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GLAMOS
Glacier Monitoring Switzerland

## GCOS Switzerland Project

# "Hundred years of Swiss glacier changes from historical terrestrial images"

## Final Report

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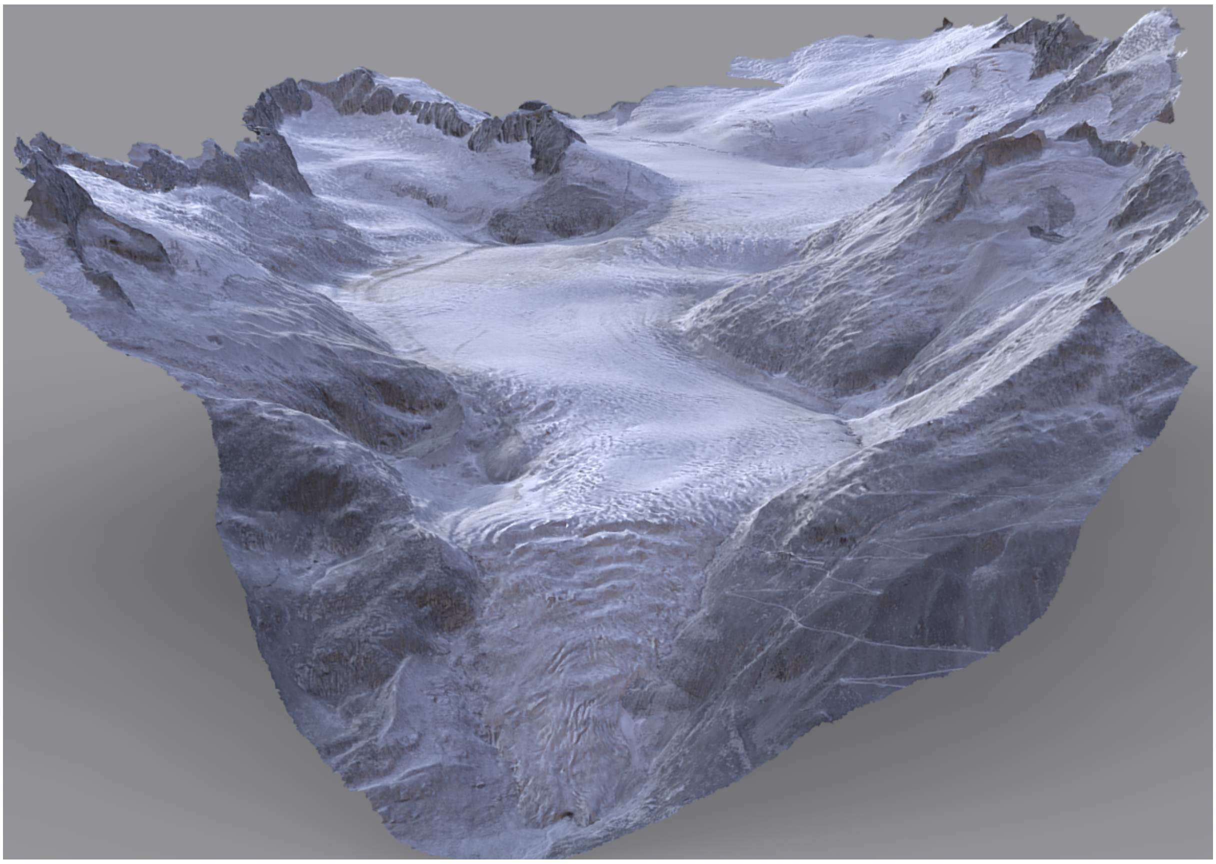
| Project period: | 01 September 2020 – 28 February 2022 |
| Project PI: | Dr. Amaury Dehecq |
| Project deputy-PI: | Dr. Andreas Bauder |
| Collaborators: | Erik Mannerfelt, Romain Hugonnet, Elias Hodel, Dr. Matthias Huss, Dr. Daniel Farinotti |
| Institutions: | ETH Zurich and WSL Birmensdorf |
| Funding: | MeteoSwiss, in the framework of GCOS Switzerland |



3D model of Rhone glacier, Switzerland, reconstructed for year 1928

# 1. Summary

Worldwide glacier decline has important consequences for water and energy resources, particularly in the Alps. Switzerland stands out as the country with the oldest records of glacier change. Despite this, only a few dozen of glaciers have observations extending further back than three decades and long-term observations are crucial in order to understand glacial processes at scales similar to that of the glaciers' response time.

In this project, we exploited a unique archive of 58,000 terrestrial images (TerrA) acquired in Switzerland from 1916 until 1947 for mapping purposes, in order to document glacier volume changes at a near centennial scale. The photographs are scanned and made available by the Federal Office of Topography (swisstopo). An automated workflow was developed to generate Digital Elevation Models (DEMs) from the stereoscopic images, using both in-house and commercial software. A first processing step was designed using image processing techniques in order to transform the scans into a distortion-free image. A second processing step was developed based on modern photogrammetry methods to reconstruct a 3D representation of the surface from stereo image pairs. The methodology was applied to about 20,000 images to provide glacier surface elevation for 45% of all Swiss glaciers for the year 1931.

We estimate a Swiss-wide glacier mass balance of $-0.52 \pm 0.09$ m w.e. $a^{-1}$ and an area reduction of $5.9 \pm 0.8$ $km^2$ $a^{-1}$ between 1931 and 2016. This translates to a halving of glacier volume compared to 2016, and a third's reduction in areal cover. Our results indicate a strong spatial variability in glacier thinning, with glaciers in the north east losing mass twice as rapidly as in the south west of Switzerland. This variability is partially explained by the fact that mass losses are found to be pronounced for glaciers at a lower elevation, with more gently-sloping termini, and with a high present-day debris-cover fraction.

The outcomes of the project will help better understand the processes responsible for recent glacier changes at a near centennial scale. In particular, they will help calibrate and validate glacier evolution models used to project future glacier mass loss in the Alps and in the world. The observations generated during the project (DEMs, ortho-photos, glacier contours), as well as the code used for processing and analysis, are publicly available. These resources are expected to be beneficial for other applications beyond glaciology such as geomorphology or natural hazards.

# 2. Scientific Report

## 2.1. Introduction

Glaciers are emblematic indicators of climate change. Their decline over the last decades has important consequences for water resources and hydro-power production (Hock et al., 2019; Zemp et al., 2019), particularly in the European Alps (Beniston et al., 2018). Switzerland is home to about 1500 glaciers, representing almost half of all glacierized areas in the Alps (Linsbauer et al., 2021). Switzerland also stands out as the country with the longest glacier monitoring program, with observations extending as far back as the late 19th century (GLAMOS, 1881-2020).

Despite this, only about a dozen glaciers have been monitored for annual mass changes over a period longer than 30 years. Yet, long-term observations of glacier changes are critical in order to calibrate models used for future projections (e.g., Zekollari et al., 2019) and to understand the impact of several processes (ice flow, development of proglacial lakes, etc) on the timing of glacier retreat. Additionally, field-based monitoring can be complemented by region-wide remote-sensing observations that can provide snapshots of glacier length, area and volume changes over the past decades (e.g., Hugonnet et al., 2021). Such observations are usually limited to the availability of satellite/aerial images and the oldest available aerial topographies in Switzerland do not extend further back than the 1960s. Volume changes have been estimated for about 20 glaciers over periods prior to the 1960s, representing only about 1/5 of all glacier areas (Bauder et al., 2007).

A large archive of terrestrial images (named *TerrA*), acquired for early mapping before the onset of aerial photography, is available from the Swiss Federal Office of Topography (swisstopo). These images were taken from 1916 to 1947 in order to generate 1:50,0000 national maps. They have been acquired from ~7,000 survey points across Switzerland (Figure 1) and stored on 58,000 glass plates[1]. Although some of the maps are readily available, they were obtained by photo-interpretation and digitized from contour lines. Hence, they do not provide the accuracy that is reached with modern photogrammetry (Bauder et al., 2007). Additionally, maps are a composite of measurements over several years/decades, and time information, crucial to estimate a rate of glacier volume change, is often missing (Fischer et al., 2015). Over the last years, swisstopo has made tremendous efforts in order to archive and preserve such historical data. The images have been scanned and can be visualized on the "A journey through time" portal[2]. Beyond the broad public interest for this data, these images have a huge potential for quantifying surface changes up to a centennial scale, in particular for rapidly changing glaciers. Moreover, while the geolocation of these images is known, the depth information provided by the stereoscopic images, and hence 3D representation of the topography, has not been exploited yet.

In this project funded by GCOS, we processed these images in a photogrammetric framework in order to derive the surface elevation of glaciers in the Swiss Alps. This information was used to estimate glaciers' volume changes over a period of about 85 years, more than doubling the observation period of existing studies at Swiss scale. This provides a truly unique, region-wide picture of glaciers changes over such a time scale. The project was conducted jointly at ETH Zurich and WSL Birmensdorf. One research assistant (E. Mannerfelt) worked full-time on the project for 18 months and was responsible for the processing of the data, scientific publication of the results and dissemination of the results. He worked under the supervision of A. Dehecq

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[1] https://www.swisstopo.admin.ch/en/knowledge-facts/histcoll/historical-images/terrestrial-images.html

[2] https://s.geo.admin.ch/668b732771

and D. Farinotti, with inputs from E. Hodel, R. Hugonnet, M. Huss and A. Bauder. Swisstopo provided us all the necessary images, metadata and useful information. In this final report we summarize the activities of the entire project duration and give an overview of the results.

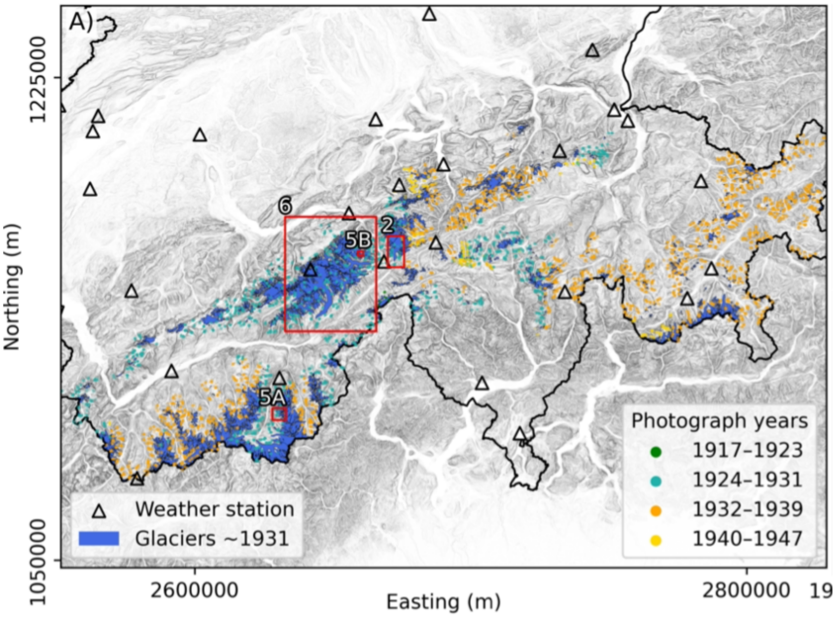

***Figure 1:*** *The distribution of Swiss glaciers around 1931 (blue areas). Country borders are outlined in black. The locations of the TerrA photographs used in the project are shown with coloured dots, whose colour indicates the year of acquisition (from Mannerfelt et al. (2022)).*

## 2.2. Methods and activities

The projects activities were divided into five main work-packages (WP): (1) the selection of the TerrA images over glaciers, (2) the development of a pre-processing workflow to convert the scans into exploitable, distortion-free images, (3) the development of a photogrammetric workflow to convert the stereoscopic images into Digital Elevation Models (DEMs), (4) the estimation of volume changes for all Swiss glaciers since the 1930s and (5) the distribution and publication of both the results and data. A flowchart summarizing the steps involved in WP2 to WP-4 is provided in Figure 3.

### WP-1: The TerrA archive - Selection of the data over glaciers.

The TerrA archive consists of 57,385 images in total, covering most of the mountains in Switzerland and were acquired from 1916 to 1947. The images were acquired from high points surrounding the surveyed areas (e.g., summits, ridges, slopes), and stereo acquisition was performed by taking two sets of pictures from locations spaced a few hundred metres apart. From each location, a panorama of about 4–5 images was acquired to increase the viewing angle.

The 13 cm × 18 cm glass-plate images were scanned by swisstopo at a resolution of 21 μm, yielding digital images of 53 Mpx. Metadata for every image includes an identifier for which stereo pair it belongs to, the acquisition date, the position, and the viewing direction of the image as determined from field measurements. The photographs used in this project were taken with 21 individual cameras of two different brands (“Wild” and “Zeiss”), which had different focal lengths and image dimensions (Figure 2).

About 21,700 (38%) of these images were selected based on the intersection of the images' approximate viewsheds (produced by swisstopo) and modern glacier outlines. The selected images were distributed free of charge by swisstopo within a few weeks of the project's start. At swisstopo's request, we checked the quality of the images to verify the performance of the scanner used for this archive. The images proved of sufficient quality for the project although we recommended to re-scan the images with a higher quality scanner if resources are available. Such a task was deemed unrealistic by swisstopo during the duration of the project and was abandoned.

***Figure 2:*** *Example of a terrestrial image TerrA (from the type "Wild") acquired over Rhone glacier in 1928. The four fiducial markers have been highlighted in red.*

## WP-2: Development of the image pre-processing workflow

In contrast to modern digital images, the scans of photographic images cannot be processed as such. Scans include unexposed image edges that must be cropped, and distortion (rotation, scaling, introduced during scanning) that must be corrected. To do so, we used the four fiducial markers, i.e., specific features printed on the four edges of the film during acquisition (Figure 2). A set of scripts were written in the programming language Python in order to semi-

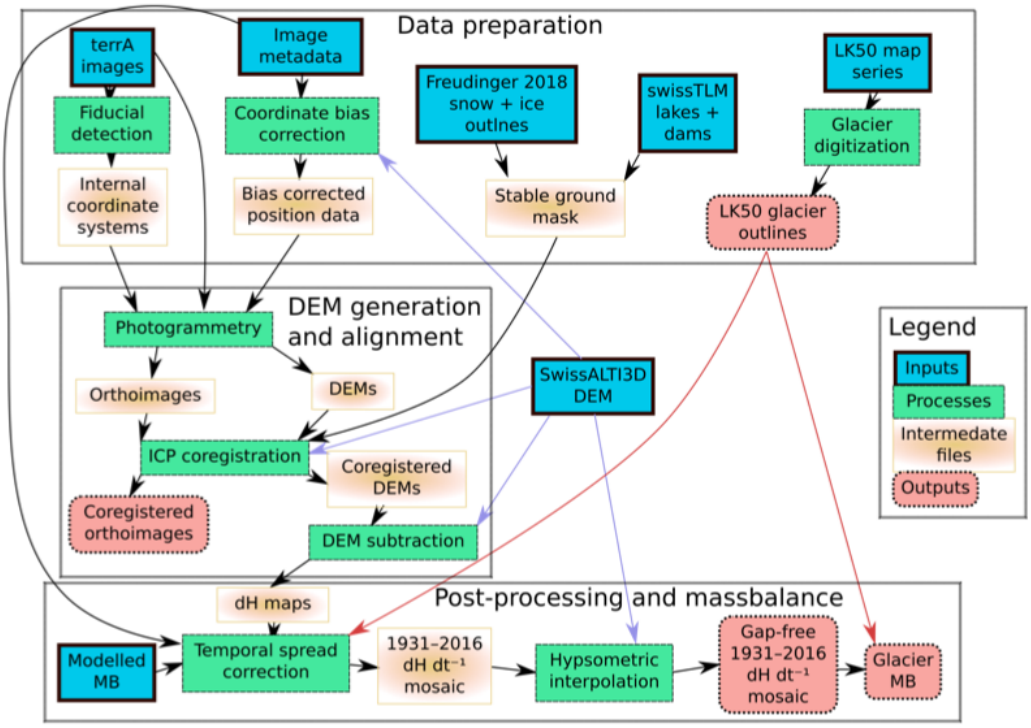

***Figure 3:*** *Flowchart synthesising the data processing (WP-2 to WP-4). Inputs refer to the external data that were used, processes are different steps in the processing chain, and outputs are files of particular interest for this and future studies. All intermediate and output files will be made available for further use.*

automatically detect those markers on images from all 21 camera types and correct distortions. The markers were manually identified for about 3,400 images, which were used to calibrate an automated detection for the remaining 81% of the images. The border of each image was also masked to avoid interferences during the next processing stages.

### WP-3: Development and validation of the photogrammetric workflow

To generate DEMs and orthophotos from the terrestrial images, a photogrammetric workflow was developed using the software Agisoft Metashape (block "DEM generation and alignment" on Figure 3). The software is adapted for the processing of historical images with fiducial markers. It also offers a Python interface that enables the use of programming scripts. This is crucial to automate the processing and ensure both reproducibility and reusability of the methods. Since the reported camera positions and orientations are affected by uncertainties, the generated DEMs were aligned to a reference DEM (here SwisssAlti3D) to ensure precise geolocation. This was performed using custom scripts. The final coregistered DEMs and orthophotos were generated at a spatial resolution of 5 m. The workflow was tested on a small sample of images to generate a DEM over Rhone glacier, which was then validated against modern DEMs (over terrain outside glaciers assumed to be stable) and historical maps (over glaciers). The processing workflow is described in more details in Mannerfelt et al. (2022).

The processing was successfully run to generate roughly 2000 DEMs covering most of the Swiss Alps (about 10 images make up a single panorama from a unique location). The processing of the data took approximately 6 weeks on 4 different high-performance computers. About 10% of the images could not be processed successfully, either due to incorrect metadata or image issues (e.g., too little overlap with other images). The output of this WP was a set of coregistered DEMs and elevation change maps for approximately 45% of Swiss glaciers by area (see an example on Figure 4, left). Gaps in observations originate from the lack of images or insufficient image quality (e.g., highly oblique images, areas of low image contrast on snow etc).

### WP-4: Geodetic mass balance of Swiss glaciers 1931-2016

The goal of WP-4 was to estimate volume changes for all Swiss glaciers, to provide reliable uncertainties and to analyse the results. The main challenges in doing so are to i) identify the extent of the glaciers during the historical period, ii) fill gaps in observations, iii) correct for temporal differences in the image's acquisitions, and iv) estimate an uncertainty for each glacier's elevation and volume change (Figure 3, "Post-processing" block).

To tackle the first challenge, orthophotos were generated from the oblique images, and glacier outlines were manually drawn for 61 glaciers. The outlines were then compared to a glacier inventory, previously generated from historical maps (LK 50). Both data sets proved to be consistent within 15 m. Therefore, the LK50 outlines were assumed to be derived from the same images for the same date, and are used for the rest of the processing.

The second challenge arose since only about 45% of glacierized terrain have a valid observation of elevation (Figure 4, left). We therefore developed an approach to interpolate missing values, which relies on the observation that glacier thinning is strongly controlled by elevation. Hence data gaps are filled with the mean value of elevation change from valid observation at similar altitude setting. The method was applied in order to estimate glacier elevation and volume changes for 100% of the Swiss glaciers (Figure 4, right).

Addressing challenge iii) was necessary to provide a temporally homogeneous observation of glacier changes, given that the historical images span a period of 32 years (1916-1947). To take into account fluctuations in glacier elevation during this time period, we relied on the sparse but well constrained mass balance time series available for selected glaciers in Switzerland (GLAMOS). These series were obtained from a combination of in-situ measurements, geodetic mass balance since 1960 and modelling. With those, it was possible to estimate each individual glacier's mass balance over the period between the actual acquisition and our reference year 1931 (the median year of all historic images), and to make all observations directly comparable.

Finally, for challenge iv), we developed a theoretical framework and a set of codes to estimate elevation and volume change uncertainties based on spatial statistics and uncertainty propagation methods.

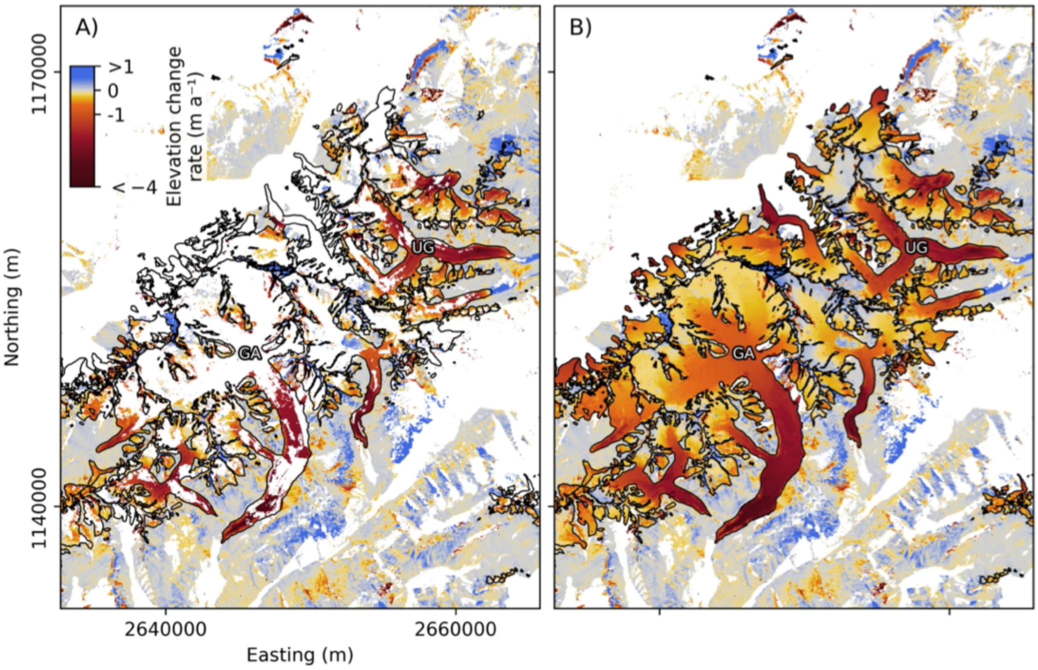

***Figure 4:*** *Example of glacier elevation change rates (1931-2016) obtained for the Bernese Alps. Raw observations are shown on panel A), and gap-filled results on panel B). Glaciers are outlined in black (Grosser Aletschgletscher = GA, Unteraargletscher = UG). (Mannerfelt et al. submitted)*

### WP-5: Publication and distribution of the results and data

An article summarizing the methodology and the main results, entitled "Halving of Swiss glacier volume since 1931 observed from terrestrial image photogrammetry", has been submitted to the journal "The Cryosphere" in January 2022. It is currently under review in The Cryosphere's discussion forum (https://doi.org/10.5194/tc-2022-14).

Beyond the glaciological results, the processed data and the developed methodology will be of interest for other applications related to land surface changes, such as geomorphology, landslides or forestry for instance. We therefore deemed it important to make all products and codes easily accessible.

The code used for processing the TerrA images (WP-2 and 3) is publicly available at https://github.com/VAW-SwissTerra/SwissTerra. The code used to estimate the glacier volume change (WP-4) is available through https://github.com/VAW-SwissTerra/terradem. It is in parts based on the broader module *xdem* (https://github.com/GlacioHack/xdem/), co-developed by three of the project's collaborators (E. Mannerfelt, R. Hugonnet, A. Dehecq).

All relevant data produced during this project (DEMs, elevation change maps, glacier outlines) are currently being prepared for archiving and public distribution. These will be made available upon final acceptance of the publication at the following DOI: 10.3929/ethz-b-000533930.

## 2.3. Results

Our analysis revealed a Swiss-wide glacier mass balance of –0.52 ± 0.09 m w.e. $a^{-1}$ and an area reduction of 5.9 ± 0.8 $km^2$ $a^{-1}$ between 1931 and 2016. This translates to a halving of the glacier volume since 1931, and to a third's reduction in areal cover. We then performed a more in-depth analysis of the variability in the glaciers' volume changes and the factors explaining it. Our results indicate a strong spatial variability in glacier thinning, with glaciers in the north east losing mass twice as rapidly as in the south west of Switzerland (Figure 6). We could partially link this variability to glacier topographic and morphological factors. We found that mass losses are more pronounced for glaciers at a lower elevation, with more gently-sloping termini, and with a higher debris-cover fraction (Figure 5).

The results of this project are unique in the fact that they are the first regional-scale reconstruction of glacier volume changes prior to 1950 based on terrestrial images.

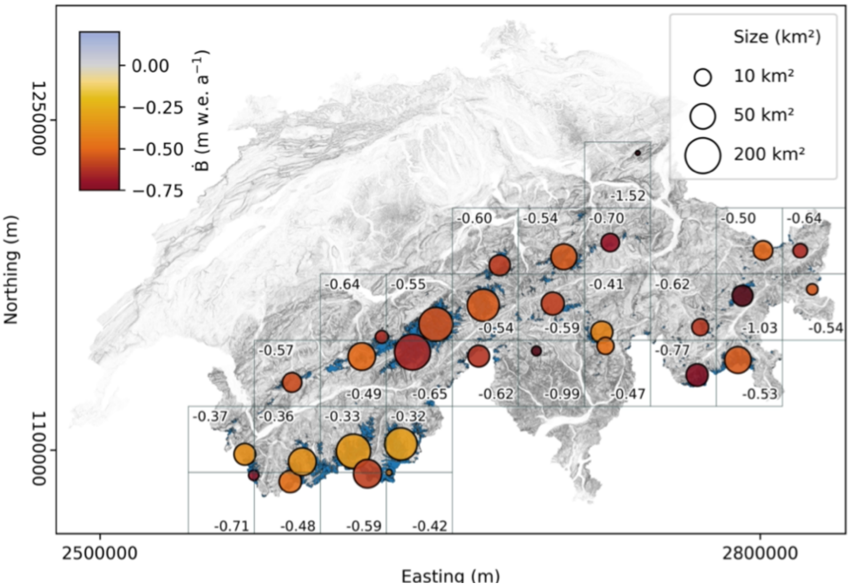

***Figure 6:*** *Area-weighted geodetic mass balance rates (colours and numbers) for 30 km×30 km tiles (grey squares). The location of each circle is the average glacier centroid weighted by area in the tile, and their sizes indicate the glacier area in ca. 1931 (Mannerfelt et al., 2022).*

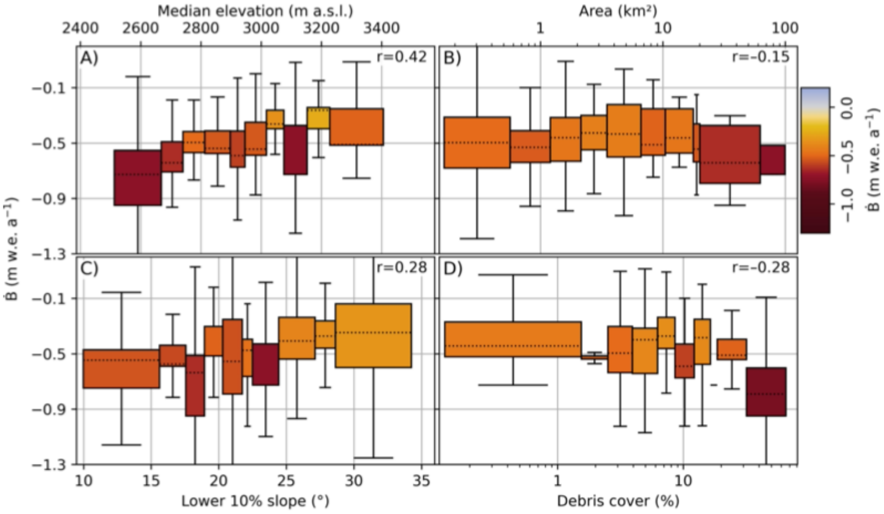

***Figure 5:*** *Boxplots showing the relations between 1931–2016 glacier mass change rates (vertical axes and colours) and different morphological parameters (horizontal axes). A) Correlation with median glacier elevation, indicating that lower elevations show larger mass loss. B) Correlation with glacier area, showing no clear relation. C) Correlation with the slope of the glaciers lowermost 10%, possibly showing higher mass change for glaciers with flatter termini. D) Correlation with debris cover, indicating that higher mass change may be found for glaciers with high debris-coverage percentage (Mannerfelt et al., 2022).*

## 2.4. Conclusion and limitations

All initially defined project objectives have been successfully achieved, or will be achieved in the coming months with the final publication and dissemination of the results.

The project demonstrated the potential and value of the TerrA archive. All selected images were successfully processed to provide scientifically relevant and quantitative observations of glacier changes. It is important to note that these centennial images were meticulously acquired, stored and catalogued by swisstopo. As such, they are an impressive demonstration of the Findable, Accessible, Interoperable and Reusable (FAIR) principles, that should guide all scientific data. By showcasing the added value of such long-term archiving efforts, we hope that this project will encourage data holders and archivists to follow the example. In this sense, our project is supporting GCOS strategic pillar #3 “Ensure applicability of Swiss GCOS data and products“.

This project demonstrated what had so far only been inferred from sparse observations: a halving of Swiss glacier volume and a thirds reduction in area over a period of 85 years. These results will help constraining glacier evolution models at an unprecedented temporal scale, and will improve our ability to predict the future of Swiss glaciers and other glaciers in the world. This project is a strong support to GCOS strategic pillar #1 “Enhance and strengthen the Swiss climate observing system”.

Finally, this project fostered collaborations between data holders (swisstopo), fieldwork specialists (A. Bauder, M. Huss), remote sensing and photogrammetry experts (E. Mannerfelt, A. Dehecq, R. Hugonnet, E. Hodel), and modelers (M. Huss, D. Farinotti). This project would not have been possible without swisstopo’s support, and field-observation and model outputs were crucial in validating and homogenizing the remote sensing observations. With three nationalities represented in the group (Sweden, France, and Switzerland), this project is in line with GCOS strategic pillar #2 “Promote collaboration nationally, regionally, and globally”.

Several limitations arose in the project too. Whilst they did not prevent us from reaching the project’s goals, they show the challenges of exploiting this data for further applications. The first challenge was in the automation of the image pre-processing. Although most fiducial markers could be identified automatically, about 21% had to be identified manually. Hence, processing the remaining 2/3 of the image archives would be possible, but would require some manual supervision. The second challenge was the automation of the DEM generation, which failed in about 20% of the cases. The two main reasons for these failures are (1) the limited extent of the observed area, hence reducing the amount of stable terrain available for DEM co-registration, and (2) the low incidence angle of the images that causes geometric distortions. While these issues are inherent to terrestrial images, they call for improved image processing methods to find correspondences between images acquired with strongly differing view-angles. Finally, while the uncertainty of our observations enabled us to derive statistically significant change estimates at the regional scale, observations at the short scale, i.e., from the metre to kilometre scale, would be too uncertain (pixel-scale elevation change error of about 11 m). Our current DEMs therefore have probably limited interest for applications interested at smaller topographic changes such as erosion or vegetation changes. The photogrammetric processing or the DEM postprocessing could however be tuned for specific applications to improve the uncertainties locally. The oblique images and orthoimages still remain of great value for visual analysis of surface changes.

## 2.5. Outreach work, publication of data and results

The methodology was presented at an early stage of the project at the “Alpine Glaciology Meeting”, held virtually in March 2021. Presentations of the final results at an international conference is not yet planned for 2022, but will happen as opportunities arise, in accordance with E. Mannerfelt’s availability beyond the project’s duration.

A press release is being prepared for the time of final publication of the article. The dissemination of the main results to the broad public will likely take the form of a 3D representation of the glaciers in 1930s along with a similar representation from modern images. A 3D reconstruction of Rhone glacier for year 1928 is already available at https://skfb.ly/osQTF.

For the scientific publication and dissemination of the code and data, see Section 2.2, and the subsection WP-5 in particular.

## 2.6. Outlook

Beyond the initial objectives, several directions are envisioned for the continuation of the project. We will consider processing the rest of the archive as resources allow and if the data set raises interest for other applications. In any case, all the codes remain publicly available, making it possible for anyone to improve upon the existing processing.

The project “Discovering forgotten glacier images in a new glance (DEFOGGING)”, also funded by GCOS, is currently assembling, digitizing, and archiving historical images of glaciers across Switzerland. The possibility of combining these images with those of the TerrA archive, with a possible repetition of modern photographs from the same locations as in the TerrA surveys, will allow to visually document the changes that we have inferred with this project. Especially re-photography might provide the means of communicating the magnitude of the changes in a very efficient and visually-appealing way, with the corresponding potential for reaching a large audience.

Finally, other historical image archives exist, which could be exploited using the expertise developed during this project. For example, the processing methodology could be applied to other terrestrial archives from other alpines countries (France, Italy, Austria) to provide an Alps wide estimate of glacier volume changes. Additionally, some Swiss archives date back as far as the second half of the 18th century (e.g., available from https://smapshot.heig-vd.ch) but in the form of monoscopic photographs. While these images do not allow for a direct reconstruction of the topography, some computer vision methods and modern topography could be used to extract scientifically relevant information on glacier retreat since the Little Ice Age, extending the project’s observations another 50 years in time.

## 2.7. Acknowledgements

We first would like to acknowledge GCOS Switzerland for providing funding to our proposal. This work would not have been possible without this support. We would also like to thank swisstopo for acquiring, archiving, scanning and distributing the TerrA images. This work is the recognition of a hundred years of efforts. We are particularly grateful to Philip Joerg and Matthias Zesiger for providing additional details on the images metadata and acquisition. We are grateful to Roxana Zehtabchi for early developments of the data processing workflow during her Master’s thesis. We would like to thank Timothée Produit and Adrien Gressin (HEIG-Vaud) for sharing initial TerrA viewsheds and for discussions on the TerrA archive.

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