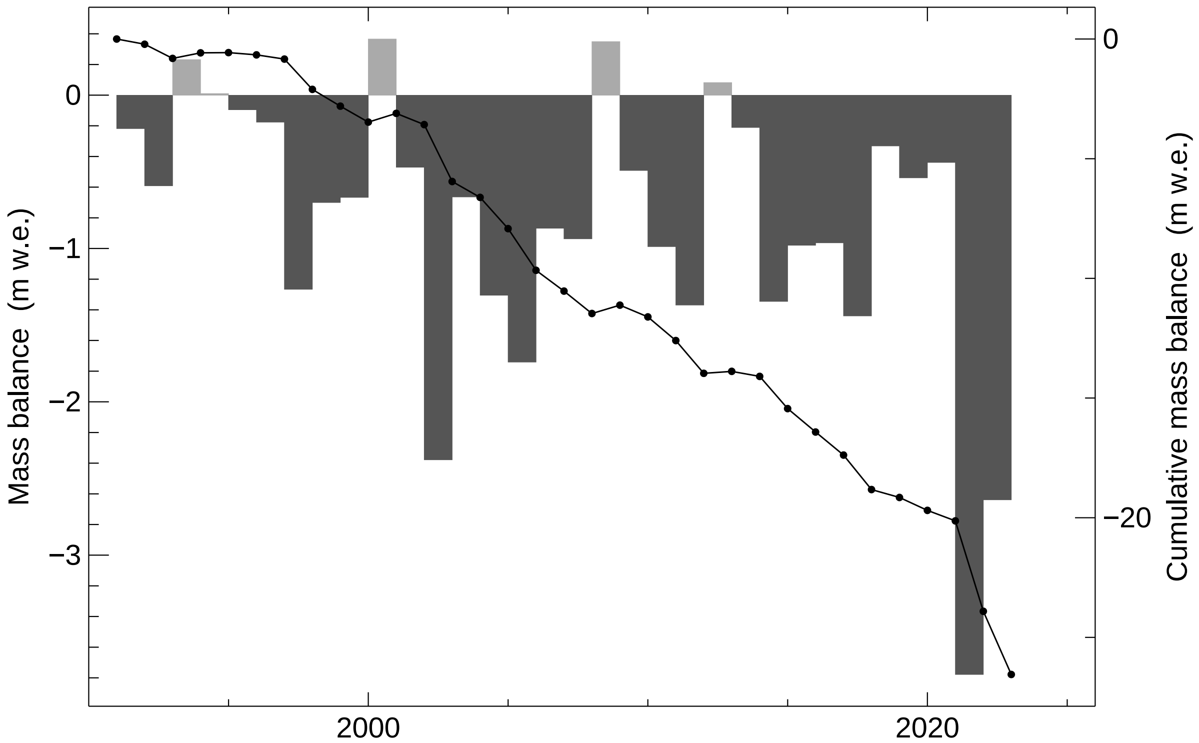


Figure 4.8: Ghiacciaio del Basòdino - Mean specific annual balance (bars) and cumulative mass balance for the period 1991-2023. Values refer to the measurement period.

Table 4.5: Ghiacciaio del Basòdino - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude (m a.s.l.)	2021/22 Area (km²)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)	2022/23 Area (km²)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)
2500 - 2600	0.001	615	−3343	0.000		
2600 - 2700	0.081	536	−3706	0.046	748	−2874
2700 - 2800	0.306	624	−3951	0.257	729	−3026
2800 - 2900	0.394	737	−3790	0.384	759	−2771
2900 - 3000	0.501	803	−3697	0.501	832	−2429
3000 - 3100	0.299	731	−3734	0.299	809	−2488
3100 - 3200	0.056	547	−3844	0.056	700	−2479
2500 - 3200	1.640	718	−3778	1.544	784	−2639

Table 4.6: Ghiacciaio del Basòdino - Individual stake measurements of winter and annual balance.

Stake	Period Start	Period Spring	Period End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	Mass balance b_a (mm w.e.)
01	10.09.2021	20.04.2022	16.09.2022	679390 / 140970 / 3030	436	−3861
02	10.09.2021	20.04.2022	16.09.2022	679790 / 140827 / 2980	880	−3654
03	10.09.2021	20.04.2022	16.09.2022	680330 / 140670 / 2920	1100	−3870
04	10.09.2021	20.04.2022	16.09.2022	679550 / 141150 / 2950	720	−4086
05	10.09.2021	20.04.2022	16.09.2022	679986 / 141022 / 2880	512	−4212
06	10.09.2021	20.04.2022	16.09.2022	680480 / 140900 / 2840	832	−4140
07	10.09.2021	20.04.2022	16.09.2022	679679 / 141273 / 2893	692	−4554
09	10.09.2021	20.04.2022	16.09.2022	680550 / 141160 / 2740	676	−4167
10	10.09.2021	20.04.2022	16.09.2022	680970 / 141101 / 2692	300	−4140
12	10.09.2021	20.04.2022	16.09.2022	680990 / 141115 / 2680	280	−3672
01	16.09.2022	19.04.2023	05.10.2023	679390 / 140970 / 3030	760	−2574
02	16.09.2022	19.04.2023	05.10.2023	679790 / 140827 / 2974	835	−2268
03	16.09.2022	19.04.2023	05.10.2023	680330 / 140670 / 2910	924	−2349
04	16.09.2022	19.04.2023	05.09.2023	679589 / 141114 / 2957	879	−2700
05	16.09.2022	19.04.2023	05.10.2023	679984 / 141019 / 2881	722	−2817
06	16.09.2022	19.04.2023	05.10.2023	680480 / 140900 / 2840	811	−2718
07	16.09.2022	19.04.2023	05.10.2023	679750 / 141259 / 2877	913	−3330
09	16.09.2022	19.04.2023	05.10.2023	680504 / 141157 / 2740	392	−3726
10	16.09.2022	19.04.2023	05.10.2023	680966 / 141052 / 2695	682	−3366
12	16.09.2022	19.04.2023	05.10.2023	679613 / 140723 / 3033	910	−2700

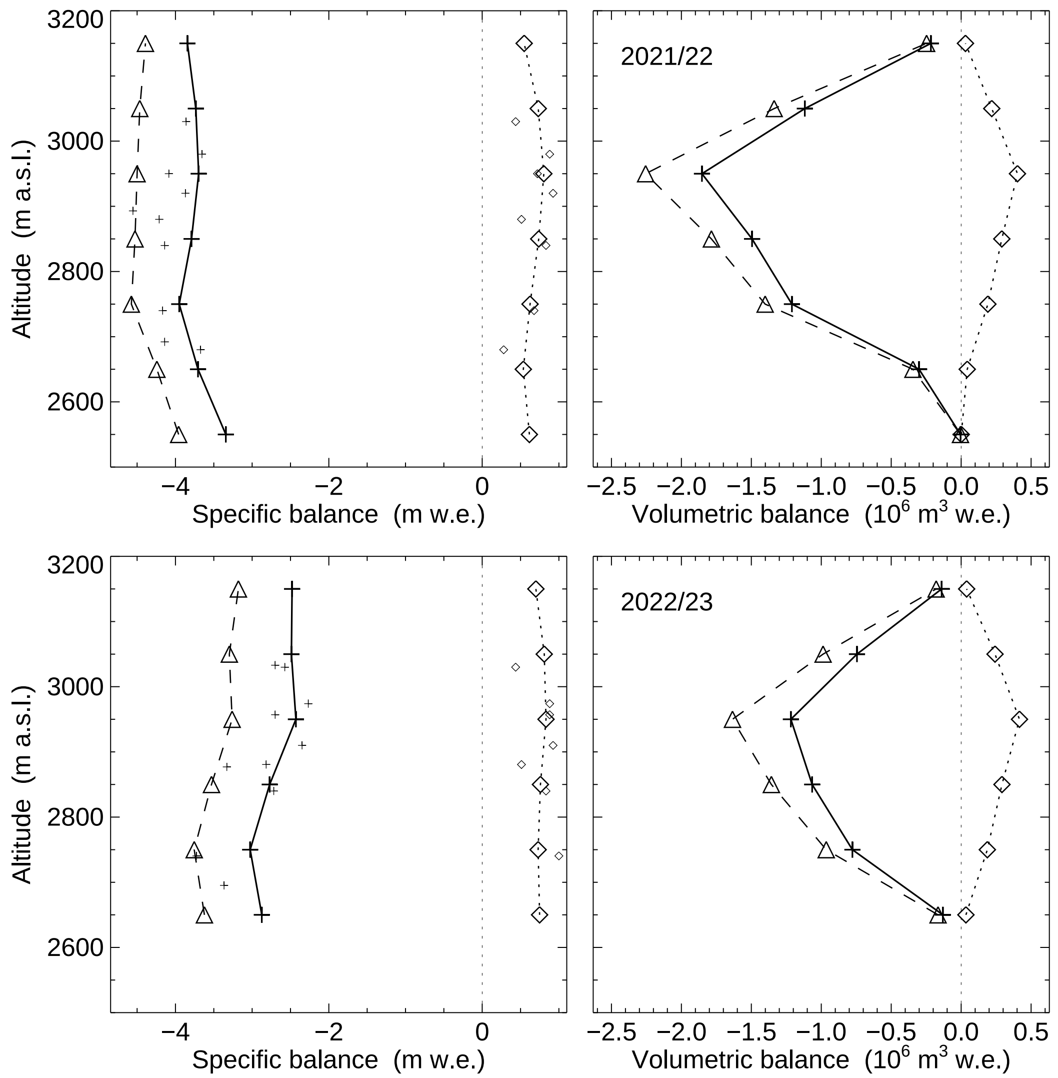


Figure 4.9: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

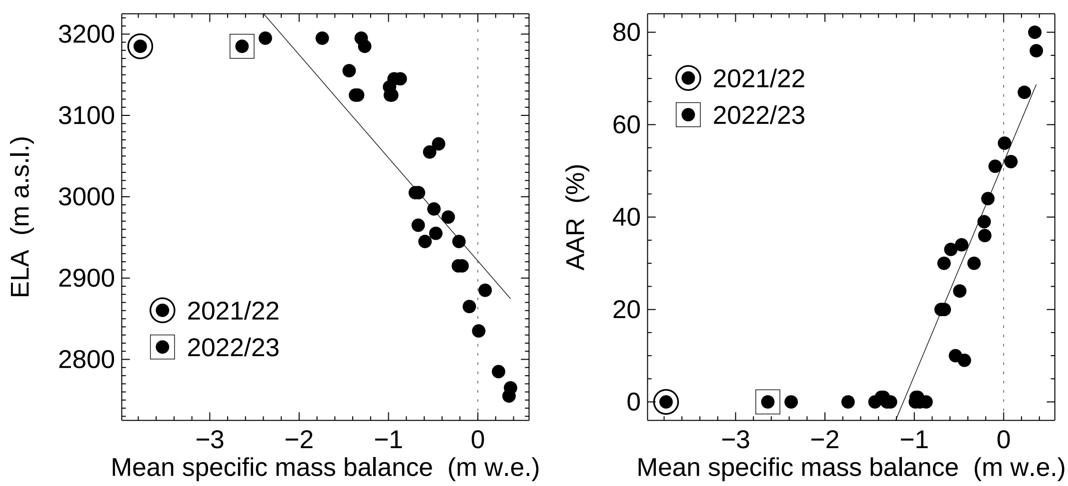


Figure 4.10: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.6 Claridenfirn

Introduction

Claridenfirn is a plateau glacier in the hydrological drainage basin of the Linth with an area of currently 4.3 km^2. It consists of several accumulation basins and independent steep glacier fronts that are partly subject to frontal ice break-off. Measurements of accumulation and melt, as well as of total precipitation near the glacier margin, have been undertaken by various researchers continuously since 1914 using a consistent methodology. The series at the two point sites on Claridenfirn is thus by far the longest direct glacier mass balance record worldwide and is characterized by an excellent documentation (Müller and Kappenberger, 1991; Geibel et al., 2022). The traditional glaciological method was applied by digging a snow pit down to a horizon marking the previous end-of-summer surface, and by measuring the water equivalent of the accumulated snow layer. Annual point balance was determined every autumn since 1914 with very few data gaps and also regularly in spring, at two sites at elevations of about 2700 and 2900 m a.s.l. The reports focusing

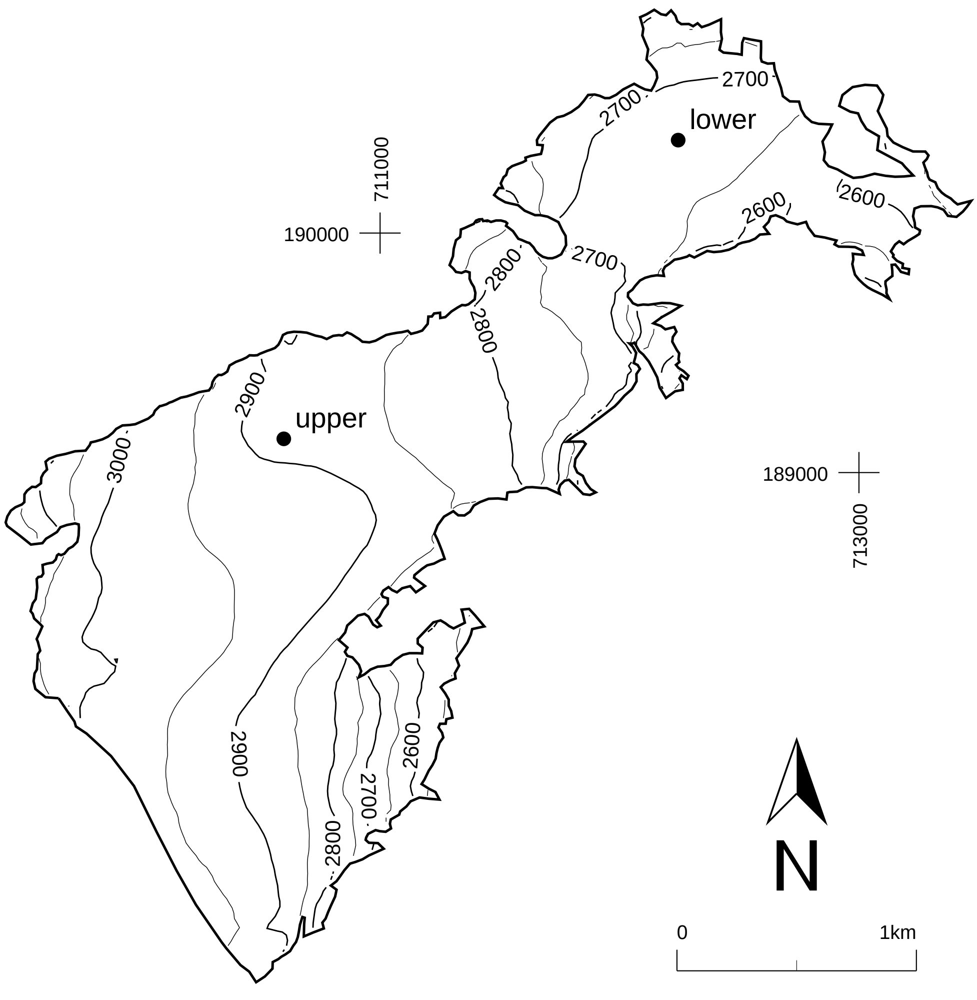


Figure 4.11: Surface topography and observational network of Claridenfirn.

on the years 1914 to 1978 are published in Kasser et al. (1986). Observational techniques and the results for the period 1914 to 1984 are published in Müller and Kappenberger (1991). A further update of the measurements until 2007 allowed Huss and Bauder (2009) to separate accumulation and melt and to interpret the entire time series in terms of climatic drivers (see Section 4.10 of Volume 127/128). Values of the entire homogenized time series of point mass balance 1914-2015 are compiled in Section 4.16 of Volume 135/136 (Figure 4.12). Based on this data, updated to 2020, Huss et al. (2021) calculated glacier-wide mass balance for the entire time series with a special consideration of the effect of mass losses by frontal ice avalanches. Even though spatial mass balance variability of the entire glacier is incompletely resolved by only two point measurements, a combination with decadal ice-volume changes from repeated digital elevation models allows constraining long-term glacier evolution. Investigations on the glacier are complemented by measurements of two precipitation storage gauges at Claridenhütte (2475 m a.s.l.) and Geissbützistock (2710 m a.s.l.) situated in the close vicinity of the glacier. Readings are taken both during spring and fall visits.

Table 4.7: Claridenfirn - Individual stake measurements of winter and annual balance.2 Note that the lowermost elevation band also includes estimated mass losses by frontal break-off of ice.

Stake	Start	Period Spring	End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	 b_a
lower	25.09.2021	11.05.2022	23.09.2022	712261 / 190406 / 2660	1585	−3537
upper	25.09.2021	11.05.2022	23.09.2022	710611 / 189126 / 2880	1772	−1884
lower	23.09.2022	04.05.2023	15.09.2023	712278 / 190427 / 2650	1643	−2322
upper	23.09.2022	04.05.2023	15.09.2023	710595 / 189120 / 2880	1966	−473

Investigations in 2021/22

Spring measurements were carried out on 11th May 2022. Density by coring to a marked horizon was obtained at both sites and supplemented by 10-20 snow depth probings in the vicinity of the stakes. Additional snow depth probings were collected between the two stakes in a 200 m interval. A snow depth of 3 m and 3.5 m was present. At the upper site the density of 502 kg m^{-3} was measured while at the lower site a value of 500 kg m^{-3} was determined. Autumn measurements were carried out on 23rd September 2022. At both sites the snow accumulation during winter was completely depleted with additional extreme loss of 2.8 m to 3.5 m firn or ice. In addition to the measurements of mass balance, surface lowering and horizontal displacement of the stakes was determined in autumn. Both stakes were redrilled at the initial location.

Investigations in 2022/23

The spring field survey was carried out on 4th May, and the late summer survey on 15th September 2023. The investigations included snow depth probings and density measurements using a core drill in spring at the two stakes. The observations were supplemented by additional snow depth sampling between the two sites in a 200 m interval. A density of 465 kg m^{-3} at the upper site and 463 kg m^{-3} at the lower was found. At the end of September, a negative mass balance was registered once again at both sites. In addition, a substantial lowering of the surface was measured and complemented by the determination of the displacement of the stakes.

Retreat of Tiefengletscher between 2014 (top) and 2023 (bottom) (Photos: L. Eggimann, AFJ/UR)

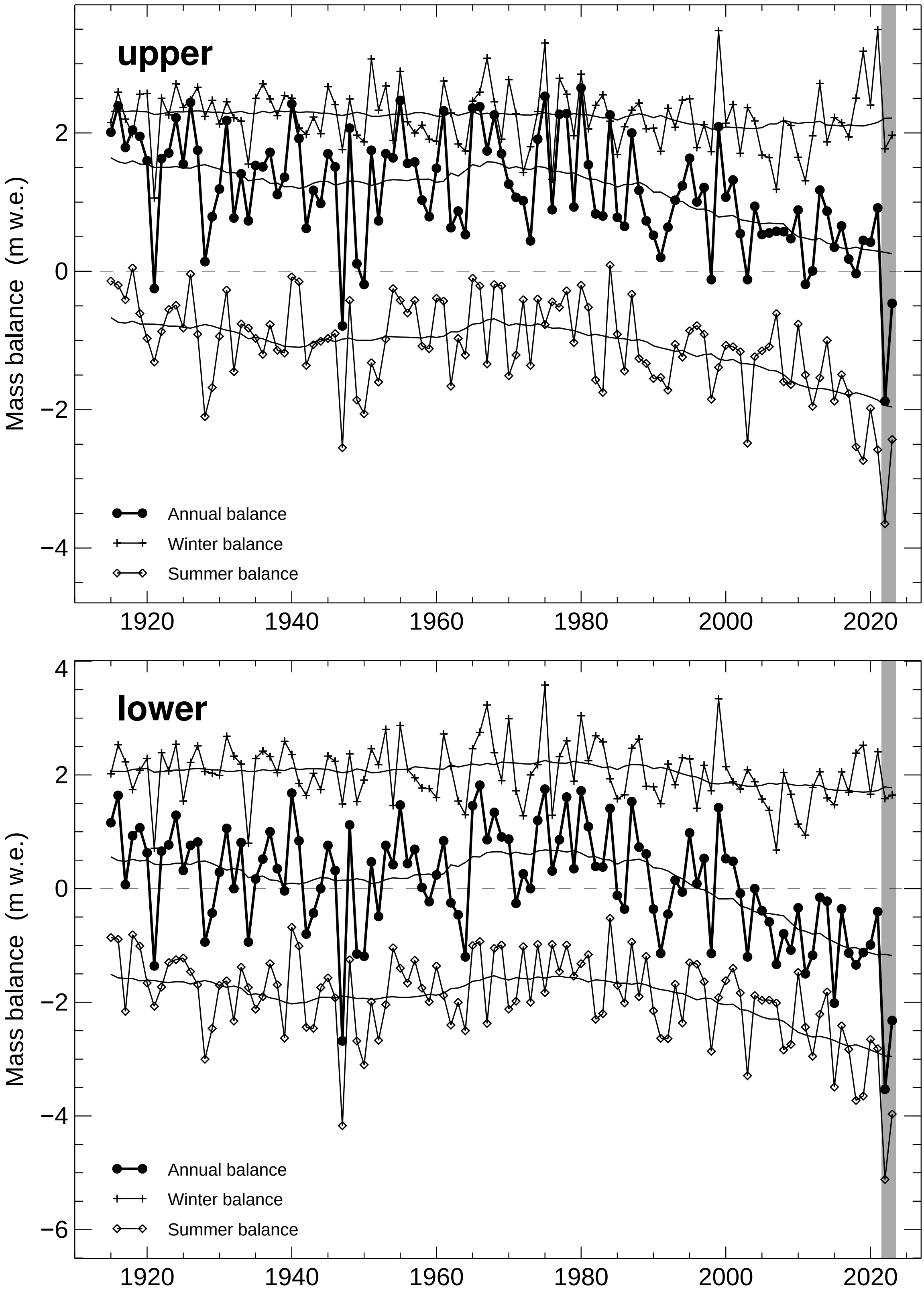


Figure 4.12: Mass balance of the upper (top) and lower (bottom) stake on Claridenfirn over the whole observation period. The gray-shaded area highlights the years of the current report.

Table 4.8: Claridenfirn - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey. Note that the lowermost elevation band also contains mass loss contributions from estimated ice break-off at the glacier snout.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2500 - 2600	0.058	1134	−4878	0.026	1011	−4026
2600 - 2700	0.723	1538	−3562	0.648	1490	−2407
2700 - 2800	0.667	1413	−3360	0.624	1355	−2233
2800 - 2900	1.332	1497	−3031	1.305	1456	−1912
2900 - 3000	1.363	1397	−2875	1.363	1347	−1777
3000 - 3100	0.152	1485	−1700	0.152	1452	−594
3100 - 3200	0.026	1126	−1666	0.026	1108	−713
2500 - 3200	4.321	1451	−3090	4.144	1405	−1950

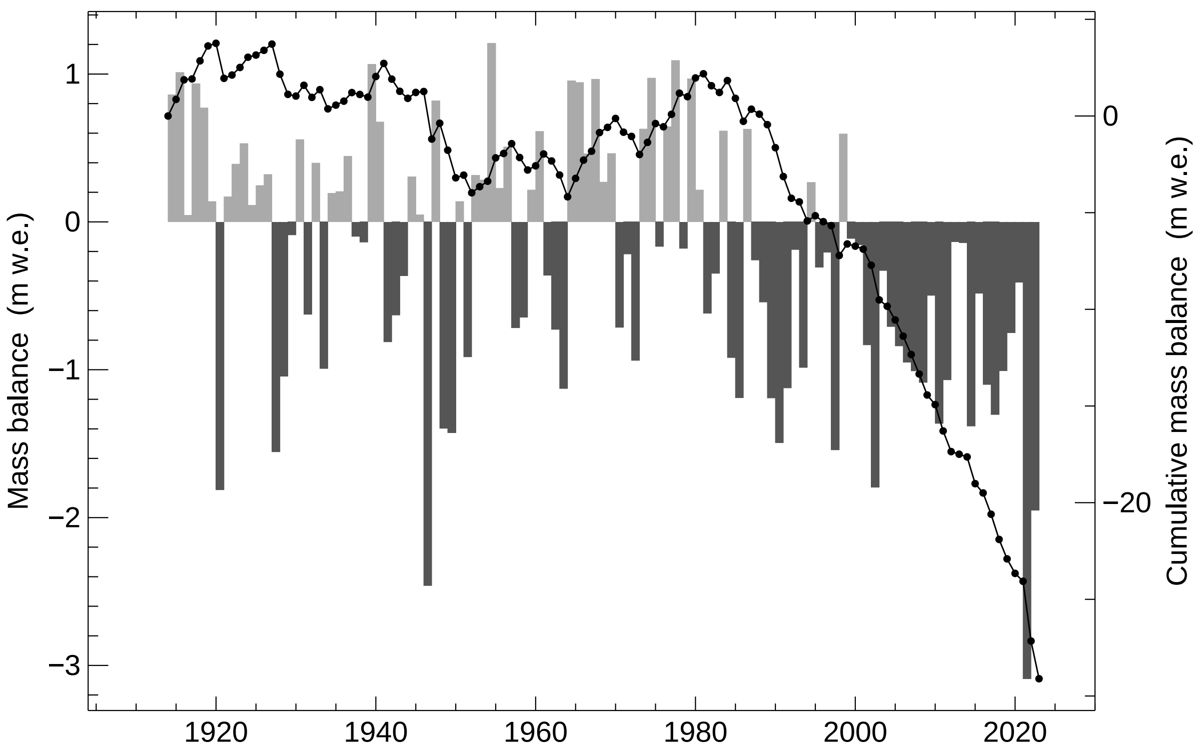


Figure 4.13: Claridenfirn - Mean specific annual balance (bars) and cumulative mass balance (line) for the period 1914-2023.

4.7 Glacier de Corbassière

Introduction

Since 1967, Glacier de Corbassière has been under observation by the Mauvoisin power company that exploits water from the catchment. Observations have been carried out on two profiles in the ablation area (Figure 4.14) where thickness change and ice flow was measured annually (see Chapter 5). Starting in 1996, stakes were maintained to measure annual quantities of ice flow velocity and local mass balance. Annual point mass balance measurements and ice volume changes have been analyzed to derive glacier-wide mean specific annual balance for comparable fixed-date for 1996 to 2015 (Huss et al., 2015). Annual updates using a consistent methodology

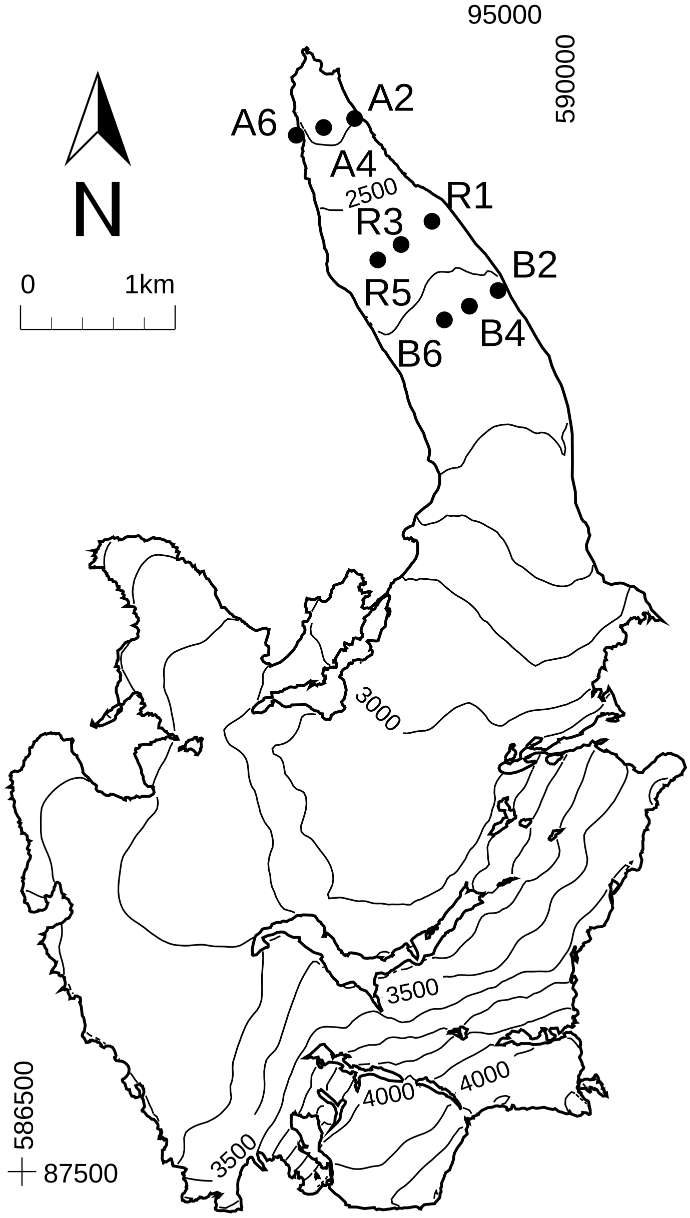


Figure 4.14: Surface topography and observational network of Glacier de Corbassière.

are performed since then (GLAMOS, 2023a). Here, we only present the results of annual point mass balance measurements. Further details on the long-term observations of ice flow velocities are given in Section 5.3.

Investigations in 2021/22

Annual observations of mass balance with maintenance of the stake network were carried out on 1st and 2nd September 2022. An extremely negative local mass balances resulted at all stakes. Due to rapid thinning and complete wastage in the past, the sites of the lowest profile (A2, A4, A6) were fated to be lost soon and the network was reorganized for more representative measurement locations in fall 2020. Only the stake A2 was maintained longer and could be measured for the last time in fall 2022 but was finally abandoned.

Investigations in 2022/23

The annual field survey took place on 12th September 2023. Six stakes of the reorganized network could be measrued and have been redrilled. Again at all stakes a pronounced negative local mass balance was determined.

Table 4.9: Glacier de Corbassière - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
B4	14.09.2021		01.09.2022	589381 / 93105 / 2611		−5085
B6	14.09.2021		01.09.2022	589231 / 93022 / 2615		−4968
R1	14.09.2021		01.09.2022	589141 / 93648 / 2567		−5562
R3	14.09.2021		01.09.2022	588948 / 93503 / 2566		−4923
R5	14.09.2021		01.09.2022	588806 / 93406 / 2566		−5175
A2	15.09.2021		02.09.2022	588655 / 94313 / 2387		−8307
B2	01.09.2022		12.09.2023	589577 / 93207 / 2602		−4842
B4	01.09.2022		12.09.2023	589383 / 93107 / 2607		−5157
B6	01.09.2022		12.09.2023	589222 / 93015 / 2611		−4950
R1	01.09.2022		12.09.2023	589142 / 93642 / 2567		−4248
R3	02.09.2022		12.09.2023	588948 / 93503 / 2562		−4842
R5	01.09.2022		12.09.2023	588799 / 93399 / 2560		−5157

4.8 Findelengletscher

Introduction

Findelengletscher (12.4 km^2) and its former tributary Adlergletscher (2.0 km^2) are located in the southern Valais in the Zermatt area. The two glaciers cover an elevation range from 2580 m a.s.l. to 4120 m a.s.l. Findelengletscher is west-facing and is characterized by gently sloping high-elevation accumulation basins and a comparatively narrow glacier tongue. The region is relatively dry with equilibrium line altitudes among the highest in the Alps. Mass balance measurements on Findelengletscher were initiated in fall 2004 and the observational network was extended to Adlergletscher one year later.

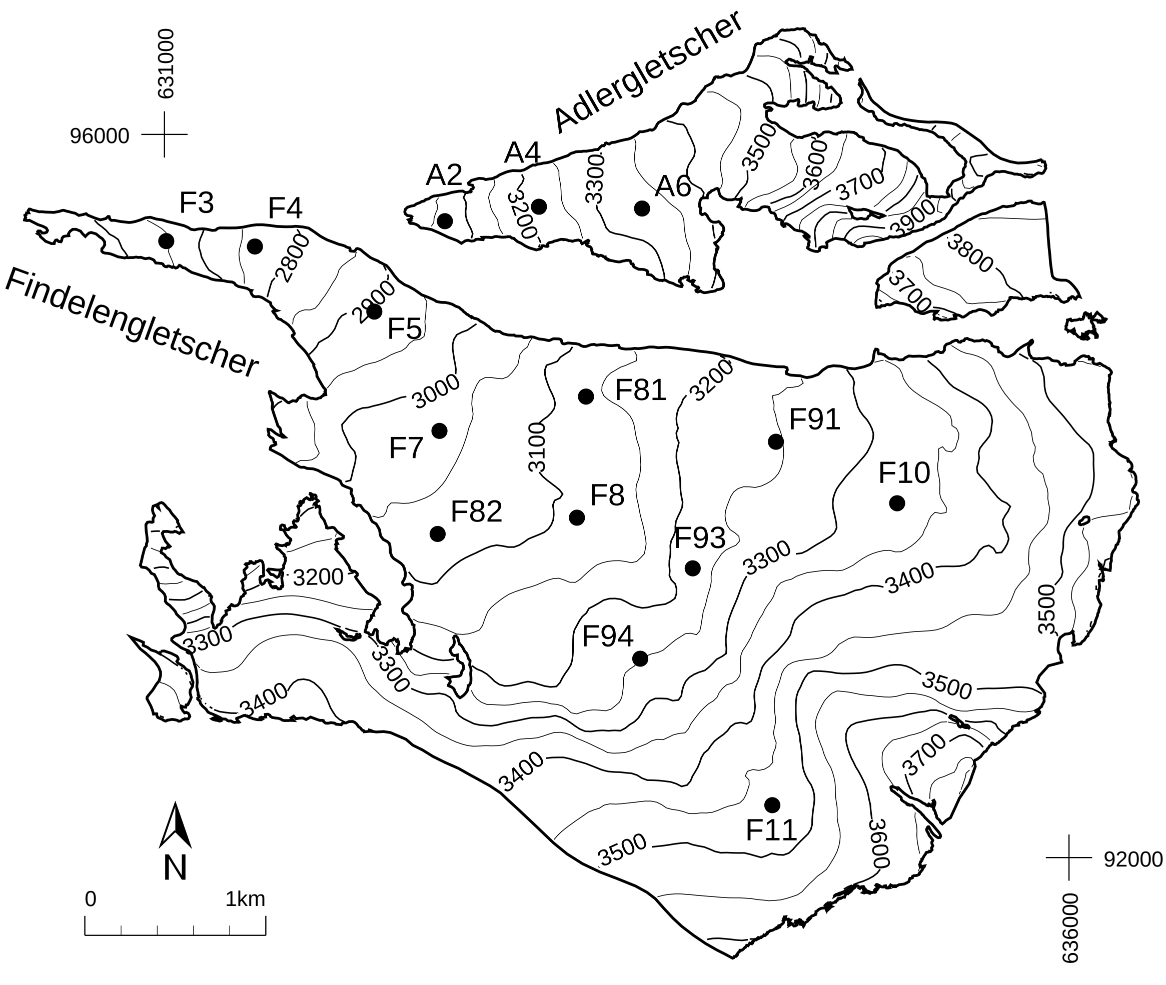


Figure 4.15: Surface topography and observational network on Findelengletscher and the former tributary Adlergletscher. Note that mass balance of Findelen- and Adlergletscher is evaluated over a homogenized perimeter that excludes some areas with very thick debris-coverage and unconnected tributaries below Stockhorn.

Investigations in 2021/22

Winter mass balance of Findelen- and Adlergletscher was determined on 6th April 2022 with three separate teams. Snow probings were acquired at 318 locations and snow density was measured by coring at five sites distributed over the glacier's entire elevation range. Related to very low snow depth, exceptionally low snow densities of between 270 kg m^{-3} and 340 kg m^{-3} were measured. An autonomous station to continuously measure snow accumulation in winter and ice ablation via a webcam observing a stake was maintained. All mass balance stakes were visited and redrilled on 5th September 2022. As no intermediate survey for maintaining the stake network was possible during the summer season despite pronounced melting, three stakes close to the usual equilibrium line altitude melted out. Even at the topmost measurement site (3480 m a.s.l.) substantial ablation occurred. The annual mass balance could be determined for ten locations on Findelen-, and three on Adlergletscher.

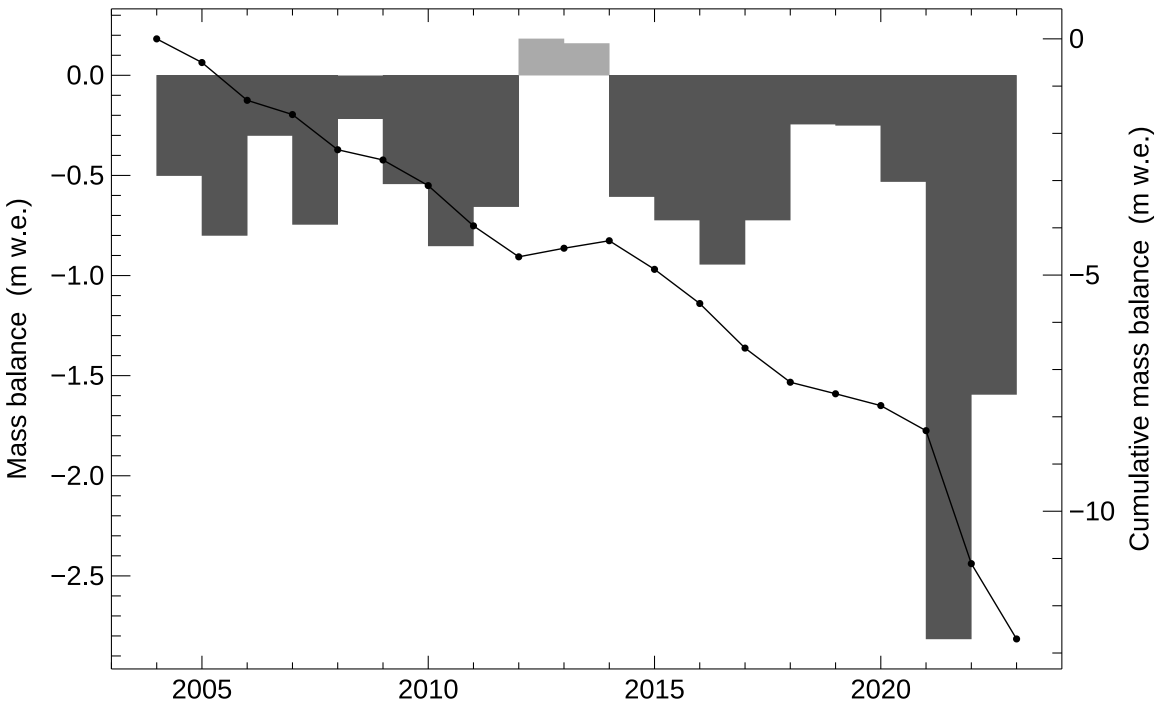


Figure 4.16: Findelengletscher - Mean specific annual balance (bars) and cumulative mass balance for the period 2004-2023.

Investigations in 2022/23

The winter survey was performed on 18th April 2023. In total, 240 snow probings distributed over the entire surface of Findelen- and Adlergletscher were obtained, and snow density was measured by coring at five sites. Snow densities were again extremely low and ranged between 210 kg m^{-3} and 290 kg m^{-3}. The limited snow depth led to a precarious situation regarding crevasse fall hazards. On 12 September 2023, the lower part of the stake network on Findelen- and Adlergletscher was redrilled, and on 19th September 2023 the entire stake network on Findelen was visited. Mass balance was determined at 13 stakes on Findelen- and at three on Adlergletscher. An autonomous real-time camera was maintained for monitoring winter snow accumulation and summer ice melt. Only the topmost site showed very limited firn accumulation, but density was not measured. After 18 years of surveys, it was decided to cease maintaining the monitoring of Adlergletscher due to issues of increasingly difficult accessibility related to glacier retreat and limited additional value of observations next to Findelengletscher.

Table 4.10: Findelengletscher and Adlergletscher - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
F3	22.09.2021	06.04.2022	05.09.2022	631010 / 95409 / 2651	181	−7011
F4	22.09.2021	06.04.2022	05.09.2022	631504 / 95383 / 2776	295	−6309
F5	22.09.2021	06.04.2022	05.09.2022	632169 / 95010 / 2916	400	−4923
F7	22.09.2021	06.04.2022	05.09.2022	632528 / 94348 / 3027	613	−4509
F8	22.09.2021	06.04.2022	05.09.2022	633276 / 93876 / 3115	535	−3438
F81	22.09.2021	06.04.2022	05.09.2022	633328 / 94554 / 3141	477	−4491
F82	22.09.2021	06.04.2022	05.09.2022	632508 / 93786 / 3081	682	−4239
F91	22.09.2021	06.04.2022	05.09.2022	634383 / 94298 / 3262	541	−3212
F93	22.09.2021	06.04.2022	05.09.2022	633924 / 93597 / 3232	632	−2709
F94	22.09.2021	06.04.2022	05.09.2022	633627 / 93102 / 3253	376	−3150
F10	22.09.2021	06.04.2022	05.09.2022	635045 / 93957 / 3338	584	−2323
F11	22.09.2021	06.04.2022	05.09.2022	634359 / 92287 / 3477	767	−900
A2	22.09.2021	06.04.2022	05.09.2022	632555 / 95518 / 3071	528	−4554
A4	22.09.2021	06.04.2022	05.09.2022	633073 / 95606 / 3230	436	−4176
A6	22.09.2021	06.04.2022	05.09.2022	633648 / 95589 / 3335	491	−3186
F3	05.09.2022	18.04.2023	19.09.2023	631006 / 95410 / 2640	193	−7200
F4	05.09.2022	18.04.2023	19.09.2023	631488 / 95378 / 2769	260	−5670
F5	05.09.2022	18.04.2023	19.09.2023	632147 / 95033 / 2904	410	−4239
F7	05.09.2022	18.04.2023	19.09.2023	632508 / 94370 / 3029	503	−3690
F8	05.09.2022	18.04.2023	19.09.2023	633276 / 93876 / 3115	498	−2990
F81	05.09.2022	18.04.2023	19.09.2023	633328 / 94554 / 3141	564	−3640
F82	05.09.2022	18.04.2023	19.09.2023	632508 / 93786 / 3081	455	−3140
F91	05.09.2022	18.04.2023	19.09.2023	634383 / 94298 / 3262	699	−2300
F93	05.09.2022		19.09.2023	633924 / 93597 / 3232		−2620
F94	05.09.2022		19.09.2023	633627 / 93102 / 3253		−2650
F10	05.09.2022	18.04.2023	19.09.2023	635045 / 93957 / 3338	555	−1790
F11	05.09.2022	18.04.2023	19.09.2023	634359 / 92287 / 3477	829	379
A2	05.09.2022	18.04.2023	12.09.2023	632553 / 95518 / 3069	530	−3663
A4	05.09.2022	18.04.2023	12.09.2023	633060 / 95601 / 3232	431	−3609
A6	05.09.2022	18.04.2023	19.09.2023	633635 / 95577 / 3338	643	−2570

Table 4.11: Findelengletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude (m a.s.l.)	2021/22 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)	2022/23 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)
2500 - 2600	0.033	74	−8068	0.014	-382	−7877
2600 - 2700	0.104	138	−7347	0.087	-269	−7125
2700 - 2800	0.165	224	−6532	0.158	-127	−5984
2800 - 2900	0.286	359	−5404	0.259	103	−4687
2900 - 3000	0.551	427	−4824	0.534	300	−3929
3000 - 3100	1.042	519	−4412	1.056	468	−3350
3100 - 3200	1.634	564	−3712	1.597	543	−3009
3200 - 3300	1.803	571	−2832	1.786	686	−2206
3300 - 3400	1.942	551	−2125	1.942	803	−1325
3400 - 3500	2.353	514	−1916	2.353	883	−265
3500 - 3600	1.601	415	−1818	1.601	813	529
3600 - 3700	0.445	298	−1741	0.445	519	53
3700 - 3800	0.290	237	−1547	0.290	456	−452
3800 - 3900	0.253	203	−1452	0.253	576	−70
3900 - 4000	0.011	162	−1183	0.011	350	−435
2500 - 4000	12.511	486	−2815	12.383	660	−1594

Table 4.12: Adlergletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude (m a.s.l.)	2021/22 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)	2022/23 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)
2900 - 3000	0.006	523	−4458	0.006	300	−4343
3000 - 3100	0.086	491	−4469	0.086	375	−3986
3100 - 3200	0.123	412	−4276	0.123	440	−3664
3200 - 3300	0.253	370	−3931	0.253	458	−3423
3300 - 3400	0.399	335	−3313	0.399	500	−2716
3400 - 3500	0.315	396	−2842	0.315	526	−2078
3500 - 3600	0.246	329	−2386	0.246	444	−1642
3600 - 3700	0.208	276	−2008	0.208	404	−1264
3700 - 3800	0.177	286	−1390	0.177	430	−654
3800 - 3900	0.103	269	−1113	0.103	427	−367
3900 - 4000	0.046	278	−981	0.046	446	−288
4000 - 4100	0.014	268	−874	0.014	462	−193
4100 - 4200	0.004	208	−1001	0.004	313	−527
2900 - 4200	1.979	344	−2814	1.979	460	−2150

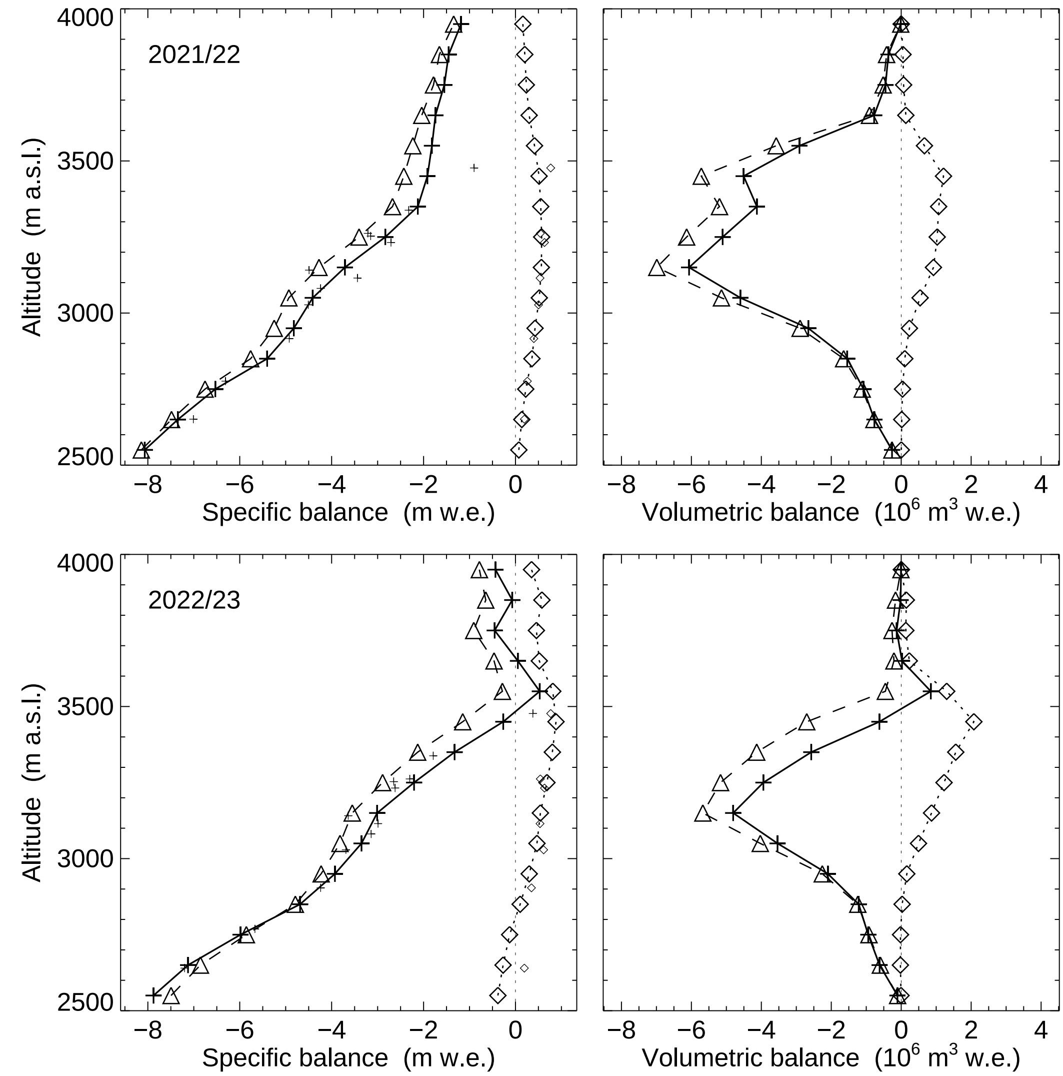


Figure 4.17: Findelengletscher - Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

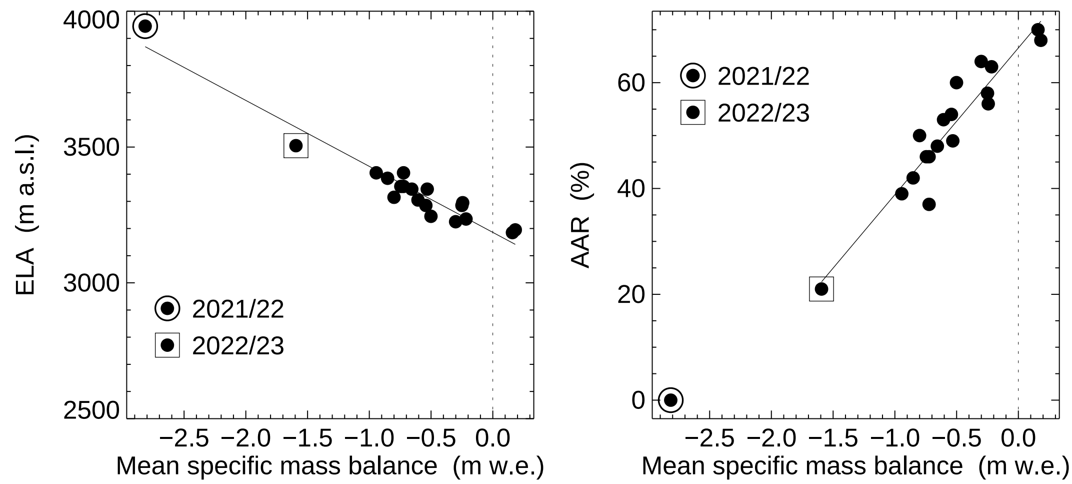


Figure 4.18: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.9 Glacier du Giétro

Introduction

Glacier du Giétro is a temperate mountain glacier in the Southern Valais Alps (Val de Bagnes). The glacier has been under observation for early recognition of glacier break-off, which can endanger the reservoir operated by the Forces Motrices de Mauvoisin SA located in the potential reach of ice avalanches. The measurements carried out since the mid-1960s include glacier evolution, ice flow, as well as mass balance. The observations of more than half a century document periods of glacier growth and recession (VAW, 1997, 1998; Bauder et al., 2002; Raymond et al., 2003). Annual mass balance is measured at stakes and glacier-wide mean specific annual balance is determined (Figure 4.20). No survey in spring to evaluate the winter snow accumulation is conducted. Data of point mass balance and ice volume changes since 1966 was re-analyzed and homogenized in order to evaluate glacier-wide mean specific annual balance for comparable fixed-date periods (Huss et al., 2015). Annual updates using a consistent methodology are performed since then (GLAMOS, 2023a). Further details on long-term observation of ice flow velocities are given in Section 5.4.

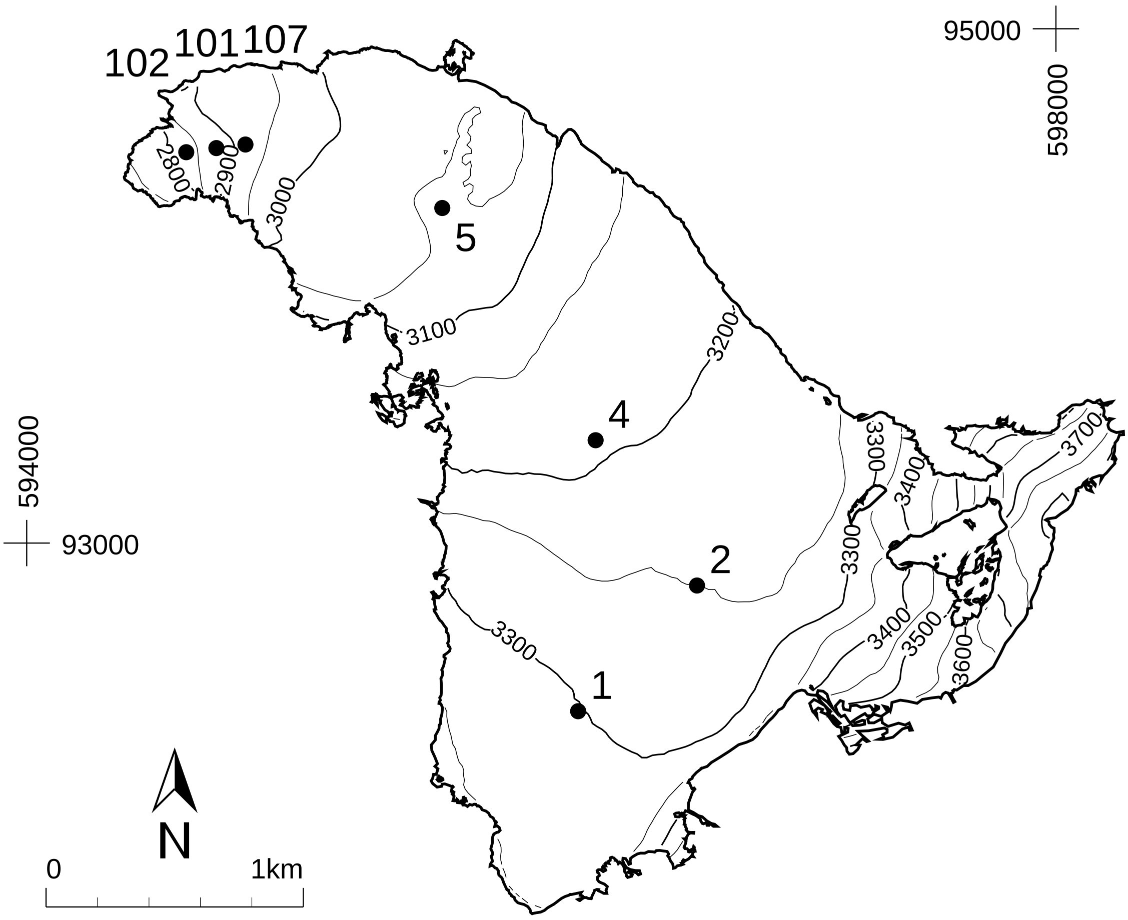


Figure 4.19: Surface topography and observational network of Glacier du Giétro.

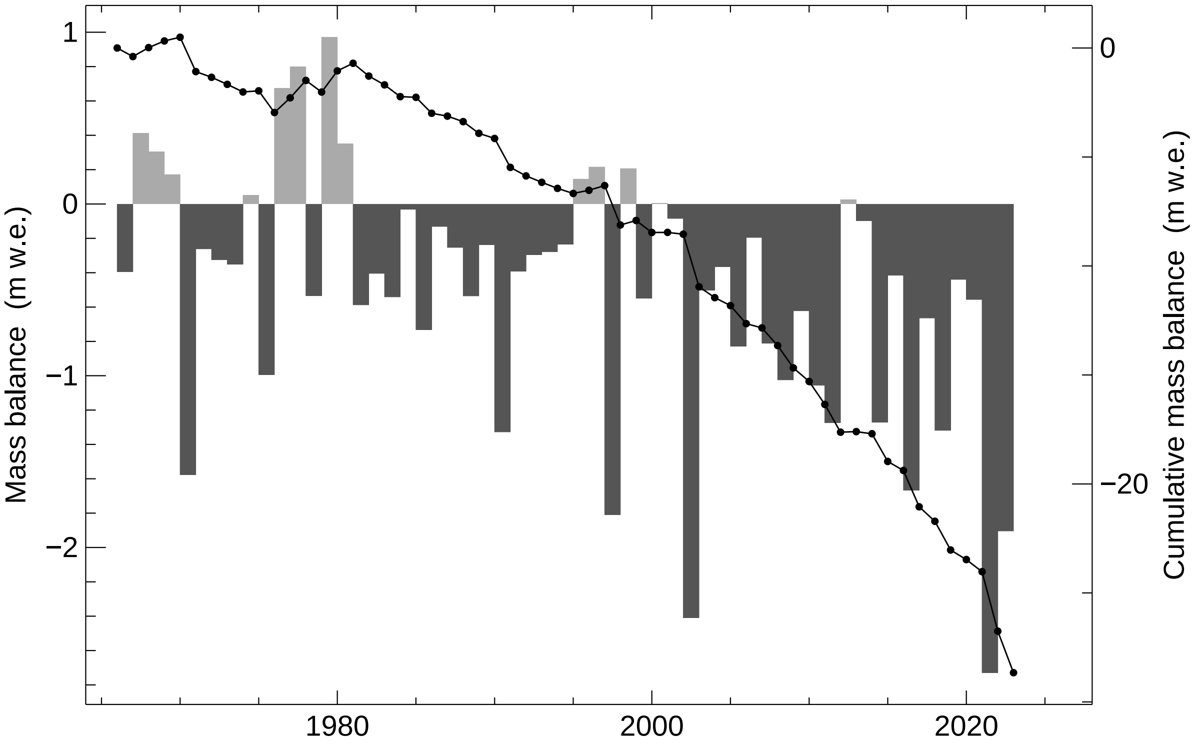


Figure 4.20: Glacier du Giétro - Mean specific annual balance (bars) and cumulative mass balance for the period 1966-2023. Values refer to the measurement period.

Investigations in 2021/22

Annual observations of mass balance with maintenance of the stake network were carried out on 1st September 2022. The winter snow accumulation completely depleted on the entire glacier. Extremely negative local mass balances resulted at all seven stakes. The most extreme melt rates on record for more than five decades at the highest measurement sites were noteworthy.

Investigations in 2022/23

The annual field survey took place on 12th September 2023. Again a negative local mass balance was found at all stakes. The recession of the glacier tongue continued unabatedly. Due to complete disintegration of the lower terrace the stake 102 could no longer be maintained.

Table 4.13: Glacier du Giétro - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude (m a.s.l.)	2021/22 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)	2022/23 Area (km^2)	$\overline{b_w}$ (mm w.e.)	$\overline{b_a}$ (mm w.e.)
2700 - 2800	0.007	513	−6110	0.007	699	−5142
2800 - 2900	0.058	582	−5508	0.058	783	−4637
2900 - 3000	0.212	691	−4755	0.213	908	−3861
3000 - 3100	0.838	773	−4022	0.855	992	−3159
3100 - 3200	0.953	835	−3151	0.956	1069	−2284
3200 - 3300	1.634	884	−2688	1.634	1140	−1551
3300 - 3400	0.916	911	−1905	0.916	1178	−1120
3400 - 3500	0.172	921	−712	0.172	1197	−228
3500 - 3600	0.117	866	−268	0.096	1164	−1
3600 - 3700	0.121	792	−65	0.072	1018	−89
3700 - 3800	0.116	791	25	0.075	979	−206
3800 - 3900	0.009	808	40	0.006	1013	−153
2700 - 3900	5.175	845	−2729	5.061	1092	−1904

Table 4.14: Glacier du Giétro - Individual stake measurements of winter and annual balance.

Stake	Period Start	Spring	End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	b_a (mm w.e.)
01	14.09.2021		01.09.2022	596153 / 92354 / 3293		−2269
02	14.09.2021		01.09.2022	596603 / 92846 / 3243		−2737
04	14.09.2021		01.09.2022	596209 / 93404 / 3179		−3096
05	14.09.2021		01.09.2022	595619 / 94169 / 3044		−4068
101	14.09.2021		01.09.2022	594726 / 94535 / 2855		−4248
102	14.09.2021		01.09.2022	594628 / 94507 / 2799		−7308
107	14.09.2021		01.09.2022	594841 / 94548 / 2898		−5049
01	01.09.2022		12.09.2023	596144 / 92347 / 3291		−1755
02	01.09.2022		12.09.2023	596604 / 92842 / 3241		−1557
04	01.09.2022		12.09.2023	596209 / 93405 / 3177		−2232
05	01.09.2022		12.09.2023	595620 / 94168 / 3042		−3249
101	01.09.2022		12.09.2023	594739 / 94531 / 2854		−3348
107	01.09.2022		12.09.2023	594848 / 94547 / 2897		−4185

4.10 Griesgletscher (Aegina)

Introduction

Griesgletscher is a temperate valley glacier located in the central Swiss Alps. The glacier currently covers an area of 4.1 km^2 flowing in north-eastern direction from 3320 m a.s.l. down to 2440 m a.s.l. Mass balance measurements started in 1961 in connection with the construction of a reservoir for hydro-power production. Determination of volumetric changes in decadal resolution extend further back to 1884 (Bauder et al., 2007; GLAMOS, 2023b). Topographic maps or photogrammetrical surveys exist for 1884, 1923, 1961, 1967, 1979, 1986, 1991, 1998, 2003, 2007 and annually since 2012. Huss et al. (2009) re-analyzed and homogenized the seasonal point mass balance data and ice volume changes for the period 1961-2007, and annual updates using a consistent methodology are performed since then (GLAMOS, 2023a).

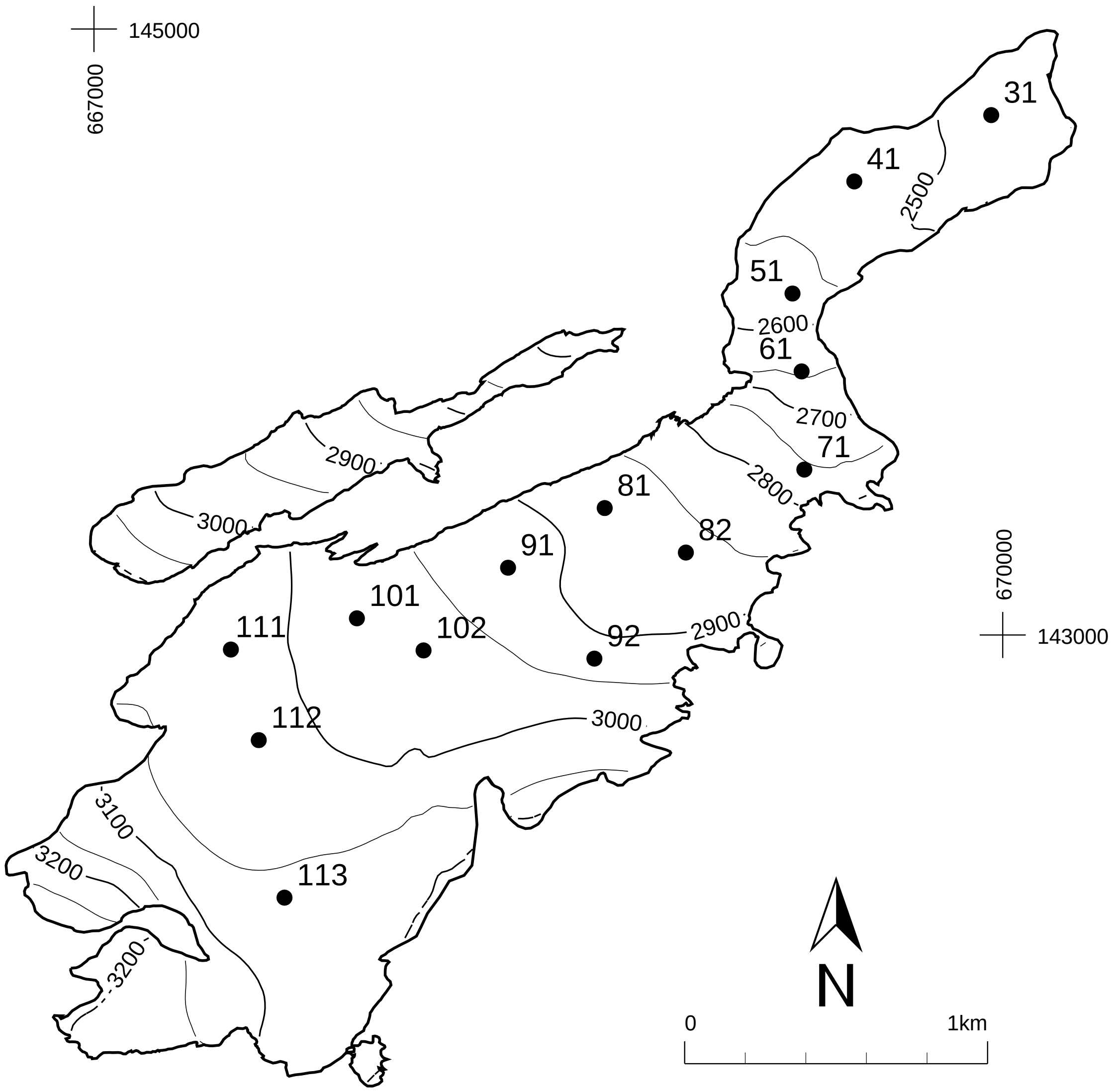


Figure 4.21: Surface topography and observational network of Griesgletscher.

Investigations in 2021/22

Winter snow depth probings were collected at 168 locations distributed across the glacier surface, and including all stake locations on 20th April 2022. Snow density was measured by coring at three sites indicating values of between 380 and 430 kg m^{-3}. On 8th June and 17th July intermediate visits of the glacier were performed, including a complete survey and partial redrilling of the network related to the extreme melt rates. On 2nd September 2022 the late summer field survey was performed and the complete stake network was redrilled. A strongly negative mass balance was determined at all 15 stakes. Even at the topmost stake profile (3030 m a.s.l.) in the former accumulation area, ice ablation rates of up to 4 m were measured. Disintegration of the glacier is accelerating with new rock outcrops appearing amidst the steeper section separating the upper plateau from the glacier tongue.

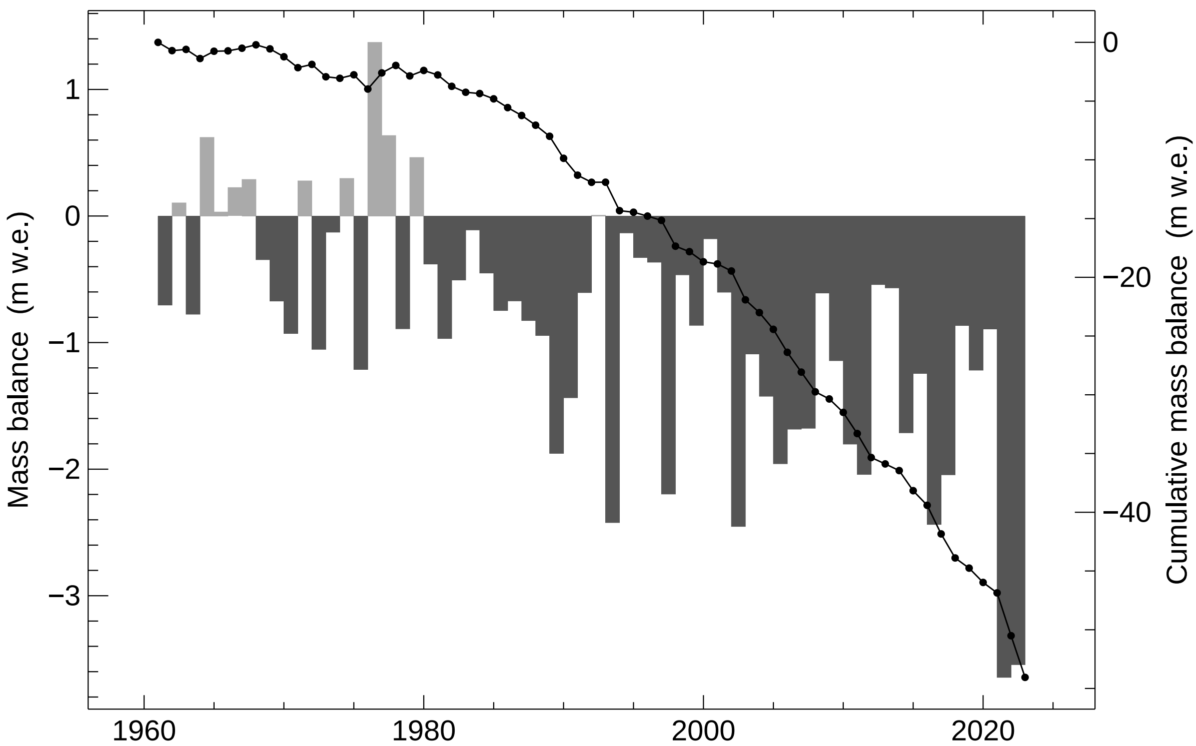


Figure 4.22: Griesgletscher - Mean specific annual balance (bars) and cumulative mass balance for the period 1961-2023.

Investigations in 2022/23

The winter mass balance was monitored on 19th April 2023. Snow probings were acquired at 180 locations over the glacier's entire elevation range. Snow density was measured by coring at four locations indicating low values of between 320 and 350 kg m^{-3}. An intermediate reading of all mass balance stakes was performed on 16th July, and the late summer survey was conducted on 11th September 2023. A strongly negative mass balance was determined at all 14 sites and the stakes were redrilled. Due to continued substantial melt rates, another full visit of the network was performed on 5th October. Compared to early September 2022, new record ice ablation of beyond 7 m was measured on the glacier tongue, while again almost 4 m of ice were lost at the topmost stake profile. A station for autonomous monitoring of snow accumulation and ice melt was installed at one site close to the glacier terminus providing real-time information on the state of the glacier.

Table 4.15: Griesgletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2400 - 2500	0.103	262	−6015	0.176	415	−6493
2500 - 2600	0.482	384	−5533	0.337	408	−5813
2600 - 2700	0.125	684	−4668	0.110	553	−4141
2700 - 2800	0.233	874	−3726	0.203	638	−3572
2800 - 2900	0.528	961	−3471	0.519	709	−3600
2900 - 3000	0.920	1086	−3278	0.901	935	−3267
3000 - 3100	1.320	1022	−3226	1.227	1035	−2874
3100 - 3200	0.275	896	−2986	0.236	909	−2591
3200 - 3300	0.113	1018	−2499	0.099	662	−2740
3300 - 3400	0.003	1019	−1160	0.001	433	−1736
2300 - 3400	4.102	907	−3645	3.809	830	−3545

Drilling an ablation stake on the completely snow-free Glacier de la Plaine Morte in August 2022. (Photo: M. Huss)

Table 4.16: Griesgletscher - Individual stake measurements of winter and annual balance.

Stake	Period Start	Spring	End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	b_a
31	18.09.2021	20.04.2022	02.09.2022	669964 / 144713 / 2503	445	−5940
41	18.09.2021	20.04.2022	02.09.2022	669508 / 144494 / 2535	449	−5229
51	18.09.2021	20.04.2022	02.09.2022	669305 / 144128 / 2576	590	−5508
61	18.09.2021	20.04.2022	02.09.2022	669334 / 143873 / 2639	706	−4797
71	18.09.2021	20.04.2022	02.09.2022	669346 / 143546 / 2763	963	−2907
81	18.09.2021	20.04.2022	02.09.2022	668684 / 143420 / 2882	831	−3897
82	18.09.2021	20.04.2022	02.09.2022	668952 / 143271 / 2861	975	−3528
91	18.09.2021	20.04.2022	02.09.2022	668364 / 143221 / 2929	903	−3960
92	18.09.2021	20.04.2022	02.09.2022	668652 / 142921 / 2928	1041	−2646
101	18.09.2021	20.04.2022	02.09.2022	667872 / 143056 / 2981	1008	−3942
102	18.09.2021	20.04.2022	02.09.2022	668086 / 142945 / 2978	968	−3060
111	18.09.2021	20.04.2022	02.09.2022	667453 / 142952 / 3032	1155	−3771
112	18.09.2021	20.04.2022	02.09.2022	667545 / 142652 / 3023	906	−3330
113	18.09.2021	20.04.2022	02.09.2022	667626 / 142136 / 3067	733	−3239
HF	18.09.2021	20.04.2022	02.09.2022	669756 / 144595 / 2515	449	−5652
31	02.09.2022	19.04.2023	05.10.2023	669960 / 144719 / 2498	585	−6678
41	02.09.2022	19.04.2023	05.10.2023	669512 / 144499 / 2528	585	−5859
61	02.09.2022	19.04.2023	05.10.2023	669337 / 143867 / 2626	544	−4824
71	02.09.2022	19.04.2023	05.10.2023	669343 / 143545 / 2752	891	−3231
81	02.09.2022	19.04.2023	05.10.2023	668687 / 143418 / 2883	785	−3735
82	02.09.2022	19.04.2023	05.10.2023	668955 / 143273 / 2865	834	−3636
91	02.09.2022	19.04.2023	05.10.2023	668369 / 143223 / 2926	923	−3897
92	02.09.2022	19.04.2023	05.10.2023	668651 / 142923 / 2927	1049	−2610
101	02.09.2022	19.04.2023	05.10.2023	667863 / 143054 / 2982	912	−3627
102	02.09.2022	19.04.2023	05.10.2023	668091 / 142953 / 2973	817	−3393
111	02.09.2022	19.04.2023	05.10.2023	667452 / 142952 / 3027	1028	−3474
112	02.09.2022	19.04.2023	05.10.2023	667542 / 142654 / 3017	982	−3375
113	02.09.2022	19.04.2023	05.10.2023	667631 / 142129 / 3068	852	−2601

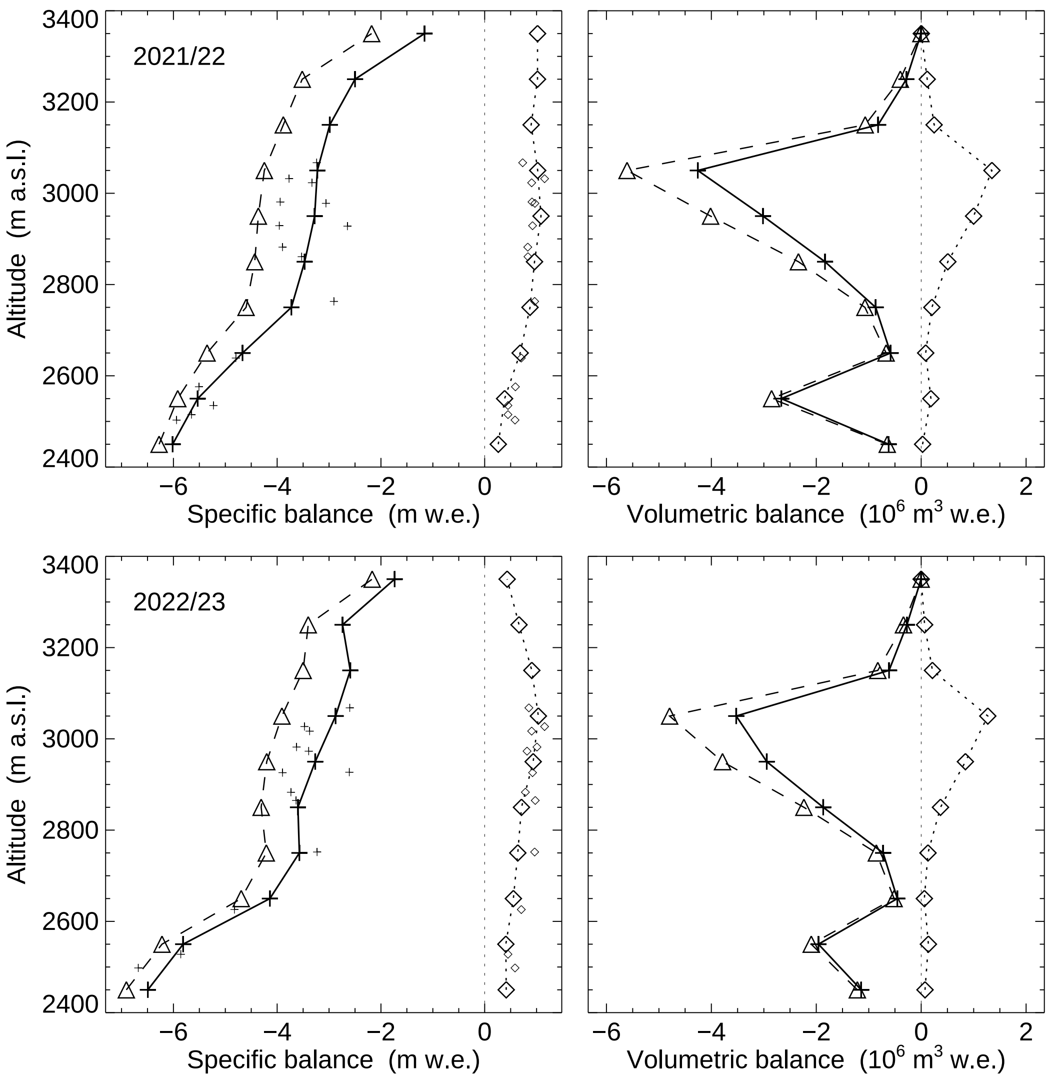


Figure 4.23: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

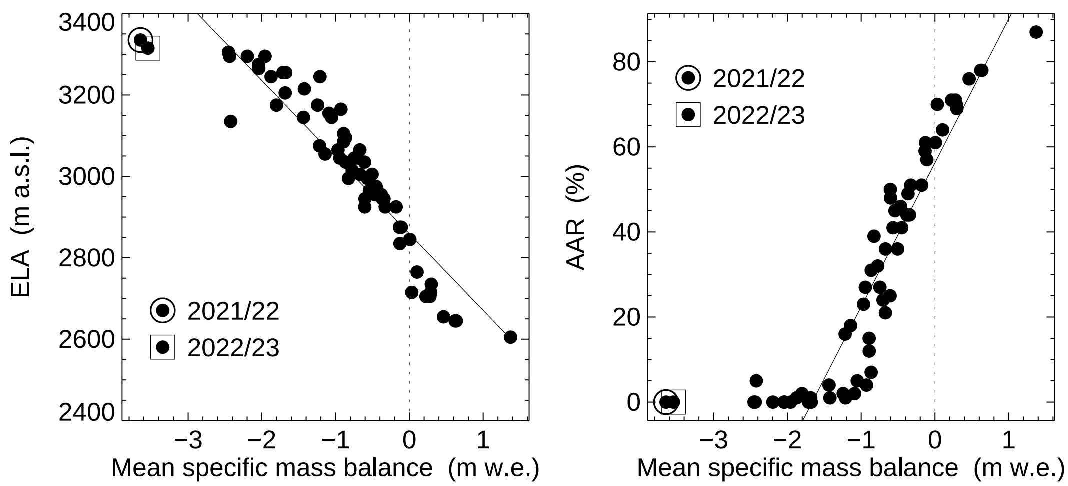


Figure 4.24: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.11 Grosser Aletschgletscher

Introduction

Grosser Aletschgletscher is the largest ice mass in the European Alps and borders the main Alpine crest. By 2017 it covered an area of 78.5 km^2 and had a volume of 11.6 km3, thus accounting for a fifth of the total ice mass of Switzerland (Linsbauer et al., 2021; Grab et al., 2021). The three main tributaries converge at the Konkordiaplatz and form the common tongue which extends southwards for about 13 km. Starting in 1918, the first stake was installed at 3350 m a.s.l. on Jungfraufirn and snow accumulation and annual mass balance was measured almost continuously until today at site 3 (Figure 4.25). Huss and Bauder (2009) compiled and homogenized all existing

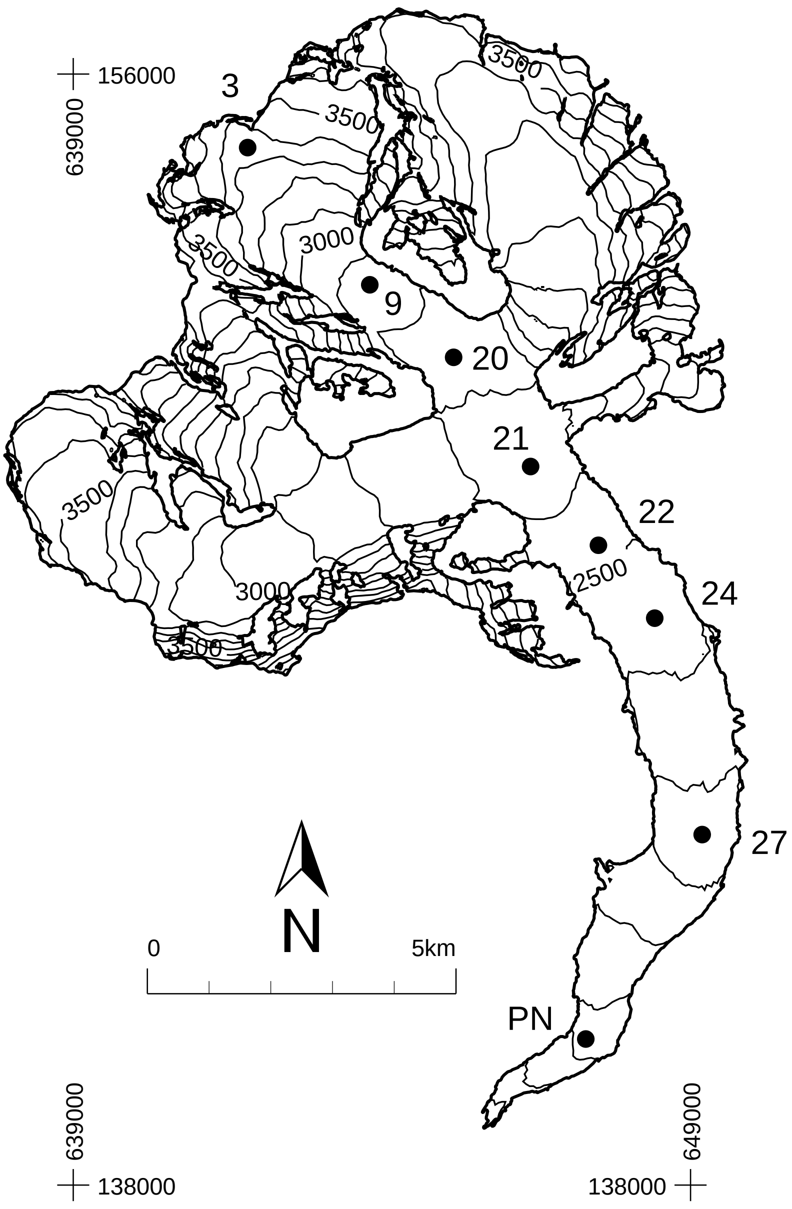


Figure 4.25: Surface topography and observational network of Grosser Aletschgletscher.

measurements to provide a continuous time series of seasonal resolution (see Section 4.10 in Volume 127/128). Between the 1940s and 1990s a network of stakes on a longitudinal and several cross profiles was maintained with a focus on both mass balance and ice flow velocity (Zoller, 2010; Geibel et al., 2022). As part of the educational activities of ProNatura, mass balance is measured at site PN on the glacier tongue at an elevation of 2000 m a.s.l. Starting in 1992, weekly readings have been carried out during the summer season, and since the year 1995/96 the annual balance has been determined as well. Since 2020, a network of six additional stakes along the longitudinal transect between Jungfraujoch and Märjelensee is maintained and observed both in April and September to provide a stronger basis for assessing the seasonal mass change of the entire glacier system. Results from additional investigations of ice flow velocities are given in Section 5.5.

Investigations in 2021/22

On 28th March 2022, a complete winter mass balance survey along the central transect of Grosser Aletschgletscher was performed. 72 Snow probings were acquired every few hundred meters and snow density was measured by coring at five sites resulting in a comprehensive altitudinal profile of snow depth and density. During the late-summer field survey on 21st September 2022 six measurement sites were visited and stakes were redrilled at their original location. Additional detailed investigations of snow depth measurements and density profiling using a core drill in spring and fall were carried out at site 3. The surface was marked at the time of the survey in the previous fall and could be located in the firn cores retrieved for density determination. The measurements were taken in spring on 17th May 2022 and in fall on 4th October 2022. In spring, mean density of the layer accumulated during winter was found to be 472 kg m^{-3}. In fall, the winter accumulation was completely melted away for the first time ever since the beginning of the measurements, and an additional loss of almost 92 cm w.e. of the accumulation from the previous period was registered. This monitoring program was supplemented by stake readings approximately twice a month. At site PN an ablation stake is maintained and reported by ProNatura with weekly readings between June and October. Due to the extraordinarily high melt rate the stake had to be redrilled four times instead of only twice in previous years. A first reading in spring was taken on 11th June 2022 and a last one in fall on 18th October 2022. An autonomous camera for monitoring glacier melt at real time (see Landmann et al., 2021) was re-installed on 8th July 2022 and operated during the summer season at site 27.

Investigations in 2022/23

The same set of measurements was conducted as in the previous period. A first winter mass balance survey was performed on 22nd March 2023 by acquiring 82 snow probings and snow density measurements at five sites between 3350 and 2260 m a.s.l. along the central transect. Observed densities between 220 and 420 kg m^{-3} were found. Rapid snow depletion on the glacier tongue necessitated to perform this survey early in the winter season. On 26th May 2023, a second snow survey was conducted between Jungfraujoch, Kranzbergfirn, Konkordiaplatz and Ewigschneefeld by acquiring snow depth probings at 114 sites. The late summer visit of the measurement sites along the central transect was performed on 20th September 2023. The stakes were redrilled. At site 3, the spring field survey was carried out on 26th May 2023 and the fall survey on 28th September 2023. Corresponding measurements from stake readings, firn drilling, and snow depth sounding in May delivered similar results. Mean density of the layer accumulated in winter was found to be 438 $\mathrm{kg\,m^{-3}}$ in spring, and a density of 573 $\mathrm{kg\,m^{-3}}$ was determined in fall for the annual layer. Mass balance investigations at site PN were undertaken again by ProNatura with measurement in spring on 19th June 2023 and on 17th October 2023 with the determination of summer and annual balance.

Table 4.17: Grosser Aletschgletscher - Individual stake measurements of winter and annual balance.

Stake	Period Start	Period Spring	Period End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	Mass balance b_a (mm w.e.)
3	30.09.2021	17.05.2022	04.10.2022	641830 / 154796 / 3334	1152	−916
9	24.09.2021	28.03.2022	21.09.2022	643881 / 152535 / 2847	804	−4113
20	24.09.2021	28.03.2022	21.09.2022	645162 / 151411 / 2733	846	−5004
21	24.09.2021	28.03.2022	21.09.2022	646284 / 149776 / 2642	646	−5400
22	24.09.2021	28.03.2022	21.09.2022	647617 / 148909 / 2553	245	−5787
24	24.09.2021	28.03.2022	21.09.2022	648532 / 147016 / 2415	259	−6399
27	24.09.2021	28.03.2022	21.09.2022	649270 / 143942 / 2261	216	−7803
PN	13.10.2021	13.06.2022	18.10.2022	647469 / 140938 / 2014	−3393	−11565
3	04.10.2022	26.05.2023	28.09.2023	641825 / 154811 / 3333	1771	928
9	21.09.2022	22.03.2023	20.09.2023	643810 / 152578 / 2851	807	−2619
20	21.09.2022	22.03.2023	20.09.2023	645197 / 151360 / 2717	833	−3087
21	21.09.2022	22.03.2023	20.09.2023	646280 / 149800 / 2635	390	−4239
22	21.09.2022	22.03.2023	20.09.2023	647508 / 148366 / 2518	387	−5715
24	21.09.2022	22.03.2023	20.09.2023	648519 / 147066 / 2412	401	−5553
27	21.09.2022	22.03.2023	20.09.2023	649255 / 143928 / 2249	150	−7884
PN	18.10.2022	19.06.2023	17.10.2023	647463 / 140900 / 2010	−3240	−11331

4.12 Hohlaubgletscher

Introduction

Hohlaubgletscher is a mountain glacier located in the Mattmark area in the Southern Valais Alps. It currently covers an area of 2.1 km^2 flowing in east direction from 4020 m a.s.l. down to 2850 m a.s.l. Mass balance measurements started in 1955 as a part of investigations for the construction of the Mattmark reservoir for hydro-power production (VAW, 1999, 2024). Initially a network of three stakes in the ablation area was maintained for mass balance and ice flow measurements (see Chapter 5). After 1967 measurements were continued at only one stake until 2019 when a second stake was installed. No measurements of winter snow accumulation have been performed between 1997 and 2022, and only annual mass balance was determined. In April 2023 measurements of snow accumulation on the lower glacier tongue were resumed. Data of point mass balance and geodetic ice volume changes since 1955 has been re-analyzed and homogenized (Huss et al., 2015). Here we only present the results of annual point mass balance measurements. Glacier-wide mass balance estimates are presented periodically in a complete form after a calibration with geodetic mass balance based on repeated digital elevation models has been performed (GLAMOS, 2023a). Further details on long-term observations of ice flow velocities are presented in Section 5.6.

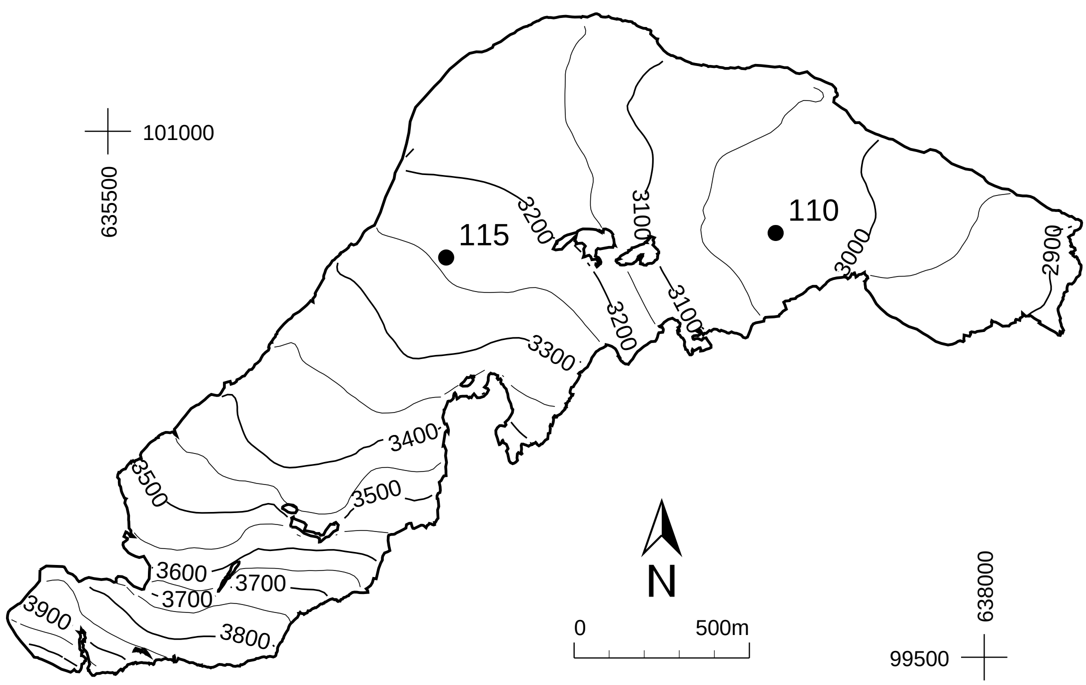


Figure 4.26: Surface topography and observational network of Hohlaubgletscher.

Investigations in 2021/22

Annual observation of local mass balance at two stakes were carried out on 6th September 2022. An extremely negative mass balance has been registered at both sites. The upper site located in the accumulation area in previous years showed ablation rates of more than 3 m. At the lower site the ablation rate was more than 2.5 m below the most negative value observed in the past three decades.

Investigations in 2022/23

In the second observation period under review, winter mass balance observations were conducted on 17th April 2023. Snow depth probings were collected at 34 locations in the area below 3050 m a.s.l. of the glacier. The field measurements in fall for the the survey of the annual balance with maintenance of the stake network were carried out on 5th September 2023. Again, a strongly negative mass balance has been measured at both stakes. Both results rank second-most negative on record.

Table 4.18: Hohlaubgletscher - Individual stake measurements of winter and annual balance.

Stake	Period Start	Period Spring	Period End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	Mass balance b_a (mm w.e.)
110	02.09.2021		06.09.2022	637410 / 100708 / 3021		−5139
115	02.09.2021		06.09.2022	636475 / 100654 / 3235		−2800
110	06.09.2022	17.04.2023	05.09.2023	637409 / 100709 / 3017	692	−4041
115	06.09.2022		05.09.2023	636465 / 100637 / 3235		−1899

4.13 Vadret dal Murtèl

Introduction

Vadret dal Murtèl is situated in the inner-alpine Upper Engadine of south-eastern Switzerland. The east-facing cirque glacier next to Piz Corvatsch (3451 m a.s.l.) covers 0.3 km^2 and extends from 3310 to 3090 m a.s.l. Exhibiting only very little debris cover along the foot of steep headwalls confining the glacier to the north and west, Vadret dal Murtèl is a typical clean-ice glacier n a cirque surrounded by steep rock slopes. Mass balance investigations were started in 2012.

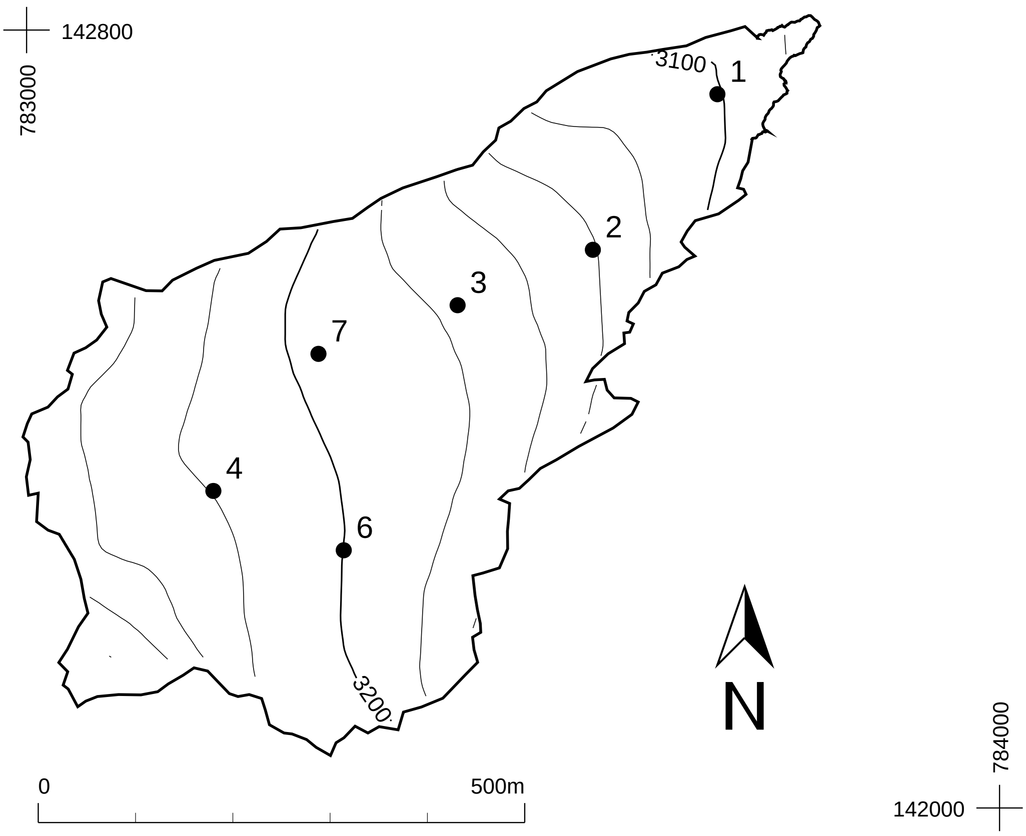


Figure 4.27: Surface topography and observational network of Vadret dal Murtèl.

Investigations in 2021/22

Winter balance was measured on 11th April 2022. Snow depth distribution of Vadret dal Murtèl was determined based on 126 probings, and snow density was measured at two sites in snow pits with values of between 250 and 340 kg m−3. At the same time 33 snow probings on Vadret dal Corvatsch were acquired. The extreme melting during the summer of 2022 resulted in the melt-out of all remaining stakes on Vadret dal Corvatsch that were not actively maintained since

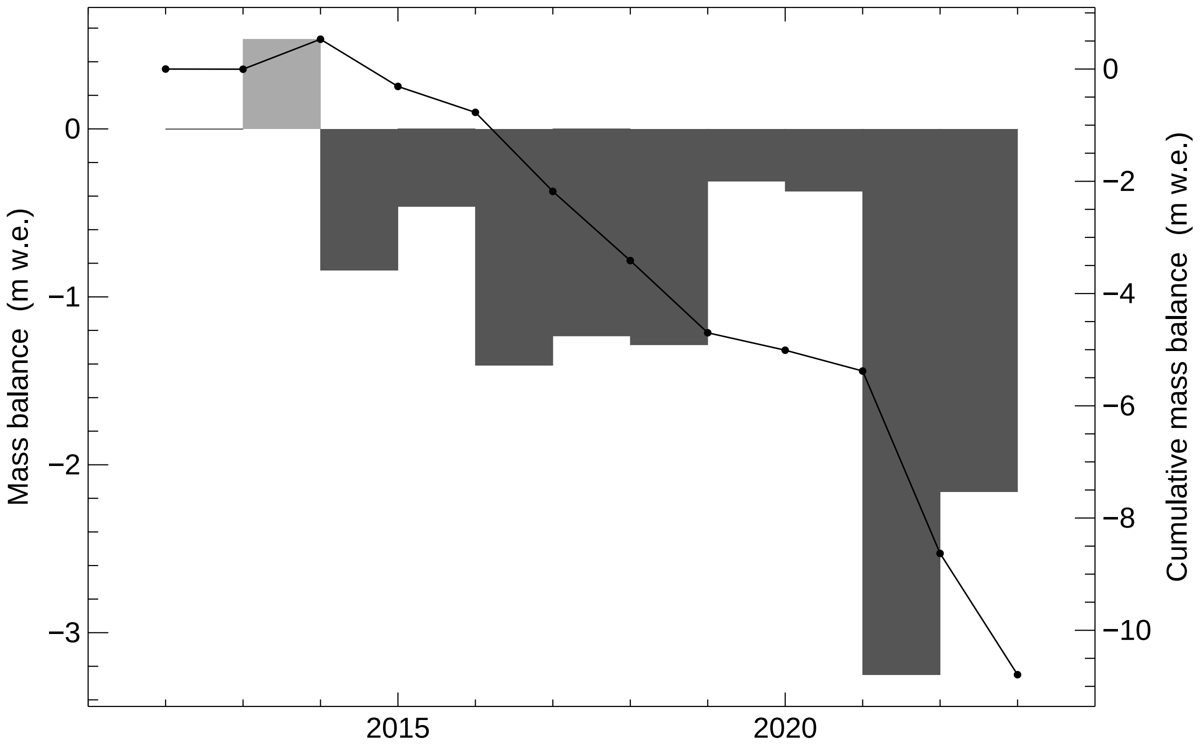


Figure 4.28: Vadret dal Murtèl - Mean specific annual balance (bars) and cumulative mass balance for the period 2012-2023.

2019. This marked the termination of the mass balance monitoring on this very small glacier. On Vadret dal Murtèl, an early survey was performed on 25th August 2022 and all stakes were redrilled. Unfortunately, no measurements could be conducted at three of the six sites due to complete melt-out of the stake. An intermediate reading on 30th June 2022, however, allowed to estimate the total ablation. A final reading of the entire network was performed on 15th October 2022. The access is becoming increasingly difficult because of downwasting of the ice and thus

Table 4.19: Vadret dal Murtèl - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
3050 - 3100	0.003	418	−5943	0.001	244	−3630
3100 - 3150	0.041	336	−4605	0.034	319	−2658
3150 - 3200	0.103	538	−3601	0.103	459	−2442
3200 - 3250	0.101	832	−2600	0.102	647	−1924
3250 - 3300	0.013	1098	−868	0.012	877	−327
3300 - 3350	0.000	1037	36	0.001	806	148
3050 - 3350	0.261	647	−3250	0.252	535	−2160

Table 4.20: Vadret dal Murtèl - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
1	06.09.2021	11.04.2022	15.10.2022	783692 / 142739 / 3051	280	−5625
2	06.09.2021	11.04.2022	15.10.2022	783584 / 142568 / 3093	596	−4491
3	06.09.2021	11.04.2022	15.10.2022	783450 / 142524 / 3139	265	−3933
4	06.09.2021	11.04.2022	15.10.2022	783191 / 142325 / 3179	743	−2720
6	06.09.2021	11.04.2022	15.10.2022	783334 / 142268 / 3165	675	−3411
7	06.09.2021	11.04.2022	15.10.2022	783308 / 142473 / 3156	641	−3096
1	15.10.2022	03.04.2023	10.09.2023	783696 / 142741 / 3050	329	−3609
2	15.10.2022	03.04.2023	10.09.2023	783584 / 142600 / 3077	371	−2493
3	15.10.2022	03.04.2023	10.09.2023	783455 / 142527 / 3137	413	−2790
4	15.10.2022	03.04.2023	10.09.2023	783187 / 142325 / 3185	532	−2188
6	15.10.2022	03.04.2023	10.09.2023	783330 / 142269 / 3162	581	−2205
7	15.10.2022	03.04.2023	10.09.2023	783302 / 142472 / 3155	639	−1737

steepening of the slopes, as well as rock face instabilities.

Investigations in 2022/23

Winter balance was determined on 3rd April 2023. Snow probings at 109 locations on Vadret dal Murtèl were performed. Snow density was measured at three sites based on coring. Again, very low snow densities of between 230 and 320 kg m^{-3} were found. The late summer field survey was performed on 10th September 2023. All six stakes showed a strongly negative mass balance, and were redrilled. An additional stake was placed close to the headwall in the region with maximum snow accumulation in order to compensate for the imminent loss of the lowermost measurement site.

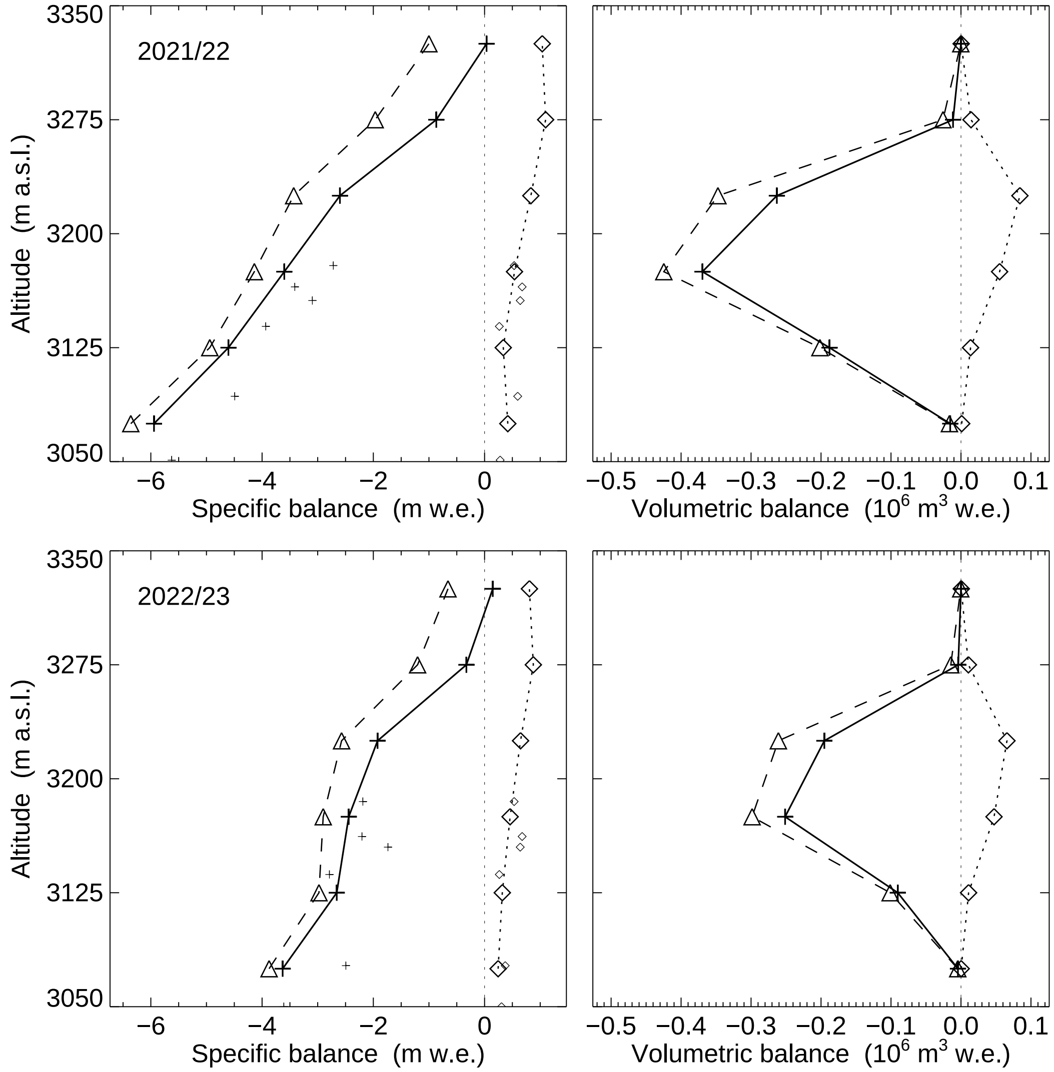


Figure 4.29: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

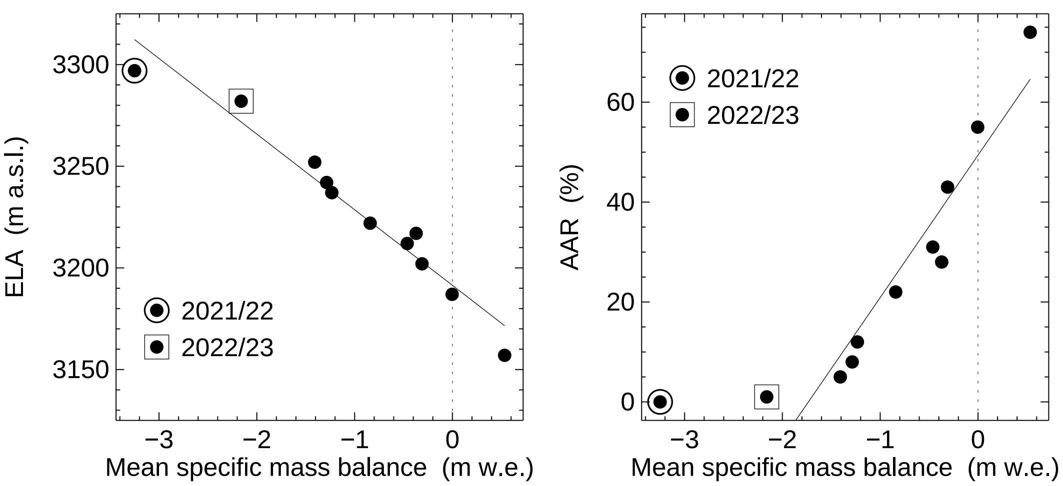


Figure 4.30: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.14 Vadret Pers

Introduction

Vadret Pers was a major tributary glacier to Vadret dal Morteratsch, the largest valley glacier in eastern Switzerland but separated in about 2017, and can thus be considered as an individual glacier. Vadret Pers currently has an area of 6.5 km^{2}and extends from 3900 down to 2450 m a.s.l. It is characterized by a glacier tongue with moderate crevassing that is increasingly constricted towards the snout, a wide and gently-sloping section at intermediate elevation and a very steep accumulation area shaped by seracs and ice avalanches. In 2019, Vadret Pers was chosen by GLAMOS as a representative site for long-term mass balance monitoring in south-eastern Switzerland because of previous local annual ablation measurements since 2002 performed by Belgian glaciologists (see Zekollari and Huybrechts, 2018), the high resilience to climate change due to an altitudinal extent up to almost 3900 m a.s.l. The monitoring is jointly performed by the Vrije Universiteit Brussel (VUB) that is conducting annual mass balance surveys at a stake network in some parts of the ablation area (Van Tricht et al., 2021). The contribution of GLAMOS adds

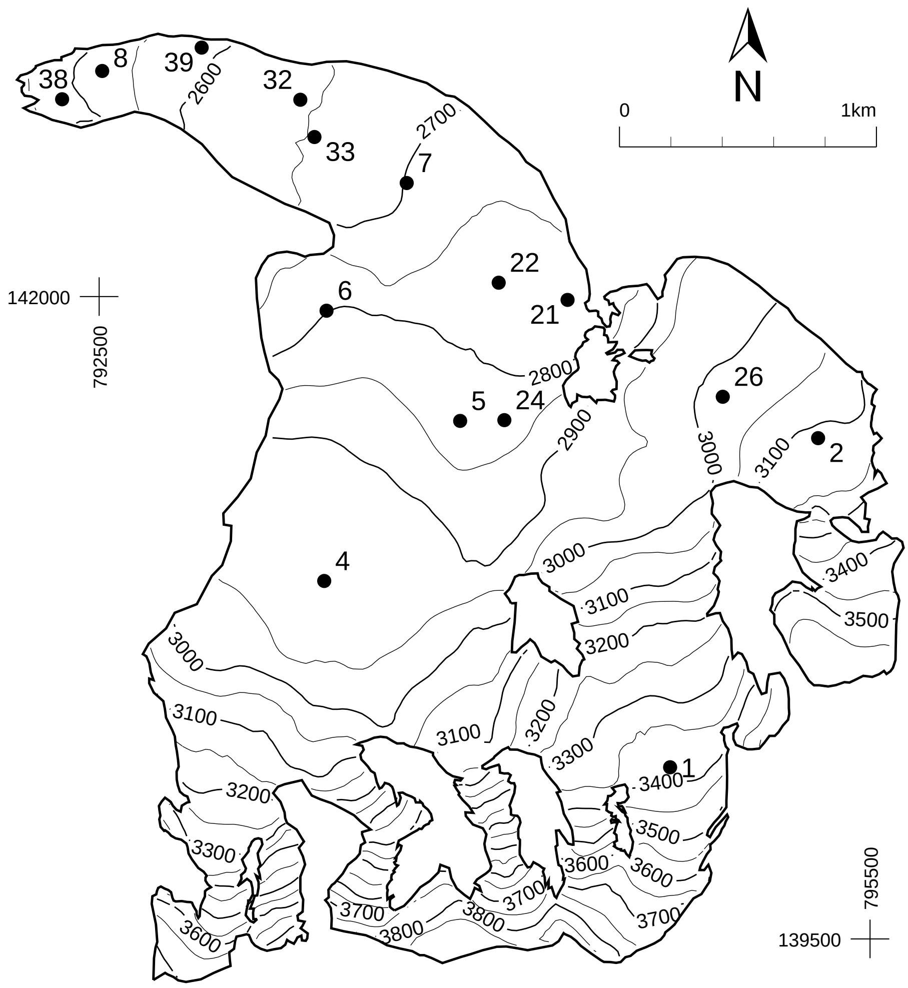


Figure 4.31: Surface topography and observational network of the Vadreat Pers.

measurements in the accumulation area and more remote parts of the ablation area, as well as winter snow accumulation.

Table 4.21: Vadret Pers - Individual stake measurements of winter and annual balance.

Stake	Period Start	Period Spring	Period End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	Mass balance b_a (mm w.e.)
04	06.09.2021	12.04.2022	12.09.2022	793385 / 140909 / 2932	593	−4167
05	06.09.2021	12.04.2022	12.09.2022	793917 / 141547 / 2808	600	−4770
06	06.09.2021	12.04.2022	12.09.2022	793388 / 141937 / 2784	249	−5085
07	06.09.2021	12.04.2022	12.09.2022	793701 / 142448 / 2687	236	−6345
21	06.09.2021	12.04.2022	12.09.2022	794328 / 141996 / 2752	511	−5751
24	06.09.2021	12.04.2022	12.09.2022	794085 / 141617 / 2798	529	−3906
26	06.09.2021	12.04.2022	12.09.2022	794906 / 141613 / 3002	670	−3933
32	06.09.2021	12.04.2022	12.09.2022	793254 / 142783 / 2618	494	−6102
33	06.09.2021	12.04.2022	12.09.2022	793297 / 142636 / 2633	557	−6624
38	06.09.2021	12.04.2022	12.09.2022	792350 / 142768 / 2457	244	−8676
39	06.09.2021		12.09.2022	792871 / 142979 / 2569		−7551
02	12.09.2022	04.04.2023	30.09.2023	795320 / 141494 / 3097	667	−416
04	12.09.2022	04.04.2023	30.09.2023	793394 / 140923 / 2928	440	−3483
05	12.09.2022	04.04.2023	30.09.2023	793908 / 141517 / 2815	322	−4005
06	12.09.2022	04.04.2023	30.09.2023	793386 / 141941 / 2779	314	−4275
07	12.09.2022	04.04.2023	30.09.2023	793678 / 142499 / 2677	243	−5076
26	12.09.2022	04.04.2023	30.09.2023	794906 / 141617 / 3000	660	−2835
28	12.09.2022		30.09.2023	794028 / 142094 / 2760		−4365
32	12.09.2022		30.09.2023	793239 / 142788 / 2607		−5148
33	12.09.2022	04.04.2023	30.09.2023	793280 / 142644 / 2627	120	−5301
40	12.09.2022	04.04.2023	30.09.2023	792853 / 142850 / 2570	108	−6804
41	12.09.2022	04.04.2023	30.09.2023	792441 / 142858 / 2477	137	−7479

Investigations in 2021/22

The winter mass balance survey was conducted on 11th April 2022. 136 snow probings were acquired across the entire glacier surface and next to all stakes, including an ascent by skis up to Schnapsboden, the only flat section of the accumulation area at an elevation of 3400 m a.s.l. Snow density was measured at three sites based on coring and low densities of between 260 and 370 kg m^{-3} were found. Due to excessive melting, an intermediate field survey on 21st July was necessary in order to redrill several stakes that were at the verge of melting out already. The GLAMOS fall survey was conducted on 12th September 2022. All stakes of the network were visited and the stakes in the upper reaches of the glacier outside of the VUB network were redrilled. Due to strong crevassing, we did not attempt to visit the topmost measurement site on Schnapsboden where no stake was maintained since 2021. VUB stakes were visited and redrilled between 1st and

3[3d] October 2022. Over the annual period, a record-negative mass balance was determined at all 11 sites of the network.

Table 4.22: Vadret Pers - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2400 - 2500	0.053	215	−8254	0.041	-73	−6261
2500 - 2600	0.152	245	−7809	0.139	-165	−6467
2600 - 2700	0.491	448	−6580	0.464	-28	−4978
2700 - 2800	0.768	496	−5559	0.721	232	−3984
2800 - 2900	0.722	635	−4220	0.703	374	−3714
2900 - 3000	1.431	772	−3739	1.427	695	−3062
3000 - 3100	0.780	950	−2428	0.779	974	−943
3100 - 3200	0.485	1101	−1337	0.485	1167	−40
3200 - 3300	0.364	1171	−602	0.364	1238	314
3300 - 3400	0.361	1305	−70	0.361	1377	785
3400 - 3500	0.307	1181	82	0.307	1284	858
3500 - 3600	0.274	970	47	0.274	1097	701
3600 - 3700	0.203	837	165	0.203	924	645
3700 - 3800	0.166	850	345	0.166	959	931
3800 - 3900	0.104	771	311	0.104	856	855
2400 - 3900	6.661	811	−3024	6.537	732	−1963

Investigations in 2022/23

On 4[th] April 2023, the winter accumulation survey was performed. In total, 138 snow probings covering the glacier up to an elevation of 3500 m a.s.l. were acquired. Snow density was measured by coring at three sites at ca. 3100, 2780 and to 2500 m a.s.l., respectively. Densities again were extremely low and ranged between 170 (little snow and depth hoar) and 360 kg m^{-3} (thicker snowpack in the accumulation area). The fall field survey was conducted on 6[th] September 2023 and all stakes were visited, whereas the stakes of the GLAMOS network were redrilled. Again, mass balance at all 12 observed sites was very negative. The VUB survey was conducted between 29[th] September and 1[st] October 2023 and all stakes in the lower ablation area where maintained. Even though no stakes are available in the middle and upper accumulation area due to restrictions of accessibility, slope and crevassing, probings of the accumulated snow layer were acquired up to an elevation of more than 3600 m a.s.l.

4.15 Glacier de la Plaine Morte

Introduction

Glacier de la Plaine Morte (6.7 km^2) is the largest plateau glacier in the European Alps and thus represents a particularly interesting site for studying the accelerating effect of climate change on Alpine glaciers. Plaine Morte is situated at the main Alpine divide between the cantons Berne and Valais. 90% of the glacier surface lie in a narrow altitudinal band of between 2650 and 2800 m a.s.l.. From the 5 km wide plateau with an average slope of less than four degrees, a small outlet glacier (Rezligletscher) flows northwards. Large circular depressions of the glacier surface, probably related to cryo-karst, are common features and are stable over several decades. Lac des Faverges, an ice marginal lake with a water volume of up to 2 million m^3 is subject to annual drainage events (Ogier et al., 2021). The seasonal mass balance is determined since 2009 using the direct glaciological method (Huss et al., 2013). The spatial variability in melt is mainly driven by differences in ice surface albedo (Naegeli et al., 2015).

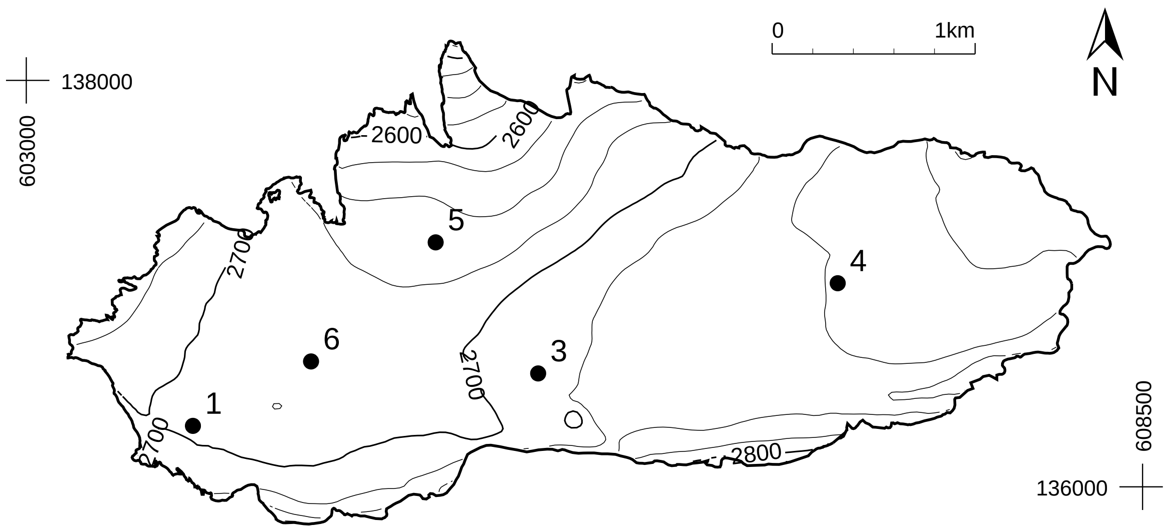


Figure 4.32: Surface topography and observational network of Glacier de la Plaine Morte.

Investigations in 2021/22

The winter mass balance was measured on 4th April 2022. Snow probings were acquired at 124 sites distributed across the entire glacier surface. Snow density was determined based on coring. Snow water equivalent is also continuously monitored at the same location using a cosmic ray sensor deployed at the snow-ice interface (Gugerli et al., 2019). An autonomous station to continuously measure ice ablation was installed (Cremona et al., 2023). The stake network was visited and redrilled on 30th August 2022. All five stakes showed record ablation rates of 4-5 meters, and winter snow was again depleted on the entire glacier surface. A final survey of all stakes was performed on 23rd September 2022 to capture the full extent of the melting season, and to

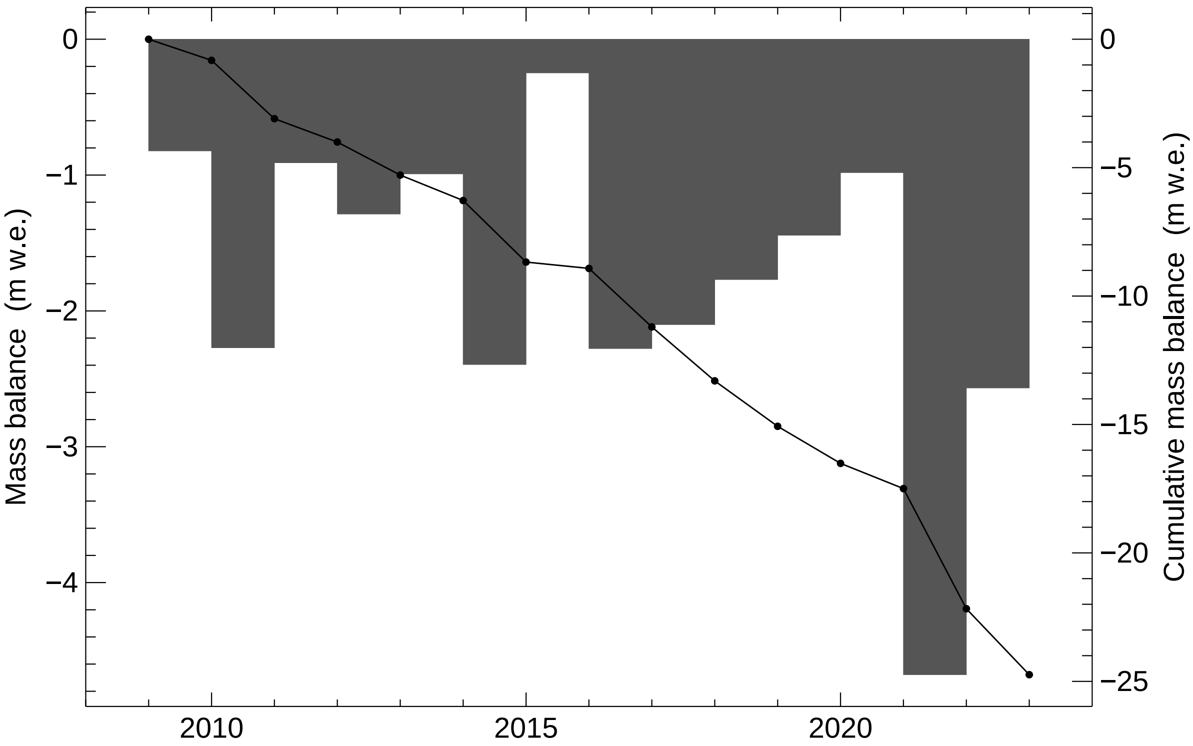


Figure 4.33: Glacier de la Plaine Morte - Mean specific annual balance (bars) and cumulative mass balance for the period 2006-2023.

dismantle the camera for real-time mass balance observations. The artificial supraglacial channel to limit the water volume in Lac des Faverges remained filled with winter snow far into the summer. The ice-dammed lake thus grew up to a substantial volume. The lake started draining through the channel on 9th July 2022, but outflow rates remained limited. For the first time, the lake did not empty completely, and a small water volume persisted until fall.

Investigations in 2022/23

During the winter field survey on 6th April 2023 snow probings at 146 locations distributed over the entire glacier surface were acquired and a snow density of 360 kg m^{-3} was measured by coring. On 5th September 2023 all five stakes were visited but no redrilling was required. Maintenance work at the meteorological station including the cosmic ray sensor to measure snow water equivalent was performed. Again, the entire glacier was snow-free and ablation rates were high, even though not reaching the maximum of the previous period. A final survey at all measurement sites was performed on 12th October 2023, indicating substantial melt since the last field visit. Lac des Faverges filled up to an intermediate volume also in this year and started draining through the artificial channel on 17th July, and subglacially on 17th August 2023 without causing impacts in the Simme valley.

Table 4.23: Glacier de la Plaine Morte - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2400 - 2500	0.005	1215	−4702	0.005	1024	−3055
2500 - 2600	0.152	1263	−4844	0.161	1059	−3108
2600 - 2700	2.709	1242	−4860	3.018	1182	−2807
2700 - 2800	4.014	1132	−4553	3.497	1295	−2338
2800 - 2900	0.008	1119	−2512	0.002	1328	−289
2400 - 2900	6.889	1178	−4678	6.682	1237	−2567

Table 4.24: Glacier de la Plaine Morte - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
1	01.09.2021	04.04.2022	23.09.2022	603821 / 136300 / 2691	1155	−5130
3	01.09.2021	04.04.2022	23.09.2022	605522 / 136558 / 2717	1302	−4248
4	01.09.2021	04.04.2022	23.09.2022	606998 / 137002 / 2751	1071	−4500
5	01.09.2021	04.04.2022	23.09.2022	605017 / 137203 / 2664	1323	−4887
6	01.09.2021	04.04.2022	23.09.2022	604403 / 136617 / 2680	1125	−4833
1	23.09.2022	06.04.2023	12.10.2023	603821 / 136300 / 2691	1188	−3213
3	23.09.2022	06.04.2023	12.10.2023	605522 / 136558 / 2717	1138	−2196
4	23.09.2022	06.04.2023	12.10.2023	606998 / 137002 / 2751	1174	−2250
5	23.09.2022	06.04.2023	12.10.2023	605017 / 137203 / 2664	1227	−2871
6	23.09.2022	06.04.2023	12.10.2023	604403 / 136617 / 2680	1102	−2700

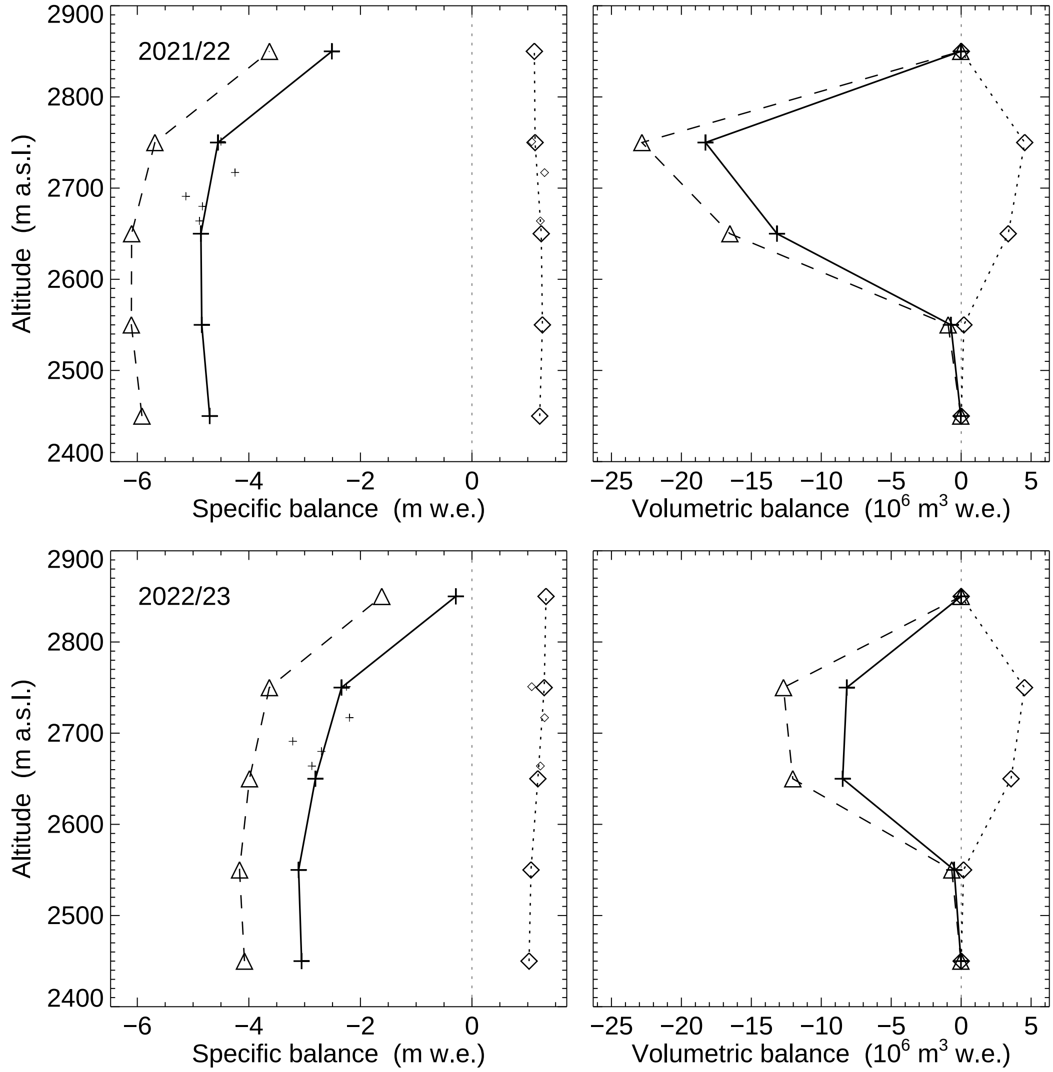


Figure 4.34: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

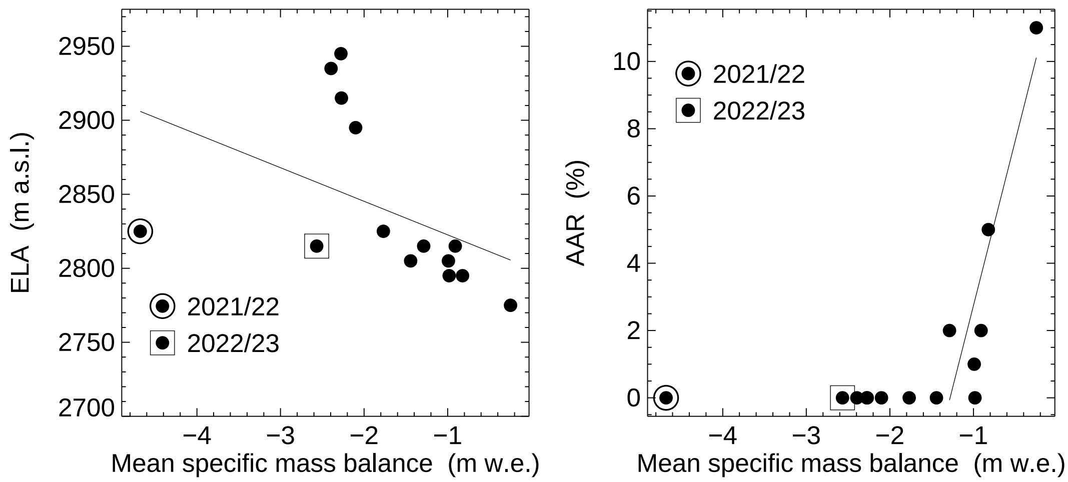


Figure 4.35: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.16 Rhonegletscher

Introduction

Rhonegletscher is a temperate valley glacier located in the central Swiss Alps, and is the source of the Rhone river. The glacier is easily accessible and therefore has been under observation since the 19th century. The total surface area of the glacier is 15.2 km^2 flowing in a southern direction from 3600 m a.s.l. down to 2200 m a.s.l. The first mass balance measurements were carried out in 1884 and are the first such observations worldwide. After two periods of measurements between 1884-1910, and 1980-1982, the mass balance monitoring was resumed in 2006. Determination of volumetric changes in decadal resolution extends even further back to 1874 (Bauder et al., 2007).

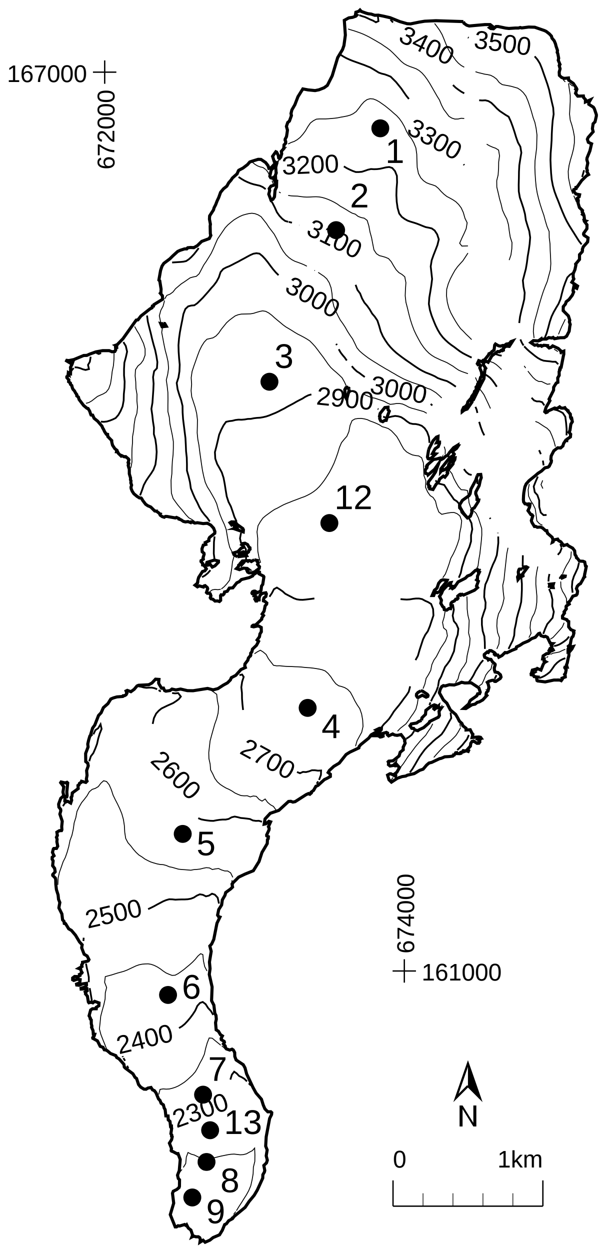


Figure 4.36: Surface topography and observational network of Rhonegletscher.

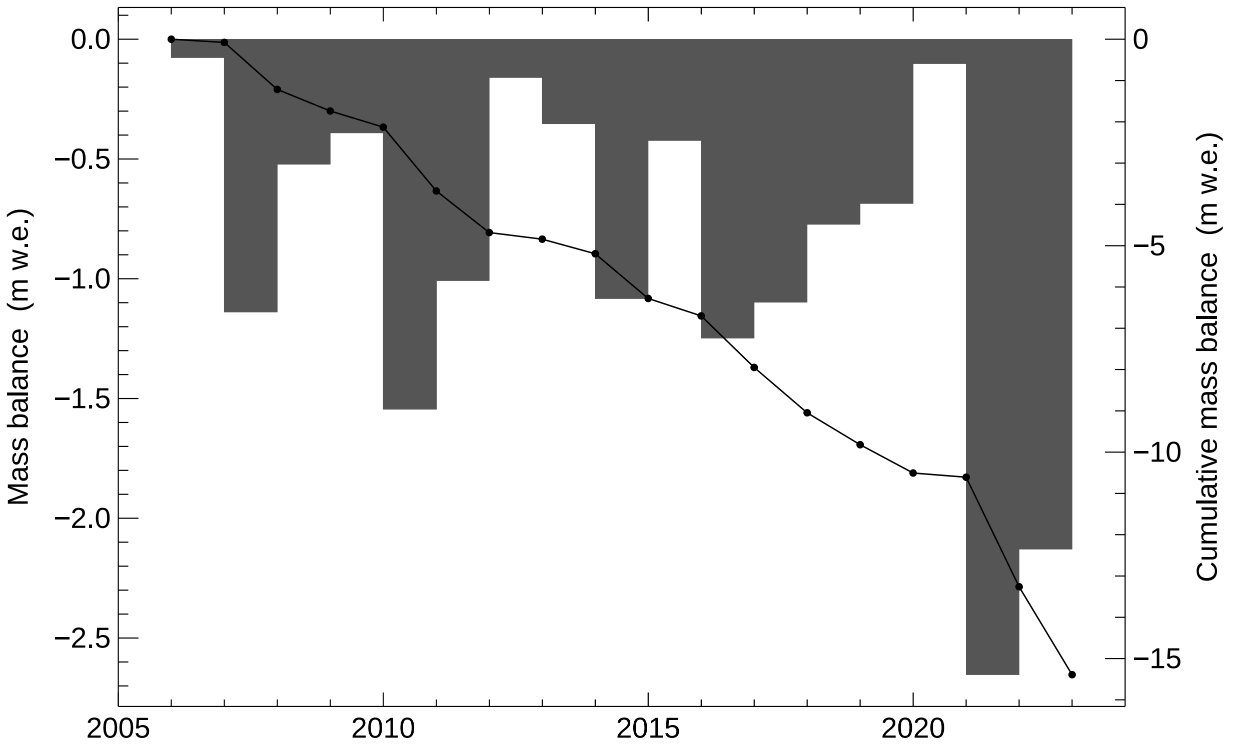


Figure 4.37: Rhonegletscher - Mean specific annual balance (bars) and cumulative mass balance (line) for the period 2006-2023.

Topographic maps or photogrammetrical surveys exist for 1874, 1929, 1959, 1980, 1991, 2000, 2007, 2016, and 2023 and annually for the glacier tongue below 2700 m a.s.l. since 2012. Further details on observations of ice flow velocities are presented in Section 5.7.

Investigations in 2021/22

The spring survey for the determination of winter mass balance was performed on 21st April 2022. A total of 373 snow probings distributed over the entire area of Rhonegletscher were obtained. The density was measured at the two sites 3 and 13 based on coring resulting values of 490 kg m^{-3} and 375 kg m^{-3}, respectively. Investigations of snow depth probing were complemented with a ground penetrating radar survey along a longitudinal central profile from stake 1 down to stake 13. The measurement sites in the ablation area have been repeatedly visited between June and August during the melting season for intermediate stake readings. Autonomous cameras for real-time monitoring of the winter snow accumulation and summer ice melting in were maintained at sites 5 and 7. The extraordinary melt rates required a redrilling of all but the three highest stakes on 11th August. On 6th and 13th September 2022 all measurement sites were visited for the determination of the annual mass balance. All sites experienced negative balances and due to complete melt out of the winter accumulation no density measurements were performed. Due to ongoing retreat of the glacier in relation with the further expansion of the proglacial lake, the site 9 has finally been abandoned.

Table 4.25: Rhonegletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2200 - 2300	0.340	127	−7878	0.331	396	−8030
2300 - 2400	0.329	-21	−7947	0.302	517	−8357
2400 - 2500	0.617	145	−7290	0.591	633	−7532
2500 - 2600	1.031	273	−6359	0.999	659	−5927
2600 - 2700	0.712	467	−5443	0.685	871	−4872
2700 - 2800	1.068	1146	−4268	1.046	1113	−3994
2800 - 2900	2.255	1532	−3166	2.274	1475	−2549
2900 - 3000	1.874	1645	−2114	1.903	1553	−1451
3000 - 3100	1.817	1651	−1417	1.771	1562	−727
3100 - 3200	1.535	1622	−1028	1.514	1527	−437
3200 - 3300	1.468	1701	−408	1.470	1589	147
3300 - 3400	0.968	1683	31	0.966	1595	595
3400 - 3500	0.781	1596	296	0.781	1469	760
3500 - 3600	0.376	1350	282	0.376	1207	583
3600 - 3700	0.003	784	−53	0.003	845	378
2200 - 3700	15.174	1309	−2653	15.011	1328	−2129

Investigations in 2022/23

The winter mass balance was determined on 19th April 2023. Snow depth soundings were performed at 280 locations including all measurement sites. A snow density of 413 kg m^{-3} and 358 kg m^{-3} was measured by coring at the two sites 3 and 13. In addition, a ground penetrating radar was operated on a longitudinal transect for a continuous snow depth survey between stakes 1 and 13. Again, intermediate stake readings were repeatedly taken during the melting season. A complete survey in the middle of the summer season was performed on 11th August when all but the highest stake were found. Measurements for annual mass balance were eventually carried out on 8th September 2023. Net accumulation was found at site 1 and 2. Density was measured at site 1 and yielded a value of 507 kg m^{-3}. Due to continued substantial melt rates throughout September and October, another full survey of the stake network was performed on 17th October 2023.

Table 4.26: Rhonegletscher - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
01	08.09.2021	21.04.2022	13.09.2022	673812 / 166605 / 3231	1813	−457
02	08.09.2021	21.04.2022	13.09.2022	673507 / 165905 / 3105	1381	−675
03	08.09.2021	21.04.2022	09.09.2022	673104 / 164905 / 2917	1499	−1920
04	08.09.2021	21.04.2022	09.09.2022	673358 / 162760 / 2737	1136	−4014
05	08.09.2021	21.04.2022	09.09.2022	672506 / 161898 / 2585	243	−6138
06	08.09.2021	21.04.2022	09.09.2022	672415 / 160847 / 2448	127	−7785
07	08.09.2021	21.04.2022	09.09.2022	672658 / 160174 / 2332	221	−8505
08	08.09.2021	21.04.2022	09.09.2022	672680 / 159725 / 2262	450	−7632
09	08.09.2021	21.04.2022	09.09.2022	672625 / 159566 / 2216	1068	−6327
12	08.09.2021	21.04.2022	09.09.2022	673508 / 163950 / 2832	1440	−3459
13	08.09.2021	21.04.2022	09.09.2022	672707 / 159939 / 2289	435	−8055
01	09.09.2022	19.04.2023	17.10.2023	673812 / 166613 / 3230	1740	572
02	09.09.2022	19.04.2023	17.10.2023	673553 / 165944 / 3116	1203	−1017
03	09.09.2022	19.04.2023	17.10.2023	673102 / 164904 / 2913	1540	−1380
04	09.09.2022	19.04.2023	17.10.2023	673342 / 162739 / 2729	1096	−3906
05	09.09.2022	19.04.2023	17.10.2023	672508 / 161900 / 2581	674	−5508
06	09.09.2022	19.04.2023	17.10.2023	672425 / 160831 / 2438	404	−7992
07	09.09.2022	19.04.2023	17.10.2023	672662 / 160166 / 2319	468	−8793
08	09.09.2022	19.04.2023	17.10.2023	672680 / 159721 / 2246	639	−8424
12	09.09.2022	19.04.2023	17.10.2023	673507 / 163968 / 2827	1548	−2484
13	09.09.2022	19.04.2023	17.10.2023	672711 / 159934 / 2276	649	−8010

Depleted surface in the firn area of Rhonegletscher in September 2022 after the extreme melting (Photo: A. Bauder)

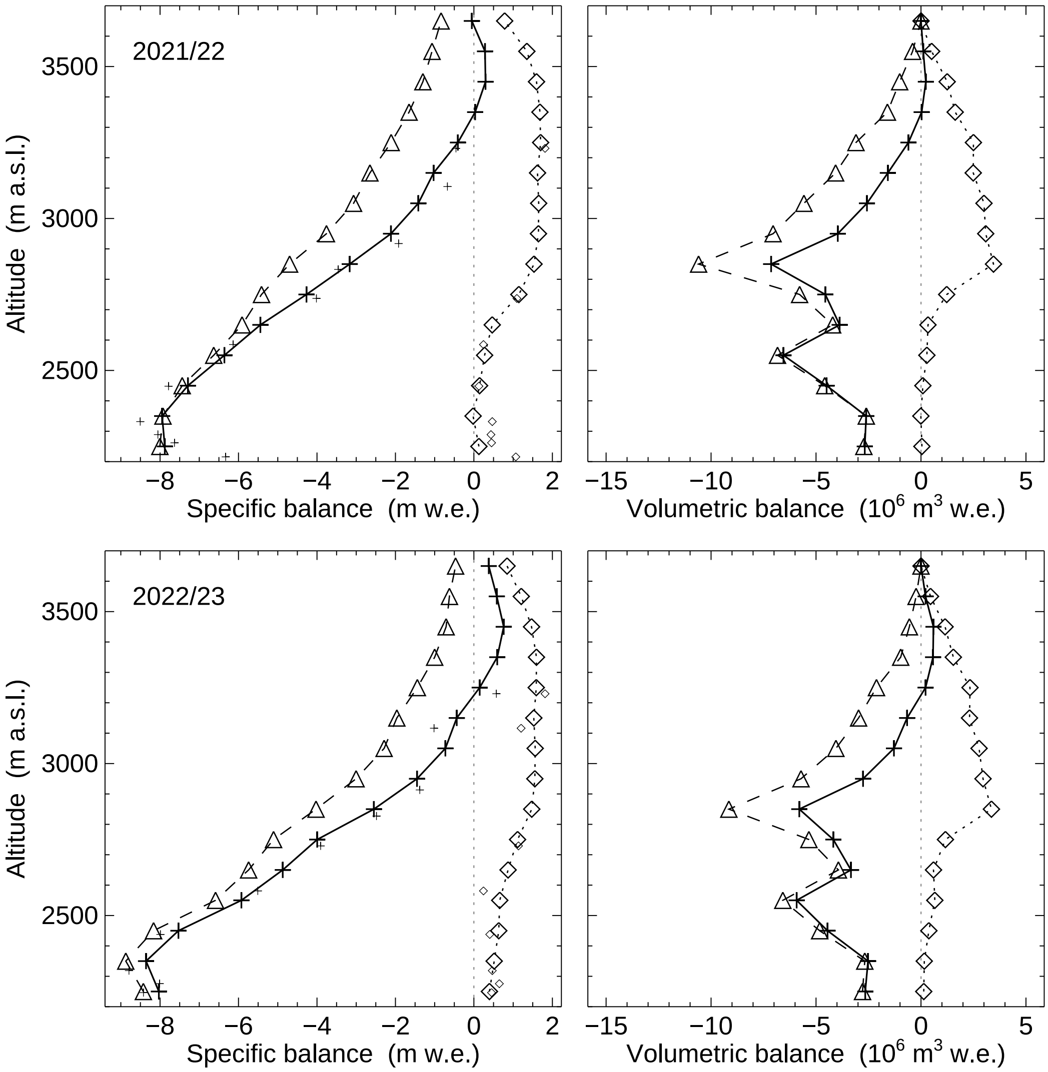


Figure 4.38: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

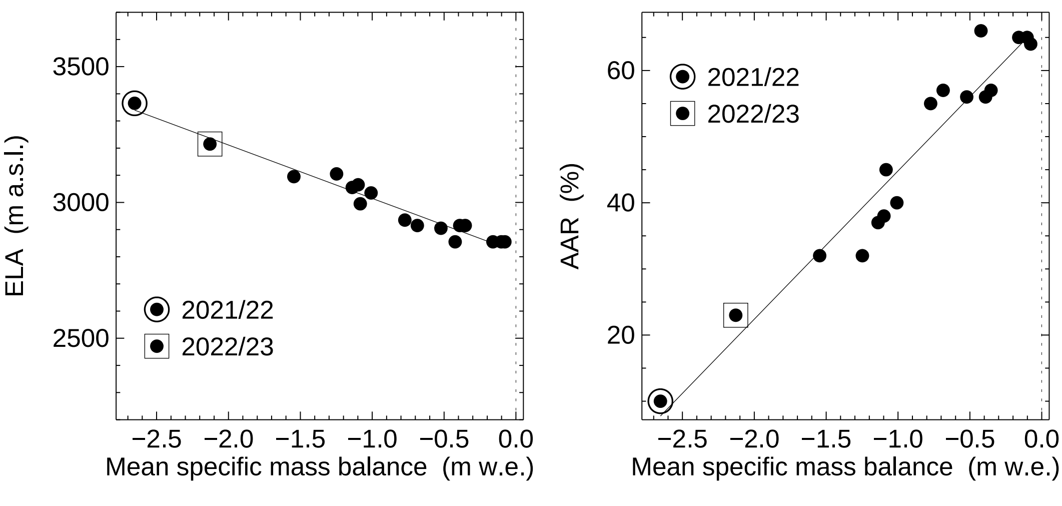


Figure 4.39: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.17 Sankt Annafirn

Introduction

Sankt Annafirn is a north-facing cirque glacier in the central Swiss Alps protected by steep rockwalls connecting Sankt Annahorn (2937 m a.s.l.) with Chastelhorn (2973 m a.s.l.). The glacier covers an area of currently 0.12 km^2. Investigations of the glacier mass balance were started in 2012. This glacier represents the size class of glacierets and delivers direct observations of seasonal glacier mass change in the hydrological catchment of the Reuss. Because of rapid disintegration, the mass balance measurements on the very small, neighboring Schwarzbachfirn were discontinued in 2021 due to almost complete disappearance of the ice. Also observations on Sankt Annafirn are increasingly impacted by operations related to the skiing area, as well as effects of fast glacier retreat, disintegration and rockfall events, and will not be continued beyond 2023.

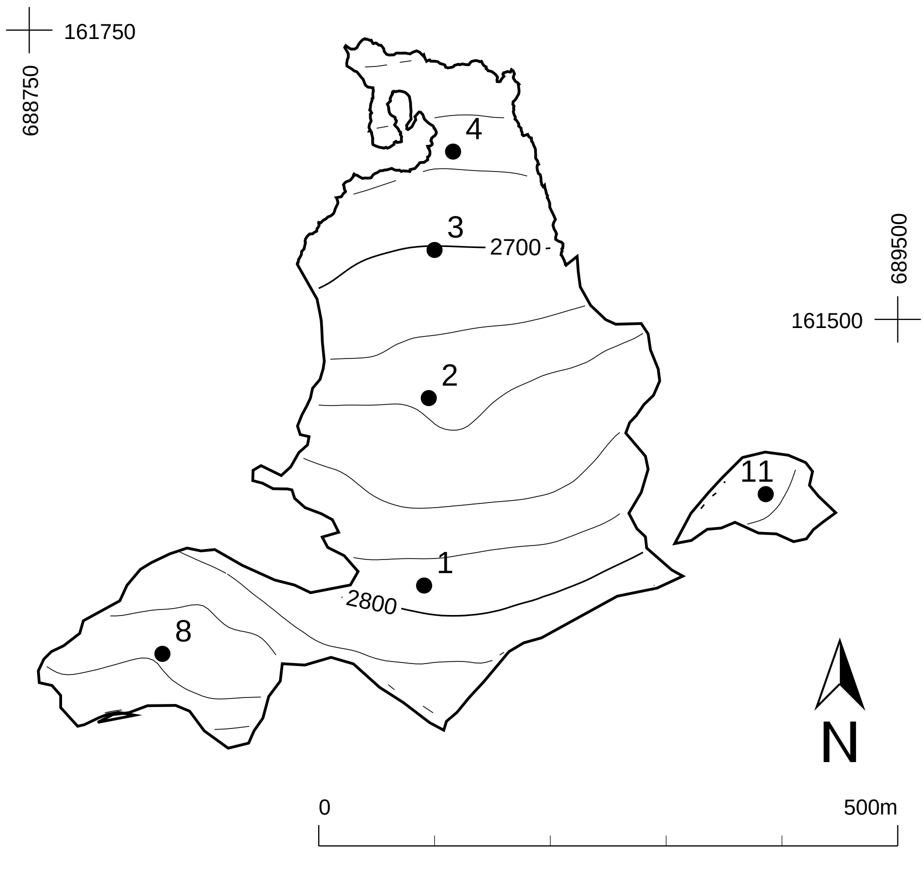


Figure 4.40: Surface topography and observational network of Sankt Annafirn.

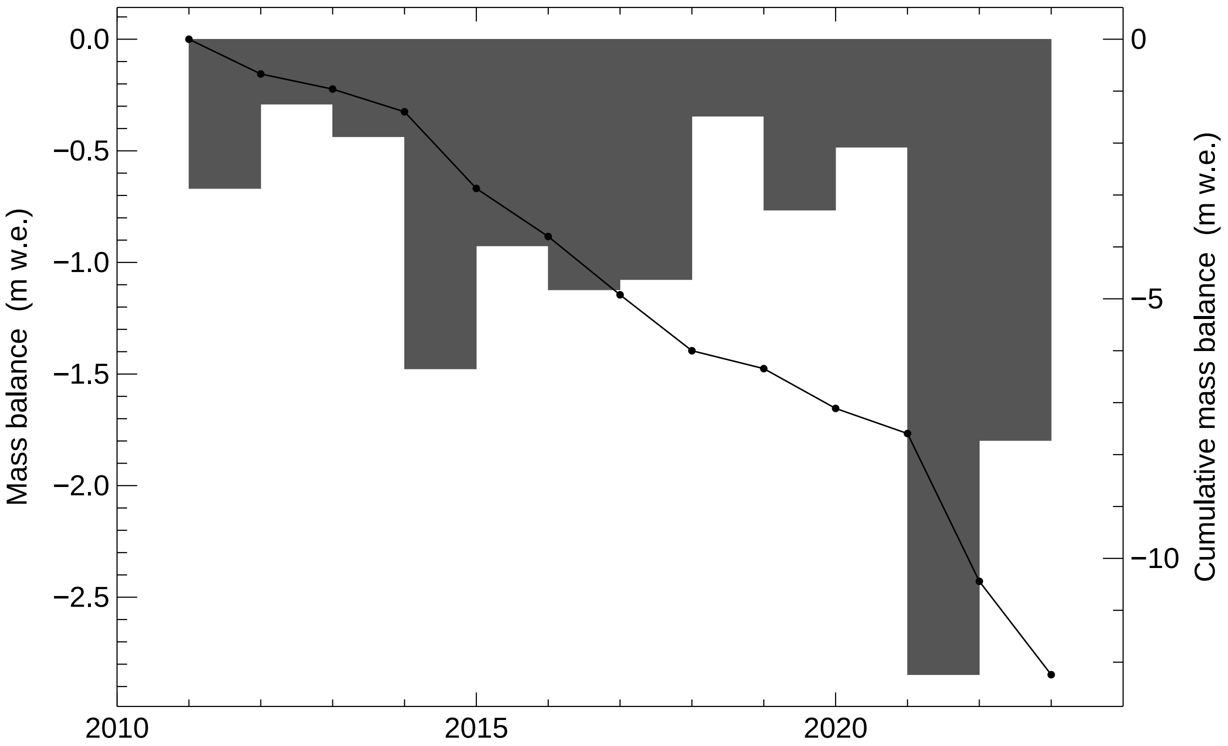


Figure 4.41: Sankt Annafirn - Mean specific annual balance (bars) and cumulative mass balance for the period 2012-2023.

Investigations in 2021/22

On 14th April 2022 the winter balance survey was performed. 26 snow probings were acquired on Schwarzbachfirn and 83 probings were distributed over the entire surface of Sankt Annafirn. On both glaciers, snow density was determined by coring at one site, resulting in densities of around 430 $kg\,m^{-3}$. Due to unprecedented melting, an intermediate field visit of Sankt Annafirn was conducted on 16th July. Related to substantial rockfall hazard in the upper reaches of the glacier, only two stakes in the lower section were redrilled in order to able to acquire measurements for the entire period. On 13th September 2022, all mass balance stakes were visited and three were redrilled. No measurements were possible anymore on Schwarzbachfirn due to complete melt-out of the remaining stakes and almost complete disappearance of the ice, except for some dead ice beneath a thick layer of debris.

Investigations in 2022/23

End-of-winter snow depth was measured at 76 locations on Sankt Annafirn on 10th April 2023, but no snow density measurements were performed for logistical reasons. The late summer field survey was conducted already on 21st August 2023 to prevent final melt-out of the remaining mass balance stakes. All measurement sites could be located but no stakes were redrilled, and the equipment was evacuated. No further measurements of the mass balance will be conducted on the glacier henceforth.

Table 4.27: Sankt Annafirn - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2650 - 2700	0.007	703	−4274	0.005	622	−2714
2700 - 2750	0.042	993	−3656	0.041	682	−2499
2750 - 2800	0.034	1224	−2693	0.034	881	−1708
2800 - 2850	0.030	1313	−1933	0.030	954	−1113
2850 - 2900	0.012	1205	−1983	0.012	960	−1003
2650 - 2900	0.125	1137	−2847	0.123	829	−1798

Table 4.28: Sankt Annafirn - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
2	14.09.2021	14.04.2022	13.09.2022	689093 / 161432 / 2702	1292	−3528
3	14.09.2021	14.04.2022	13.09.2022	689102 / 161549 / 2661	1160	−4248
1	13.09.2022	10.04.2023	21.08.2023	689074 / 161325 / 2708	1032	−1908
2	13.09.2022	10.04.2023	21.08.2023	689100 / 161448 / 2686	665	−2421
3	13.09.2022	10.04.2023	21.08.2023	689105 / 161550 / 2661	682	−2736

Remains of Sankt Annafirn in September 2022 after intense melting in summer covered with some fresh snow (Photo: L. Eggimann, AFJ/UR)

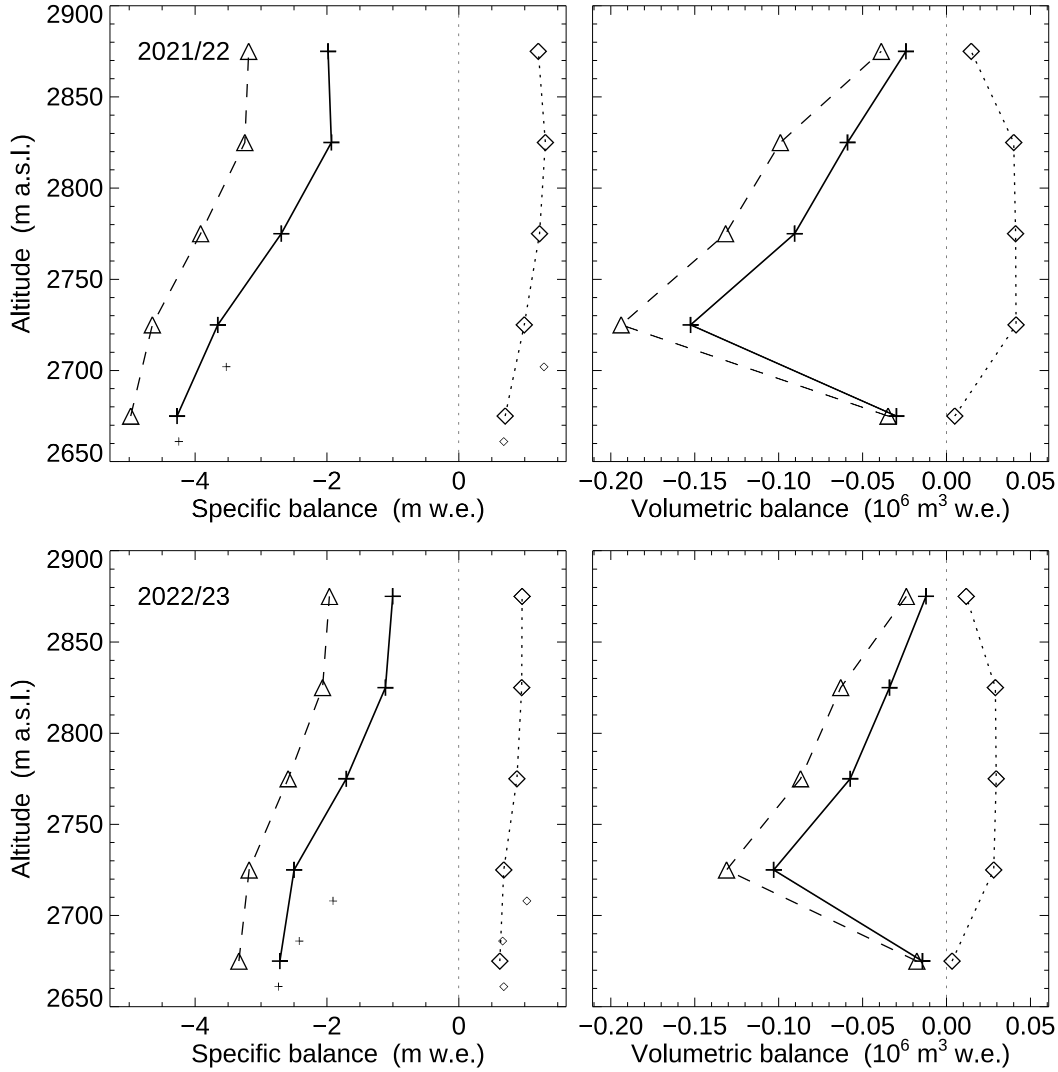


Figure 4.42: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

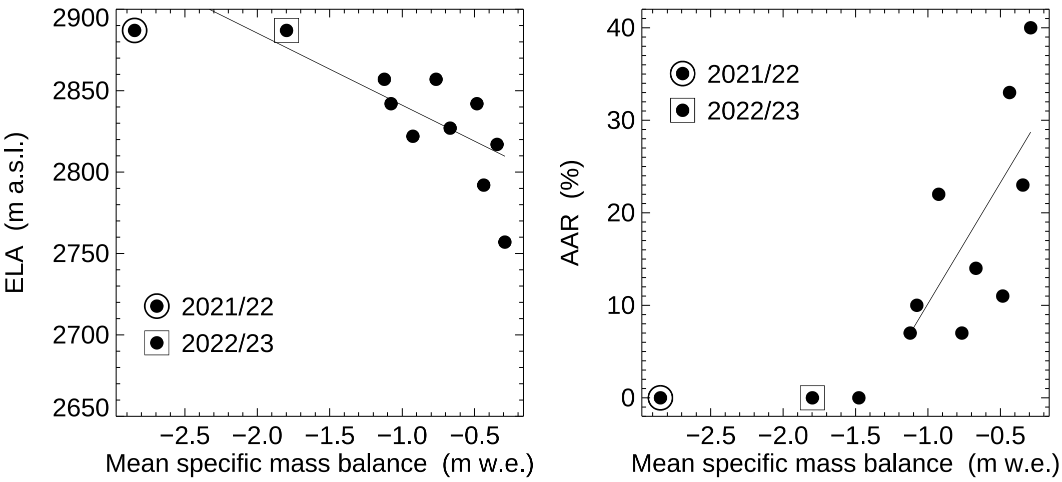


Figure 4.43: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.18 Schwarzberggletscher

Introduction

Schwarzberggletscher is a temperate mid-sized mountain glacier located in the Mattmark area in the Southern Valais Alps. It currently covers an area of 4.9 km^2 flowing in north direction from 3570 m a.s.l. down to 2690 m a.s.l. Mass balance measurements started in 1955 as a part of investigations for the construction of the Mattmark reservoir for hydro-power production (VAW, 1999, 2024). Initially a network of seven stakes distributed over the entire area was maintained for mass balance and ice flow measurements (see Chapter 5). After 1967 measurements were continued at only four sites. Presently, annual observations at three sites are maintained. Collected data of point mass balance and geodetic ice volume changes since 1955 have been re-analyzed and homogenized (Huss et al., 2015). The results of the glacier-wide mean specific annual balance for comparable fixed-date periods were presented in Section 4.17 of Volume 135/136. Further details on long-term observations of ice flow velocities are in Section 5.8.

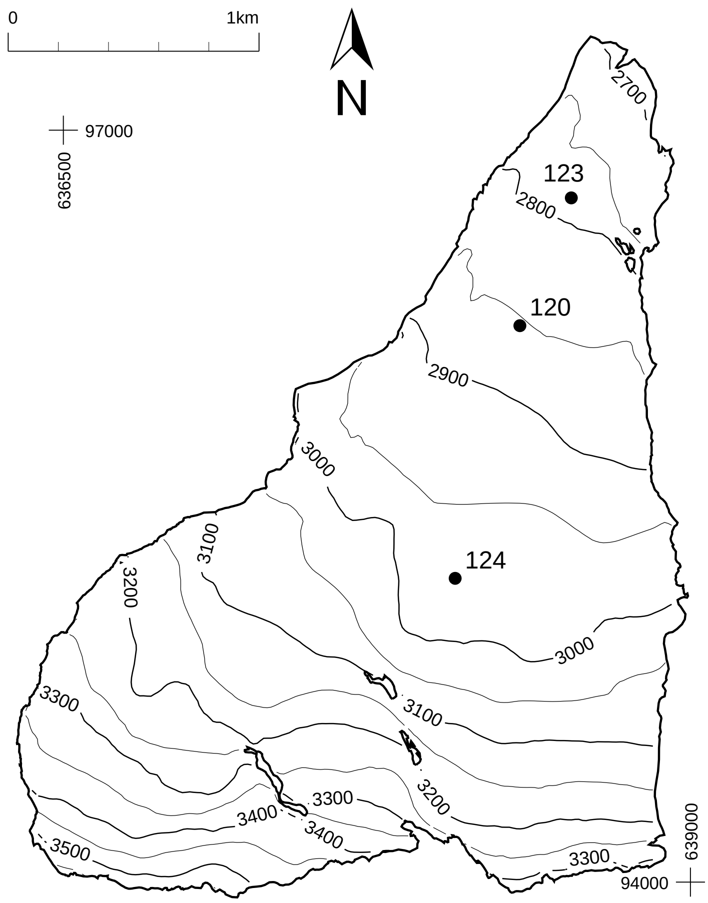


Figure 4.44: Surface topography and observational network of Schwarzberggletscher.

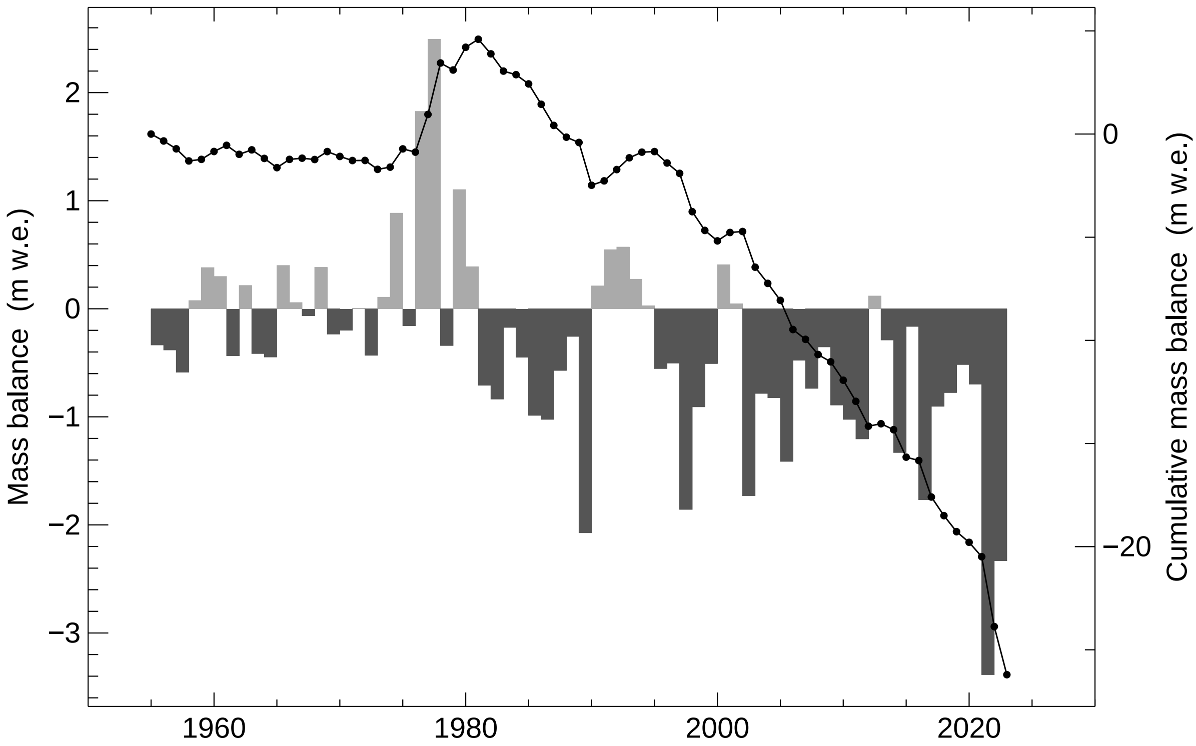


Figure 4.45: Schwarzberggletscher - Mean specific annual balance (bars) and cumulative mass balance for the period 1955-2023. Values refer to the measurement period.

Investigations in 2021/22 and 2022/23

Annual observations of mass balance with maintenance of the stake network were carried out on 6th September 2022. All three stakes were located and set back to the initial position. Extremely negative mass balances were measured for all stakes that almost doubled previous record melt rates. No winter accumulation was left already in mid-August, when the stake at the lowest site was redrilled to prevent loss of complete melt out.

In the second observation period under review, the annual field measurements were carried out on 5th September 2023. Again, strong negative mass balances resulted at all stakes that rank second negative on record. The transient snowline reached the highest point of the glacier and, as in the previous year, no winter accumulation was left on the entire area.

Table 4.29: Schwarzberggletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2600 - 2700	0.001	429	−6666	0.001	591	−5087
2700 - 2800	0.228	496	−6205	0.228	723	−4568
2800 - 2900	0.627	603	−5115	0.627	894	−3888
2900 - 3000	1.107	693	−4431	1.107	1033	−3219
3000 - 3100	0.838	738	−3590	0.838	1147	−2424
3100 - 3200	0.788	758	−2739	0.788	1214	−1746
3200 - 3300	0.648	772	−1919	0.648	1266	−1080
3300 - 3400	0.367	764	−1209	0.367	1272	−555
3400 - 3500	0.229	754	−664	0.229	1264	−180
3500 - 3600	0.058	670	−486	0.058	1126	−209
2600 - 3600	4.891	708	−3386	4.891	1110	−2332

Table 4.30: Schwarzberggletscher - Individual stake measurements of winter and annual balance.

Stake	Period			Coordinates	Mass balance	
	Start	Spring	End		b_w	b_a
				(m / m / m a.s.l.)	(mm w.e.)	
120	02.09.2021		06.09.2022	638321 / 96223 / 2835		−5094
123	02.09.2021		06.09.2022	638525 / 96733 / 2749		−5967
124	02.09.2021		06.09.2022	638064 / 95217 / 2974		−4482
120	06.09.2022		05.09.2023	638319 / 96222 / 2831		−3960
123	06.09.2022		05.09.2023	638524 / 96731 / 2744		−4275
124	06.09.2022		05.09.2023	638062 / 95218 / 2971		−3128

4.19 Silvrettagletscher

Introduction

Silvrettagletscher is a small temperate mountain glacier located in the north-eastern part of Switzerland in the Silvretta massif at the border to Austria. The present surface area is 2.5 km^2, extending from 3080 m a.s.l. down to 2470 m a.s.l. First mass balance measurements date back to the 1910s (Firnberichte, 1978). Seasonal observations at two stakes were conducted until 1959, when the stake network was increased to about 40 stakes. In 1986, the network was drastically reduced to six sites along a longitudinal transect but was gradually expanded between 1991 and 2008 to reach its current spatially distributed configuration. Determination of volumetric changes in decadal resolution extends even further back to 1892 (Bauder et al., 2007). Topographic maps and photogrammetrical surveys exist for 1892, 1938, 1959, 1973, 1986, 1994, 2003, 2007, 2012 and every year since then. Huss et al. (2009) re-analyzed and homogenized the seasonal point mass balance data and geodetic ice volume changes for the period 1959 to 2007 to derive glacier wide mass balances. Annual updates using a consistent methodology are performed since then (GLAMOS, 2023a). Further details on observations of ice flow velocities are presented in Section 5.9.

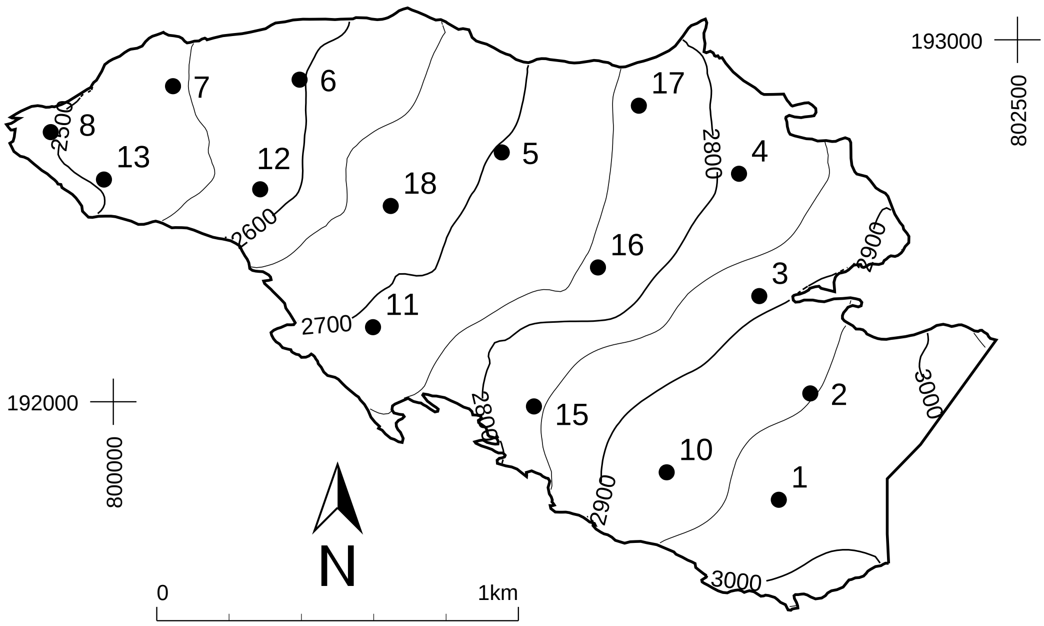


Figure 4.46: Surface topography and observational network of Silvrettagletscher.

Investigations in 2021/22

Field measurements of winter mass balance were conducted on 2nd May 2022. Snow depth probings were taken at 183 locations including all sites in the observational network. Density profiles using

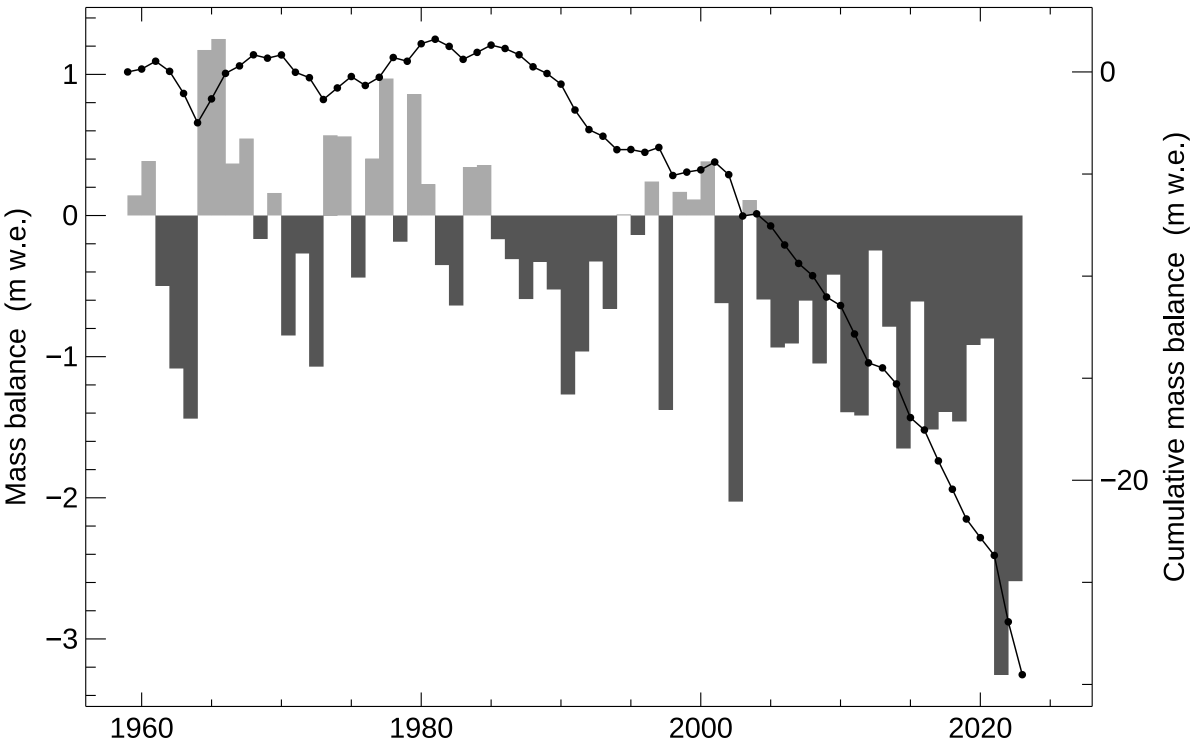


Figure 4.47: Silvrettagletscher - Mean specific annual balance (bars) and cumulative mass balance (line) for the period 1959-2023.

a core drill method were acquired at the sites 2, 4 and 7 ranging between 367 and 427 kg m^{-3}. The glacier remained completely snow-covered until mid-June 2022. During the melting season intermediate readings of the stakes were repeatedly taken in monthly intervals on 12th June, 17th July, and 14th August. The extraordinarily high melt rates in summer required redrilling of four stakes in mid-August. Observations of the annual balance in fall with maintenance of the stake network were carried out on 11th and 12th September 2022. By end of July the winter snow was completely depleted over the entire area. Extremely high melt rates were registered at all sites and no measurements of firn density were possible. A late-season survey at the end of October 2022 showed an additional melt of 90 mm to 225 mm w.e. that occurred after the fall campaign. Melt eventually was terminated by the formation of the winter snow cover after 3rd November 2022. At site 6 an autonomous camera was operated to acquire winter snow accumulation and summer ice melt in real-time. Daily pictures from a time-lapse camera taken from June until October document progressive melt-out and snowfall events during and after the summer season.

Investigations in 2022/23

The spring survey to evaluate the winter mass balance was performed on 3rd May 2023. Snow depth probings were collected at 155 locations distributed over the entire glacier surface. A mean snow depth of 332 cm was found. Snow density was determined at the same three locations as in the previous period using a core drill. A density of 408 kg m^{-3} at 2550 m a.s.l., 419 kg m^{-3} at

Table 4.31: Silvrettagletscher - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2400 - 2500	0.024	809	−4946	0.046	1175	−5018
2500 - 2600	0.319	927	−4686	0.309	1214	−4115
2600 - 2700	0.407	931	−3794	0.403	1298	−2966
2700 - 2800	0.578	952	−3139	0.538	1410	−2493
2800 - 2900	0.480	990	−2602	0.466	1448	−2123
2900 - 3000	0.522	930	−2649	0.516	1392	−1770
3000 - 3100	0.058	654	−2826	0.048	1075	−1656
2400 - 3100	2.389	939	−3253	2.325	1356	−2589

2830 and 378 $kg\,m^{-3}$ at 2950 m a.s.l. was determined, respectively. First bare-ice patches on the glacier were already observed at the beginning of July. Three visits during the melt season were carried out on 20th June, 20th July and 19th August for intermediate surveys of all stakes on the glacier. The late-summer field survey took place on 17th and 18th September 2023. All stakes registered a negative mass balance. The winter snow accumulation completely disappeared on the entire area. No density measurements were thus performed. Due to continued substantial melt rates throughout September and October, another full survey of the stake network was performed on 14th October 2023. After a snow fall event on 21st October the glacier remained snow-covered. The investigations are again supplemented by a camera at site 6 for real-time information on accumulation and melt as well as a time-lapse camera for monitoring the evolution of the transient snowline and snowfall events operated between mid June and early November 2023.

Table 4.32: Silvrettagletscher - Individual stake measurements of winter and annual balance.

Stake	Start	Period Spring	End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	b_a
10	18.09.2021	02.05.2022	12.09.2022	801524 / 191809 / 2926	976	−2720
01	18.09.2021	02.05.2022	12.09.2022	801838 / 191730 / 2971	899	−2886
02	18.09.2021	02.05.2022	12.09.2022	801927 / 192023 / 2947	888	−2690
03	18.09.2021	02.05.2022	11.09.2022	801786 / 192292 / 2884	1134	−1830
04	17.09.2021	02.05.2022	11.09.2022	801727 / 192632 / 2808	889	−3060
05	17.09.2021	02.05.2022	11.09.2022	801072 / 192691 / 2702	839	−3438
06	17.09.2021	02.05.2022	11.09.2022	800517 / 192888 / 2596	913	−4455
07	17.09.2021	02.05.2022	12.09.2022	800165 / 192872 / 2542	926	−4581
08	17.09.2021	02.05.2022	11.09.2022	799827 / 192741 / 2491	913	−4446
10	18.09.2021	02.05.2022	12.09.2022	801526 / 191807 / 2926	976	−2327
11	17.09.2021	02.05.2022	12.09.2022	800719 / 192205 / 2706	970	−3312
12	17.09.2021	02.05.2022	11.09.2022	800406 / 192585 / 2569	1093	−4293
13	17.09.2021	02.05.2022	11.09.2022	799979 / 192618 / 2507	644	−5850
15	17.09.2021	02.05.2022	12.09.2022	801160 / 191989 / 2841	897	−3186
16	17.09.2021	02.05.2022	11.09.2022	801335 / 192373 / 2755	981	−3087
17	17.09.2021	02.05.2022	11.09.2022	801452 / 192823 / 2763	927	−3420
18	17.09.2021	02.05.2022	12.09.2022	800762 / 192540 / 2671	924	−3303
01	12.09.2022	03.05.2023	14.10.2023	801840 / 191729 / 2967	1360	−1627
02	12.09.2022	03.05.2023	14.10.2023	801926 / 192024 / 2942	1171	−2065
03	11.09.2022	03.05.2023	14.10.2023	801780 / 192294 / 2878	1621	−1818
04	11.09.2022	03.05.2023	14.10.2023	801733 / 192630 / 2804	1445	−3159
05	11.09.2022	03.05.2023	14.10.2023	801072 / 192690 / 2696	1203	−2979
06	11.09.2022	03.05.2023	14.10.2023	800515 / 192890 / 2589	1203	−4041
07	12.09.2022	03.05.2023	14.10.2023	800165 / 192872 / 2534	1183	−4266
08	11.09.2022	03.05.2023	14.10.2023	799828 / 192743 / 2483	1170	−4752
10	12.09.2022	03.05.2023	14.10.2023	801529 / 191806 / 2922	1387	−1845
11	12.09.2022	03.05.2023	14.10.2023	800720 / 192207 / 2700	1487	−2673
12	11.09.2022	03.05.2023	14.10.2023	800406 / 192588 / 2562	1437	−3924
13	11.09.2022	03.05.2023	14.10.2023	799979 / 192628 / 2499	1024	−4968
15	12.09.2022	03.05.2023	14.10.2023	801162 / 191988 / 2837	1453	−2574
16	11.09.2022	03.05.2023	14.10.2023	801338 / 192372 / 2751	1416	−2430
17	11.09.2022	03.05.2023	14.10.2023	801455 / 192818 / 2758	1395	−2916
18	12.09.2022	03.05.2023	14.10.2023	800766 / 192541 / 2666	1294	−2844

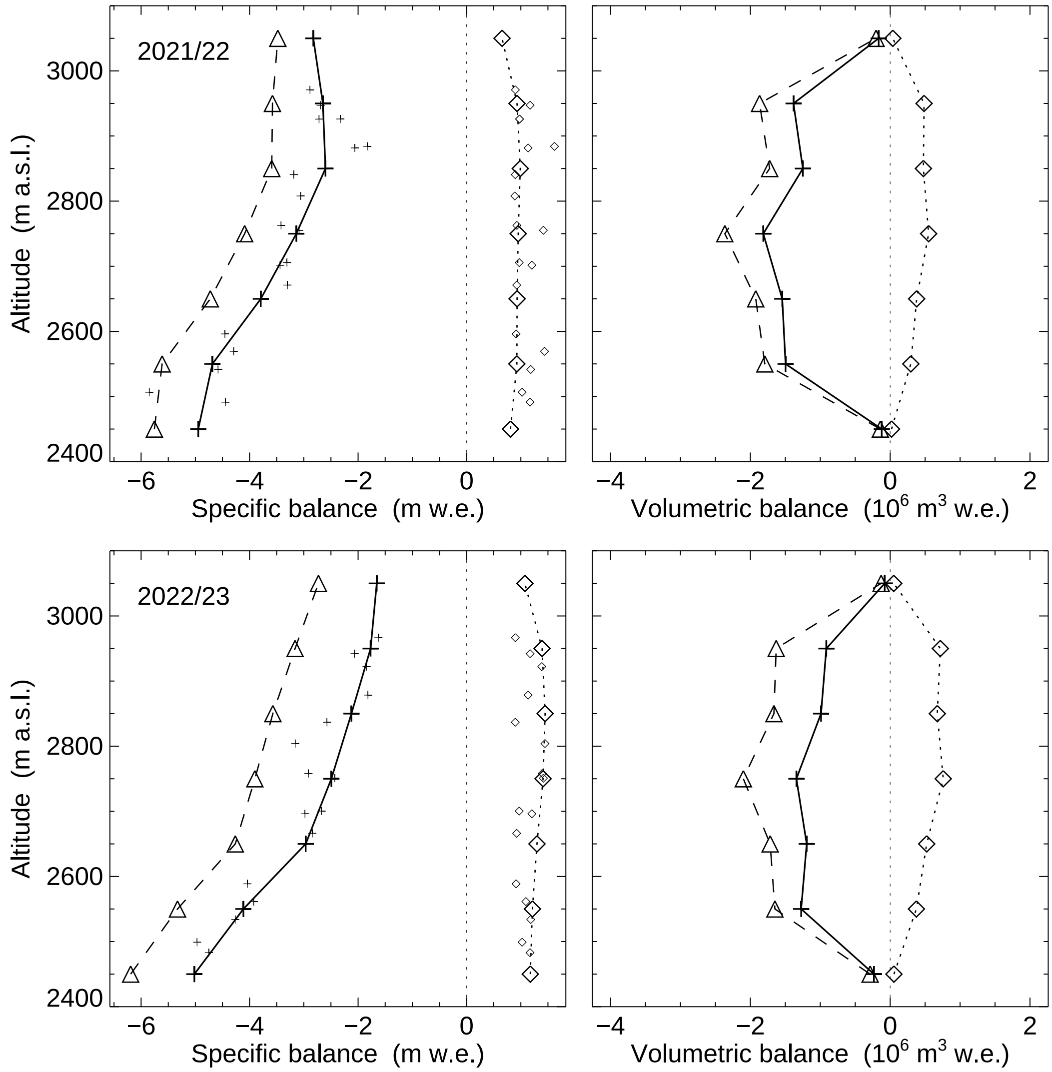


Figure 4.48: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

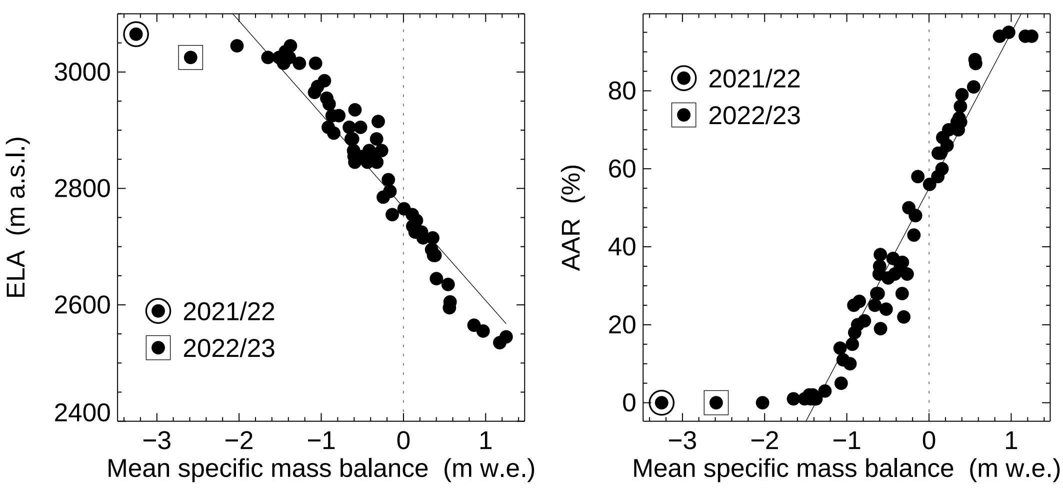


Figure 4.49: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

4.20 Glacier de Tsanfleuron

Introduction

Glacier de Tsanfleuron is a well-accessible medium-sized glacier at the border between the cantons of Valais, Vaud and Berne. The glacier currently has an area of 2.3 km^2 and exhibits relatively small surface slopes. Glaciological investigations were started in 2009. In addition, measurements are also performed on the very small Glacier du Sex Rouge (0.3 km^2) connected to Tsanfleuron in its accumulation area. This glacier lost its connection to Tsanfleuron in its accumulation area during the extreme melt events of summer 2022.

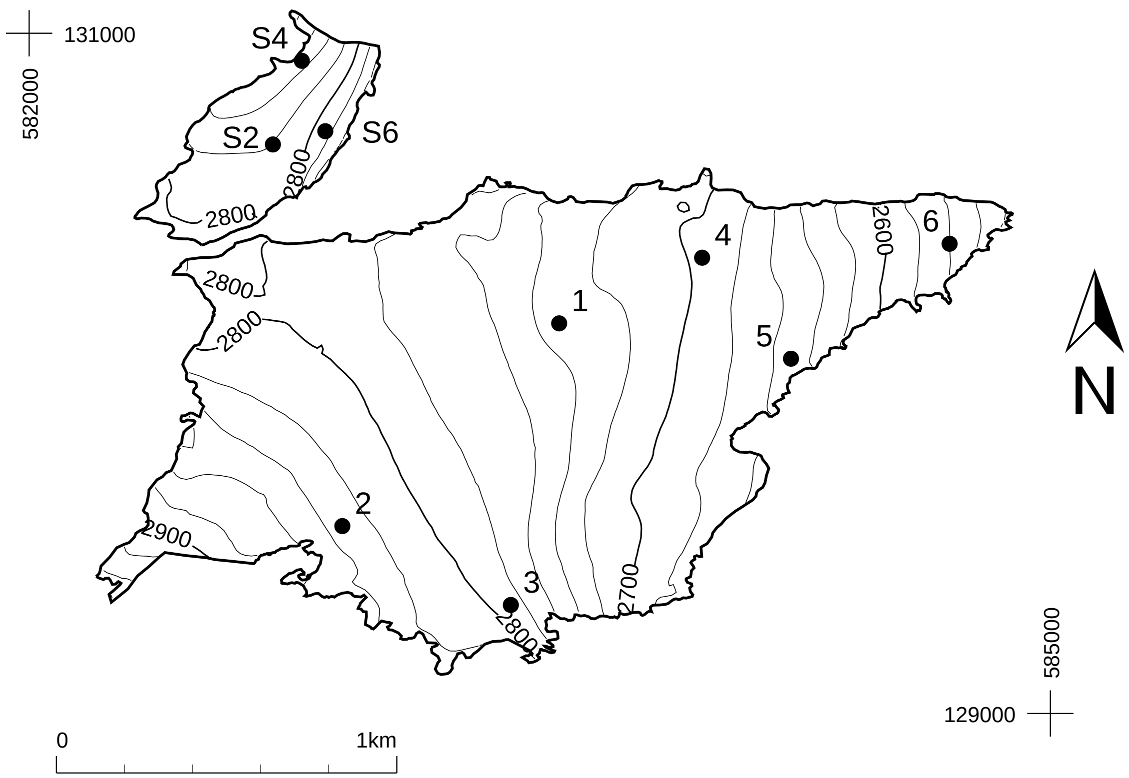


Figure 4.50: Surface topography and observational network of Glacier de Tsanfleuron and Glacier du Sex Rouge.

Investigations in 2021/22

The winter mass balance observations were conducted on 27th April 2022. A snow density of 420 and 460 kg m^{-3} was determined by coring at two locations in the lower and upper reaches of the glacier. Snow depth was measured based on 92 snow probings on Glacier de Tsanfleuron and 73 probings on Glacier du Sex Rouge. Due to extraordinary melting in summer, stakes were visited and partly redrilled on 18th July, 1st and 28th August. A final mass balance survey was conducted

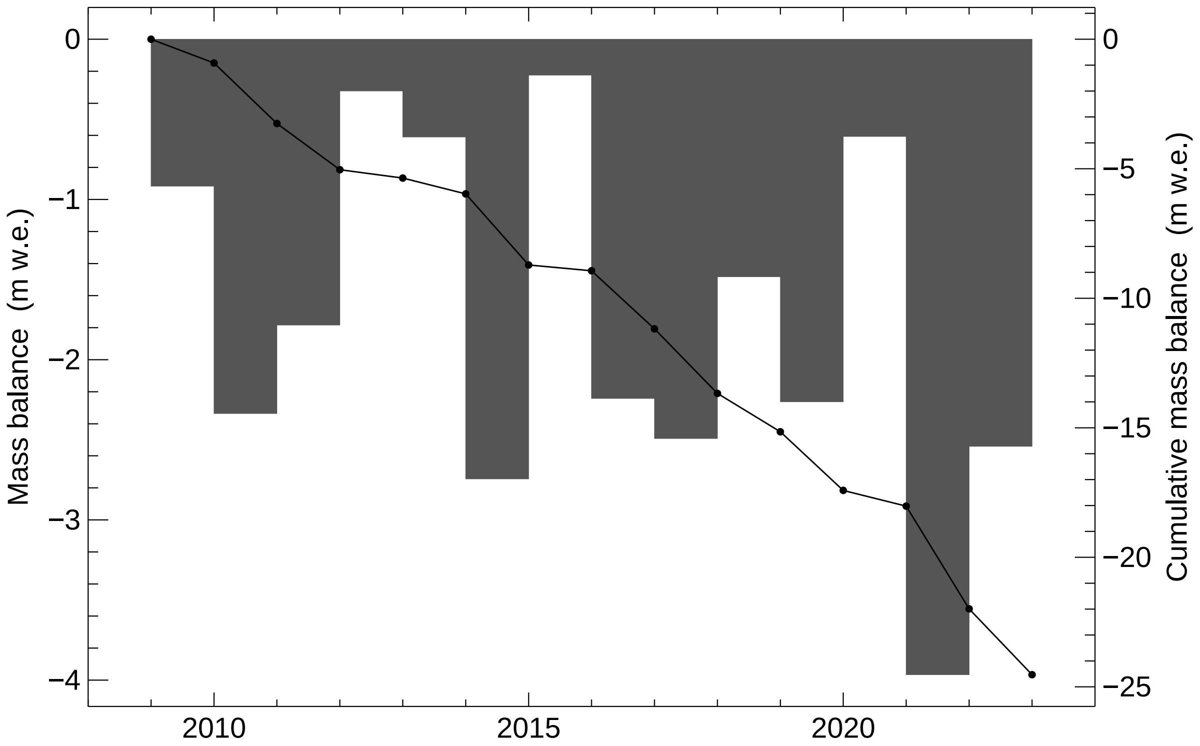


Figure 4.51: Glacier de Tsanfleuron - Mean specific annual balance (bars) and cumulative mass balance for the period 2009-2023.

on 10th September 2022 and the stakes were redrilled again. Record-negative mass balances were measured at all sites both on Tsanfleuron and Sex Rouge.

Investigations in 2022/23

During the winter field survey on 18th/19th April 2023, snow depth was measured based on 71 probings on Glacier du Tsanfleuron, and 36 on Glacier du Sex Rouge. A snow density of 450 kg m^{-3} was determined in a snow pit. Above-average snow depth was found on both glaciers, in

Table 4.33: Glacier de Tsanfleuron - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2500 - 2600	0.029	1269	−5553	0.021	2022	−4189
2600 - 2700	0.338	1389	−5007	0.338	2195	−3391
2700 - 2800	1.081	1573	−4058	1.081	2292	−2432
2800 - 2900	0.827	1678	−3440	0.827	2275	−2330
2900 - 3000	0.049	1503	−2728	0.049	1962	−1995
2500 - 3000	2.324	1578	−3966	2.315	2262	−2541

Table 4.34: Glacier du Sex Rouge - Specific winter (b_w) and annual (b_a) balance according to elevation bands for the two periods 2021/22 and 2022/23. Results refer to the measurement period, defined by the dates of the field survey.

Altitude	2021/22			2022/23		
	Area	$\overline{b_w}$	$\overline{b_a}$	Area	$\overline{b_w}$	$\overline{b_a}$
(m a.s.l.)	(km^2)	(mm w.e.)	(mm w.e.)	(km^2)	(mm w.e.)	(mm w.e.)
2700 - 2750	0.005	1560	−4310	0.005	2258	−1992
2750 - 2800	0.080	1513	−4027	0.080	2210	−1822
2800 - 2850	0.161	1522	−4087	0.161	1988	−2116
2850 - 2900	0.011	1795	−2709	0.011	2292	−1050
2700 - 2900	0.257	1532	−4011	0.257	2075	−1975

Table 4.35: Glacier de Tsanfleuron and Glacier du Sex Rouge - Individual stake measurements of winter and annual balance.

Stake	Period Start	Period Spring	Period End	Coordinates (m / m / m a.s.l.)	Mass balance b_w (mm w.e.)	Mass balance b_a (mm w.e.)
1	02.10.2021	27.04.2022	10.09.2022	583555 / 130151 / 2737	1613	−3341
2	02.10.2021	27.04.2022	10.09.2022	582917 / 129550 / 2844	1797	−2807
3	02.10.2021	27.04.2022	10.09.2022	583421 / 129320 / 2789	1890	−3465
4	02.10.2021	27.04.2022	10.09.2022	583974 / 130341 / 2703	1613	−4500
5	02.10.2021	27.04.2022	10.09.2022	584238 / 130041 / 2658	1376	−4995
6	02.10.2021	27.04.2022	10.09.2022	584707 / 130376 / 2587	1292	−5499
S2	12.09.2021	27.04.2022	11.09.2022	582712 / 130672 / 2786	1415	−4158
S4	12.09.2021	27.04.2022	11.09.2022	582791 / 130935 / 2752	1419	−3933
S6	12.09.2021	27.04.2022	11.09.2022	582868 / 130710 / 2819	1673	−3780
1	10.09.2022	19.04.2023	07.10.2023	583557 / 130147 / 2730	2169	−1811
2	10.09.2022	19.04.2023	07.10.2023	582920 / 129551 / 2832	2241	−1787
3	10.09.2022	19.04.2023	07.10.2023	583415 / 129319 / 2789	2664	−1701
4	10.09.2022	19.04.2023	07.10.2023	583977 / 130340 / 2695	2011	−3132
5	10.09.2022	19.04.2023	07.10.2023	584238 / 130043 / 2651	2038	−3231
6	10.09.2022	19.04.2023	07.10.2023	584704 / 130381 / 2559	2101	−4347
S2	11.09.2022	18.04.2023	17.09.2023	582716 / 130673 / 2781	2047	−1746
S4	11.09.2022	18.04.2023	17.09.2023	582801 / 130919 / 2752	2443	−1818
S6	11.09.2022	18.04.2023	17.09.2023	582870 / 130712 / 2813	2119	−2115
TK	11.09.2022	18.04.2023	17.09.2023	582606 / 130599 / 2788	1908	−2088

contrast to all other regions in the Swiss Alps during that period. An intermediate field visit was performed on 18th August. All stakes were redrilled on 17th September, and the measurement sites on Glacier du Tsanfleuron were visited again on 7th October 2023 after a melt-intense fall. Related to the operations of the skiing area, geotextiles are placed at some locations to limit the melt rates. The affected areas are too small to have an effect on overall glacier mass balance.

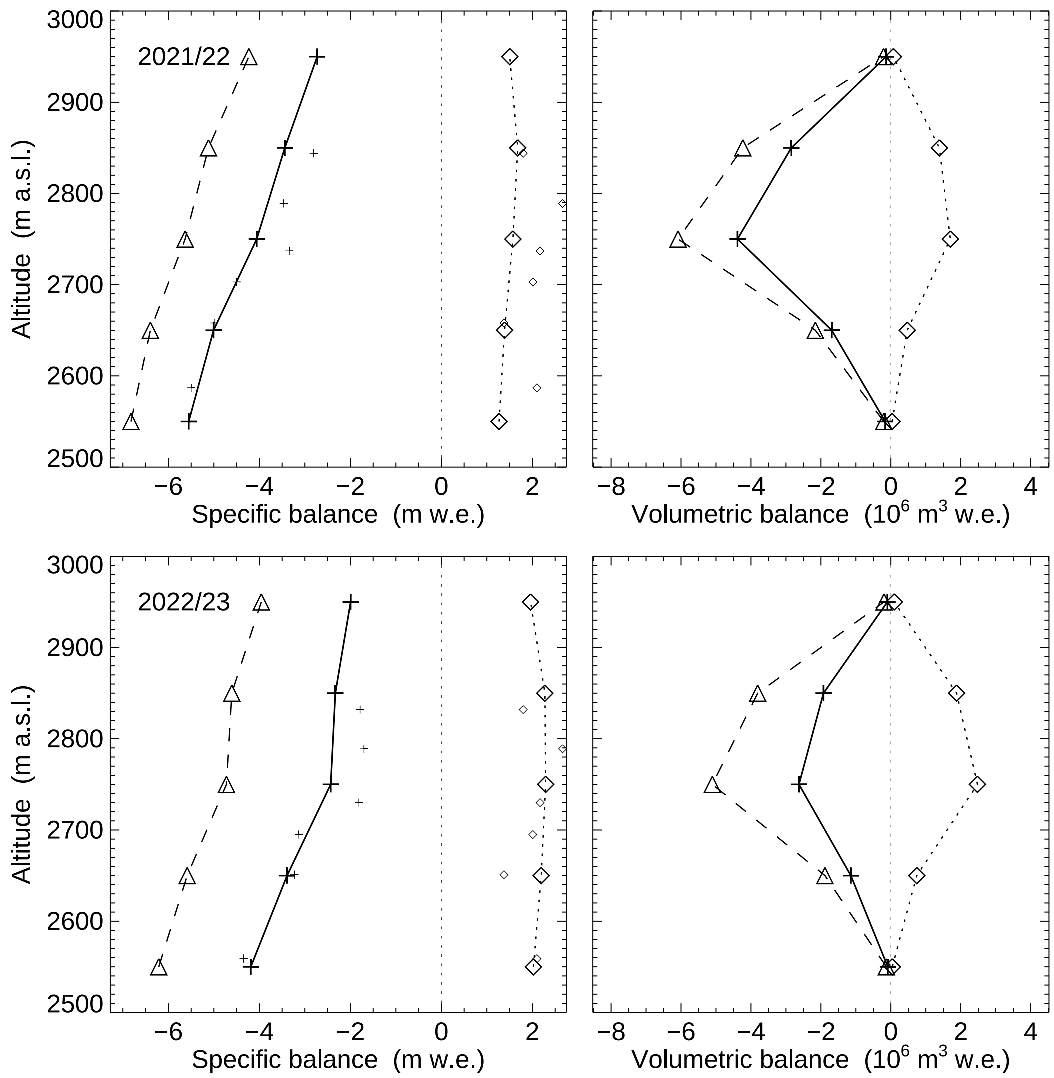


Figure 4.52: Specific (left) and volumetric (right) winter (dotted, ◇), summer (dashed, △) and annual (continuous line, +) balance in elevation bands for 2021/22 (top) and 2022/23 (bottom). Small symbols mark the individual measurements.

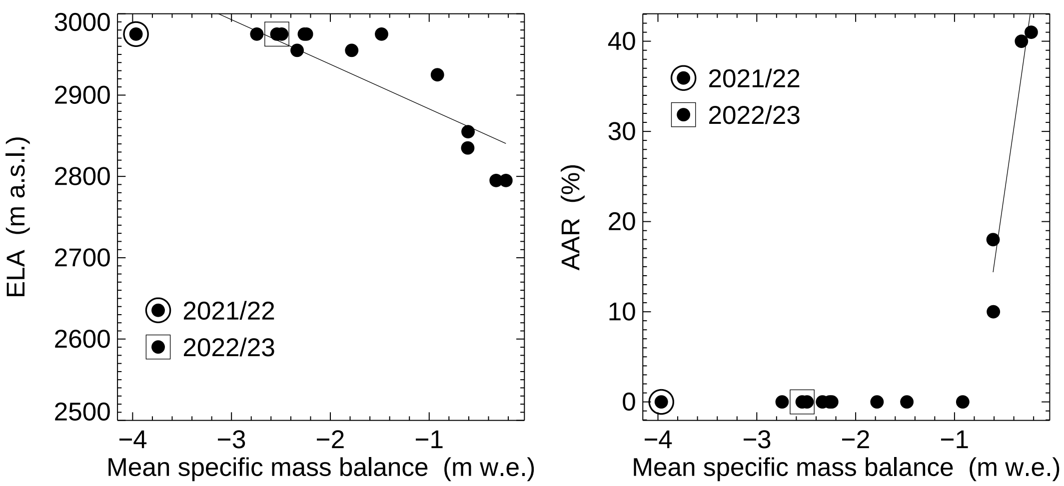


Figure 4.53: Equilibrium line altitude (ELA) and accumulation area ratio (AAR) versus mean specific balance including all previous observations.

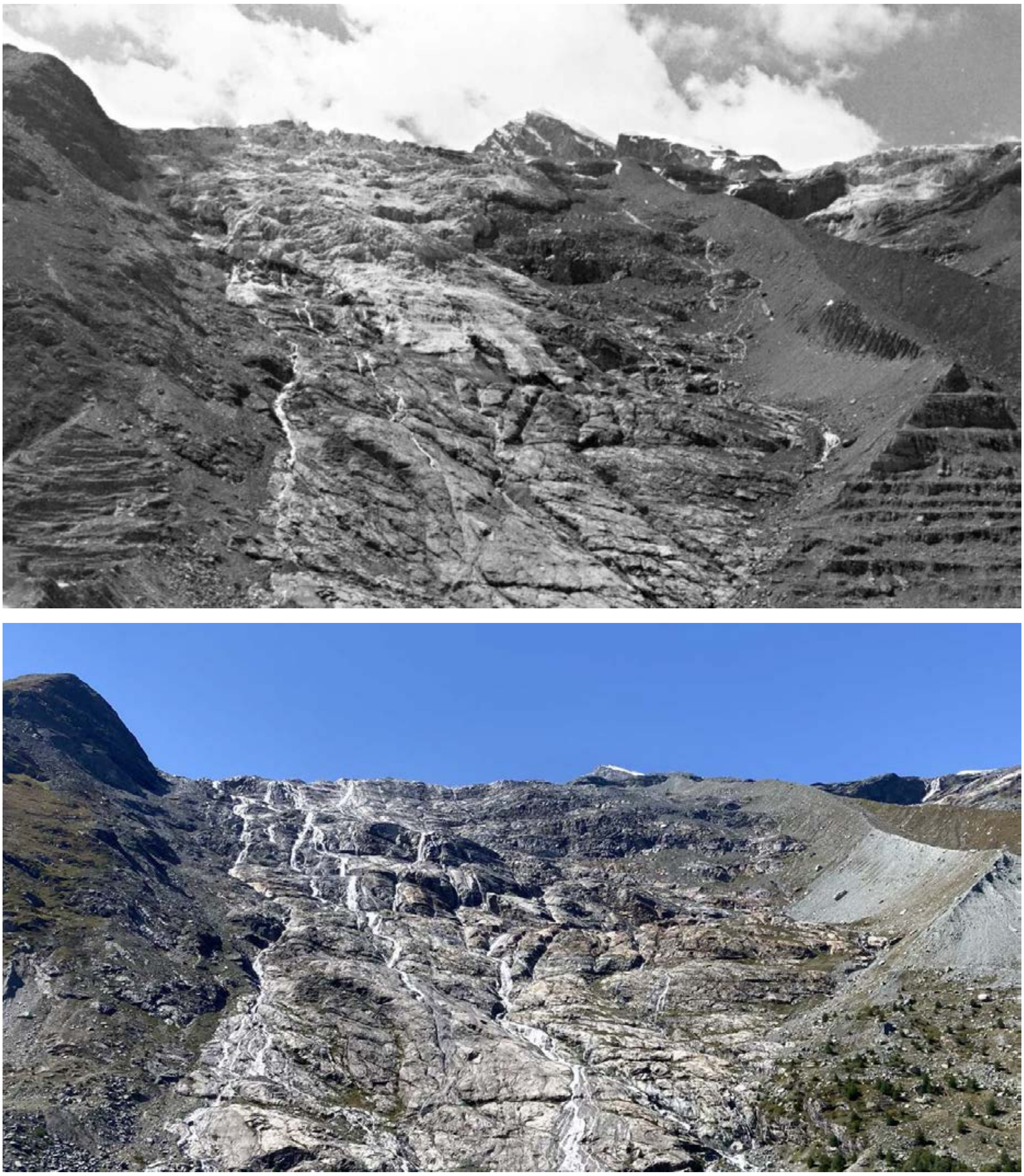
5 Flow Velocity

5.1 Introduction

On eight glaciers (Figure 5.1) long-term investigations for the measurement of local surface ice flow velocity are carried out. These observations are acquired at a network of one to 16 stakes per glacier. Presented numbers are annual velocities for a normalized period of 365 days to allow comparability, while corresponding thickness change is determined directly between successive surveys and is shown cumulatively. The VAW/ETHZ has been contracted by two hydro-electric power companies Kraftwerke Mattmark, and Forces Motrices de Mauvoisin SA to survey the glaciers in the operated catchments. The main objective of these investigations is to observe the ice flow dynamics of the glaciers, particularly with regard to their potential threat to the buildings and the operation of the power station in the valley. The observations are mainly focused on the two glaciers Corbassière and Giétro in the Mauvoisin area (Val de Bagnes), and the three glaciers

Figure 5.1: Investigated glaciers for surface velocity measurements.

Allalin, Hohlaub and Schwarzberg in the Mattmark area (Saastal). Further measurements are acquired related to long-term mass balance programmes (see Chapter 4) on Grosser Aletschgletscher, Rhonegletscher and Silvrettagletscher. Thanks to reduced efforts in surveying using global navigation satellite system (GNSS) technology, positions of stakes used for mass balance observations are available in necessary precision for evaluation of the surface flow velocity (GLAMOS, 2022).



The tongue of Allalingletscher in August 1965 (top, Photo: P. Kasser) and out of sight after complete disappearance from the steep section in September 2023 (bottom, Photo: A. Bauder)

5.2 Allalingletscher

Introduction

The first ice flow velocity measurements at Allalingletscher date back to 1955 (VAW, 1999). Initially, investigations were carried out at a network of nine stakes with the aim to determine glacier mass balance for planning and construction of the Mattmark reservoir for hydro-power production (VAW, 1999). In 1967 the observation network was re-arranged to the present configuration with a main focus for ice flow measurements. Measurements are currently being continued on seven selected stakes (Figure 4.5) as part of the investigations by VAW/ETHZ for the Mattmark hydro-power company (VAW, 2024). Figure 5.2 shows the horizontal surface flow velocities on Allalingletscher. In addition to ice flow velocity, annual mass balance is measured at the stakes (Table 4.4).

Investigations in 2021/22 and in 2022/23

The field surveys were carried out on 6th September 2022 and on 5th September 2023. During both field campaigns all seven stakes were located, surveyed and set back to their initial position. The position of the stakes was surveyed using differential GNSS relative to a local reference station. Results for horizontal flow velocity and thickness change are given in Table 5.1.
The ice flow velocity decreased further during the two periods under review. The general long-term trend of decreasing speed accompanied by a lowering of the ice surface was maintained.

Table 5.1: Allalin - Individual measurements of surface flow velocity and thickness change

Stake	Period Start	End	Coordinates (m / m / m a.s.l.)	Thickness change (m)	Velocity (m a^{-1})
100	02.09.2021	06.09.2022	636360 / 98710 / 3230	−3.67	28.59
100	06.09.2022	05.09.2023	636360 / 98710 / 3230	−2.15	25.10
101	02.09.2021	06.09.2022	638400 / 99360 / 2850	−5.58	7.81
101	06.09.2022	05.09.2023	638400 / 99360 / 2850	−3.30	6.50
102	02.09.2021	06.09.2022	638350 / 99480 / 2850	−4.25	9.08
102	06.09.2022	05.09.2023	638350 / 99480 / 2850	−3.39	6.75
103	02.09.2021	06.09.2022	638325 / 99575 / 2855	−4.51	8.73
103	06.09.2022	05.09.2023	638325 / 99575 / 2855	−3.60	7.11
104	02.09.2021	06.09.2022	638290 / 99665 / 2865	−4.47	9.44
104	06.09.2022	05.09.2023	638290 / 99665 / 2865	−3.74	6.59
105	02.09.2021	06.09.2022	638260 / 99755 / 2885	−6.49	10.03
105	06.09.2022	05.09.2023	638260 / 99755 / 2885	−4.48	7.24
106	02.09.2021	06.09.2022	637095 / 97810 / 3375	−4.26	3.04
106	06.09.2022	05.09.2023	637095 / 97810 / 3375	−5.51	2.18

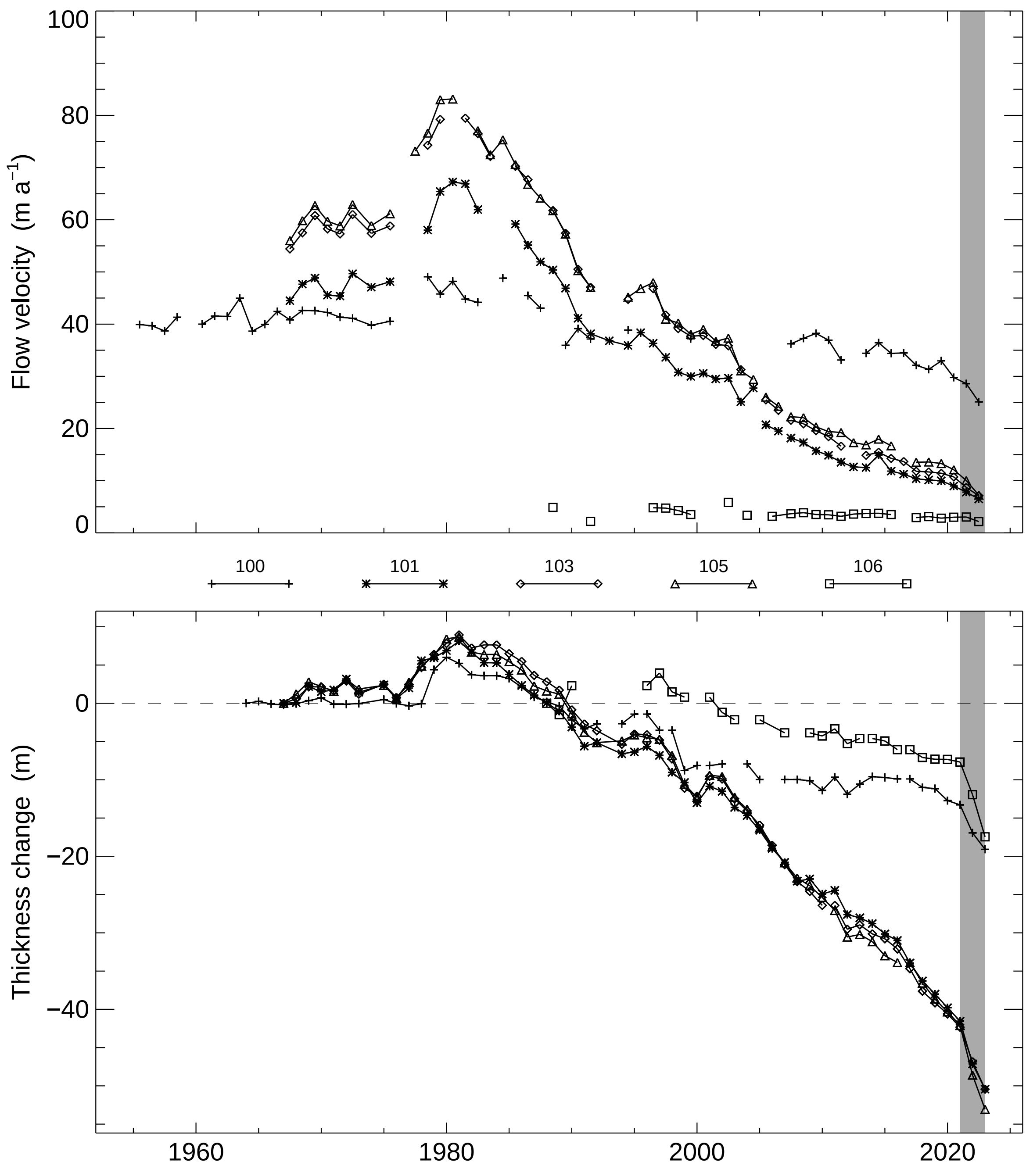


Figure 5.2: Surface flow velocities (top) and thickness change (below) of Allalingletscher at five stakes. The gray-shaded area highlights the years of the current report.

5.3 Glacier de Corbassière

Introduction

Since 1967, Glacier de Corbassière (Figure 4.14) has been under observation regarding surface ice flow velocities. On two cross-profiles in the ablation area, flow markers were placed on the surface and annually moved back to the initial position. In 1996 the flow markers were replaced by ablation stakes. Annual surveying has been carried out to determine the ice flow velocities and local mass balance (Section 4.7, Table 4.9). Figure 5.3 shows the horizontal surface flow velocities for the two profiles since 1967.

Investigations in 2021/22 and in 2022/23

The field surveys were carried out on 1st/2nd September 2022 and on 12th September 2023. Results from all six stakes of the new setup with two cross-profiles of three stakes implemented in fall 2020 were acquired in both periods. (Figure 4.14) In the first period a last measurement at site A2 was collected after the previous profile on the lower area of the glacier tongue was no longer maintained since fall 2021 due to the complete disintegration of the glacier in this area.

Table 5.2: Glacier de Corbassière - Individual measurements of surface flow velocity and thickness change

Stake	Period		Coordinates	Thickness change	Velocity
	Start	End	(m / m / m a.s.l.)	(m)	(m a^{-1})
B2	14.09.2021	01.09.2022	589577 / 93202 / 2605	−4.04	6.70
B2	01.09.2022	12.09.2023	589577 / 93202 / 2605	−3.82	7.16
B4	14.09.2021	01.09.2022	589392 / 93101 / 2610	−4.14	12.85
B4	01.09.2022	12.09.2023	589392 / 93101 / 2610	−4.04	12.18
B6	14.09.2021	01.09.2022	589230 / 93012 / 2615	−4.29	13.60
B6	01.09.2022	12.09.2023	589230 / 93012 / 2615	−4.08	12.36
R1	14.09.2021	01.09.2022	589150 / 93650 / 2570	−4.71	7.40
R1	02.09.2022	12.09.2023	589150 / 93650 / 2570	−4.39	7.42
R3	14.09.2021	01.09.2022	588950 / 93500 / 2570	−4.47	7.28
R3	02.09.2022	12.09.2023	588950 / 93500 / 2570	−4.43	5.99
R5	14.09.2021	01.09.2022	588805 / 93400 / 2565	−5.56	5.34
R5	01.09.2022	12.09.2023	588805 / 93400 / 2565	−4.97	4.46
A2	14.09.2021	01.09.2022	588650 / 94315 / 2385		1.20

The ice flow velocity decreased further during the two periods under review. As an exception of this general evolution the two sites (B2, R1) both at the right edge of the two profiles experienced slightly higher speeds in the second period. The long-term decline in flow speed is accompanied by a lowering of the ice surface due to ongoing thickness loss. This overall trend of decreasing speed persists.

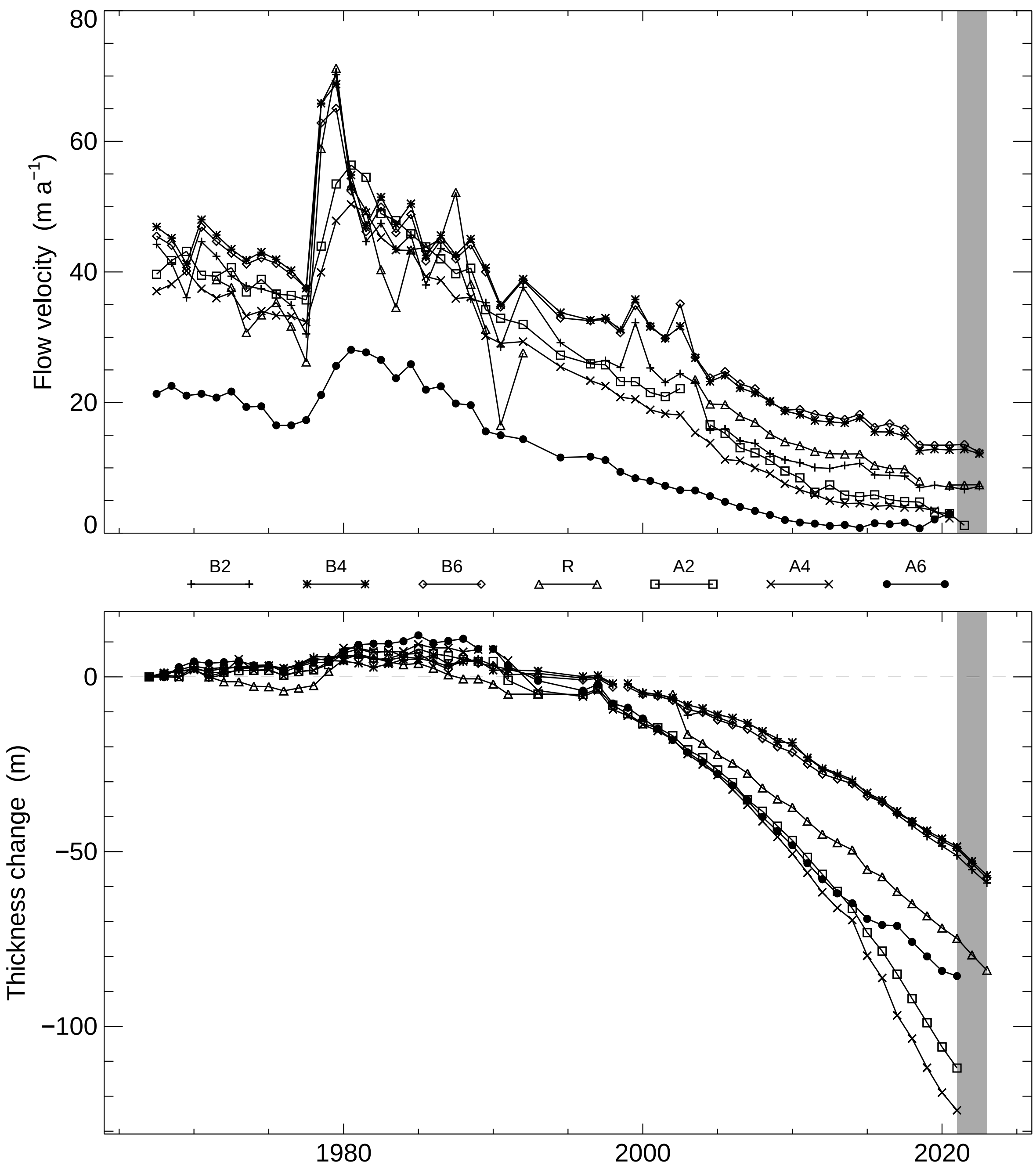


Figure 5.3: Surface flow velocities (top) and thickness change (bottom) of Glacier de Corbassière at two profiles with three stakes each and the additional stake in between. The gray-shaded area highlights the years of the current report.

5.4 Glacier du Giétro

Introduction

For Glacier du Giétro (Figure 4.19) in the Val de Bagnes (Valais) a very long measurement series of ice flow velocity is being maintained by VAW/ETHZ under contract with Forces Motrices de Mauvoisin SA. The aim of these annual observations was the early recognition of glacier break-offs, which could endanger the dammed lake located in the outreach of ice avalanches. The glacier tongue shrank drastically in recent years reducing the hazard potential substantially. The measurements, which have been carried out for more than 55 years, include periods of glacier growth and recession (VAW, 1997, 1998; Bauder et al., 2002; Raymond et al., 2003). In addition to ice flow velocity, annual mass balance is measured at the stakes (Section 4.9, Table 4.14).
Figure 5.4 shows the horizontal surface flow velocity measurements at seven stakes along the central longitudinal profile of the glacier, acquired since 1966. There are three distinct periods: in the first period (1966 to 1976), the velocities in the accumulation area (stakes 1, 2 and 4) were approximately 5-20 $m\,a^{-1}$, in the central region of the glacier (stake 5) about 35 $m\,a^{-1}$ and in the steep tongue area (stakes 102, 8 and 10) they were in the range of 50-90 $m\,a^{-1}$. The second period (1977 to 1982) is marked by a distinct acceleration, in which the speeds (for example at stake 102) increased from 90 $m\,a^{-1}$ to 120 $m\,a^{-1}$. From the mid-1980s onward, the velocities decreased sharply, and in the last years reached the lowest values measured since 1966.

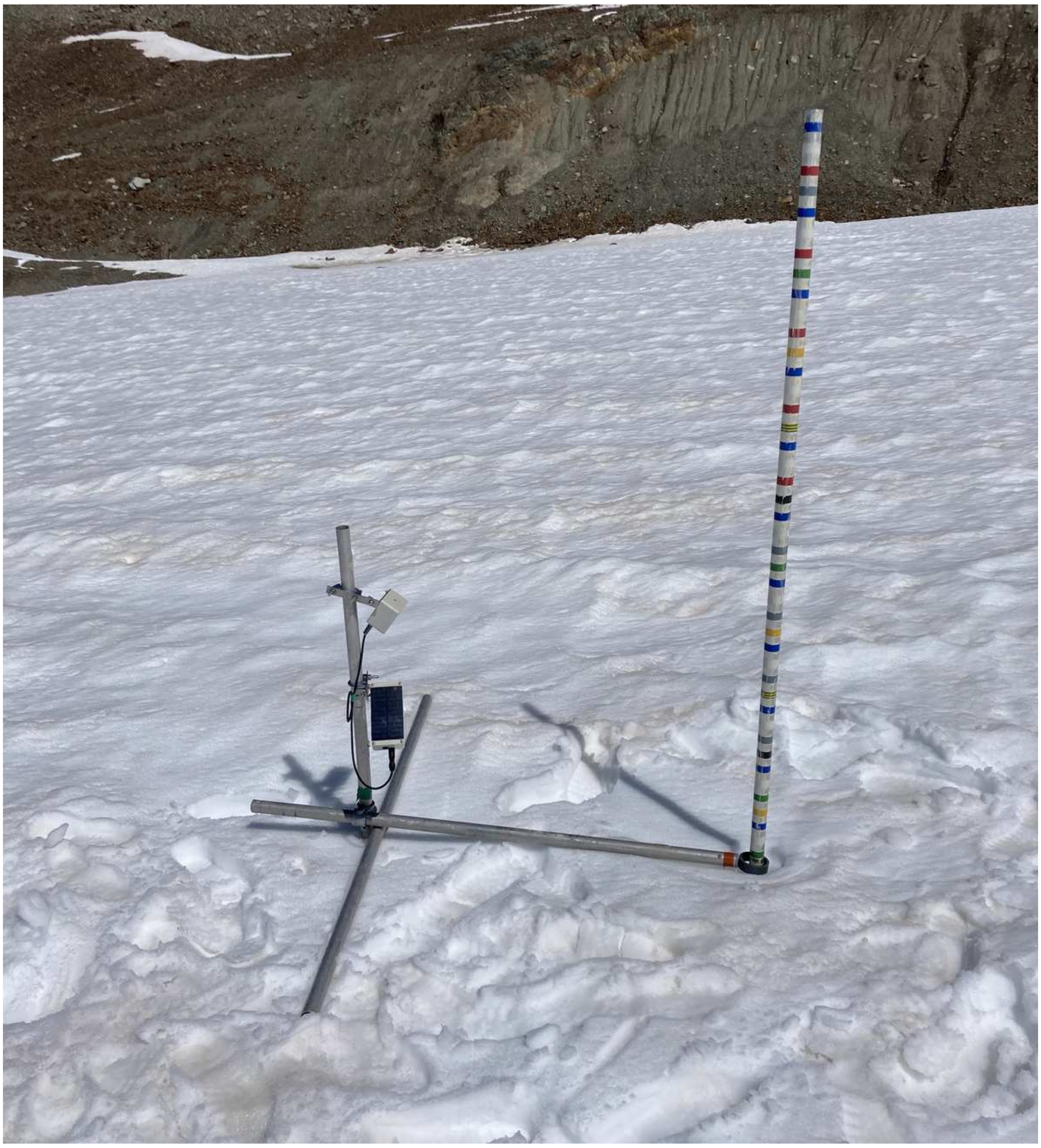
Table 5.3: Glacier du Giétro - Individual measurements of surface flow velocity and thickness change

Stake	Period Start	End	Coordinates (m / m / m a.s.l.)	Thickness change (m)	Velocity ($m\,a^{-1}$)
1	14.09.2021	01.09.2022	596143 / 92346 / 3290	−3.00	2.10
1	01.09.2022	12.09.2023	596143 / 92346 / 3290	−2.03	1.85
2	14.09.2021	01.09.2022	596605 / 92835 / 3240	−3.04	7.22
2	01.09.2022	12.09.2023	596605 / 92835 / 3240	−1.99	6.6
4	14.09.2021	01.09.2022	596211 / 93400 / 3180	−3.19	10.27
4	01.09.2022	12.09.2023	596211 / 93400 / 3180	−1.92	9.62
5	14.09.2021	01.09.2022	595615 / 94303 / 3045	−3.15	13.71
5	01.09.2022	12.09.2023	595615 / 94303 / 3045	−2.56	12.47
101	14.09.2021	01.09.2022	594735 / 94540 / 2855	−4.64	19.79
101	01.09.2022	12.09.2023	594735 / 94540 / 2855	−4.27	17.94
107	14.09.2021	01.09.2022	594859 / 94560 / 2905	−4.58	18.92
107	01.09.2022	12.09.2023	594859 / 94560 / 2905	−5.35	14.08

Investigations in 2021/22 and in 2022/23

Measurements of surface flow velocity and local mass balance were performed at six stakes in both periods. Due to the extreme melt in summer 2022, the additional site 102 available in previous years melted out completely before the end of the period and the measurement site had to given up. The field survey in fall 2022 was carried out on 1st September. All stakes have been located and moved back to the initial position. On 12th September 2023, the field measurements were carried out for the second period. Again, all stakes have been located and surveyed.

The decrease in ice flow velocity over the past years continued during the two periods covered by this report. Due to the glacier retreat with complete ice wastage at the glacier snout, the two sites 8 and 10 had to be abandoned already in 2010 and are no longer under observation but kept in Figure 5.4 for comparison. The former site 6 has eventually replaced by the new site 107 in close vicinity. The change observed at the lower sites still reflects to large extent the lowering of the surface but is also hampered by local effects caused by the formation of large crevasses and shifts of the initial position.



Setup of an automatic camera for real-time observations of snow and ice melt in June 2022 on Silvrettagletscher (Photo: A. Bauder)

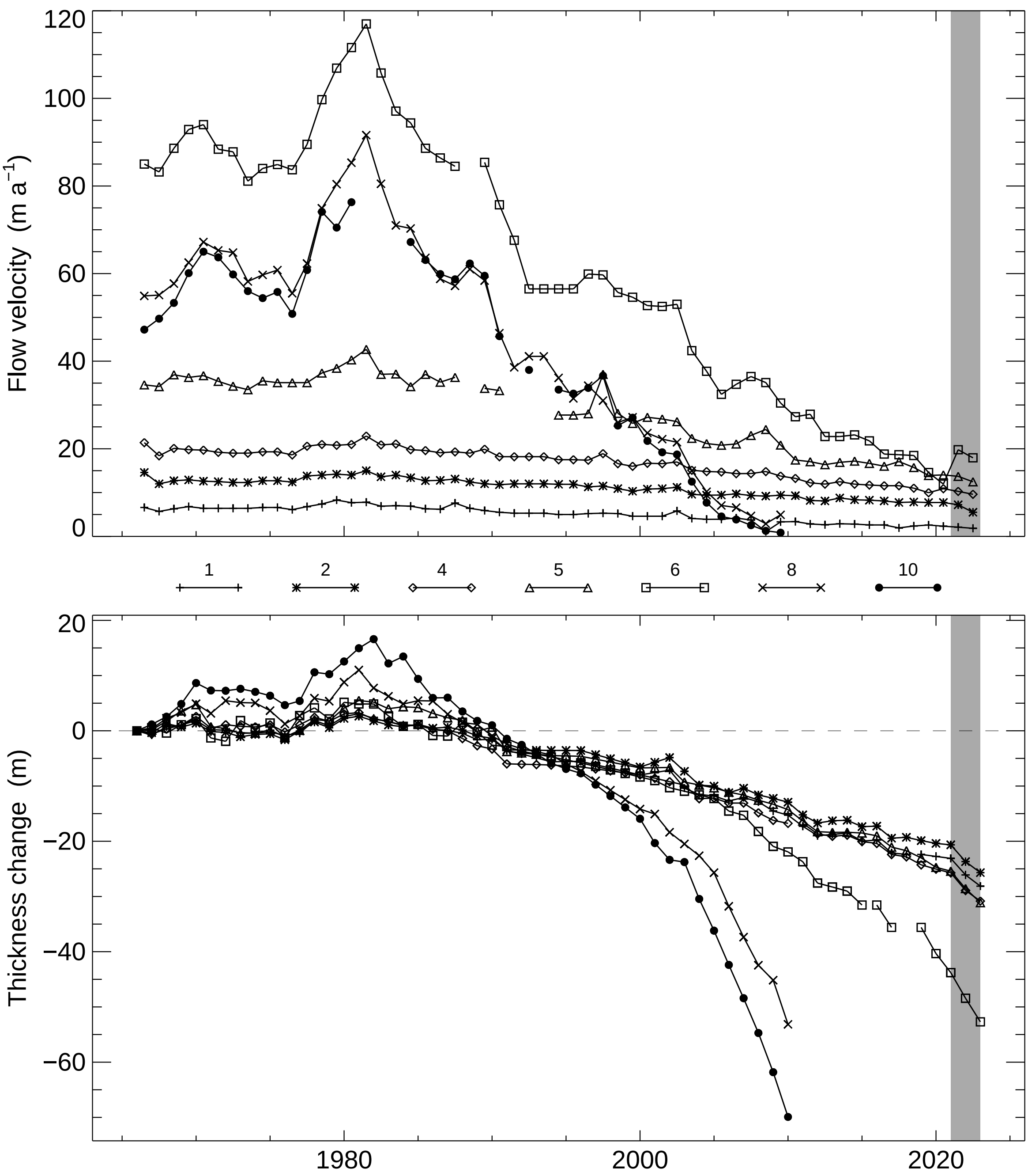


Figure 5.4: Surface flow velocities (top) and thickness change (bottom) of Glacier du Giétro at seven stakes. The gray-shaded area highlights the years of the current report.

5.5 Grosser Aletschgletscher

Introduction

Grosser Aletschgletscher (Figure 4.25) has been under observation for surface ice flow velocities since several decades. Between 1940s and 1980s a network of stakes on a longitudinal and several cross profiles was maintained with a focus on both mass balance and ice flow velocity (Zoller, 2010). As a part of the ongoing mass balance investigations at stake 3 close to Jungfraujoch the position is surveyed systematically since 2004, thus allowing the determination of the surface flow velocity and thickness change. The results of the mass balance observations are presented in Section 4.11 and Table 4.17 of this report.

Investigations in 2021/22 and in 2022/23

Field surveys were carried out on a seasonal basis on 17th May and 4th October in 2022, and 26th May and 28th September in 2023, respectively. Using high-precision differential GNSS the position of stake 3 was surveyed. In fall, the stake was moved back to the initial position. The results of the annual horizontal surface flow velocity and the change in ice thickness during the two measurement periods of this report are presented in Table 5.4.

Table 5.4: Grosser Aletschgletscher - Individual measurements of surface flow velocity and thickness change

Stake	Period		Coordinates	Thickness change	Velocity
	Start	End	(m / m / m a.s.l.)	(m)	(m a^{-1})
3	30.09.2021	04.10.2022	641825 / 154810 / 3335	−3.24	31.98
3	04.10.2022	28.09.2023	641825 / 154810 / 3335	−1.45	27.35

During the second period, the annual horizontal surface flow velocity reached its lowest value since 2004. While in the first period a 10% higher velocity in the summer season compared to the winter was recorded, variations in the second period were lower with 3%. The results of the annual horizontal surface flow velocity as well as the change in thickness since 2004 are shown in Figure 5.5. Only relatively small year-to-year fluctuations are evident. In an evaluation of historical measurements at site 3 between 1957 and 1966, Zoller (2010) determined annual surface flow velocities of 30 m a^{-1} to 40 m a^{-1} that were slightly higher than the observed values in the recent two decades. During the past 17 years with continuous observation, the ice thickness decreased by about 7 m at site 3. The inter-annual fluctuations are attributed to mass balance variations.

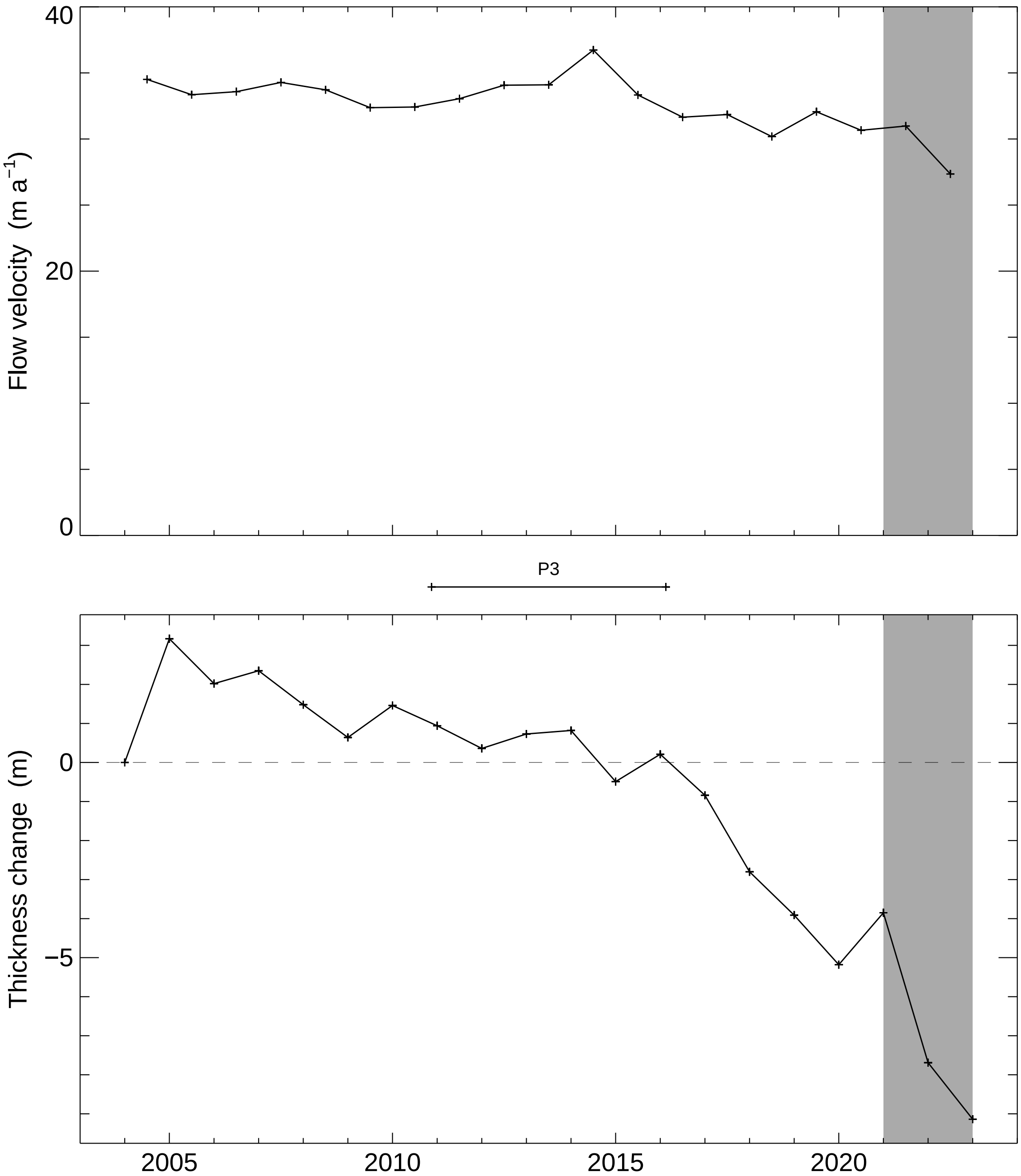


Figure 5.5: Surface flow velocities (top) and thickness change (bottom) at stake P3 on Grosser Aletschgletscher. The gray-shaded area highlights the years of the current report.

5.6 Hohlaubgletscher

Introduction

The first ice flow velocity measurements on Hohlaubgletscher date back to 1955 (VAW, 1999). Initially, investigations were carried out at a network of three stakes with the aim to determine glacier mass balance for planning and construction of the Mattmark reservoir for hydro-power production (VAW, 1999). In 1967 the observation network the glacier was reduced. Measurements were continued at only one stake and extended by a second site in 2019 (Figure 4.26) as part of the investigations by VAW/ETHZ for the Mattmark hydro-power company (VAW, 2024). In addition to ice flow velocity, annual mass balance is measured at the two stakes (Table 4.18).

Investigations in 2021/22 and in 2022/23

The field surveys were carried out on 6th September 2022 and on 5th September 2023. During both field campaigns all stakes were located, surveyed and set back to their initial position. The position of the stakes was surveyed using differential GNSS relative to a local reference station. Results for horizontal flow velocity and thickness change are given in Table 5.5.

A decrease in the annual horizontal surface flow velocity was registered at both sites. An extraordinarily high thickness change was observed in the first period as a direct consequence of the intensive melting during summer 2022.

Table 5.5: Hohlaub - Individual measurements of surface flow velocity and thickness change

Stake	Period		Coordinates	Thickness change	Velocity
	Start	End	(m / m / m a.s.l.)	(m)	(m a^{-1})
110	02.09.2021	06.09.2022	637405 / 100710 / 3025	−4.66	9.73
110	06.09.2022	05.09.2023	637405 / 100710 / 3020	−2.54	7.70
115	02.09.2021	06.09.2022	636465 / 100640 / 3240	−4.7	33.33
115	06.09.2022	05.09.2023	636460 / 100625 / 3240	−2.5	28.80

5.7 Rhonegletscher

Introduction

Starting in 2006, as part of the mass balance investigations at Rhonegletscher (Figure 4.36), the positions of all stakes are also surveyed for the evaluation of surface flow velocity. The substantial glacier melt and the associated retreat over the past two decades required modification of the observational network. However, several continuous time series of surface flow velocity distributed along a longitudinal transect have been acquired. The corresponding results of the mass balance observations are presented in Section 4.16 and Table 4.26 of this report.

Investigations in 2021/22 and in 2022/23

Measurement of surface flow velocity and mass balance were performed at 11 stakes. Due to the ongoing retreat of the glacier the lower-most stake had to be given up after the first period. The field survey in fall 2022 was carried out on 9th September. All 11 stakes have been located and but only 10 moved back to the initial position. On 8th September 2023, the field measurements were

Table 5.6: Rhonegletscher - Individual measurements of surface flow velocity and thickness change

Stake	Period		Coordinates	Thickness change	Velocity
	Start	End	(m / m / m a.s.l.)	(m)	(m a^{-1})
01	08.09.2021	09.09.2022	673815 / 166615 / 3235	−3.88	20.38
01	09.09.2022	08.09.2023	673815 / 166615 / 3230	−0.97	
02	08.09.2021	09.09.2022	673552 / 165950 / 3125	−5.3	57.45
02	09.09.2022	08.09.2023	673552 / 165950 / 3120	−1.3	50.05
03	08.09.2021	09.09.2022	673100 / 164930 / 2920	−5.3	45.47
03	09.09.2022	08.09.2023	673100 / 164930 / 2915	−2.6	43.28
04	08.09.2021	09.09.2022	673357 / 162758 / 2735	−3.95	54.71
04	09.09.2022	08.09.2023	673357 / 162758 / 2730	−3.59	52.67
05	08.09.2021	09.09.2022	672521 / 161919 / 2590	−5.42	53.75
05	09.09.2022	08.09.2023	672521 / 161919 / 2585	−3.22	50.77
06	08.09.2021	09.09.2022	672423 / 160843 / 2445	−5.30	26.99
06	09.09.2022	08.09.2023	672423 / 160843 / 2440	−5.74	23.92
07	08.09.2021	09.09.2022	672657 / 160173 / 2330	−7.68	21.29
07	09.09.2022	08.09.2023	672657 / 160173 / 2325	−7.58	17.49
08	08.09.2021	09.09.2022	672680 / 159724 / 2260	−9.70	8.84
08	09.09.2022	08.09.2023	672680 / 159724 / 2250	−9.53	7.02
09	08.09.2021	09.09.2022	672605 / 159500 / 2210	−8.68	5.87
12	08.09.2021	09.09.2022	673500 / 163990 / 2835	−4.88	38.66
12	09.09.2022	08.09.2023	673500 / 163990 / 2830	−2.79	37.46
13	08.09.2021	09.09.2022	672705 / 159937 / 2290	−8.85	11.09
13	09.09.2022	08.09.2023	672705 / 159937 / 2280	−8.21	8.50

carried out for the second period. High-precision real-time differential GNSS relative to a local reference station was used for surveying the positions of the stakes in both periods. The results of annual horizontal surface flow velocity and change in ice thickness determined during the two measurement periods of this report are presented in Table 5.6.

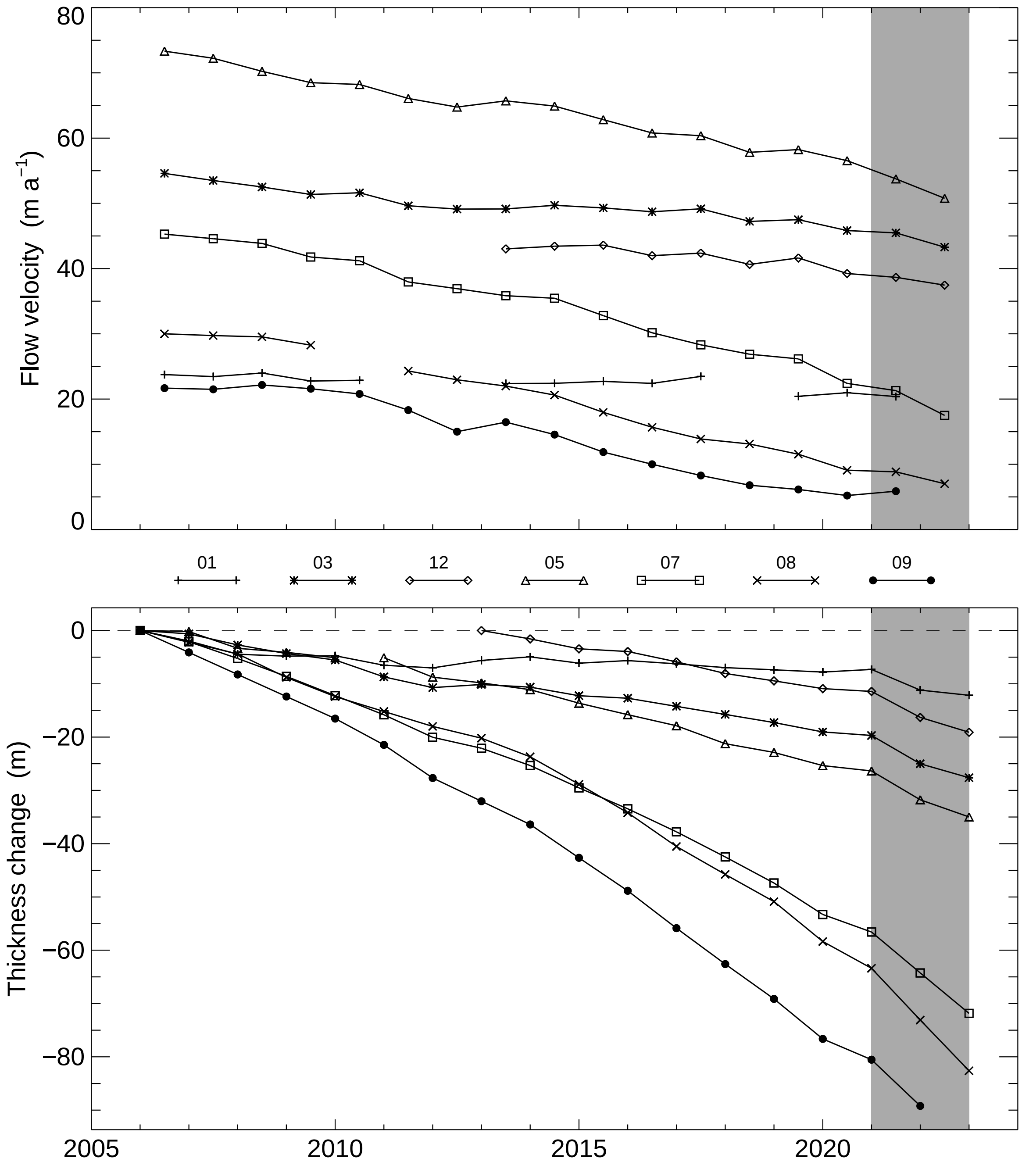


Figure 5.6: Surface flow velocities (top) and thickness change (bottom) of Rhonegletscher at selected stakes. The gray-shaded area highlights the years of the current report.

Observed flow velocities in the two measurement periods range from about 6 m a^{-1} at the lowermost stake on the glacier tongue to about 60 m a^{-1} at the stake at about 2700 m a.s.l., 2750 m a.s.l. and 3100 m a.s.l., respectively.

5.8 Schwarzberggletscher

Introduction

The first ice flow velocity measurements on Schwarzberggletscher date back to 1955 (VAW, 1999). Initially, investigations were carried out at a network of seven stakes with the aim to determine glacier mass balance for planning and construction of the Mattmark reservoir for hydro-power production (VAW, 1999). In 1967 the observation network was reduced to two stakes. Measurements are currently being continued on three selected stakes (Figure 4.44) as part of the investigations by VAW/ETHZ for the Mattmark hydro-power company (VAW, 2024). In addition to ice flow velocity, annual mass balance is measured at the stakes (Table 4.30).

Investigations in 2021/22 and in 2022/23

The field surveys were carried out on 6th September 2022 and on 5th September 2023. During both field campaigns all stakes were located, surveyed and set back to their initial position. The position of the stakes was surveyed using differential GNSS relative to a local reference station. Results for horizontal flow velocity and thickness change are given in Table 5.7.
Annual velocities in the two measurement periods varies between 1.5 $\mathrm{m\,a^{-1}}$ and 8.5 $\mathrm{m\,a^{-1}}$ and reflect the limited ice thickness and the generally gentle slope. The decrease in ice flow velocity over the past two periods was extraordinary. With a reduction of up to two thirds, this glacier experienced the highest relative change in flow speed of all measurements presented in this report. Hence, the general long-term trend of decreasing speed accompanied by a lowering of the ice surface was maintained.

Table 5.7: Schwarzberg - Individual measurements of surface flow velocity and thickness change

Stake	Period Start	Period End	Coordinates (m / m / m a.s.l.)	Thickness change (m)	Velocity (m a^{-1})
120	02.09.2021	06.09.2022	638320 / 96220 / 2840	−5.58	6.87
120	06.09.2022	05.09.2023	638320 / 96220 / 2835	−3.85	3.64
123	02.09.2021	06.09.2022	638525 / 96730 / 2750	−5.93	4.39
123	06.09.2022	05.09.2023	638525 / 96730 / 2745	−4.57	1.52
124	02.09.2021	06.09.2022	638062 / 95212 / 2975	−4.36	8.46
124	06.09.2022	05.09.2023	638062 / 95212 / 2970	−2.40	5.43

5.9 Silvrettagletscher

Introduction

Starting in 2003, as part of the mass balance monitoring programme at Silvrettagletscher (Figure 4.46), the positions of the available stakes are also surveyed for the evaluation of surface flow velocity. In 2008 the number of stakes were increased from initially 11 to presently 16 stakes that are annually surveyed. The corresponding results of the mass balance observations are presented in Section 4.19 and Table 4.32 of this report.

Investigations in 2021/22 and in 2022/23

In the two periods under review in this report, measurements of surface flow velocity were performed at 16 stakes. The field survey in fall 2022 was carried out on $11^{th}/12^{th}$ September. All stakes have been located and surveyed. On $17^{th}/18^{st}$ September 2023, the field measurements were taken for the second period. Positions have been surveyed using high-precision real-time differential GNSS. Some stakes are moved back annually to their initial position while maintenance of others is only needed every second year. The results of annual horizontal surface flow velocity and change in ice thickness determined during the two measurement periods covered by this report are presented in Table 5.8.

Observed ice flow velocities on Silvrettagletscher are small due to limited ice thickness and generally gentle slopes. Annual velocities in the two measurement periods vary between less than one and several metres per year. A further decrease in flow speed was found. This decrease reflects the ongoing reduction of ice thickness registered over the past two decades at all sites. Figure 5.7 shows the results of the annual horizontal surface flow velocity as well as the cumulative change in thickness since 2003.

Table 5.8: Silvrettagletscher - Individual measurements of surface flow velocity and thickness change

Stake	Period		Coordinates	Thickness change	Velocity
	Start	End	(m / m / m a.s.l.)	(m)	(m a^{-1})
01	17.09.2021	11.09.2022	801840 / 191729 / 2970	−3.42	0.98
01	11.09.2022	17.09.2023	801840 / 191729 / 2970	−2.69	0.60
02	17.09.2021	11.09.2022	801927 / 192023 / 2945	−3.55	3.63
02	11.09.2022	17.09.2023	801927 / 192023 / 2945	−2.79	3.35
03	17.09.2021	11.09.2022	801783 / 192252 / 2880	−3.58	4.88
03	11.09.2022	17.09.2023	801783 / 192252 / 2880	−2.55	3.60
04	17.09.2021	11.09.2022	801730 / 192630 / 2805	−3.47	3.02
04	11.09.2022	17.09.2023	801730 / 192630 / 2805	−2.43	2.75
05	17.09.2021	11.09.2022	801074 / 192689 / 2700	−3.98	3.25
05	11.09.2022	17.09.2023	801074 / 192689 / 2700	−3.14	2.74
06	17.09.2021	11.09.2022	800515 / 192890 / 2590	−4.69	1.73
06	11.09.2022	17.09.2023	800515 / 192890 / 2590	−4.02	1.48
07	17.09.2021	11.09.2022	800165 / 192872 / 2535	−5.26	0.27
07	11.09.2022	17.09.2023	800165 / 192872 / 2535	−4.52	0.08
08	17.09.2021	11.09.2022	799827 / 192745 / 2485	−6.08	0.13
08	11.09.2022	17.09.2023	799827 / 192745 / 2485	−5.32	0.14
10	17.09.2021	11.09.2022	801530 / 191805 / 2925	−3.03	2.16
10	11.09.2022	17.09.2023	801530 / 191805 / 2925	−2.45	1.87
11	17.09.2021	11.09.2022	800718 / 192206 / 2700	−3.94	0.74
11	11.09.2022	17.09.2023	800718 / 192206 / 2700		0.26
12	17.09.2021	11.09.2022	800406 / 192587 / 2565	−5.29	1.30
12	11.09.2022	17.09.2023	800406 / 192587 / 2565	−4.05	1.24
13	17.09.2021	11.09.2022	799949 / 192607 / 2495	−6.85	1.97
13	11.09.2022	17.09.2023	799949 / 192607 / 2495	−5.58	0.68
15	17.09.2021	11.09.2022	801163 / 191987 / 2840	−3.19	2.89
15	11.09.2022	17.09.2023	801163 / 191987 / 2840	−2.57	2.67
16	17.09.2021	11.09.2022	801340 / 192371 / 2755	−3.42	4.54
16	11.09.2022	17.09.2023	801340 / 192371 / 2755	−2.62	4.14
17	17.09.2021	11.09.2022	801453 / 192818 / 2760	−3.66	2.30
17	11.09.2022	17.09.2023	801453 / 192818 / 2760	−3.01	1.86
18	17.09.2021	11.09.2022	800767 / 192541 / 2670	−3.78	3.49
18	11.09.2022	17.09.2023	800767 / 192541 / 2670	−3.03	2.88

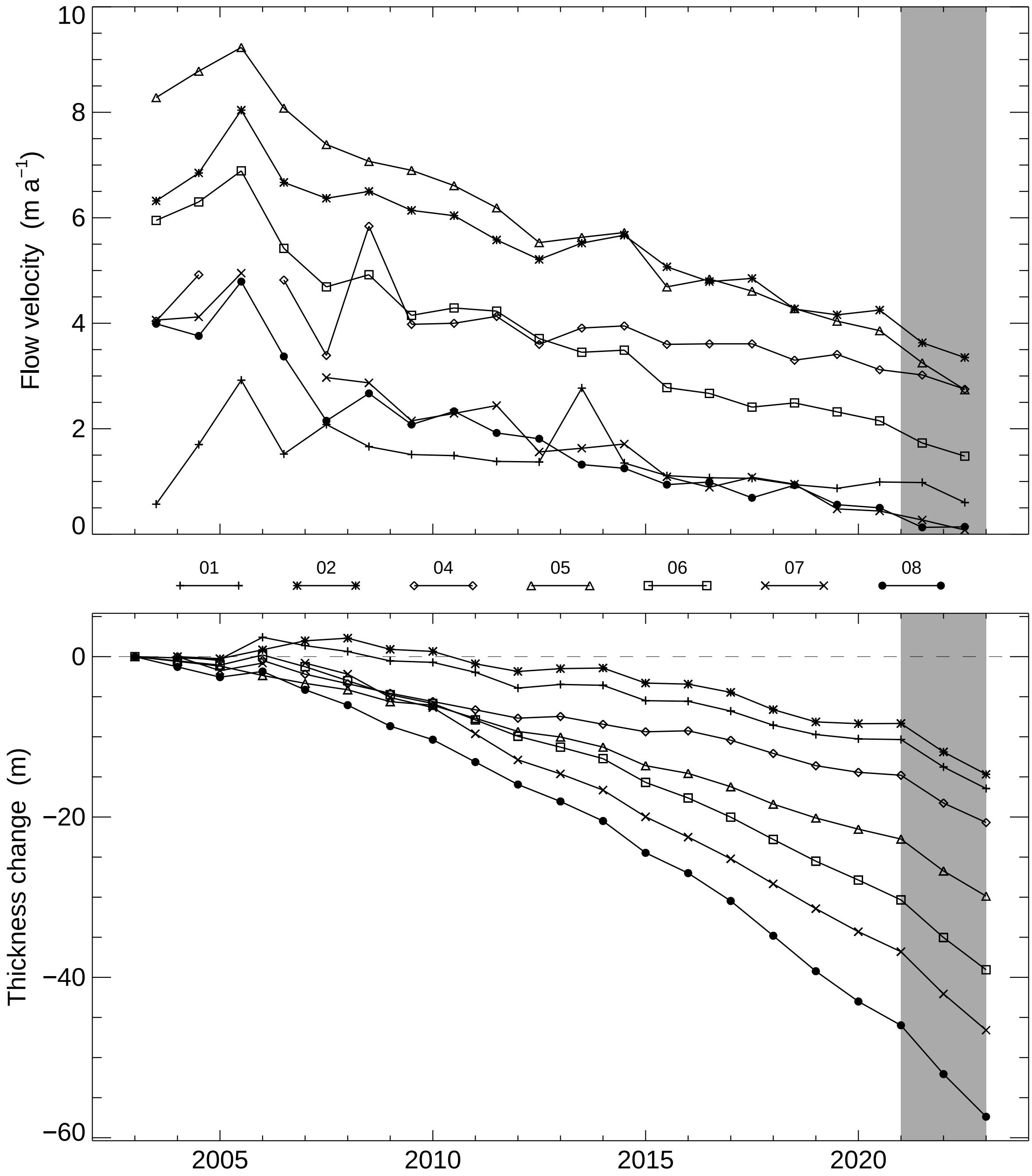


Figure 5.7: Surface flow velocities (top) and thickness change (bottom) of selected stakes at Silvrettagletscher. The gray-shaded area highlights the years of the current report.

6 Englacial Temperature

6.1 Introduction

Besides glacier mass balance, firn and ice temperatures can be considered as a key parameter in detecting global warming trends at high elevation. These temperatures have a sort of a memory function as they register short- and mid-term evolution of the energy balance at the surface. By measuring firn and ice temperatures, it is possible to assess climate change in areas where no direct observations of common climatic parameters are available. Cold firn and ice in glaciers, ice caps and ice sheets occur when the firn and ice show permanently negative temperatures over the minimum time span of a year. If this is not the case, glaciers are temperate, thus their temperature is at the pressure melting point. Ice bodies that contain both cold and temperate parts are called polythermal (Blatter and Hutter, 1991; Cuffey and Paterson, 2010).

Englacial temperature measurements on the Colle Gnifetti site are part of GLAMOS monitoring

Figure 6.1: Investigated site for englacial temperatures.

programme. The Colle Gnifetti site was selected to perform regular measurements updating the surveys made in the years 1983, 1991, 1999, 2000, 2007, 2008, 2013, 2014, 2015, 2018, 2019 and 2021. The results of measurements taken in 2022 and 2023 are presented in this report. The previous results of 2007 until 2021 have been reported in Volumes 129/130, 135/136, 139/140 and 141/142.

6.2 Colle Gnifetti (Monte Rosa)

Introduction

Colle Gnifetti is a small and very wind-exposed firn saddle at 4450 m a.s.l. in the region of Monte Rosa, Valais Alps, Switzerland. The saddle is situated between Zumsteinspitze and Signalkuppe with the famous Margerita hut, and belongs to the accumulation area of Grenzgletscher, a tributary of Gornergletscher. Strong wind erosion causes extraordinarily low annual accumulation of snow. Alean et al. (1983) and Lüthi and Funk (2001) showed accumulation rates of 0.1 m w.e. a^{-1} at the north-west slope of Signalkuppe to 1.2 m w.e. a^{-1} at the sunny south slope of Zumsteinspitze. Several boreholes have been drilled around the Colle Gnifetti saddle point in the past with the intention of measuring englacial temperatures. In 2018, a new borehole (CG18-1) was drilled at the saddle point, with a permanently installed thermistor chain, enabling annual monitoring to be carried out at the site. Differences in surface exposition produce strong firn temperature gradients across the saddle (Suter and Hoelzle, 2002; Mattea et al., 2021). However, several historic measurements are considered within sufficient proximity to the CG18-1 borehole location to enable an assessment of englacial warming over the last 40 years.

Investigations in 2022 and in 2023

Repeat measurements were carried out in the borehole CG18-1 (Table 6.1) at the Colle Gnifetti saddle point during site visits in 2022 and 2023. In Figure 6.2, measured temperature profiles acquired during the reporting period are shown together with results since 1982. Since 1991, firn temperatures at 20 m depth, isolated from annual variance, show a sustained warming of 0.46 °C per decade. This interpretation excludes the measurements from 2008 and 2013 (see previous Volumes) that are currently being re-assessed due to their strong irregularities with this long-term trend and the high uncertainties associated with the calculation of their thermally equilibrated temperatures (Gastaldello et al., 2024).
A distinct rotation in the thermal gradient of the profiles in the uppermost 30 m of the firn is also visible during this 40-year period. While the CG82-1/82 profile can be seen as representative of steady state conditions (Haeberli and Funk, 1991), the latest CG18-1/23 profile has developed a strongly negative gradient of -0.042 °C m^{-1} as a result of the influence of atmospheric warming at the surface. Evidence from recent deeper profiles taken towards the Signalkuppe flank (CG21-1/21) suggest warming is currently less pronounced beyond 40 m and, following an inflexion point in

the thermal gradient, englacial temperatures revert back to increasing with depth towards -12.3 °C at the bedrock (Haeberli and Funk, 1991).

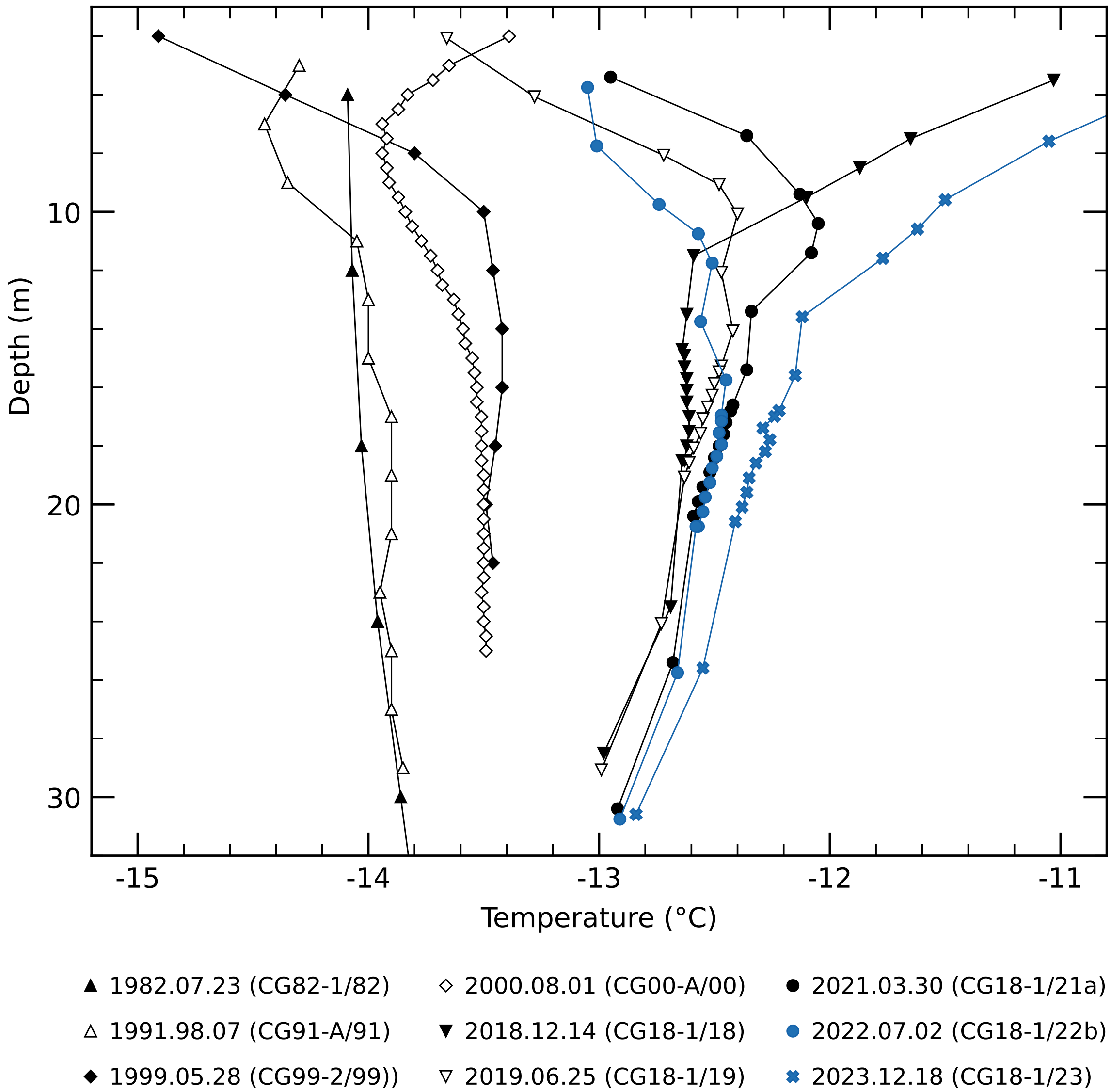


Figure 6.2: Firn temperature profiles at the Colle Gnifetti saddle, measured in 1982 (Haeberli and Funk, 1991), 1991 (Laternser, 1992; Suter et al., 2001), 1999 (Suter, 2002; Suter and Hoelzle, 2002), 2000 (Suter, 2002; Suter and Hoelzle, 2002), 2018/2019 (Mattea et al., 2021), 2021, 2022 and 2023. Most recent measurements of the periods in this report are highlighted in blue. Boreholes CG82-1, CG08-1 are located at the same position while CG91-A and CG00-A are slightly offset to the north-east.

Table 6.1: Colle Gnifetti - Englacial temperature measurements in 2022 and 2023 in the borehole CG18-1. Repeat measurements with a fixed thermistor chain.

Borehole:	CG18-1/22a	Borehole:	CG18-1/22b	Borehole:	CG18-1/23
	27.04.2022		02.07.2022		18.12.2023
depth (m)	temperature (°C)	depth (m)	temperature (°C)	depth (m)	temperature (°C)
5.48	−13.56	5.75	−13.05	5.59	−10.48
7.48	−12.87	7.75	−13.01	7.59	−11.05
9.48	−12.51	9.75	−12.74	9.59	−11.50
10.48	−12.34	10.75	−12.57	10.59	−11.62
11.48	−12.31	11.75	−12.51	11.59	−11.77
13.48	−12.45	13.75	−12.56	13.59	−12.12
15.48	−12.40	15.75	−12.45	15.59	−12.15
16.68	−12.45	17.15	−12.47	16.79	−12.22
17.28	−12.47	17.55	−12.48	17.39	−12.29
17.68	−12.47	17.95	−12.47	17.79	−12.26
18.08	−12.49	18.35	−12.49	18.19	−12.28
18.48	−12.51	18.75	−12.51	18.59	−12.32
18.98	−12.53	19.25	−12.52	19.09	−12.35
19.48	−12.54	19.75	−12.54	19.59	−12.36
19.98	−12.57	20.25	−12.55	20.09	−12.38
20.48	−12.59	20.75	−12.58	20.59	−12.41
25.48	−12.66	25.75	−12.66	25.59	−12.55
30.48	−12.91	30.75	−12.91	30.59	−12.84

7 Repeat Photography

7.1 Introduction

Repeated photographs of glaciers are a powerful tool to communicate the effects of climate change. Images of glaciers have been taken for many decades. In some cases, even several century-old paintings depicting glacier snouts are available (Nussbaumer and Zumbühl, 2012). If the position of the photographer has been documented, or can be reconstructed, historical images can be repeated, thus illustrating the stunning ice loss that has occurred in the elapsed time. Such glacier comparisons have proven to be highly effective in making the broader public aware of the rapid pace of glacier retreat and the corresponding changes to the high-alpine landscape. Therefore, GLAMOS has started a structured compilation of glacier photographs that is expected to substantially grow in the coming years. The aim is to establish a comprehensive data set of glacier images acquired

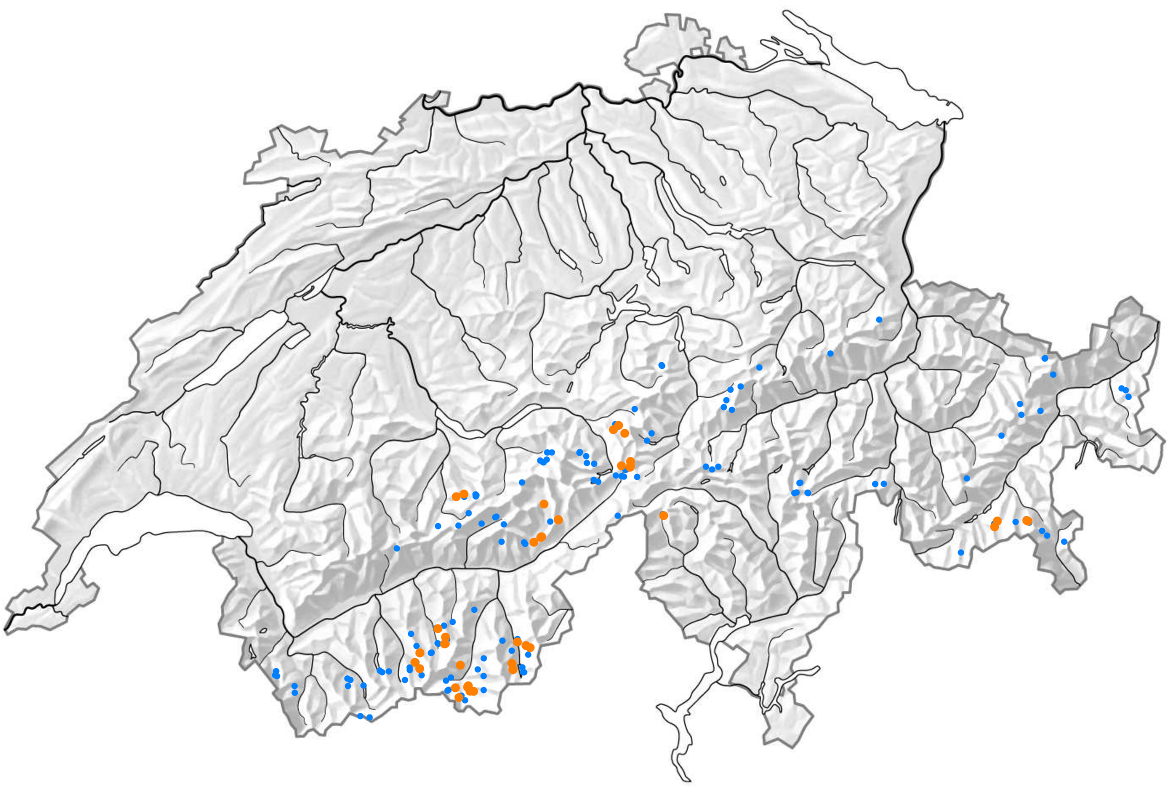


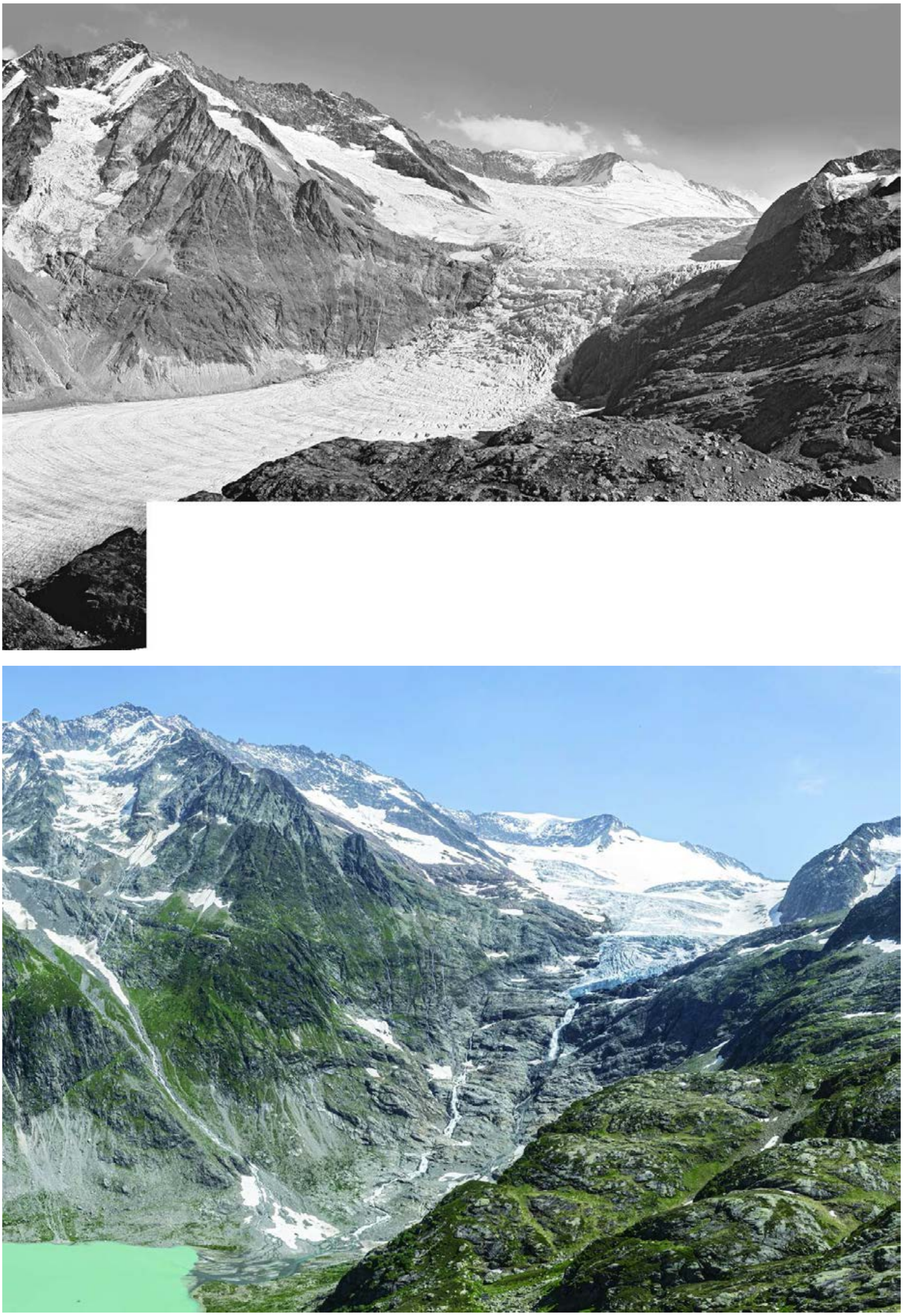
Figure 7.1: Glaciers in the dataset of repeat photography where panoramas have been retaken (orange) and are selected to be visited (blue).

at the same position covering periods of up to a century and short periods of a few years or even days (e.g. from automatic cameras), and different glacier types. This photograph collection is made publicly available for outreach efforts. At the moment, it is not planned to quantitatively evaluate the data set, but to exploit its qualitative potential for climate change communication. In this report we present a few selected examples and discuss aspects of data availability, acquisition and handling, as well as the resulting photographical comparisons.

7.2 Data collection

Glacier photographs from various sources are available. In a recent project (Discovering forgotten glacier images in a new glance - DEFOGGING) supported by MeteoSwiss in the frame of GCOS Switzerland several thousand glacier images from many years of coordinated glacier monitoring in Switzerland were digitized, geo-referenced and ingested into the state-of-the-art database e-pics of the ETH library where they are openly accessible. One of the richest data sets for documenting the glaciers' state around 100 years ago is the collection of terrestrial images by swisstopo (https://www.swisstopo.admin.ch/en/terrestrial-images). These high-resolution ground-based stereo-photographs were acquired mostly in the 1930s (between 1916 and 1947) related to national mapping activities and resolve glaciers at that time with an unprecedented detail, including excellent metadata that allow revisiting the same spots for repeating these image acquisitions. Mannerfelt et al. (2022) extracted digital elevation models based on photogrammetric techniques from these images to determine that more than half of the Swiss ice volume has been lost since 1930. Between 2021 and 2024, 41 photographical panoramas from the 1930s, covering major Swiss glaciers, were retaken. Another 109 locations of historical photographs from the TERRA data set have been detected to be particularly suitable, and will be revisited during the next summer seasons (see Figure 7.1).
A database has been established to store and visualize finalized photographic comparisons of glaciers (http://doi.glamos.ch/repeatphoto/index.html), and to indicate exact coordinates of high-quality historical images that shall be repeated. Experience shows that the acquisition of repeated images does not require exactly the same focal length of the camera, as images will need to be overlain and distorted in any case. Nevertheless, a high image resolution and a wide coverage with a suite of individual, overlapping shots is recommended. While superimposed panoramas are stored with their raw extent, often still containing earmarks of the photographs at their side, final treatment can focus on extracting zoomed views, and animating the comparison for better ease of the user.
On the following pages four selected examples of key glaciers illustrate the impressive retreat of the glacier and the evolution of the surrounding landscape. See also the comparison for Fieschergletscher on the front cover of this report.

Triftgletscher



Comparison of repeated photographs of the former tongue of Triftgletscher in 1928 (top, Photo: swisstopo) and and 2021 (bottom, Photo: VAW/ETHZ)

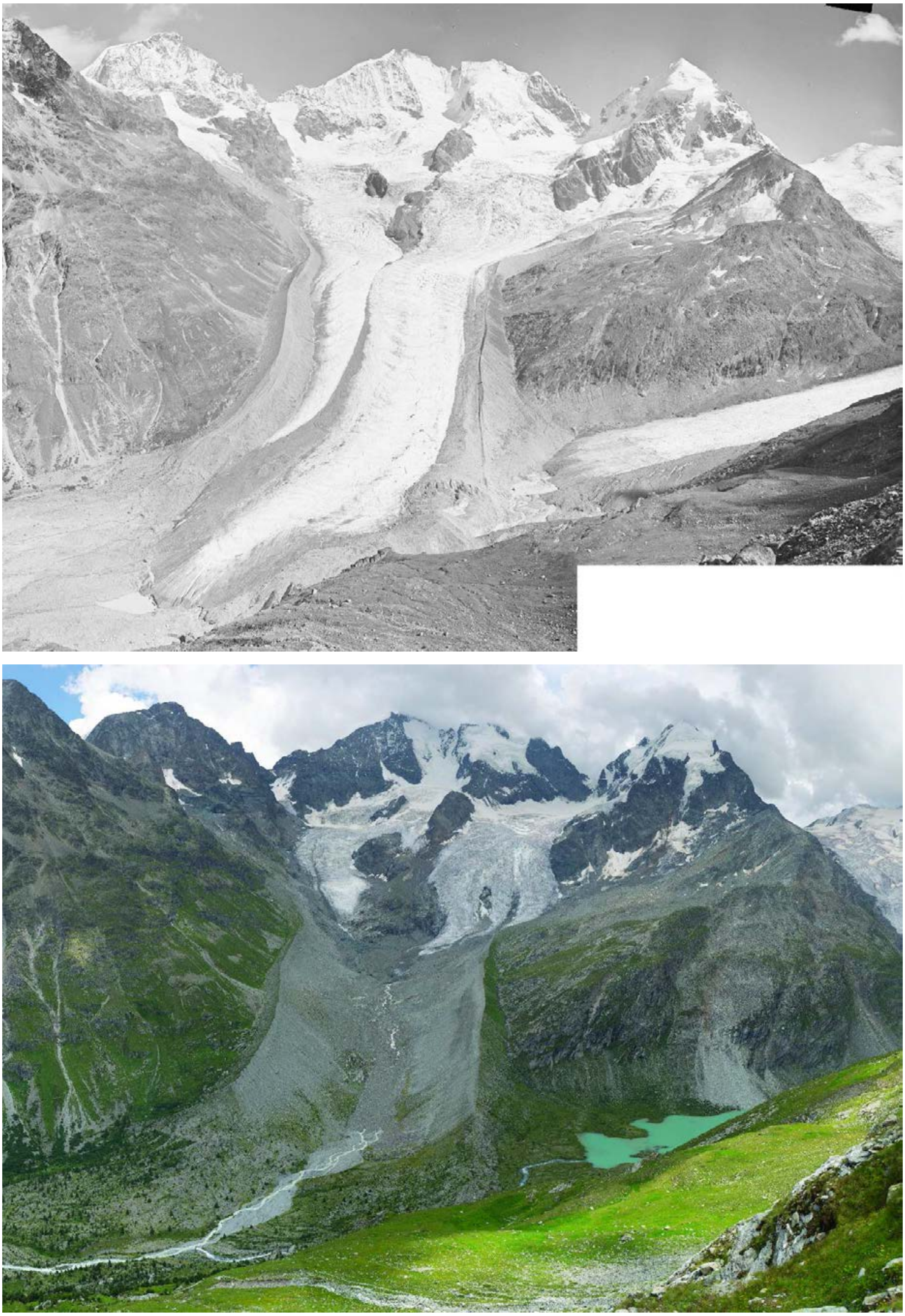
Ghiacciaio del Basòdino

Comparison of repeated photographs of Ghiacciaio del Basòdino in 1929 (top, Photo: swisstopo) and and 2021 (bottom, Photo: VAW/ETHZ)

Findelengletscher

Comparison of repeated photographs of Findelengletscher in 1930 (top, Photo: swisstopo) and and 2023 (bottom, Photo: VAW/ETHZ)

Vadret da Tschierva



Comparison of repeated photographs of Vadret da Tschierva in 1935 (top, Photo: swisstopo) and and 2022 (bottom, Photo: VAW/ETHZ).

References

Alean, J., Haeberli, W., and Schädler, B. (1983). Snow accumulation, firn temperature and solar radiation in the area of the Colle Gnifetti core drilling site (Monte Rosa, Swiss Alps): distribution patterns and interrelationships. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 19(2):131–147.

Bauder, A., Funk, M., and Bösch, H. (2002). Glaziologische Untersuchungen am Glacier de Giétro im Zusammenhang mit der Sicherheit der Stauanlage Mauvoisin. In *Moderne Methoden und Konzepte im Wasserbau*, volume 175, (Band 2), pages 419–431. Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich. Internationales Symposium 7.-9. Oktober 2002 in Zürich.

Bauder, A., Funk, M., and Huss, M. (2007). Ice volume changes of selected glaciers in the Swiss Alps since the end of the 19th century. *Annals of Glaciology*, 46:145–149.

Begert, M. and Frei, C. (2018). Long-term area-mean temperature series for Switzerland – Combining homogenized station data and high resolution grid data. *International Journal of Climatology*, 38(6):2792–2807.

Blatter, H. and Hutter, K. (1991). Polythermal conditions in Arctic glaciers. *Journal of Glaciology*, 37(126):261–269.

Cremona, A., Huss, M., Landmann, J. M., Borner, J., and Farinotti, D. (2023). European heat waves 2022: contribution to extreme glacier melt in Switzerland inferred from automated ablation readings. *The Cryosphere*, 17(5):1895–1912.

Cuffey, K. M. and Paterson, W. S. B. (2010). *The Physics of Glaciers*. Elsevier B.V., New York, forth edition. pp. 480.

Firnberichte (1914–1978). *Der Firnzuwachs 1913/14–1976/77 in einigen schweizerischen Firngebieten*, number 1-64 in Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich. Jahresberichte herausgegeben von der Gletscher-Kommission der Physikalischen Gesellschaft Zürich, später Schweizerische Meteorologische Zentralanstalt und ab 1973 durch A. Lemans.

Gabbi, J., Huss, M., Bauder, A., Cao, F., and Schwikowski, M. (2015). The impact of Saharan dust and black carbon on albedo and long-term mass balance of an Alpine glacier. *The Cryosphere*, 9(4):1385–1400.

Gastaldello, M., Mattea, E., Hoelzle, M., and Machguth, H. (2024). Modelling cold firn evolution at Colle Gnifetti, Swiss/Italian Alps. *EGUsphere [preprint]*, pages 1–34.

Geibel, L., Huss, M., Kurzböck, C., Hodel, E., Bauder, A., and Farinotti, D. (2022). Rescue and homogenisation of 140 years of glacier mass balance data in Switzerland. *Earth System and Science Data*, 14(7):3293–3312.

GLAMOS (2020a). Computation of glacier-wide mass balance: evaluating the potential of the linear mass balance model. Internal Report 3, Glacier Monitoring Switzerland.

GLAMOS (2020b). Revised strategy for monitoring glacier length variation. Internal Report 4, Glacier Monitoring Switzerland.

GLAMOS (2022). Swiss glacier flow velocity, release 2022. Glacier Monitoring Switzerland.

GLAMOS (2023a). Swiss glacier mass balance, release 2023. Glacier Monitoring Switzerland.

GLAMOS (2023b). Swiss glacier volume change, release 2023. Glacier Monitoring Switzerland.

Grab, M., Mattea, E., Bauder, A., Huss, M., Rabenstein, L., Hodel, E., Linsbauer, A., Langhammer, L., Schmid, L., Church, G., Hellmann, S., Dééze, K., Schaer, P., Lathion, P., Farinotti, D., and Maurer, H. (2021). Ice thickness distribution of all Swiss glaciers based on extended ground-penetrating radar data and glaciological modeling. *Journal of Glaciology*, 67(266):1074–1092.

Gugerli, R., Salzmann, N., Huss, M., and Desilets, D. (2019). Continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on an alpine glacier. *The Cryosphere*, 13(12):3413–3434.

Haeberli, W. and Funk, M. (1991). Borehole temperatures at the Colle Gnifetti core drilling site (Monte Rosa, Swiss Alps). *Journal of Glaciology*, 37(125):37–46.

Hoelzle, M., Haeberli, W., Dischl, M., and Peschke, W. (2003). Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change*, 36(4):295–306.

Huss, M. and Bauder, A. (2009). 20th-century climate change inferred from four long-term point observations of seasonal mass balance. *Annals of Glaciology*, 50(50):207–214.

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

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

Huss, M., Schwyn, U., Bauder, A., and Farinotti, D. (2021). Quantifying the overall effect of artificial glacier melt reduction in Switzerland, 2005-2019. *Cold Regions Science and Technology*, 184(4):103237.

Huss, M., Voinesco, A., and Hoelzle, M. (2013). Implications of climate change on Glacier de la Plaine Morte, Switzerland. *Geographica Helvetica*, 68(4):227–237.

Kasser, P., Aellen, M., and Siegenthaler, H. (1986). Clariden. In *Die Gletscher der Schweizer Alpen, 1977/78 und 1978/79*, volume 99/100 of *Glaziologisches Jahrbuch der Gletscherkommission SNG*, pages 142–148. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich.

Landmann, J. M., Künsch, H. R., Huss, M., Ogier, C., Kalisch, M., and Farinotti, D. (2021). Assimilating near-real-time mass balance stake readings into a model ensemble using a particle filter. *The Cryosphere*, 15(11):5017–5040.

Laternser, M. (1992). Firntemperaturmessungen in den Schweizer Alpen. Diploma thesis (unpublished), ETH Zürich. pp. 99.

Linsbauer, A., Huss, M., Hodel, E., Bauder, A., Fischer, M., Weidmann, Y., Bärtschi, H., and Schmassmann, E. (2021). The New Swiss Glacier Inventory SGI2016: From a Topographical to a Glaciological Dataset. *Frontiers in Earth Science*, 9:774.

Lüthi, M. P. and Funk, M. (2001). Modelling heat flow in a cold, high altitude glacier: interpretation of measurements from Colle Gnifetti, Swiss Alps. *Journal of Glaciology*, 47(157):314–324.

Mannerfelt, E. S., Dehecq, A., Hugonnet, R., Hodel, E., Huss, M., Bauder, A., and Farinotti, D. (2022). Halving of Swiss glacier volume since 1931 observed from terrestrial image photogrammetry. *The Cryosphere*, 16(8):3249–3268.

Mattea, E., Machguth, H., Kronenberg, M., van Pelt, W., Bassi, M., and Hoelzle, M. (2021). Firn changes at Colle Gnifetti revealed with a high-resolution process-based physical model approach. *The Cryosphere*, 15(7):3181–3205.

Müller, H. and Kappenberger, G. (1991). Claridenfirn-Messungen 1914-1984. Heft 40, Zürcher Geographische Schriften, Geographisches Institut der ETH Zürich. pp. 79.

Naegeli, K., Damm, A., Huss, M., Schaepman, M., and Hoelzle, M. (2015). Imaging spectroscopy to assess the composition of ice surface materials and their impact on glacier mass balance. *Remote Sensing of Environment*, 168:388–402.

Nussbaumer, S. U. and Zumbühl, H. J. (2012). The little ice age history of the Glacier des Bossons (Mont Blanc massif, France): a new high-resolution glacier length curve based on historical documents. *Climatic Change*, 111(2):301–334.

Ogier, C., Werder, M. A., Huss, M., Kull, I., Hodel, D., and Farinotti, D. (2021). Drainage of an ice-dammed lake through a supraglacial stream: hydraulics and thermodynamics. *The Cryosphere*, 15(11):5133–5150.

Ohmura, A., Bauder, A., Müller, H., and Kappenberger, G. (2007). Long-term change of mass balance and the role of radiation. *Annals of Glaciology*, 46:367–374.

Østrem, G. and Brugman, M. (1991). Glacier mass-balance measurements – a manual for field and office work. Technical report, National Hydrology Research Institute. NHRI Science Report No. 4.

Raymond, M., Wegmann, M., and Funk, M. (2003). Inventar gefährlicher Gletscher in der Schweiz. Mitteilungen 182, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, Gloriastrasse 37-39, CH-8092 Zürich. pp. 368.

Suter, S. (2002). Cold firn and ice in the Monte Rosa and Mont Blanc areas: spatial occurrence, surface energy balance and climatic evidence. Mitteilung 172, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich. pp. 188.

Suter, S. and Hoelzle, M. (2002). Cold firn in the Mont Blanc and Monte Rosa areas, European Alps: spatial distribution and statistical models. *Annals of Glaciology*, 35(1):9–18.

Suter, S., Laternser, M., Haeberli, W., Frauenfelder, R., and Hoelzle, M. (2001). Cold firn and ice of high-altitude glaciers in the Alps: measurements and distribution modelling. *Journal of Glaciology*, 47(156):85–96.

Van Tricht, L., Huybrechts, P., Van Breedam, J., Vanhulle, A., Van Oost, K., and Zekollari, H. (2021). Estimating surface mass balance patterns from unoccupied aerial vehicle measurements in the ablation area of the Morteratsch-Pers glacier complex (Switzerland). *The Cryosphere*, 15(9):4445–4464.

VAW (1997). Gletscherveränderungen im Val de Bagnes 1966 – 1996. Untersuchungen im Zusammenhang mit den Anlagen der Kraftwerke Mauvoisin AG. Zusammenfassend dargestellte Hauptergebnisse der jährlichen Messungen. Bericht Nr. 7903.55.04 (M. Aellen, unveröffentlicht). Im Auftrag der Kraftwerke Mauvoisin AG.

VAW (1998). Mauvoisin – Giétrogletscher – Corbassièregletscher. Glaziologische Studien im Zusammenhang mit den Stauanlagen Mauvoisin. Bericht Nr. 55.05.7903 (M. Funk, unveröffentlicht). Im Auftrag der Elektrizitätsgesellschaft Lauffenburg AG.

VAW (1999). Mattmark – Zusammenfassender Bericht über die hydrologischen und glaziologischen Messungen im Mattmarkgebiet. Bericht Nr. 7902.52.45 (H. Bösch und M. Funk, unveröffentlicht), Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich. Im Auftrag der Kraftwerke Mattmark AG.

VAW (2024). Allalin-Gletscher – Bericht über die hydrologischen und glaziologischen Verhältnisse im Mattmarkgebiet 2022/2023. Bericht Nr. 7902-VAW-2024-03 (A. Bauder, unveröffentlicht), Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich. Im Auftrag der Kraftwerke Mattmark AG.

WGMS (2023). Global Glacier Change Bulletin No. 5 (2020–2021). ISC(WDS)-IUGG(IACS)-UNEP-UNESCO-WMO, World Glacier Monitoring Service, Zurich, Switzerland.

Zekollari, H., Huss, M., and Farinotti, D. (2020). On the imbalance and response time of glaciers in the european alps. *Geophysical Research Letters*, 47(2):e2019GL085578.

Zekollari, H. and Huybrechts, P. (2018). Statistical modelling of the surface mass-balance variability of the Morteratsch glacier, Switzerland: strong control of early melting season meteorological conditions. *Journal of Glaciology*, 64(244):275–288.

Zoller, N. (2010). Fliessbewegung des Grossen Aletschgletschers. Bachelorarbeit, Departement Erdwissenschaften / Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich. pp. 45.

Acknowledgements

The Cryospheric Commission through its GLAMOS programme acknowledges long-term funding by the Federal Office for the Environment (BAFU), MeteoSwiss within GCOS Switzerland, the Swiss Academy of Sciences (SCNAT), and the support by the Federal Office of Topography swisstopo. GLAMOS again received solid support in this $143^{st}/144^{nd}$ measuring period from its reliable team of observers. Sincere thanks for their cooperation are extended to: the forestry services from the cantons of Berne, Glarus, Grisons, Obwalden, St. Gallen, Uri, Ticino, Vaud and Wallis, the staff of the hydro-power stations Aegina, Mattmark and Mauvoisin, all the individual helpers and the Aerial Photography Flying and Coordination Service (CCAP) of the Swiss Federal Office of Topography swisstopo. Colleagues from VAW / ETH Zürich and the Geographical Institutes of the University of Fribourg and Zürich provided valuable contributions to the publication of this glaciological report.

A Remote Sensing

A.1 Aerial photographs

Aerial photographs are taken at periodic intervals by Swiss Federal Office of Topography swisstopo in order to provide a baseline documentation for various applications (mapping, glacier change, natural hazards, etc). In addition to the periodical surveys, high-resolution aerial photographs have been acquired which are designed in particular for glaciological applications. These are listed in the following tables (A.1 and A.2). Not listed are the routinely acquired aerial photographs by swisstopo for updating their standard products (National Maps, orthophoto or DEM). In the year 2022, pictures were taken for the area of the Cantons GL, GR and SG, and in 2023 of the Cantons VD and VS, respectively. More detailed information is available on swisstopo's webviewer http://www.luftbildindex.ch.

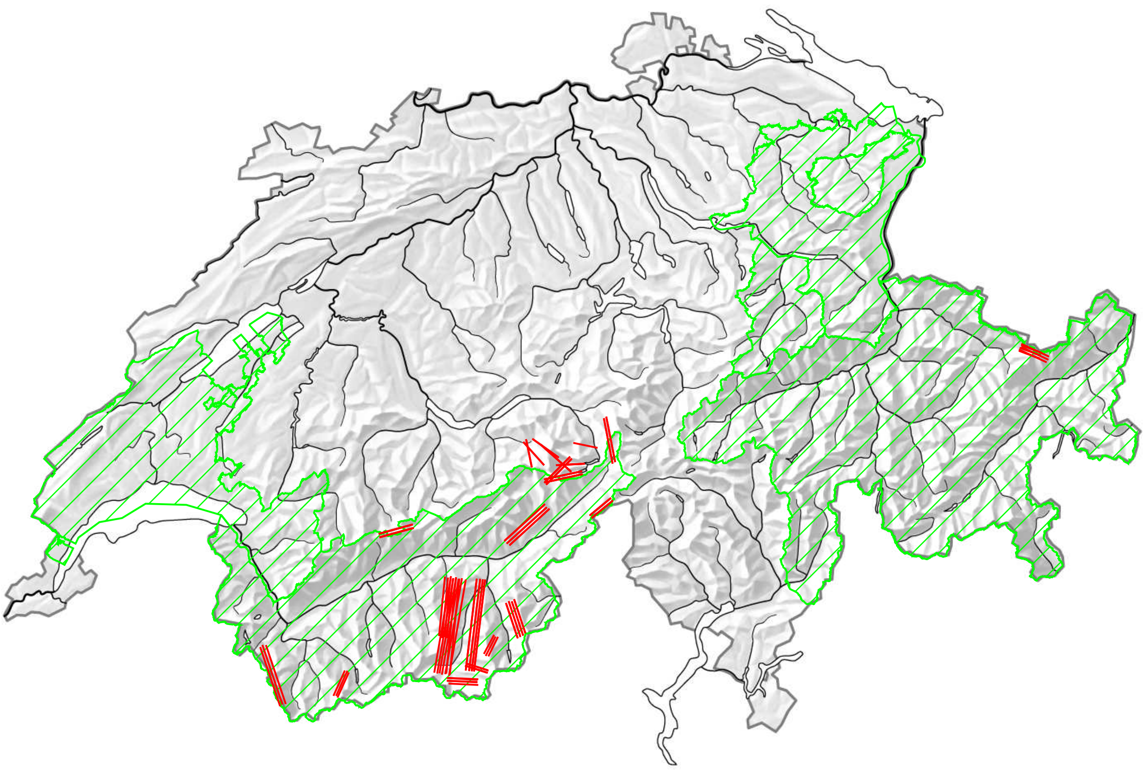


Figure A.1: Aerial photographs from the years 2022 and 2023 with specific surveys on glaciers (red) and coverage of swisstopo's periodic survey (green)

Table A.1: Aerial photographs taken in 2022.

Glaciers	Ct.	Date	Line No.	GSD
Ärlen ^{c}, Wiisenbach ^{p}, Golegg ^{p}	BE	13.07.22	12501202207130959	0.12
Bis ^{p}, Brunegg ^{p}, Schali ^{p}, Hohlicht ^{p}, Jung ^{p}, Stelli ^{p}, Abberg ^{p}	VS	15.07.22	12501202207150858	0.12
Bis ^{p}, Brunegg ^{p}, Schali ^{p}, Hohlicht ^{p}, Jung ^{p}, Stelli ^{p}, Abberg ^{p}	VS	15.07.22	12501202207150848	0.12
Bis ^{p}, Brunegg ^{p}, Schali ^{p}, Hohlicht ^{p}, Rothorn ^{p}, Gabelhorn ^{p}, Jung ^{c}, Brandji ^{p}, Stelli ^{c}, Piipji ^{p}, Schölli ^{c}, Abberg ^{c}	VS	15.07.22	12501202207150837	0.12
Bis ^{p}, Brunegg ^{p}, Schali ^{p}, Hohlicht ^{p}, Trift (Zermatt) ^{p}, Rothorn ^{c}, Gabelhorn ^{p}, Jung ^{c}, Brandji ^{p}, Stelli ^{c}, Piipji ^{p}, Schölli ^{c}	VS	15.07.22	12501202207150827	0.12
Bis ^{p}, Turtmann ^{p}, Brunegg ^{p}, Weisshorn ^{p}, Schali ^{p}, Moming ^{p}, Hohlicht ^{p}, Trift (Zermatt) ^{p}, Rothorn ^{p}, Gabelhorn ^{p}, Jung ^{p}, Brandji ^{c}, Piipji ^{c}	VS	15.07.22	12501202207150816	0.12
Corbassière ^{p}, Bochgeresse ^{c}, Tournelon Blanc ^{p}. Sonadon ^{p}	VS	15.07.22	12501202207151112	0.1
Corbassière ^{p}, Bochgeresse ^{c}, Tournelon Blanc ^{p}. Sonadon ^{p}	VS	15.07.22	12501202207151106	0.1
Corbassière ^{p}, Bochgeresse ^{p}, Metin ^{c}	VS	15.07.22	12501202207151100	0.1
Fee ^{p}, Hohlaub ^{p}	VS	15.07.22	12501202207151045	0.1
Fee ^{p}, Mellich ^{p},	VS	15.07.22	12501202207151033	0.12
Fee ^{p}, Mellich ^{p},	VS	15.07.22	12501202207151039	0.1
Findelen ^{p}	VS	15.07.22	12501202207151018	0.1
Findelen ^{p}	VS	15.07.22	12501202207151024	0.1
Gorner ^{p}	VS	15.07.22	12501202207150948	0.1
Gorner ^{p}	VS	15.07.22	12501202207150920	0.12
Gries ^{p}, Corno ^{p}	VS	12.09.22	12501202209121034	0.1
Gries ^{p}, Corno ^{p}	VS	13.07.22	12501202207131059	0.11
Gries ^{p}, Sulz ^{c}, Ritz ^{p}	VS	13.07.22	12501202207131053	0.11
Gries ^{p}, Sulz ^{c}, Ritz ^{p}	VS	12.09.22	12501202209121028	0.1
Grosser Aletsch ^{p}	VS	13.07.22	12501202207131105	0.12
Grosser Aletsch ^{p}	VS	13.07.22	12501202207131121	0.11
Grosser Aletsch ^{p}	VS	13.07.22	12501202207131113	0.11
Grüebu ^{p}, Mattwald ^{p}, Gamsa ^{p}, Griessernu ^{c}, Rossboden ^{p}, Fletschhorn ^{p}, Holutrift ^{p}, Hohlaub ^{p}, Laggin ^{c}, Weissmies ^{p}, Zwischbergen ^{p}, Rotblatt ^{p}	VS	24.08.22	12501202208241010	0.1
Grüebu ^{p}, Mattwald ^{p}, Tälli ^{p}, Fletschhorn ^{p}, Lagginhorn ^{p}, Hohlaub ^{c}, Trift ^{p}, Rottal ^{c}, Rotblatt ^{c}	VS	24.08.22	12501202208241054	0.1
Grüebu ^{p}, Tälli ^{c}, Fletschhorn ^{p}, Lagginhorn ^{p}, Hohlaub ^{p}, Trift ^{p}, Mälliga ^{p}, Rottal ^{p}	VS	24.08.22	12501202208241042	0.1
Hohbärg ^{p}, Festi ^{p}, Kin ^{p}	VS	15.07.22	12501202207150926	0.12

Ob. Grindelwald p, Wächselberg p	BE	13.07.22	12501202207131006	0.09
Oberaar c, Fiescher p, Minstiger p	BE, VS	13.07.22	12501202207131045	0.1
Oberaar c, Fiescher p, Minstiger p	BE, VS	23.08.22	12501202208231027	0.1
Oberaar p, Unteraar p, Fiescher p	BE, VS	23.08.22	12501202208231020	0.1
Oberaar p, Unteraar p, Fiescher p	BE, VS	13.07.22	12501202207131039	0.1
Plaine Morte p, Lämmern c, Wildstrubel p	BE, VS	16.07.22	12501202207160925	0.12
Plaine Morte p, Lämmern c, Wildstrubel p	BE, VS	12.09.22	12501202209121057	0.1
Plaine Morte p, Tierberg c, Wildstrubel p	BE, VS	16.07.22	12501202207160918	0.12
Plaine Morte p, Tierberg c, Wildstrubel p	BE, VS	12.09.22	12501202209121051	0.1
Rhone p, Trift p	VS, BE	16.07.22	12501202207161008	0.1
Rhone p, Trift p, Alpli p	VS, BE	16.07.22	12501202207161000	0.1
Ried p, Hohbärg p, Festi p, Kin p	VS	15.07.22	12501202207150937	0.12
Ried p, Hohbärg p, Festi p, Kin p, Weingarten p	VS	15.07.22	12501202207151007	0.1
Ried p, Hohbärg p, Festi p, Kin p, Weingarten p	VS	15.07.22	12501202207150954	0.12
Silvretta c, Tiatscha p	GR	12.09.22	12501202209120942	0.1
Silvretta c, Tiatscha p	GR	17.07.22	12501202207171018	0.1
Silvretta p, Verstancla c, Vernela p, Maisas p, Tiatscha p, Plan Rai c	GR	12.09.22	12501202209120953	0.1
Silvretta p, Verstancla c, Vernela p, Maisas p, Tiatscha p, Plan Rai c	GR	17.07.22	12501202207171029	0.1
Silvretta p, Verstancla p, Tiatscha p, Plan Rai p	GR	12.09.22	12501202209120948	0.1
Silvretta p, Verstancla p, Tiatscha p, Plan Rai p	GR	17.07.22	12501202207171023	0.1
Trient p, Grands p, Saleina p, A Neuve p, Dolent p	VS	16.07.22	12501202207160855	0.12
Trient p, Grands p, Saleina p, A Neuve p, Dolent p	VS	16.07.22	12501202207160847	0.12
Trient p, Orny p, Saleina p, A Neuve p, Planeureuse p, Tretsebo c, Dolent p	VS	16.07.22	12501202207160904	0.12
Turtmann p, Brunegg p, Weisshorn p, Moming p, Hohlicht p, Mountet p, Zinal p, Trift (Zermatt) p, Gabelhorn p, Arben p	VS	15.07.22	12501202207150805	0.12
Tälli p, Trift p, Mälliga p	VS	24.08.22	12501202208241036	0.1
Unt. Grindelwald p	BE	13.07.22	12501202207131022	0.12
Unt. Grindelwald p	BE	13.07.22	12501202207131028	0.12
Unteraar p	BE	23.08.22	12501202208231011	0.1
Unteraar p	BE	13.07.22	12501202207131032	0.09
Unteraar p, Fiescher p	BE, VS	16.07.22	12501202207160951	0.1
Unteraar p, Fiescher p	BE, VS	23.08.22	12501202208231104	0.1
Unteraar p, Fiescher p	BE, VS	16.07.22	12501202207160945	0.1
Unteraar p, Fiescher p	BE, VS	23.08.22	12501202208231057	0.1
Unteraar p, Ob. Grindelwald p	BE	24.08.22	12501202208240956	0.1
Unteraar p, Ob. Grindelwald p	BE	13.07.22	12501202207131015	0.11

c Glacier shown completely
p Glacier shown partially

GSD: Ground sampling distance in (m)

Table A.2: Aerial photographs taken in 2023.

Glaciers	Ct.	Date	Line No.	GSD
Bis [p], Brunegg [p], Schali [p], Hohlicht [p], Jung [c], Brandji [c], Piipji [p], Stelli [c], Schölli [c], Abberg [p]	VS	23.08.23	12501202308231012	0.12
Bis [p], Brunegg [p], Schali [p], Jung [p], Brandji [c], Piipji [c], Stelli [p], Schölli [c]	VS	23.08.23	12501202308231022	0.1
Bis [p], Brunegg [p], Turtmann [p], Schali [p], Brandji [p], Piipji [p]	VS	23.08.23	12501202308231030	0.1
Bis [p], Schali [p], Hohlicht [p], Jung [p], Stelli [p], Abberg [p], Holz [c], Ross [c]	VS	23.08.23	12501202308231002	0.12
Brunegg [p], Turtmann [p], Weisshorn [p]	VS	23.08.23	12501202308231039	0.12
Brunegg [p], Turtmann [p], Weisshorn [p]	VS	23.08.23	12501202308231047	0.12
Findelen [p]	VS	21.08.23	12501202308210925	0.08
Findelen [p]	VS	21.08.23	12501202308210930	0.08
Gorner [p]	VS	21.08.23	12501202308210907	0.1
Gorner [p]	VS	21.08.23	12501202308210913	0.1
Gorner [p], Unt. Theodul [p]	VS	21.08.23	12501202308210918	0.1
Gries [c], Sulz [c], Ritz [p]	VS	20.08.23	12501202308200840	0.1
Gries [p], Sulz [c], Ritz [p]	VS	20.08.23	12501202308200834	0.1
Grosser Aletsch [p]	VS	10.08.23	12501202308100959	0.1
Grosser Aletsch [p]	VS	10.08.23	12501202308101106	0.1
Grosser Aletsch [p]	VS	10.08.23	12501202308101006	0.1
Grüebu [p], Mattwald [p], Gamsa [p], Griessernu [c], Rossboden [p], Fletschhorn [p], Holutrift [p], Hohlaub [p], Laggin [c], Weissmies [p], Zwischbergen [p], Rotblatt [p]	VS	10.08.23	12501202308101014	0.1
Grüebu [p], Mattwald [p], Gamsa [p], Tälli [p], Fletschhorn [p], Lagginhorn [c], Hohlaub [c], Trift [p], Rottal [c], Rotblatt [c]	VS	10.08.23	12501202308101019	0.1
Grüebu [p], Tälli [c], Fletschhorn [p], Lagginhorn [p], Hohlaub [p], Trift [p], Mälliga [p], Rottal [p]	VS	10.08.23	12501202308101026	0.1
Hohbärg [p], Festi [p]	VS	21.08.23	12501202308210948	0.12
Ob. Grindelwald [p], Wächselberg [p]		20.08.23	12501202308200855	0.1
Oberaar [c], Fiescher [p], Minstiger [p]	BE, VS	23.08.23	12501202308231106	0.1
Oberaar [p], Unteraar [p], Fiescher [p]	BE, VS	23.08.23	12501202308231111	0.08
Plaine Morte [p], Lämmern [c], Wildstrubel [p]	BE, VS	20.08.23	12501202308201001	0.1
Plaine Morte [p], Tierberg [c], Wildstrubel [p]	BE, VS	20.08.23	12501202308200955	0.1
Rhone [p], Trift [p]	VS, BE	20.08.23	12501202308200928	0.1
Rhone [p], Trift [p], Alpli [p]	VS, BE	20.08.23	12501202308200921	0.1
Ried [p], Hohbärg [p], Festi [p], Kin [p]	VS	21.08.23	12501202308210959	0.12
Ried [p], Hohbärg [p], Festi [p], Kin [p], Weingarten [p], Findelen [p]	VS	21.08.23	12501202308211009	0.1

Ried [p], Hohbärg [p], Festi [p], Kin [p], Weingarten [p], Findelen [p]	VS	21.08.23	12501202308211019	0.1
Silvretta [c], Tiatscha [p]	GR	24.08.23	12501202308240939	0.1
Silvretta [p], Verstancla [c], Vernela [p], Maisas [p], Tiatscha [p], Plan Rai [c]	GR	24.08.23	12501202308240924	0.1
Silvretta [p], Verstancla [p], Tiatscha [p], Plan Rai [p]	GR	24.08.23	12501202308240930	0.1
Tälli [p], Trift [p], Mälliga [p]	VS	10.08.23	12501202308101032	0.1
Unt. Grindelwald [p]	BE	20.08.23	12501202308200902	0.12
Unt. Grindelwald [p]	BE	22.08.23	12501202308220938	0.12
Unteraar [p]	BE	20.08.23	12501202308200913	0.1
Unteraar [p], Fiescher [p]	BE, VS	22.08.23	12501202308220918	0.1
Unteraar [p], Fiescher [p]	BE, VS	22.08.23	12501202308220911	0.1
Unteraar [p], Ob. Grindelwald [p]	BE	20.08.23	12501202308200847	0.1

c Glacier shown completely
p Glacier shown partially

GSD: Ground sampling distance in (m)

Many small glaciers like Hintersulzfirn shown in September 2023 are heavily debris covered and show only little variations of the terminus in the past decade. (Photo: U. Aerne, AWN/GL)

B Remarks on Individual Glaciers

1 Rhone

2022: Luftbildaufnahmen am 16.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

3 Gries

2022: Luftbildaufnahmen am 12.9.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

5 Grosser Aletsch

2022: Luftbildaufnahmen am 13.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 10.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

7 Kaltwasser

2022: Gletscher ist nördlich dem Kaltwassertälli und ganz im Süden stark mit Schutt bedeckt, was die Bestimmung vom Eisrand erschwerte. (A. Brigger)

10 Schwarzberg

2023: Luftbildaufnahmen am 7.9.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ im Auftrag der Kraftwerke Mattmark AG. (VAW/ETHZ – A. Bauder)

11 Allalin

2023: Luftbildaufnahmen am 6.9.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ im Auftrag der Kraftwerke Mattmark AG. (VAW/ETHZ – A. Bauder)

12 Chessjen

2023: Luftbildaufnahmen am 6.9.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ im Auftrag der Kraftwerke Mattmark AG. (VAW/ETHZ – A. Bauder)

14 Gorner

2022: Luftbildaufnahmen am 15.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 21.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

16 Findelen

2022: Luftbildaufnahmen am 15.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 21.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

18 Lang

2023: Gletscherzunge ist sehr schmal und stark mit Schutt bedeckt. (A. Brigger)

19 Turtmann

2022: Neuer Gletscherrand oberhalb der Felsstufe nicht zugänglich und keine terrestrische Aufnahmen möglich. (A. Brigger)

2023: Eisrand weiterhin am oberen Rand er Felsstufe an unveränderter Lage. Die vorgelagerte Toteismasse ist jedoch inzwischen fast komplett zusammengeschmolzen. (A.Brigger)

20 Brunegg

2023: Der linke Teil der Glscherzunge ist schuttbedeckt und der Eisrand deshalb nur schlecht bestimmbar. (A. Brigger)

27 Arolla

2022: Le Bas Glacier d'Arolla (glace morte) est maintenant séparé du tributaire glacier du Mont Collon. (F. Fellay)

28 Tsidjiore Nouve

2022: L'interprétation de la position du glacier est délicate étant donné l'épaisse couche de blocs qui le recouvre. (F. Fellay)

2023: La position du glacier en rive droite est située sous d'épais dépôts de blocs et est très difficile à évaluer. (F. Fellay)

33 Tsanfleuron

2022: formation d'un petit lac à la sortie d'eau (F. Fellay)

40 Tseudet

2022: Il y a une importante masse de glace morte juste à l'aval. Le front actuel n'est plus rattaché au glacier par une mince bande. (P. Stoebener)

41 Boveire

2023: De nombreux éboulis recouvrent le glacier et la délimitation exacte est donc difficile, surtout latéralement. (P. Stoebener)

43 Trient

2022: La langue glaciaire s'est rétractée de manière très importante en 2022. La fonte se remarque tant sur l'épaisseur de l'appareil glaciaire que sur la largeur de la langue. Celle-ci présente une série de crevasses à 100 mètres en amont du front qui pourraient couper la langue en deux dans les prochaines années. Le point aval de la langue forme une sorte de corne, engagée dans un sillon rocheux bien visible. Visite 26.9.2022: Buts: Evaluer visuellement l'état du glacier. Couper des branches et des troncs qui bouchent la vue du glacier depuis le point älpha". Le ciel était couvert, cachant la Pointe des Ecandies et la Petite Pointe d'Orny qui permettent normalement le cadrage des photos à partir du point älpha" (2'567'313 / 1'097'365 / 1727 m). Comme la végétation a beaucoup poussé depuis 20 ans, le glacier n'est presque plus visible, ce qui a motivé une demande de coupe adressée au garde forestier du secteur. L'accord a été immédiat et j'ai pu procéder au début des coupes nécessaires, afin de continuer la série de photos commencée en 1969 par Monsieur Pierre Mercier. Les photos de 2022 montrent le terrain partiellement dégagé, mais ne peuvent pas compléter la série initiée en 1969, en raison du ciel couvert. La photo P1130062 montre la vue bouchée par la végétation, avant les coupes. La langue glaciaire présentait une fonte importante, tant en épaisseur qu'en largeur. La position du front s'est déplacée vers l'amont. Visite du dimanche 2.10.2022: Evaluer visuellement l'état du glacier. Prendre des photos. Mesurer la position du front du glacier. Lever le plus grand nombre possible de points en bordure de la langue glaciaire. Prendre des photos depuis le point älphaäfin de continuer la série commencée en 1969 par Monsieur Pierre Mercier. Le ciel était bien dégagé durant une grande partie de la journée, avec des passages nuageux en altitude. Comme toujours à cette époque de l'année, la lumière rasante générait un effet de contre-jour qui compliquait un peu les prises de vue. La fonte durant l'année 2022 a été très importante, comme partout dans les Alpes. Le débit du torrent émissaire était élevé durant l'été et lors de mon passage également. L'amincissement de la langue glaciaire se poursuit inexorablement. La langue occupe depuis 2021 un épaulement qui domine une forte pente, tracée de sillons rocheux parfois assez profonds. La ligne de rupture de pente est nettement hors de la glace. La langue glaciaire est devenue plus mince et plus étroite durant l'année écoulée, avec de nombreuses crevasses assez profondes. La langue semble se fragmenter par endroits. La photo P113011 présente une vue d'ensemble de la langue glaciaire, du bord du plateau du Trient, vers 3000 mètres, jusqu'au front, situé à 2230 mètres en 2022. La glace présente un aspect typique d'une zone de fonte, comme si la langue s'effondrait sur elle-même. On observe de nombreuses crevasses profondes, qui s'approchent du substrat rocheux. Il y a également de la glace éboulée le long du bord de la langue, qui témoigne de la démolition en cours de l'appareil glaciaire. L'extrémité de la langue forme une sorte de rognon, de couleur foncée, qui semble mal alimenté par l'amont. Il se pourrait que cette zone devienne un paquet de glace morte dans les années suivantes. En amont, à une centaine de mètres du front, on remarque une zone fortement crevassée et déprimée, qui pourrait fondre plus vite que le reste de la langue, en séparant la langue en deux parties, l'une active et connectée à l'amont, l'autre, en aval, inerte et fondant sur place. La photo P1130130 montre le front de la langue en détail. On remarque bien une sorte de corne, à droite, qui constitue la partie la plus en aval de la langue glaciaire. Cette excroissance se trouve dans le sillon rocheux qui a servi de repère pour mesurer le retrait du front depuis 2004. On voit encore mieux le découpage de la langue par de nombreuses crevasses profondes, assez larges par endroits. A gauche de la photo, on repère la zone effondrée et plus claire qui pourrait disparaître plus vite que le rognon de glace, de couleur foncée, qui constitue l'extrémité de la langue. De la glace éboulée forme plusieurs paquets plus clairs que la masse principale, en périphérie de la langue. La pointe de la langue, de forme arquée, se trouve en haut du sillon rocheux dans lequel la glace était engagée depuis 2004-2005. L'amincissement général de la langue glaciaire s'est poursuivi en 2022, de manière très importante et ne montre aucun signe de reprise. La photo 1130136 a été prise du point älpha"(2'567'313 / 1'097'365 / 1727 m). Après la coupe des troncs et des branches, on voit à nouveau le glacier du Trient, ou ce qui en reste. Mais il faudra encore mieux dégager la vue en 2023 afin de retrouver le cadrage des années 1990-2000. Sur le plan Front Trient 2022", on retrouve l'ensemble des périmètres de la langue glaciaire, de 2002 à 2022. Le dernier périmètre, en vert foncé, est nettement plus petit que tous les précédents, témoignant de la fonte importante de l"année 2022. Le point aval du front a été cerclé en rouge. Il s'agit de la position du front en 2022, dont les coordonnées sont les suivantes: 2567716 / 1096224 / 2230 mètres. Le relevé du périmètre de la langue glaciaire a été réalisé à l'aide de jumelle laser LEICA-Locator, sans couplage GPS, à partir du point de mesure Ï". Coordonnées du point Ï", en usage depuis 2004: 2'567'889 / 1'097'100 / 1994 m. Azimut principal du point Ï"vers le front: 180° (le nord est à 0° ou 360°). Les coordonnées de 21 points ont été relevées, en tout, ce qui est inférieur aux années précédant 2021. En effet, la bordure de la langue comporte moins de digitations depuis qu'elle s'est retirée sur l'épaulement. La langue glaciaire s'est rétractée de manière très importante en 2022. La fonte se remarque tant sur l'épaisseur de l'appareil glaciaire que sur la largeur de la langue. Celle-ci présente une série de crevasses à 100 mètres en amont du front qui pourraient couper la langue en deux dans les prochaines années. Le point aval de la langue forme une sorte de corne, engagée dans un sillon rocheux bien visible. (J. Ehinger)

2023: Une bande de 35 à 50 mètres de largeur a disparu en rive gauche. Le sillon rocheux qui servait de référence de 2004 à 2022 se trouve dépourvu de glace. Un autre sillon rocheux a été pris comme nouveau repère. Visite 26.9.2023: Buts: Evaluer visuellement l'état du glacier. Couper les troncs qui bouchent la vue sur le glacier depuis le point älpha". Prendre des photos depuis le point älphaäfin de continuer la série commencée en 1969. Le ciel était bleu, sans nuage, permettant une bonne vue sur la Pointe des Ecandies et la Petite Pointe d'Orny qui servent à cadrer les photos à partir du point älpha"(2'567'313 / 1'097'365 / 1727 m). Comme la végétation a beaucoup poussé depuis 20 ans, le glacier n'était presque plus visible de 2018 à 2022, ce qui a motivé une demande de coupe adressée au garde forestier du secteur. L'accord a été immédiat et il a été possible de procéder au début des coupes nécessaires en 2022, afin de continuer la série de photos commencée en 1969 par Monsieur Pierre Mercier. Les coupes effectuées en 2023 ont bien élargi la vue sur le glacier. La langue glaciaire présentait une fonte importante, tant en épaisseur qu'en largeur, surtout en rive gauche. La position du front n'était plus identifiable sur l'ancien talweg local, il faudra changer de repère et suivre un autre sillon rocheux. Visite 1.10.2023: Buts: Evaluer visuellement l’état du glacier. Prendre des photos. Mesurer la position du front du glacier. Lever le plus grand nombre possible de points en bordure de la langue glaciaire. Le ciel était bien dégagé durant la journée. Comme toujours à cette époque de l’année, la lumière rasante générait un effet de contre-jour qui compliquait un peu les prises de vue. L’amincissement de la langue glaciaire se poursuit toujours. La langue occupe depuis 2021 un épaulement qui domine une forte pente, tracée de sillons rocheux parfois assez profonds. La ligne de rupture de pente est nettement hors de la glace. La langue glaciaire est devenue plus mince et plus étroite durant l’année écoulée, avec une fonte marquée en rive gauche. Une bande de 35 à 50 mètres de largeur, par endroits, a totalement disparu, emportant également le point de mesure de 2022. Un nouvel axe de référence, un autre sillon rocheux, a été choisi. La pointe de la langue, se trouve donc en amont d’un autre sillon rocheux que celui qui avait été retenu de 2004 à 2022. La position du front: 2’567’776 / 1’096’240 / 2205. Le relevé du périmètre (24 points) de la langue glaciaire a été réalisé à partir du point de mesure Ï”(2’567’889 / 1’097’100 / 1994). (J. Ehinger)

44 Paneyrosse

2022: Entlang Eisrand zwei kleine Seen. (J. Desarzens)

53 Stein

2022: Der Gletscher hat sich auf der rechten Seite stark ausgedünnt. (D. Rohrer)

55 Trift (Gadmen)

2022: Luftbildaufnahmen am 16.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

57 Oberer Grindelwald

2022: Luftbildaufnahmen am 13.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

58 Unterer Grindelwald

2022: Luftbildaufnahmen am 13.7.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

59 Eiger

2022: (R. Schai)

60 Tschingel

2023: orographisch ganz links hat sich der Gletscher stark zurückgezogen, das können wir terrestrisch nicht erfassen. Ebenfalls auf der linken Seite fällt viel Material nach unten. Vor dem Gletscher hat sich ein See gebildet, das Material ist matschig und mit Wasser durchtränkt. (R. Schai)

61 Gamchi

2023: Messung konventionell mit Distanzmessung ab Punkt A der kürzester Distanz zum Eisrand (161 gon) und Aufnahme von Randpunkten mit GPS, wo Eis unter dem Schutt ersichtlich war. (M. Schenk)

63 Lämmern

2023: Nachdem 2021 die Distanz von Punkt h zum Gletscher geschätzt (50m) wurde, erfolgte die Messung nun per elektronischer Distanzmessung (116m). Der Aufstieg direkt an den Gletscherand ist möglich. Koordinate Punkt h: 2'608'532 / 1'138'840 (M. Brügger)

64 Blümlisalp

2022, 2023: Fotostandort am Gegenhang bei 2'624'213 / 1'150'931 (U. Burgener)

65 Plaine Morte (Rätzli)

2022: Luftbildaufnahmen am 12.9.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 20.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

66 Tiefen

2022: Der östliche Teil des Gletschers ist stark zurückgegangen, insbesondere am Seitenrand. Der westliche Teil, steiler Gletscher vom Galenstock, ist im untersten Teil durch Schutt bedeckt. (L. Eggimann)

2023: Östlicher Teil des Gletschers weiterhin starker Höhenverlust, hingegen Längenänderung im Rahmen. Westl. Teil (rechter, steiler Gletscher vom Galenstock) ist nun im untersten Teil unter Schutt vollständig abgeschmolzen. Dadurch starke Längenänderung von rund 70 m. Lokal ist unter Schutt noch Toteis vorhanden. Auf Tiefengletscher rund 100m oberhalb Zunge bildet sich eine kreisförmige Mulde. (L. Eggimann)

67 St. Anna

2022: Der Gletscher ist weiter stark in sich zusammengefallen¿ Die grössen Veränderungen zeigen sich entlang der Seitenrändern. (L. Eggimann)

2023: Gletschermächtigkeit weiterhin starke Abnahme, Gletscherzunge hat gegenüber letztem Jahr nur wenig abgenommen (evtl. in Zusammenhang der Topographie, da Gletscherzunge nun oberhalb einer Steilstufe). (L. Eggimann)

68 Chelen

2023: Der Gletscher hat sich nun fast vollständig über die Steilstufe zurückgezogen und es sieht so aus, als ob das Gelände jetzt etwas flacher wird. (R. Planzer)

70 Damma

2023: Der Gletscher hat sich nun komplett über eine Steilstufe zurückgezogen. Alle Referenzpunkte (Messlinien) wurden näher an den Gletscherrand verschoben und neu bezeichnet. (M. Planzer)

71 Wallenbur

2022: Die mit viel Schutt bedeckte Gletscherzunge im Talboden ist nun nicht mehr mit dem Seitenzufluss unterhalb des Sustenhorns verbunden. Der Eisrand hat sich dort über die Steilstufe auf ca. 2600 m.ü.M zurückgezogen. (R. Planzer)

2023: Der gesamte Gletscher im Talboden ist mit viel Schutt bedeckt. Aus diesem Grund ist der Gletscherrand auch nicht immer genau erkennbar. Im Gletschervorfeld haben die Bäche sehr viel abgelagertes Schuttmaterial abtransportiert und es sind neu tiefe Gräben entstanden. (R. Planzer)

72 Brunni

2022: Der Gletschersee im nördlichen Bereich des Gletschers wird immer grösser, im Gegenzug wird der Gletscher im Randbereich zunehmend flacher. (R. Planzer)

2023: Zwischen den Messpunkten 1B und 9 ist ein zweiter See entstanden und der bereits bestehende See hat sich vergrössert. (R. Planzer)

74 Griess

2023: Der Gletscher ist mit sehr viel Schutt bedeckt. (R. Wüthrich)

77 Biferten

2022: Im Jahre 2022 führe ich die Messung am Bifertengletscher nochmals 5 Tage später als im 2021 und auch 3 Tage nach der Messung am Glärnischgletscher durch. Am Sonntag 30.10.2022 ziehen wir los um das Schicksal des Gletschers am Tödi weiter zu beobachten. Diesmal bereits zu dritt, denn das Interesse an einer Begehung vor Ort, nimmt zu. So darf ich wiederum auf die Hilfe von meinen zwei Edelhelfern Hansruedi Hösli Ennenda und Noël Dobler Reichenburg zählen, zusätzlich hat sich Gabi Heer von Visit Glarnerland AG Braunwald ebenfalls angeschlossen um das Unternehmen Gletschermessung mit zu verfolgen. Um 07.30 Uhr treffen wir drei Männer aus Ennenda kommend, auf Gabi Heer, am Parkplatz im Tierfed, um von dort gemeinsam im Bus nach Hintersand zu fahren. (Gletschermesser mit Fahrbewilligung der Kraftwerksstrasse) Das Wetter ist einmal mehr prächtig, der Föhn ist zwar mächtig am Blasen, trotzdem sind die Temperaturen auch am Gletscher erträglich. (+13.6°C) Bereits beim Treffen im Tierfed stellen wir uns die Frage, ob denn nun die Nabelschnur noch besteht, oder ob sie bereits weggeschmolzen ist. Gespannt auf das was uns erwartet, starten wir die Fahrt Richtung Hintersand. Nach dem überqueren der Pantenbrücke und dem Tiefblick in die Linthschlucht schlängelt sich die Strasse Richtung Ziel. Doch dieses Jahr ist alles anders: plötzlich steht kurz nach dem Sandwaldstutz im Sandwald ein Bagger mitten in der Strasse und verwehrt uns die Weiterfahrt nach Hintersand. Das heisst, dass wir dieses Jahr, einen einstündig verlängerten Fussmarsch vor uns haben. Doch wir wissen um unsere Kondition und nehmen diese Herausforderung recht gelassen. Also heisst es Rucksack packen und Richtung Tödi und seinem Gletscher losmarschieren. Der erste Fotostandort ist natürlich kurz nach dem Austritt aus dem Sandwald erreicht; der Tödi, höchster Glarner Gipfel begrüsst uns, sein Haupt ist leicht weiss überzuckert. (Schnee) Wir kommen gut voran und diskutieren während des Aufstieges über den Sommer und seine heissen Temperaturen und dessen Auswirkungen auf den Gletscher. So erreichen wir beinahe im Fluge die Unterkunftshütte der KLL. Dort "wartet"ja das Stativ auf uns, um mitgenommen zu werden. So wird das Gepäck auf den Schultern nochmals etwas schwerer, aber dies nur für eine kurze Zeit, bis wir an der Anfangsstation 12003 angelangen. Ein kurzer Znüni und dann beginnen wir die Messung. Nach der Orientierung auf der Station E und den Fernzielen Fridolinshüttengiebel und Grünhornhüttengiebel sind die Helfer bereits am Kartieren der Zunge. Wie eh und je ist der Einstieg auf der Ostseite schwierig, da man den Rand kaum ausmachen kann. Wiederum ist am Anfang der Messung der tiefste Punkt zu finden: er liegt einen halben Meter höher als im Vorjahr auf 1964.30 m.ü.M. Gabi Heer beobachte erst noch meine Arbeit, bevor sie sich dann den beiden Helfern Hansruedi und Noël anschliesst. Als ebenfalls begeisterte Berggängerin ist sie beeindruckt, wie schlimm es eigentlich um unser ewiges Eis so aussieht. Bei den Gipfelzustiegen wird einem nicht immer so klar vor Augen geführt wie es eben um die Gletscher steht. Man sieht und merkt wohl, dass es immer schwieriger wird gewisse Passagen zu meistern, aber den effektiven Vergleich hat man nicht überall. Mit 13 Punkten ist die Zunge im unteren Bereich wiederum angegeben. Das heisst für die Helfer, warten bis der Operateur seine Position gewechselt hat und sich auf dem oberen Fixpunkt 20101 wiederum installiert hat. Bereits die "guteNachricht von meinen Helfern über Funk; die Nabelschnur besteht noch, wir können die Messung wie gewohnt fortsetzen. Nach weiteren 15 Punkten die nun eindeutig die Zunge präsentieren, erreichen die Messgehilfen das Gletschertor 2 und seinen Gletscherbach. Die Begehung ist ohne grosse Probleme möglich und so kommen die drei Helfer gut voran. Da ja das Gletschertor 2 noch als einziger wirklicher Lichtblick dasteht, ist dies natürlich ein guter Standort um Fotos zu schiessen, die eben noch nach Gletscher aussehen. Das Tor ist gut 5.5m hoch und der Gletscherbach liegt auf der Meereshöhe von 2007.6 m.ü.M. Wie klein wir Menschen hier erscheinen, auch wenn der Gletscher, mehr und mehr weg schmilzt und in sich zerfällt. Behände klettert Noël entlang der Gletscherzunge und übertragt mir mittels Reflektor seine Position. Mit 19 weiteren Punkten ist schliesslich auf der Höhe von 2051.5 m.ü.M, die Messung 2022 abgeschlossen. Der optische Eindruck vor Ort ist auch in den Augen meiner Begleiter: immer prekärer. Dass ein derart grosses Gebilde in einer so kurzen Zeit in sich zusammen fallen kann, tut weh und schmerzt. Nicht nur, dass einfach auf den Bergbildern mit dem ewigen Eis das Krönchen fehlt, nein auch das Bewusstsein, dass unser Wasser Reservoir immer mehr Schaden nimmt, macht einem nachdenklich. (H. Klauser)

78 Limmern

2022: Neuschneeresten auf der Gletscherzunge; im rechten Teil der Zunge hat sich ein Toteistel abgetrennt. (U. Steinegger)

81 Pizol

2022: Gletscher und Vorfeld ist mit Neuschnee bedeckt, was das Auffinden des Eisrandes erschwerte. (Th. Brandes)

82 Lavaz

2022: Der Gletscher ist mit viel Geröll überdeckt. Teilweise war es schwierig den Gletscherrand zu eruieren. Im vorderen Teil ist die Gletscherzunge stark unterhöhlt. Teilweise ca. 10 - 20 m und bis ca. 1 m ab Boden. Wegen Steinschlag konnte nur der vordere Teil und nicht der ganze Gletscherumriss vermessen werden. Östlich ausserhalb des Messsektors wurde Eis im Hang beobachtet, welches noch mit dem Hauptgletscher verbunden ist. (F. Cathomas)

2023: Starker Schwund auf der rechten Seite oben entlang der Route zur Fuorcla Sura da Lavaz. (F. Cathomas)

83 Punteglias

2022: Der neue Gletscherrand in der Steilstufe ist nicht zugänglich. Die Front ist mächtig und mehrere Meter hoch. (F. Cathomas)

84 Länta

2023: Starker Schwund auf der rechten Hälfte der Zunge. In diesem steilen Bereich ist die Mächtigkeit geringer. (F. Cathomas)

85 Vorab

2022: Im Vorfeld sind zahlreiche Seen entstanden. (R. Deflorin)

2023: Die terrestrischen Aufnahmen am Gletscher wurden zusätzlich durch eine Befliegung mit der Drohne (Mavic 3 Enterprisemit RTK) ergänzt. (R. Deflorin)

86 Paradies

2022: Im Frühsommer hat sich unterhalb vom Passo dei Cadabi ein See gebildet. Im Laufe des Sommers hat er sich entleert, aber dessen Spuren auch im Herbst noch sichtbar waren. (C. Fisler)

2023: Der oberen Teil der Gletscherzunge hat sich auf der Höhe des Passo dei Cadabi abgetrennt. Im Vorfeld des Gletschers befinden sich viele kleine Seen. (C. Fisler)

88 Porchabella

2022: Gletscher aper, aber viele Steine, Geröll und feines Gesteinsmaterial liegen auf der Eisoberfläche. Massiver Schmelzwasserabfluss an der Oberfläche. Der Gletscherrand war sehr gut erkennbar und konnte eindeutig vom Gletschervorfeld abgegrenzt werden. Am westlichen Rand des Messsektors verdecken die Felssturzablagerungen den Eisrand. (C. Bieler)

2023: Der Gletscherrand wurde mit dem GPS und der Drohne vermessen. Der Vergleich der beiden Messmethoden soll zeigen, mit welcher Genauigkeit die Drohne arbeitet, sowie ob und welche Unterschiede die beiden Methoden zeigen. Auf der westlichen Seite verdeckt die alte Felssturzablagerung von 2014 weiterhin den Gletscherrand. (I. Castelberg)

89 Verstancla

2022: Luftbildaufnahmen am 12.9.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Der Gletscherrand ist sehr stark gefranst. Eisrand nicht sichtbar, da er vollständig mit Steinen überdeckt ist. Die Zunge reicht auf der schattigeren Westseite noch weiter nach unten als auf der östlichen Talseite. (A. Beilstein)
Luftbildaufnahmen am 24.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

90 Silvretta

2022: Luftbildaufnahmen am 12.9.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 24.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

91 Sardona

2022: Gletscher und Vorfeld bedeckt mit Neuschnee. Im Bereich der Messlinie 1 hat sich ein Schmelzwasserkanal tief eingefressen. (Th. Brandes)

93 Tschierva

2023: Der rechte (östliche) Gletscherarm hat sich abgetrennt. (G.A. Godly)

95 Calderas

2022: In Folge des Gletscherschwundes ist am Fuss des Piz Calderas am Nordwest-Rand des Gletschers eine Senke in der sich das Schmelzwasser ansammelt entstanden. Der Abfluss erfolgt natürlich über die Felsschwelle und den Bach nach NW in Richtung Alp Flix. Gegen Osten ist die Eisoberfläche noch höher. (VAW/ETHZ – A. Bauder)

2023: Die bisherige Gletscherzunge unterhalb vom Felsband hat sich abgetrennt und ist nicht mehr mit dem Nährgebiet verbunden. Östlich davon reicht noch ein Eislappen üeber das Felsband hinunter. Es gibt einen kleinen See im Vorfeld der Toteismasse. (G.-A. Godly)

96 Tiatscha

2022: Luftbildaufnahmen am 12.9.2022 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

2023: Luftbildaufnahmen am 24.8.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ. (VAW/ETHZ – A. Bauder)

97 Sesvenna

2022: Auf mittlerer Höhe im flachen Bereich vom Gletscher gibt es zwei imposante Gletschermühlen. (G. Renz)

2023: Etwas links von der Mitte hat sich der Schmelzwasserabfluss tief in die Oberfläche eingeschnitten, am unteren Ende bereits bis auf den Untergrund. (G. Renz)

98 Lischana

2022: Zwei Gletscherreste durchtrennt in der Mitte durch einen Felsriegel, seitlich stark schuttbedeckt. (G. Renz)

2023: Praktisch kein Gletscher mehr vorhanden, nur Fotodukumentation (G. Renz)

99 Cambrena

2023: Eisrand mittels Drohnenaufnahmen besimmt. Die letztjährigen Fotopunkte (5 und 6) mit GPS aufgenommen. (R. Nyfeler)

100 Palü

2022: Gletscherende hat den Kontakt zum proglazialen See inzwischen verloren. (VAW/ETHZ – A. Bauder)

2023: Die Gletscherzunge ist nur noch über den rechten, östlichen Arm unterhalb Piz Canton / Piz Varuna mit dem Nährgebiet verbunden. Der westliche, steilere Arm direkt Richtung Passo di Gambré hat sich in der Steilstufe durchgetrennt. (R. Nyfeler)

101 Paradisino

2023: Wegen wiederholten Steinschlägen auf der linke Seite (Corn da Camp) keine Messungen bis zur Seitenmoräne aufgenommen (Abstand Moräne ca. 5-10m). (R. Nyfeler)

102 Forno

2022: Im Gletschervorfeld erstreckt sich der mäandrierende Bach inzwischen über die gesamte Breite. (M. Keiser)

103 Bresciana

2022: La copertura nevosa era quasi completamente assente e presente solo in pochi punti isolati. (M. Soldati)

2023: Glacier and margin covered with fresh snow (J. Cuzzocrea)

104 Basòdino

2022: La copertura nevosa era praticamente assente. Diverse placche di ghiaccio si sono staccate dal resto del ghiacciaio e affiorano sempre più rocce, alcune delle quali anche all'interno del ghiacciaio. (M. Soldati)

2023: Glacier partly covered with some fresh snow. (J. Cuzzocrea)

109 Alpetli (Kanderfirn)

2023: Fotostandort: 2 625 548 / 1 146 024 (U. Burgener)

111 Ammerten

2022: Eindrücklich sind die Gletschertore, die sich nach dem warmen Sommer weiter öffnen und grosse Höhlen unter der Oberfläche bilden. (W. Hodel)

2023: Auf den Steilstufen oben und unten beginnt sich der Gletscher fast gleichzeitig abzutrennen. Rings um die Gletscherzunge sind viele neue Öffnungen entstanden. Die Gletscherbrücke und ein Teil des Tunnels ist am Tor bei Punkt 5 eingebrochen. Auf das Plateau im Mittelteil ist aus der Nordwand noch im Herbst ein Steinschlag niedergegangen. (W. Hodel)

114 Plattalva

2022: Gletscher bedeckt mit Neuschnee. (U. Steinegger)

115 Scaletta

2022: Die verbliebenen Gletscherreste sind bereits ab Mitte Juli komplett ausgeapert. (B. Teufen)

116 Albigna

2022: Auf der orographisch rechten Seite hat sich eine Schneise gebildet und ein Teil vom Toteis wurde abgetrennt. (M. Keiser)

117 Valleggia

2022: Copertura nevosa praticamente assente. Il lago postglaciale che si è formato assume dimensioni sempre maggiori. (M. Soldati)

2023: The proglacial lake is growing in size. (J. Cuzzocrea)

119 Cavagnoli

2022: La piccola placca di ghiaccio che rimane era completamente privo di copertura nevosa. A valle del nuovo limite del ghiacciaio ci sono ancora delle placche di ghiaccio morto isolate e staccate dal resto e molti detriti e rocce. (M. Soldati)

120 Corno

2022: Copertura neve quasi assente. Estremità laterali del ghiacciaio ricoperte da detrito. (M. Soldati)

2023: Glacier snout covered with debris, difficult to identify the ice margin. (J. Cuzzocrea)

173 Seewjinen

2023: Luftbildaufnahmen am 7.9.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ im Auftrag der Kraftwerke Mattmark AG. (VAW/ETHZ – A. Bauder)

174 Hohlaub

2023: Luftbildaufnahmen am 6.9.2023 und photogrammetrische Bearbeitung durch swisstopo, glaziologische Interpretation und Analyse durch VAW/ETHZ im Auftrag der Kraftwerke Mattmark AG. (VAW/ETHZ – A. Bauder)

352 Croslina

2022: Ghiacciaio completamente libero da neve (M. Soldati)

C Investigators

C.1 Length Variation (2023)

Glacier	No.	Investigator
Albigna	116	AWN/GR, Martin Keiser
Allalin	11	VAW/ETHZ, Andreas Bauder
Alpetli (Kanderfirn)	109	KAWA/BE, Ueli Burgener
Ammerten	111	Walter Hodel
Arolla (Mont Collon)	27	DN/VS, François Fellay
Basòdino	104	SF/TI, Mattia Soldati
Biferten	77	Hanspeter Klauser
Blüemlisalp	64	no observation during report period
Boveyre	41	DN/VS, Pascal Stoebener
Breney	36	VAW/ETHZ, Andreas Bauder
Bresciana	103	SF/TI, Mattia Soldati
Brunegg (Turtmann)	20	DN/VS, Alban Brigger
Brunni	72	AFJ/UR, René Planzer
Calderas	95	AWN/GR, Gian Andri Godly
Cambrena	99	AWN/GR, Renata Nyfeler
Cavagnoli	119	SF/TI, Mattia Soldati
Cheillon	29	DN/VS, Sébastien Tremp
Chessjen	12	VAW/ETHZ, Andreas Bauder
Corbassière	38	VAW/ETHZ, Andreas Bauder
Corno	120	SF/TI, Mattia Soldati
Croslina	352	SF/TI, Mattia Soldati
Damma	70	AFJ/UR, René Planzer
Dungel	112	no observation during report period
Eiger	59	no observation during report period
En Darrey	30	DN/VS, Sébastien Tremp
Fee	13	VAW/ETHZ, Andreas Bauder
Ferpècle	25	DN/VS, François Fellay
Fiescher	4	VAW/ETHZ, Andreas Bauder
Findelen	16	VAW/ETHZ, A. Bauder & E. Hodel
Firnalpeli (Ost)	75	no observation during report period
Forno	102	AWN/GR, Martin Keiser
Gamchi	61	KAWA/BE, Martin Schenk
Gauli	52	no observation during report period
Gelten	113	no observation during report period

Glacier	No.	Investigator
Giétro	37	VAW/ETHZ, Andreas Bauder
Glärnisch	80	Hanspeter Klauser
Gorner	14	VAW/ETHZ, A. Bauder & E. Hodel
Grand Désert	31	DN/VS, Frédéric Bourban
Grand Plan Névé	45	FFN/VD, Julien Desarzens
Gries	3	VAW/ETHZ, A. Bauder & E. Hodel
Griess	74	AFJ/UR, Roland Wüthrich
Griessen	76	AWL/OW, Urs Hunziker
Grosser Aletsch	5	VAW/ETHZ, A. Bauder & E. Hodel
Hohlaub	174	VAW/ETHZ, Andreas Bauder
Hüfi	73	no observation during report period
Kaltwasser	7	DN/VS, Alban Brigger
Kehlen	68	AFJ/UR, René Planzer
Lang	18	DN/VS, Alban Brigger
Lavaz	82	AWN/GR, Flurin Cathomas
Lenta	84	AWN/GR, Flurin Cathomas
Limmern	78	Urs Steinegger
Lischana	98	AWN/GR, Giorgio Renz
Lämmern	63	KAWA/BE, Michel Brügger
Mittelaletsch	106	VAW/ETHZ, Andreas Bauder
Moiry	24	DN/VS, François Fellay
Moming	23	VAW/ETHZ, Andreas Bauder
Mont Durand	35	VAW/ETHZ, Andreas Bauder
Mont Fort (Tortin)	32	DN/VS, Frédéric Bourban
Mont Miné	26	VAW/ETHZ, Andreas Bauder
Morteratsch	94	AWN/GR, Gian Andri Godly
Mutt	2	VAW/ETHZ, Andreas Bauder
Oberaar	50	VAW/ETHZ, A. Bauder & E. Hodel
Oberaletsch	6	VAW/ETHZ, Andreas Bauder
Oberer Grindelwald	57	VAW/ETHZ, AA. Bauder & E. Hodel
Otemma	34	VAW/ETHZ, Andreas Bauder
Palü	100	AWN/GR, Renata Nyfeler
Paneyrosse	44	FFN/VD, Julien Desarzens
Paradies	86	AWN/GR, Cristina Fisler
Paradisino (Campo)	101	AWN/GR, Renata Nyfeler
Pizol	81	KFA/SG, Thomas Brandes
Plattalva	114	Urs Steinegger
Porchabella	88	AWN/GR, Claudia Bieler
Prapio	48	VAW/ETHZ, Andreas Bauder
Punteglias	83	AWN/GR, Flurin Cathomas
Rhone	1	VAW/ETHZ, A. Bauder & E. Hodel
Ried	17	VAW/ETHZ, Andreas Bauder
Roseg	92	no observation during report period
Rossboden	105	VAW/ETHZ, Andreas Bauder
Rotfirn (Nord)	69	AFJ/UR, René Planzer
Rätzli	65	VAW/ETHZ, A. Bauder & E. Hodel

Glacier	No.	Investigator
Saleina	42	DN/VS, Pascal Stoebener
Sankt Anna	67	AFJ/UR, Lukas Eggimann
Sardona	91	KFA/SG, Thomas Brandes
Scaletta	115	VAW/ETHZ, Andreas Bauder
Schwarzberg	10	VAW/ETHZ, Andreas Bauder
Seewjinen	173	VAW/ETHZ, Andreas Bauder
Sesvenna	97	AWN/GR, Giorgio Renz
Sex Rouge	47	VAW/ETHZ, Andreas Bauder
Silvretta	90	VAW/ETHZ, A. Bauder & E. Hodel
Stein	53	KAWA/BE, Daniel Rohrer
Steinlimi	54	no observation during report period
Sulz	79	WN/GL, Ulrich Aerne
Suretta	87	AWN/GR, Cristina Fisler
Tiatscha	96	VAW/ETHZ, A. Bauder & E. Hodel
Tiefen	66	AFJ/UR, Lukas Eggimann
Trient	43	Jacques Ehinger
Trift (Gadmen)	55	VAW/ETHZ, A. Bauder & E. Hodel
Tsanfleuron	33	DN/VS, François Fellay
Tschierva	93	AWN/GR, Gian Andri Godly
Tschingel	60	KAWA/BE, Ralf Schai
Tseudet	40	DN/VS, Pascal Stoebener
Tsidjiore Nouve	28	DN/VS, François Fellay
Turtmann	19	DN/VS, Alban Brigger
Unteraar	51	VAW/ETHZ, A. Bauder & E. Hodel
Unterer Grindelwald	58	VAW/ETHZ, AA. Bauder & E. Hodel
Val Torta	118	no observation during report period
Valleggia	117	SF/TI, Mattia Soldati
Valsorey	39	DN/VS, Pascal Stoebener
Verstankla	89	AWN/GR, Annabarbara Beilstein
Vorab	85	AWN/GR, Renato Deflorin
Wallenbur	71	AFJ/UR, René Planzer
Zinal	22	DN/VS, François Fellay
Zmutt	15	VAW/ETHZ, Andreas Bauder

AFJ/UR	Amt für Forst und Jagd, Uri
AWN/GR	Amt für Wald und Naturgefahren, Graubünden
AWL/OW	Amt für Wald und Landschaft, Obwalden
DN/VS	Dienststelle Naturgefahren/Service des dangers naturels, Wallis/Valais
FFN/VD	Service des forêts, de la faune et de la nature, Vaud
KAWA/BE	Amt für Wald, Bern
KFA/SG	Waldregion 3 Sargans, St. Gallen
SF/TI	Sezione forestale, Ticino
VAW/ETHZ	Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich
WN/GL	Wald und Naturgefahren, Glarus

C.2 Mass Balance and Velocity

Glacier	No.	Investigator
Allalin	11	VAW/ETHZ, Andreas Bauder
Basòdino	104	VAW/ETHZ, Giovanni Kappenberger
Clariden	141	VAW/ETHZ, Urs Steinegger
Corbassière	38	VAW/ETHZ, Andreas Bauder
Findelen	16	DGUF / GIUZ, Matthias Huss, Andreas Linsbauer
Giétro	37	VAW/ETHZ, Andreas Bauder
Gries	3	VAW/ETHZ, Matthias Huss
Grosser Aletsch	5	VAW/ETHZ, Andreas Bauder, Matthias Huss
Hohlaub	174	VAW/ETHZ, Andreas Bauder
Murtèl	377	DGUF, Matthias Huss
Pers	317	VUB, Philippe Huybrechts
		DGUF, Matthias Huss, Andreas Linsbauer
Pizol	81	VAW/ETHZ / DGUF, Matthias Huss
Plaine Morte	65	DGUF, Matthias Huss
Rhone	1	VAW/ETHZ, Andreas Bauder
Sankt Anna	67	DGUF, Matthias Huss
Schwarzberg	10	VAW/ETHZ, Andreas Bauder
Silvretta	90	VAW/ETHZ, Andreas Bauder
Tsanfleuron	33	DGUF, Mauro Fischer

C.3 Englacial Temperature

Site (Glacier)	No.	Investigator
Colle Gnifetti (Gorner)	14	DGUF, Martin Hoelzle, Marcus Gastaldello

DGUF	Département des Géosciences, Université de Fribourg
GIUZ	Geographisches Institut, Universität Zürich
VUB	Vrije Universiteit Brussel
VAW/ETHZ	Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich