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WSL

GLAMOS Glacier Monitoring Switzerland

GCOS Switzerland Project

"Operational near-real-time glacier monitoring"

Final Report

Project period:	01.08.2019 – 31.05.2022
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Institutions:	WSL Birmensdorf and ETH Zurich
Funding:	MeteoSwiss, in the framework of GCOS Switzerland

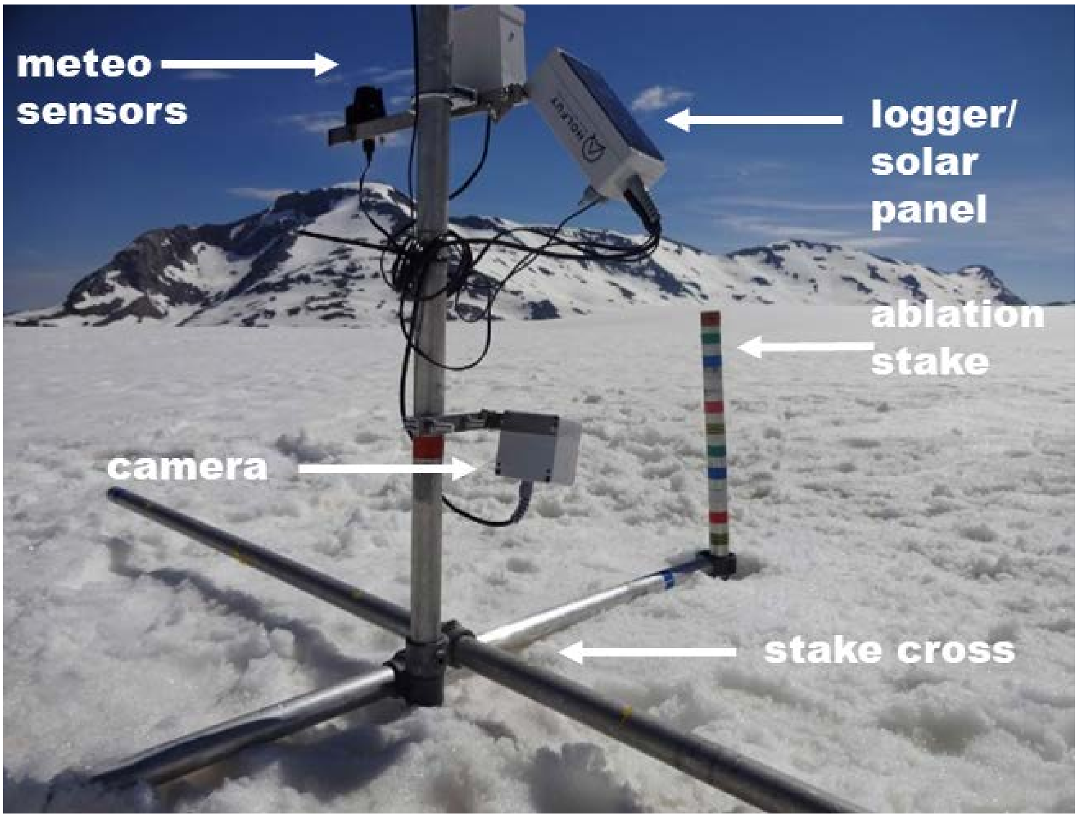

Figure 1: An automatic mass balance monitoring station installed on Glacier de la Plaine Morte, Switzerland. Image from Landmann et al. (2021a).

1. Summary

Glaciers are important indicators of climate change, and play an essential role in Switzerland's hydrological budget. Public interest in the status of glaciers is particularly high during summer, when melt is at peak and when runoff from other sources can be low.

The project "Operational near-real-time glacier monitoring" set out to satisfy the public demand for near-real-time information, and to overcome the problem that traditional field observations are generally not available during summer. The main goal was to develop an observational system that would provide measurements of glacier mass balance at selected locations and in near-real-time. In addition, the project aimed at providing an operational modelling framework capable of ingesting these field-based measurements, and at blending them with (i) glacier-related observations obtained from remote sensing platforms, and (ii) short-term meteorological forecasts. The framework aimed at developing and implementing state-of-the-art techniques for data assimilation, and at presenting near-real-time glacier mass balances on a web platform.

The project resulted in the creation of a model-based framework that has been presented under the name of "Cryospheric Monitoring and Prediction Online (CRAMPON)". At its heart is a newly developed data assimilation procedure based on the concept of particle filtering. In essence, a number of model simulations (the particles) are launched with various sets of model parameters, and the model results are compared to observations obtained either in the field or from remote sensing platforms. Simulations that are in line with the observations are selected (filtered), thus ensuring consistency between model results and observations.

In-situ observations were gained through camera-based installations acquiring images of glacier ablation stakes at high temporal resolution. These images were evaluated with the help of computer vision algorithms, and were successful in providing daily information on glacier melt for a selected set of glaciers across the Swiss Alps. The extension of the framework to remote sensing observations posed some challenges, but showed potential for gaining spatially distributed information at the larger scale.

The above works were conducted in the frame of a doctorate hosted at both the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, and ETH Zurich's Laboratory of Hydraulics, Hydrology and Glaciology (VAW), the resulting doctoral thesis having been defended successfully on 13.01.2022. The activities received widespread attention from the research community, and triggered a number of follow-up activities. Amongst the most notable ones are a follow-up doctorate that started in late 2021, and the formation of a project consortium aiming at obtaining funding for upscaling the project's concepts to the European level. Albeit not fully achieving all goals that were envisioned in the initial project proposal, the project can be seen as successful.

2. Scientific Report

2.1. Introduction

Glaciers are amongst the most prominent and visible indicators of climate change. Due to glacier retreat, mountainous landscapes are changing, and so are runoff regimes in glacierized catchments. For Switzerland, model-based projections anticipate that most of the glaciers will have completely disappeared by the end of the century, and some estimates even suggest that "peak water" – that is the timing by which the maximal water yield of a glacierized catchment occurs – might already have passed for some of the major rivers.

Due to the above importance, the present status of glaciers is not only of relevance to glaciologists or other researchers in the geosciences, but is also of interest to the general public. The same is true for specific sectors of the economy, notably including hydropower production and water management. Evidence for this interest is probably best given by the strong presence of the topic "glacier retreat" in the Swiss media: Especially during warm summer months, dozens of articles and reportages inform on the status of the glaciers' decline, the possible impacts, and the projected future evolution.

As was noted during a series of two GCOS-supported workshops around the communication strategy of the Swiss cryosphere monitoring networks[1], it is somewhat unfortunate that reliable information about the glacier's status was traditionally missing exactly during these periods of highest interest. Traditional glacier mass balance measurements performed within the Glacier Monitoring in Switzerland (GLAMOS) programme, in fact, were only available for the end of the accumulation or melt seasons. Media requests during summer had thus often to be answered with the statement that reliable information about the glaciers' state would only be available in a few months' time. This had not only caused frustration at some occasions, but also fostered the spread of unreliable information in others.

This project set out to rectify the above situation, and to reply to a need that had emerged out of public interest. The goal was to set up an operational platform that – similarly to meteorological services – would provide information about Swiss glaciers in near-real-time. The aim of the envisioned model-based platform was to assimilate a variety of information including field-based measurements, remote-sensing observations, and meteorological forecasts. Whilst the focus was clearly on glacier mass balance, the extension to the delivery of runoff-information was originally intended as well.

2.2. Methods and activities

The project was conceived around five main tasks which included (1) the development of a glacier mass balance modelling framework capable of operational model runs, (2) the development of a suitable procedure for assimilating various types of data into the model framework, (3) the acquisition of glacier mass balance field data with high temporal resolution, (4) the extension of the modelling framework to the nowcasting and prediction of glacier runoff, and (5) the realization of web portal for the display of the results elaborated in the various tasks. The methods used and activities performed in the various tasks are briefly described hereafter while some of the main results are summarized in Section 2.3.

[1] The workshops "Kommunikationsstrategie Kryosphärenmessnetze" were held in 2018, i.e. about a year before the start of the here presented project.

Task 1: Glacier mass balance modelling framework

The modelling framework established for computing glacier mass balances in the context of this project is now known under the acronym *CRAMPON*, for *"Cryospheric Monitoring and Prediction Online"* (Landmann et al., 2020a). The framework draws from the computing infrastructure developed by the Open Global Glacier Model (OGGM) consortium (Maussion et al., 2019) and is based on the open-source programming language Python. CRAMPON aims at delivering daily mass balance estimates – including an estimate for their uncertainties – for all Swiss glaciers. CRAMPON relies on pre-defined glacier geometries (glacier outlines and digital elevation model of the surface), is driven by meteorological data obtained from the Federal Office of Meteorology and Climatology (MeteoSwiss), relies on an ensemble of accumulation and ablation parameterizations, and is calibrated with various data obtained from glaciological observation.

More specifically, CRAMPON uses gridded analyses of daily mean and maximum temperature, precipitation, and global radiation as input, and uses this input to drive a mass balance model. The mass balance model resolves the processes of accumulation (mainly snowfall) and ablation (mainly surface melt) and does so by representing the glacier geometry along elevation bands. This simplified representation enables fast computations, which are required when assimilating observational data (see Task 2). To account for uncertainties in the representation of individual mass balance components, CRAMPON computes ablation by relying on an ensemble of four parameterizations. The latter range from a simple temperature index model to a simplified energy balance model. The parameters of the individual parameterizations are calibrated to (i) long-term geodetic ice volume changes and (ii) long-term glacier-wide mass balance observations provided by GLAMOS.

Provided that the necessary input data are available, the CRAMPON framework can be run operationally (i.e. without the necessity of manual interventions) for all glaciers in Switzerland on a daily basis. For such an application, it is important to note that the quality of the results will be directly linked to the quality of both the input data and the observations that are available to constrain the model.

Task 2: Data assimilation

The assimilation of data within the CRAMPON framework is to be considered the main methodological advance carried out within the project. Assimilation is performed with a customized particle filtering algorithm that was developed in collaboration with ETH Zurich's Seminar for Statistics.

In a nutshell, the ensemble of mass balance models implemented within CRAMPON is used to produce prior estimates of glacier mass balance at the daily time scale. The models are thereby run with distributions of a-priori parameters obtained by calibrating the model to mass balance observations obtained from GLAMOS. The resulting mass balance estimates are then fed into a Bayesian data assimilation procedure, implemented as a particle filter. The usage of such a Bayesian data assimilation scheme aims at minimizing the uncertainty of the obtained glacier mass balance estimate at any point in time. This is done by conditioning the a-priori estimates on all available observations, thus yielding a posterior mass balance estimate. Apart from glacier outlines and digital elevation models of the glacier surface (which are directly used to prescribe the glacier geometry), all considered data are assimilated sequentially, i.e. one at a time starting from the point in time at which the data

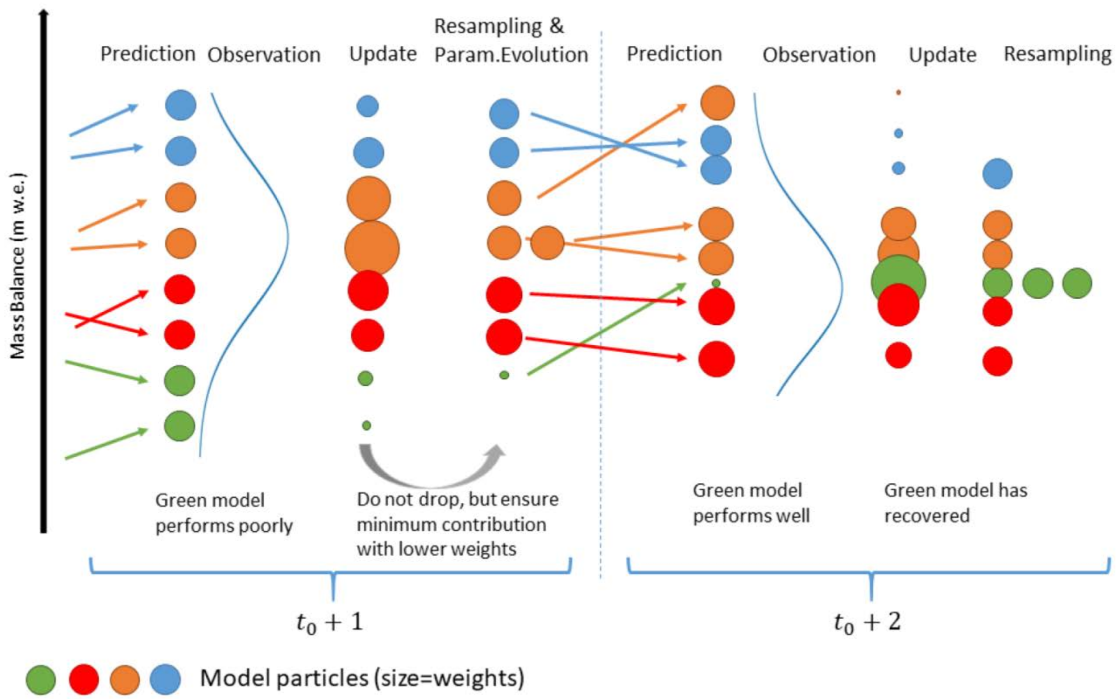

Figure 2: Illustration of the individual particle filter steps. The example refers to a case in which four models (blue, orange, red, and green) start with two particles each. The blue curve represents the observation distribution. The figure is from Landmann et al. (2021a), where additional explanations are found.

become available. The functioning of the individual particle filter steps is shown in Figure 2. For details on the developed procedure, please refer to Landmann et al. (2021a).

The data assimilation procedure was mainly developed for ingesting point mass balance data acquired in situ with a specifically designed observational setup (see Task 3, here below). Conceptually, however, the methodology is very versatile, and was used for the assimilation of satellite-borne observations too. Amongst the latter are surface reflectance extracted from Sentinel-2 imagery, which were interpreted in terms of both surface albedo and transient snow line elevation (Geibel, 2019; Geibel et al., 2019; 2020).

Task 3: Field data with high temporal resolution

One of the project's starting points was the lack of direct observations of glacier mass balance during the summer season. This lack was addressed by acquiring and installing a camera-based, autonomous observation system (Figure 1, on the title page), and developing a framework enabling the system to be used for glaciological measurements. The system consisted of an off-the-shelf camera and logger box from the company Holfuy Ltd, which were mounted the to a construction of aluminium stakes that could be left unattended during an ablation season. The on-ice camera would take pictures of an ablation stake with 20 min intervals, and transmit these pictures in near real-time through the Swiss mobile phone network. The ablation stake was prepared with markings made of coloured tape, thus enabling surface elevation changes to be detected (as surface melt occurs, the surface would lower while the stake itself would not change position, thus resulting in a relative motion between the tape markings and the glacier surface). A total of seven to nine cameras were installed over three years, covering the fiver glaciers Findelengletscher, Glacier de la Plaine Morte, Grosser Aletschgletscher, Rhonegletscher, and Silvrettagletscher. Whereas most stations were operative only during summer, some stations were also active over the winter season. The winter set-up only required the camera to be mounted on the top of a higher pole (to prevent the camera from being buried underneath the snow during the course

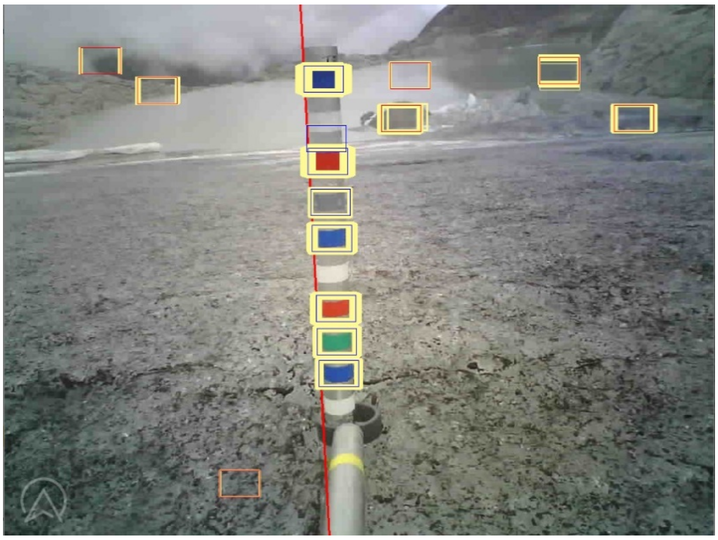

Figure 3: Automated recognition of the markers on an ablation stake. Clusters of matches (yellow frames) are reduced to single matches (red frames). Additional erroneous matches not aligned with the stake are filtered out. Figure from Borner and Cremona (2020).

of the winter), and winter snow accumulation could be observed at daily resolution by observing a second, labelled stake placed at a distance of 5 to 10m from the camera.

The above installations resulted in the acquisition of several hundreds of mass balance observations per season. At first, the resulting images were evaluated manually, i.e. by manually digitizing the positions at which the positions at which the glacier surface would intersect the ablation stake in a given image. Since such a procedure is time consuming, automation was sought. This happened by exploring the use of so-called “template matching” and “mean shift” procedures – two algorithms borrowed from the field of computer vision (Figure 3). The implementation was performed in the frame of a semester project (Borner and Cremona, 2020) and a master thesis (Cremona, 2020), and validation with independent observations indicate a high performance of the approach (Cremona et al., in prep.).

Task 4: Extension to runoff nowcasting and predictions

The original project proposal envisioned the possibility of extending the model framework to the projection of runoff from glacierized basins. Such an extension did not happen during the project’s lifetime due to the unexpectedly large and time consuming methodological developments that were necessary within the CRAMPON framework (cf. Tasks 1–3). The CRAMPON framework itself was however extended for producing prediction, and predictions of glacier mass balance in particular.

To do so, the CRAMPON modelling framework (cf. Task 1) was forced with both (i) 5-day meteorological predictions from the Consortium for Small-Scale Modelling (COSMO), and (ii) 30-day predictions from the European Centre for Medium-Range Weather Forecasts (ECMWF). Both predictions enabled CRAMPON to deliver operational mass balance predictions at the corresponding lead time – an application that was not proposed in the context of glacier mass balance modelling so far. An important limitation in this respect is that the performance of the corresponding model predictions could not be systematically evaluated in the frame of the project. Again, the time requirements for Task 1–3 are the reason for this, and means that no information on the reliability of the corresponding results is available at present.

Task 5: Display web portal

For visualizing the results generated by CRAMPON, a prototype for a dedicated web platform was developed (https://crampon.glamos.ch/). The prototype is based on OGGM's "World Glacier Explorer", and was adapted to accommodate some of CRAMPON's specificities. The prototype's central feature is a map of Switzerland, in which all modelled glaciers are shown, and color-coded according to their status (Figure 4): glaciers that are experiencing a mass loss that is more severe than in the long term average are coloured red, while glaciers that are experiencing less mass loss than during a reference period are shown in blue. The map is zoomable, clickable, and selectable, allowing the user to retract specific information for a given glacier or for a given set of glaciers. When hovering over a glacier on the map, meta-information such as the glacier name, area, inventory ID, last model update date, and the type of observation that is available for that glacier is displayed. When clicking on a given glacier, additional information is displayed on a popup window. The latter shows (i) the mass balance evolution of the current year, (ii) its relation to the long-term mass balance, and (iii) the mass balance evolution as projected on the basis of the COSMO and ECMWF predictions (cf. Task 4).

The prototype as developed within the frame of the project still suffers from various limitations (see also Section 2.4, further down), making the corresponding web-page unsuitable for public release. These limitations will be tackled during the follow-up activities that are planned after the termination of this project (cf. Section 2.6).

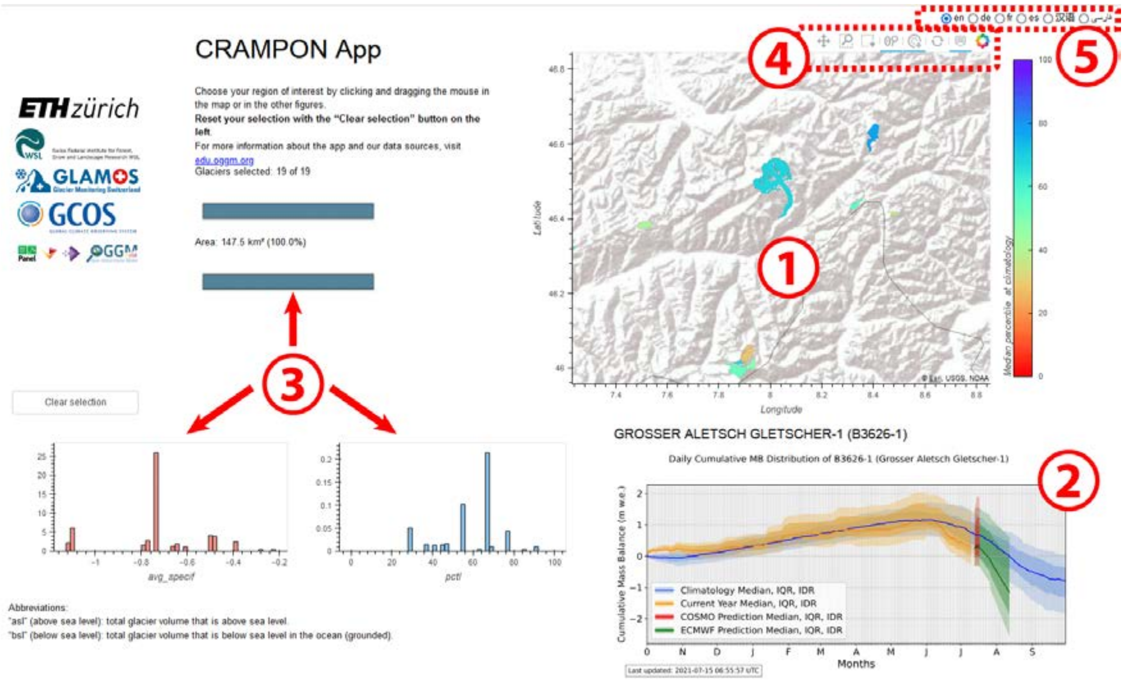

Figure 4: Overview of the developed web-portal prototype. The main features (labelled with red numbers) are: (1) map of Switzerland colour-coding the mass-balance status of each glacier (scale to the right); (2) evolution of the daily glacier mass balance, popping-up when selecting a glacier on the map; (3) various aggregated data (e.g. number of glaciers, total glacier area, or histograms of long-term mass balance) for the selected glaciers; (4) map selection tools; and (5) language bar. Note that the prototype is still affected by limitations (cf. Section 2.5) that will be tackled during follow-up activities to this project (Section 2.6).

2.3. Results

The project's main results is the establishing of the CRAMPON framework, most notably including the methodological developments related to the assimilation of data in the glaciological context. While the specific methodologies used for this data assimilation are described in Landmann et al. (2021a), the large number of additional activities performed in the frame of the project have found an outlet in Landmann (2022), i.e. in the doctoral thesis of the main project collaborator. The thesis has been very positively commented upon by the jury that evaluated the thesis (the thesis was successfully defended on 13.01.2022), corroborating the strong interest in the addressed subject.

Besides the methodological development, the most tangible outcome of the project is the system of automatic on-ice cameras (Task 2 and Figure 1) which are now fully integrated in the continuous monitoring activities of GLAMOS. A concrete example for the information provided by such an installation is shown in Figure 5, which shows the daily and cumulative glacier melt rates as observed on Findelengletscher during summer 2019. Such information has become important for assessing the state of Swiss glaciers during summer, i.e. when public interest is high but when traditional glacier mass balance surveys have not yet been performed.

Within reach is also the release of the established web platform prototype (cf. Task 5 and Figure 4). Once the remaining limitations have been addressed (cf. Section 2.5), we anticipate the platform to be of high interest to researchers and the general public alike.

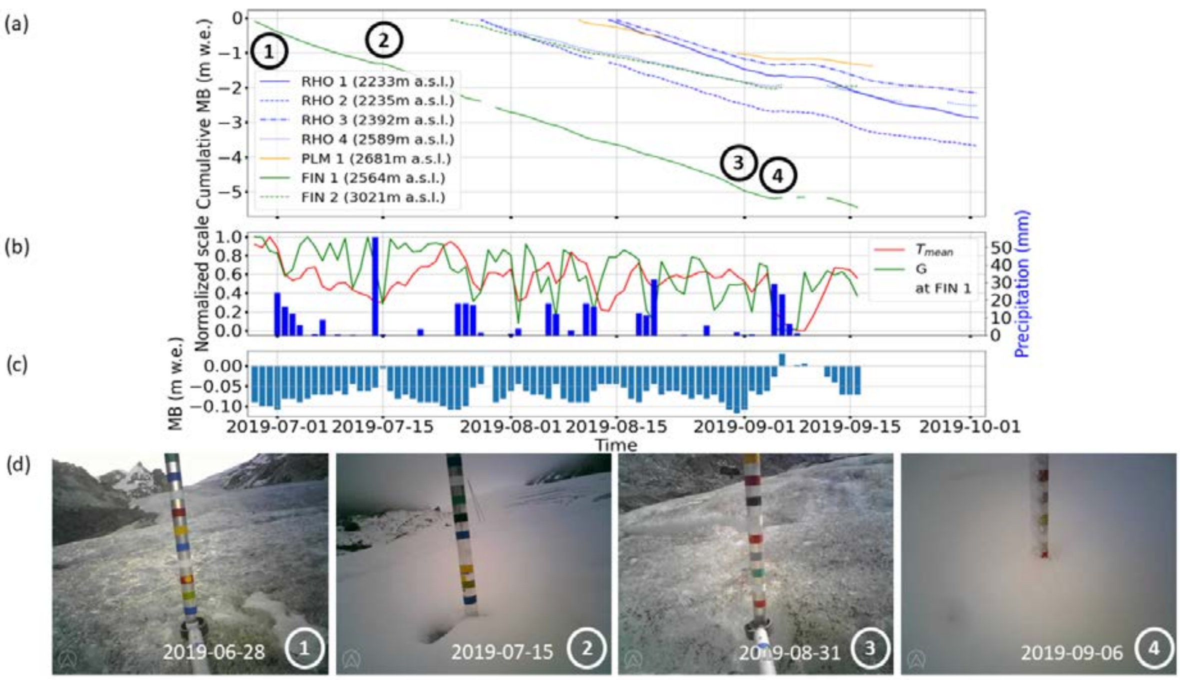

Figure 5: Example for the data delivered by the on-ice cameras (see Figure 1 for setup). (a) Cumulative mass balance at individual cameras during summer 2019. Circled numbers refer to the pictures shown in panel (d). (b) Normalized mean temperature (T_{mean}) and shortwave radiation (G), as well as precipitation for station FIN1. (c) Daily mass balance rate observed at FIN1. (d) Sample images as captured by the camera at FIN1: (1) camera right after setup, (2) glacier after light snowfall, (3) picture from the day with the highest melt, and (4) snowfall event hampering the stake readout. The image is from Landmann et al. (2021a).

2.4. Conclusion and limitations

With the vision of establishing a framework that would constantly inform the research community and the broader public about the state of all glaciers in Switzerland throughout the year, the project set out with a bold goal. At the project's end and in hindsight, one can say that (i) the project sparked much interest in the glaciological research community, as the project's vision was deemed to be compelling, (ii) a highly versatile, light and low-cost system to observe daily point mass balance in near-real-time has been developed, (iii) a number of methodological advances have been achieved, notably including the development of a model framework by which frequent mass balance observation can be assimilated or by which operational model runs can be performed, and (iv) work is still required to ensure the reliability of the framework's results. The latter is a pre-requisite for utilizing the project results in an operational context, especially if the results were to be disseminated beyond the glaciological community.

At present, two major limitations affect the established framework. First is the spatial representativeness of the acquired measurements. The logistical difficulties in maintaining a given measuring device on any glacier puts obvious constraints on the number of sites that can be equipped with such devices. In turn, this means that the observations for which a high temporal resolution can be achieved are only available with poor spatial sampling (observations are available for less than 10 locations across Switzerland, despite the ca. 1,400 glaciers that exist in the country in total). The spatial inter- and extrapolation that becomes necessity because of this can introduce uncertainties that can be both large and difficult to quantify. The project's intention of addressing this difficulty by using remote-sensing observations showed promising results, but additional work is required to efficiently blend these spatially extensive, temporally patchy remote observations with the temporally frequent but spatially sparse information stemming from field installations.

Second are the limitations that affect the web-portal prototype developed within Task 5. Amongst these limitations are (i) the reliability of some of the displayed results, especially related to glaciers that do not have direct observations (i.e. glaciers for which the mass balance is extrapolated from observations located far away), (ii) the reliability of the displayed confidence intervals (some of these appear to be too wide, thus undermining the trust that can be put in the corresponding results), and (iii) the overall responsivity of the web-page (the large quantities of data that are loaded in the background make the website very slow, negatively impacting the browsing experience for the users).

It is our intention to tackle the above limitations and challenges during the follow-up activities extending beyond this project. Indeed, we remain convinced that the project's ideas have strong merits and that the interest in the topic remains high. A follow-up doctoral thesis already started towards the end of the project, and the new doctorate will ensure continuity in both know-how and progress.

2.5. Outreach work, publication of data and results

The project developments and results were disseminated to the research community through (1) contributions at scientific conferences, (2) a peer-reviewed research article, (3) students' theses including semester projects, master theses, and doctoral theses, and (4) social media channels and media coverage.

Contributions at scientific conferences included the presentation of (i) the overall project framework (Landmann et al., 2020a; 2021b), (ii) individual components of the data assimilation framework (Landmann et al., 2020b), (iii) the algorithm implemented for the automatic detection of snow-covered areas (Geibel et al., 2019; 2020), (iv) the procedures developed for reading out the ablation stakes installed on individual glacier at high temporal frequency (Sold et al., 2021), (v) and the venues explored for a possible stake read-out though UAVs (Cremona et al., 2022).

The peer-reviewed research article emerging from the project (Landmann et al. 2021a) specifically dealt with how the developed particle filter was used to assimilate the acquired mass balance stake readings in near-real-time. The article appeared in “The Cryosphere”, which is an open-source journal published by the European Geosciences Union.

A total of five students’ theses were conducted in the frame of the project, and included theses at different levels: (i) a semester project, developing a first prototype for the computer-vision schemes later used for automated stake read-outs (Borner and Cremona, 2020); three master theses, (ii) further exploring the possibilities offered by computer-vision schemes and focusing on object recognition (Cremona, 2021), (iii) implementing an algorithm for the automated mapping of snow over glaciers (Geibel, 2019), and (iv) preparing the ground for including information stemming from short-term glacier volume changes into the project framework (Schweizer, 2018); as well as (v) a doctoral thesis, which developed the overall modelling framework which is at the base of the project (Landmann, 2022).

In terms of communication with the broader public, regular project news have been shared through the hosting group’s twitter channel (@VAW_glaciology). The audience showed particular interests for the time-lapse videos of glacier melt emerging from the observations conducted with the on-ice cameras (see e.g. https://twitter.com/VAW_glaciology/status/1156286693575733251). Such videos were covered by established media channels such as *Arte* or *Euronews*, for example, and have been used in a number of science-divulgation events, such as ETH Zurich’s and University of Zurich’s “Scientifica” and outreach seminars (e.g. with the Swiss Study Foundation).

2.6. Outlook

Since the presentation of its main goals at scientific conferences, the here presented project was able to spark high interest in the glaciological community dealing with glacier mass balance and glacier changes. Indeed, the vision of an operational system, capable of assimilating the wealth of observations that are available at present and specifically focusing on the state of glaciers, has been perceived as compelling. The activities initiated through this project will thus be continued in future, both at the institutions that were involved in the project so far and elsewhere. For the former, the continuation of the activities in the frame of a follow-up doctorate that started in the glaciology group of ETH Zurich and WSL Birmensdorf has to be mentioned. For the latter, the most noteworthy initiative is probably the one that has led submitting a project proposal to the research scheme “Horizon Europe” (that is the 7-year research initiative of the European Commission that succeeds the former “Horizon 2020”-scheme). Initiated by the World Glacier Monitoring Service, coordinated by the Austrian Academy of Science, and including a number of scientific partners across Europe. The project proposal entitled *“Glacier monitoring in real-time across Europe and the Arctic (GLAMORE)”* aims at extending the ideas generated within the GCOS funded project to the large scale. While it is difficult to assess the likelihood of the proposal to be actually funded, this type of follow-up activity certainly shows how the ideas developed within the frame of this project have been picked up by the wider glaciological community.

2.7. Acknowledgements

We would like to very much thank GCOS Switzerland for providing funding for this project. The support was instrumental to launch a novel activity that has sparked much interest in the glaciological community. Special thanks go to Prof. Dr. Hansruedi Künsch (ETH Zurich), who supported the project with his unrivalled statistical know-how. His contribution was instrumental for the development of the particle filtering techniques that are at the base of the established assimilation framework. Dr. Mauro Marti (WSL Birmensdorf) is very much acknowledged for elaborating and providing access to repeated digital elevation models over the Swiss Alps. Access to operational meteorological data were obtained from MeteoSwiss, with Dr. Massimiliano Zappa and his team from WSL Birmensdrof providing essential support in setting up the procedures for direct access. We also thank Gergely Mátyus from Holfuy Ltd, who provided extensive technical support for the automatic cameras used in the frame of this project.

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