# Development of an early warning system to reduce the impact of floods related to glacial lake outburst floods (SAGAZ)

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## Abstract

The retreat of glaciers has led to increasing in natural hazards due, for example, by emptying of lakes dammed by unconsolidated glacial deposits (moraines) or ice, which are susceptible to catastrophic erosion, generating rapid floods, phenomena known as “Glacial Lake Outburst Floods” (GLOFs). Current systems that warn of the occurrence of a GLOF are activated when the emptying begins, which leaves little time to act, so they should be considered early alarm systems. The challenge is to predict the onset of the flood allowing the generation of an early warning system. To address this problem, SAGAZ ultimately aims to develop a system capable of identifying periods of increased GLOF risk using a predictive model fed by weather forecasts and monitoring station data. This system identifies a period of higher risk, which allows informing authorities several days in advance. This paper presents the results of the first phase of SAGAZ implementation, which aimed to (1) develop and validate a prototype monitoring station and deploy a network of stations on glacial lakes across southern Patagonia, (2) collect the necessary data for the development, training and validation of predictive models and (3) begin the implementation and testing of the predictive model. As a result, a network of 10 monitoring stations was installed in the Aysén and Magallanes regions of Chile and 1 in the Province of Santa Cruz in Argentina, of which 6 are currently operational and transmitting data in real time. The rest went off due to power failures and icebergs damaging sensors. The measures we have taken to avoid station’s failures are described, as well as some characteristics of the implemented prototype, the installed networks and the data obtained so far.

## 1. Introduction

Chile and Argentina have recently defined their national strategies to address the lack of glacier data, the first step being the completion of the inventories in each country. That task was carried out in Chile by the Dirección General de Aguas (DGA). The inventory in Argentina was completed by IANIGLA (IANIGLA & CONICET, 2018). Both inventories are available on the official government portals.

These national inventories have been useful in determining the regional distribution of glaciers, their morphometric and typological characteristics, as well as the volumes of ice stored there. In the extreme south of South America (46-55ºS), the sum of both national inventories results in 24,202 ± 1,200 km$^2$ of ice.

In the long term, these glaciers have been shrinking since the last generalized advance during the period known as the Little Ice Age (LIA), which, in the case of Patagonia, peaked approximately in the second half of the 19th century, using 1870 A.D. as a general reference for Patagonia (Davies and Glasser, 2012).

The LIA is responsible for the generation of many belts of thrust moraines covered by forests in some cases, many of them damming lakes, from where glaciers have been retreating until today leaving behind pronounced *trimlines* indicating a historical recession (Aniya, 2013). According to Davies and Glasser (2012), the reduction of glacier area from the LIA to our times is 4,131 km$^2$ or 15.4%, while in the case of Meier et al. (2018) this was estimated at 5,455 km$^2$. In both studies it is noticed that the reduction trend seems to be accelerating un recent decades.

Glacial change in the region was probably one of the most researched topics in recent decades, thanks to the use of early historical records, aerial photographs and more recently satellite images that are freely available, of progressively better resolution and frequency of capture, all of which have helped to compile glacial changes at the individual and regional level (Masiokas et al., 2020). The main reason to explain the ongoing deglaciation in the region, meaning retreats, area reductions, and thinning, is climate change (Ruiz et al., 2022), however, there are cases in which glacier-volcano relationships have been relevant (Rivera & Bown, 2013) or in many other cases, especially in the Northern and Southern Patagonian Icefields (NPI and SPI respectively) in which glaciers are calving into fjords or lakes where they produce icebergs, the accelerated retreat is due to dynamic factors derived from the role played by local factors such as the bathymetry of the water bodies where the glaciers terminate (Minowa et al., 2021).

Apart from some notable exceptions of advances such as the experienced by Pío XI also known as Brüggen glacier of the SPI since 1945 (Rivera et al., 2023), most of the Patagonian glaciers have retreated increasing the hazards due to the sudden emptying of proglacial lakes formed during these retreats, phenomena known as GLOF's (Glacial Lake Outburst Flood), which can have serious hydrological consequences and impacts for the population, which requires monitoring of glaciers and their related lakes, with geophysical methods and meteorological stations on and around the ice/lake. All these measurement systems need to be integrated in order to generate models to detect possible glacier threats that need to be communicated in a rapid and timely manner so that decision makers can fulfill their responsibility.

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GLOFs have killed more than 5,745 people in the last century along the Andes Mountains (Carrivick & Tweed, 2016) and some 37 glacier-related flood events have been recorded in Chile, which have caused considerable damage to infrastructure and population (Iribarren Anacona et al., 2015). In addition, glacial lakes are becoming more numerous and larger (Shugar et al., 2020), so their possible emptying is expected to increase in frequency in Chile and the rest of the world due to climate change (Harrison et al. 2018). Notwithstanding the above, it is very likely that the impact on infrastructure and population will be increasing, mainly due to the expansion of human activity in vulnerable areas without consideration of natural hazards.

Therefore, there is a need to prepare for an increase in this type of phenomena, for which it is necessary, among other things, to develop early warning systems that anticipate the events themselves. The problem with the warning systems currently in place is that the measurement networks that feed them allow detecting when the draining has already begun, which leaves little time for the population in vulnerable areas to take measures against this threat, because the most destructive GLOFs are usually those that develop very quickly, leaving very little time to prepare before the emergency occurs. The ideal is to predict the onset of the outbreak, allowing the population to prepare well in advance.

To address this challenge, an early warning system called SAGAZ has been proposed to identify the periods of greatest GLOF risk using a prediction model fed by meteorological forecasts and data from monitoring stations. This system will allow the authorities to be informed several days in advance of the possible occurrence of an emergency associated with the emptying of proglacial lakes.

This paper presents the results of the first phase of this system implementation, where the two main objectives proposed have been met: (1) to develop, validate and implement a prototype of the warning system in Chile and (2) to collect the necessary data for the development, training and validation of predictive models. These data consist of time series of lake level, local temperatures and precipitation, which are necessary to understand the normal state of lakes with GLOF potential and how they respond to meteorology.

In a next stage, pending funding, it is expected to develop the predictive model that generates a GLOF alert, mainly considering that, in most cases, GLOFs are associated with the combination of an unusually high lake level and a trigger, which can be an intense rainfall or a landslide. For this purpose, we will take advantage of the experience of the existing volcanic warning systems in Chile, which, although they do not allow to predict with accuracy the time of occurrence of a natural disaster, they provide very useful warning levels. These warning systems allow, for example, the population to prepare for emergency scenarios by moving away from high-risk areas. Another future improvement is the re-installation of damaged stations in new locations, some of them in the same lakes and some in new ones as discussed and agreed with DGA. The idea is avoiding lake coastal areas under frequent presence of icebergs and brash ice accumulated by predominant wind directions.

In this effort, remotely sensed imagery has been crucial for detecting study sites with GLOF susceptibility and for mapping glaciers and glacial lakes, especially their areal changes. Satellite and Airborne LiDAR have also been used to map surface elevation and changes, allowing to calibrate lake surface heights used in the forecasting models that will be described later on in this manuscript.

## 2. Data and methods

In this work we have extensively used Landsat and ASTER imagery freely obtained from the NASA Earth observatory web site. These images have been processed in order to obtain band compositions useful for glacier mapping. They were temporally compared for detecting glacier area and lake changes.

The SRTM and TanDEM-X models (Jaber et al., 2019) have been used for estimating surface elevations of glaciers and associated proglacial lakes. The accuracy of these data sets were estimated by comparing rock outcrops.

An airborne LiDAR survey was conducted on July 2, 2007 using a system called CAMS (Rivera et al., 2014) comprised by a laser scanner RIEGL LMS-Q240-60 with a wave length of 904 nm and a scan angle of 60º which allows the measurement of distances within a maximum range of 500 m and a vertical accuracy of 20 cm. For the georeferencing of the laser measurements, the system is equipped with an Inertial Measurement Unit (IMU), IMAR iNAV-FMS AIRSURV, and dual-frequency GPS receivers. The system is completed by an SLR camera Canon EOS5D (Wendt et al., 2010).

The GNSS-IR technology using reflected signals captured by GNSS receivers, has been tested for detecting elevation changes. This technology uses the interference of the multiple trajectories followed by the GNSS signals to estimate the height of coherent, relatively flat surfaces located under the GNSS antenna (Durand et al., 2019).

## 3. The SAGAZ system

The SAGAZ early warning system has several components described below (Fig. 1):

1.- A lake monitoring network composed of meteorological stations, each of which has 3 sensors (temperature and atmospheric pressure, precipitation and water level and temperature), a *datalogger* controller, a power supply system with solar panels and a real-time data transmission system via satellite telephony using the *Iridium* network.

2.- A predictive model is based on online servers (*Cloud based servers*) containing a control system that receives data transmitted via Iridium and weather forecasts from open systems available on the network. Finally, there is a backup server and network monitoring.

3.- A web interface (www.sagaz.org) that makes the data generated and early warnings available to authorities and emergency teams. After consideration of the pertinence and permission of the authorities, the idea is also giving access of these warnings to the general public.

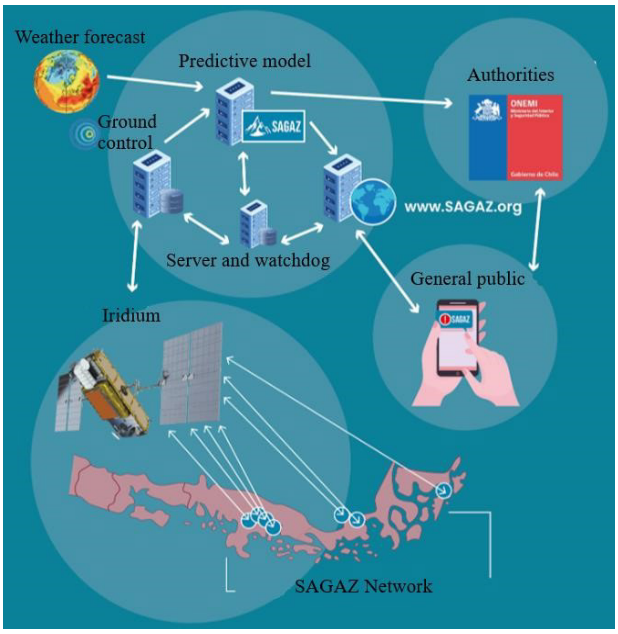

Figure 1. SAGAZ advanced glacier warning system.

| Sensor | Brand | Model | Approximate price (USD) |
|---|---|---|---|
| Rainfall | Rainwise | Rainew | 70 |
| Temperature | Tatmosfèrica | DS18B20 | 10 |
| Water level | Honeywell | MLH150 | 140 |
| Datalogger | Arduino | Pro mini | 10 |
| Satellite broadcasting | Iridium | RockBlock 9603n | 268 |
| Power | Solar pannel 5-10 w amp | n/d | 15 |

Table 1. Sensors that make up the monitoring network stations

The monitoring network has sensors described in Table 1. The stations were designed and built in Chile with low-cost components, which in total did not exceed 1,000 USD. The objective is to use components of easy installation (small height) and low maintenance. The configuration, connection and integration of the electronics controlling the sensors and communication system is performed by SAGAZ.

One example of a station sensors installation in Figure 2a with north-facing solar panels mounted in a waterproof box that holds the sensor controllers, some of which are mounted on top of an iron mast. The internal configuration of the typical electronic system could be seen in Figure 2b.

The mast is fixed with the help of the weight of a rock mound, avoiding the need for bolts or cement, which makes the installation slower, more expensive and increases the equipment needed for the installation. In this station the rain gauge is located a couple of meters away as well as the water pressure sensor, which is submerged at a depth of about 1m.

The modeling system that is still under development will calculate runoff using the WRF-Hydro hydrological model (Somos-Valenzuela & Manquehual-Cheuque, 2020) that should integrate meteorological data at both the meteorological station and spatial (reanalysis, satellite and forecast) levels. The filling level of each lake is thus estimated from the modeled runoff, relating it to the height and morphology of the dam characterized preliminary by using a Digital Elevation Model (DEM). The available freely available DEMs are of low resolution and vertical accuracies of several meters, but they provided a first approach to the geographical setup and possible changes. The SRTM and TanDEM-X models allowed the comparison of the reference water level with the level modeled in WRF-Hydro, determining errors and adjustment coefficients.

a.

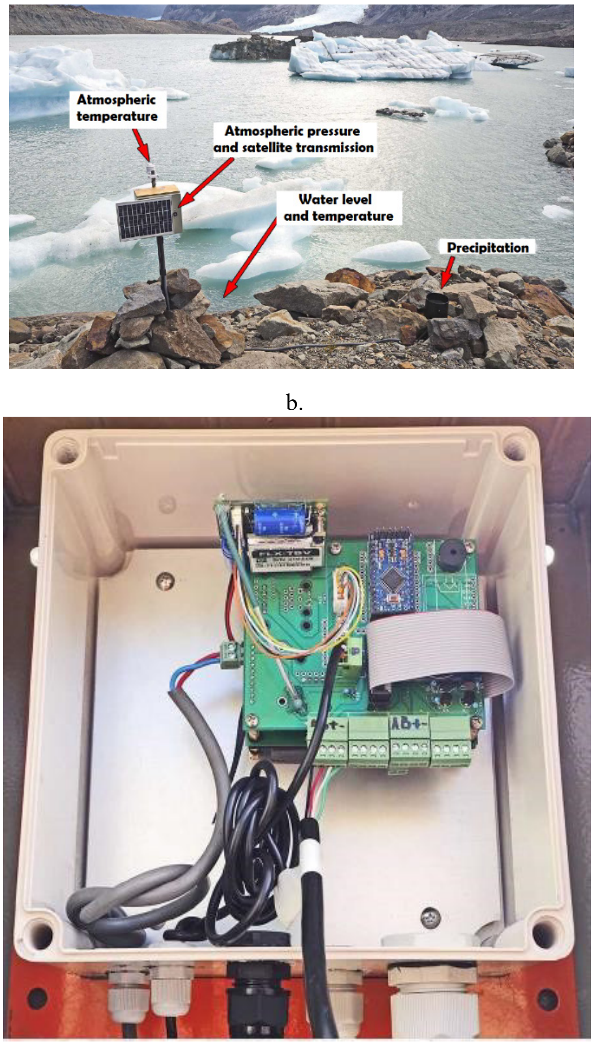

Figure 2. a. Sensors installed in a monitoring station and b. Datalogger with controllers (Photos by Camilo Rada).

## 4. Results and discussion

Table 2 describes the stations installed since the beginning of the project and their present status. Figure 3 shows the location of each station.

The sites where the stations were installed were selected based on their recent history, the possibilities of emptying, access facilities and their glaciological and social relevance. All the glaciers and lagoons studied here have had, to a greater or lesser extent, some relevant activity that has been recorded in the morphology of the surrounding slopes, the available satellite images and/or in direct observations of recent emptying.

| Number and Station name | Glacier | Lat.<br>Long.<br>h msnm | Area lake $km^2$ | Active |
|---|---|---|---|---|
| 1.- Laguna Témpanos | Ventisquero colgante, Nevados de Queulat | -44.4648<br>-72.5322<br>116 | 1.29 | No |
| 2.- Laguna marginal Glaciar Exploradores | Exploradores, CHN | -46.5277<br>-73.1653<br>188 | 5.32 | Yes |
| 3.- Laguna del 40 | CL 111420040 | -46.5341<br>-73.0501<br>330 | 2.28 | Yes |
| 4.- Laguna Silvestre | CL 111420027 | -46.5542<br>-72.9484<br>604 | 3.48 | Yes |
| 5.- Laguna Cachorro | CL 111516022 | -46.7741<br>-73.1123<br>385 | 12 | No |
| 6.- Laguna de los Témpanos | Steffen, CHN | -47.4545<br>-73.7557<br>177 | 6.3 | Yes but without rain gauge |
| 7.- Laguna glaciar Calluqueo | Calluqueao, Monte San lorenzo | -47.5939<br>-72.4987<br>450 | 2.8 | Yes |
| 8.- Lago Bernardo | Bernardo, CHS | -48.5995<br>-73.8116<br>225 | 23.66 | Yes |
| 9.- Lago Frías superior | Frías, CHS | -50.7380<br>-73.1052<br>290 | 8.83 | No |
| 10.- Laguna los Perros | Olvidado, CHS | -50.9332<br>-73.1257<br>548 | 4.21 | No |
| 11.- Laguna Encantada | Cordillera Darwin | -54.6267<br>-68.7574<br>535 | 0.84 | No |

Table 2. Installed SAGAZ stations.

For example, Lake Bernardo is dammed by the Bernardo and Témpanos glacier of the SPI (Fig. 4). At the junction of both glaciers, a proglacial lake was formed, which had a significant emptying in May 2007 when it almost completely disappeared due to the formation of a large *Moulin* through which all the dammed water flowed out (Fig. 5). The course of this water was subglacial, until it surfaced on the margins of the Bernardo glacier, through which it flowed until it reached the fjord of the same name. This event occurred in response to a strong retreat and thinning of the ablation zone of these glaciers between 2000 (SRTM data) and 2007 (CAMS airborne LiDAR data), with a rate of -4.9 ± 3 m/a for the Témpanos glacier and -8.1 ± 3 m/a for the Bernardo glacier (Fig. 6).

The data from the stations are transmitted in real time until they are displayed in the web interface shown in Figure 7, having an example of data collected at the Laguna de los Témpanos station (Table 2), where the top panel shows the lake level (in m), the middle panel the temperatures (°C) and the bottom panel the precipitation data (in mm). Air temperature and precipitation forecasts for the station are also added in yellow. In this specific case, the water level shows a relative smooth stability with little noise. A couple of single interferences to this trend are visible as sudden descends on August 4-5 and 6-7 generated by single wrong reading values. They are not emptying events as immediately after the sudden descends, the values are back to the previous lake level keeping the same trend.

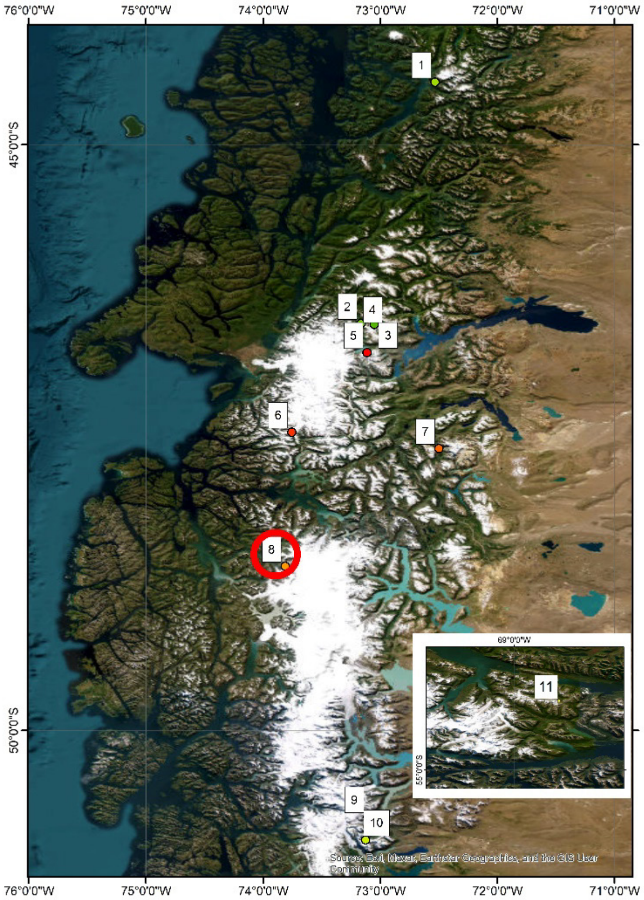

Figure 3. Location map of stations described in Table 2. The red circle shows the location of Fig. 4. Background image; ESRI Maxar, Earthstar Geographics, and the GIS User Community

The planned forecast will start from the data measured by the SAGAZ monitoring stations, that will be compared with the meteorological stations of the Chilean stable network (e.g. DGA) and will take advantage of different model products (ERA5, CMORPH and MSWEP), following the recommendations of Baez-Villanueva et al., (2020). Considering that these models are available with a 6-day delay from actual measurements, the Global Forecast System (GFS) model providing weather forecasts for nearly 2 weeks in advance, will be tested to simulate future scenarios. The forecast of variables still has a high level of uncertainty and complexity, so for now it has been sought to begin with precipitation, a fundamental variable in hydrological modeling (Seo et al., 2019). The errors and uncertainties of the hydrological model we are testing is high so machine learning procedures will be used to analyze and correct outputs for each future day (Shen et al., 2022).

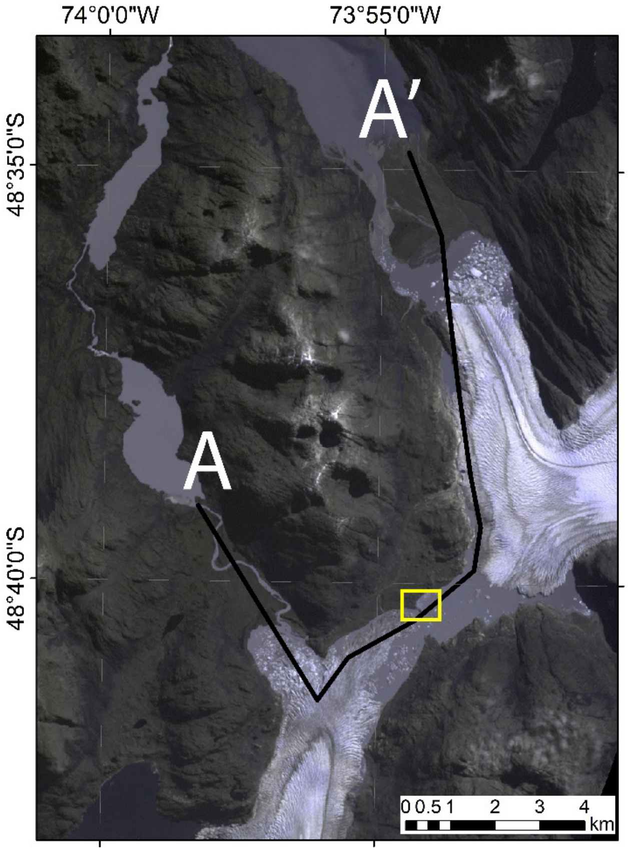

Figure 4. Témpanos and Bernardo glaciers on the western side of the SPI. The yellow rectangle is the location of the vertical aerial photograph in Figure 5. Also shown location of profile A-A’ detailed in Figure 6. Background: ASTER images 2007/04/04 band composite 3N,2,1

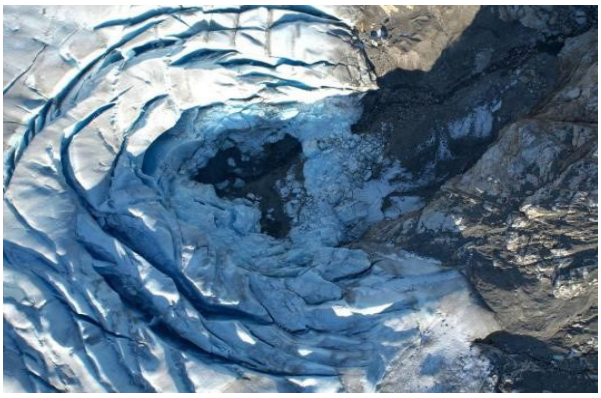

Figure 5. Vertical aerial photo of the place where the proglacial lake emptied in 2007 obtained by the airborne LiDAR CAMS system.

Considering the difficulties experienced with water level sensors (damage caused by icebergs, level fluctuations not well registered due to freezing of the sensor, etc.), the use of GNSS-IR technology (Purnell et al., 2024) is being tested to replace or add to the water level sensors, using reflected signals captured by GNSS receivers, with which elevation changes can be estimated, in this case, of a nearby body of water. This technology is being tested at the Laguna Frías Superior station (Table 2) where a prototype was installed (Fig. 8). This technology was successfully used in the SPI to estimate snow accumulation (Durand et al., 2019), for which measurements with a Sonic Range sensor measuring the distance to the snow surface for several months were compared with the heights derived using GNSS-IR methodology.

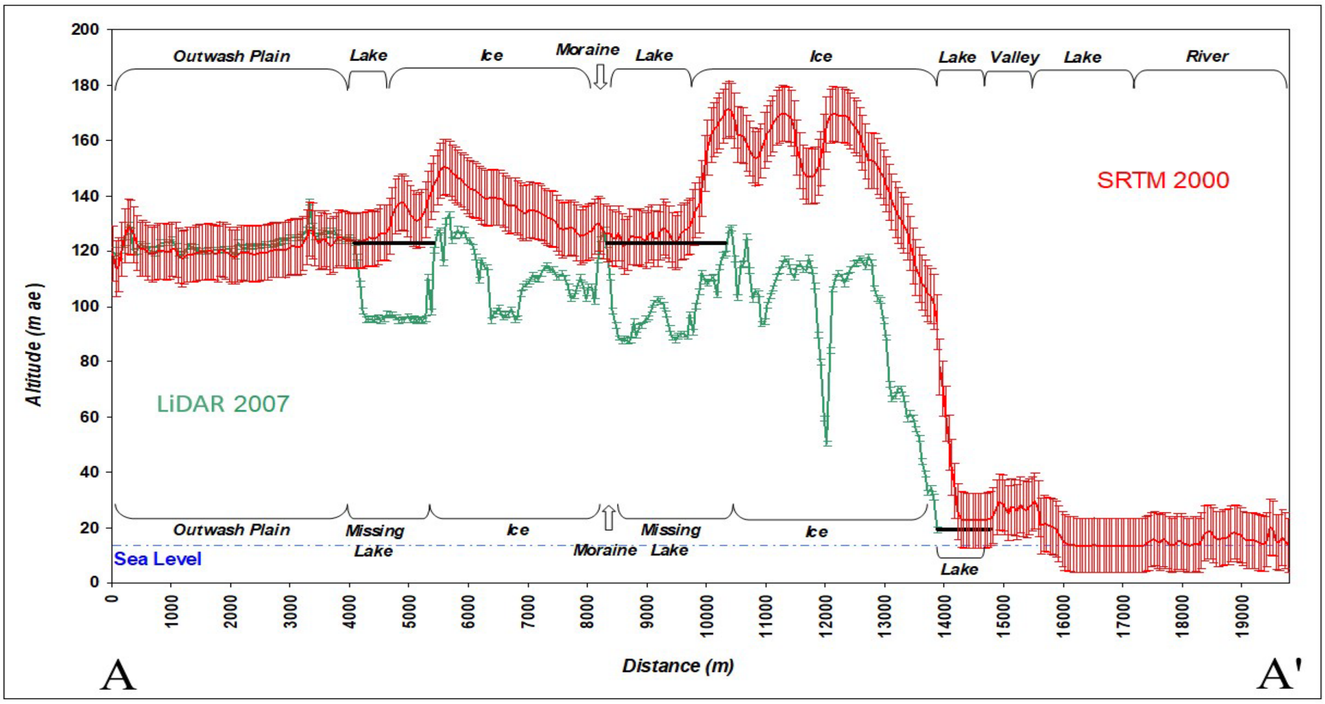

Figure 6. Topographic profile A-A’ (location in Fig. 4) of the Bernardo and Témpanos glaciers in the area of the lake that disappeared in 2007 (Missing lake).

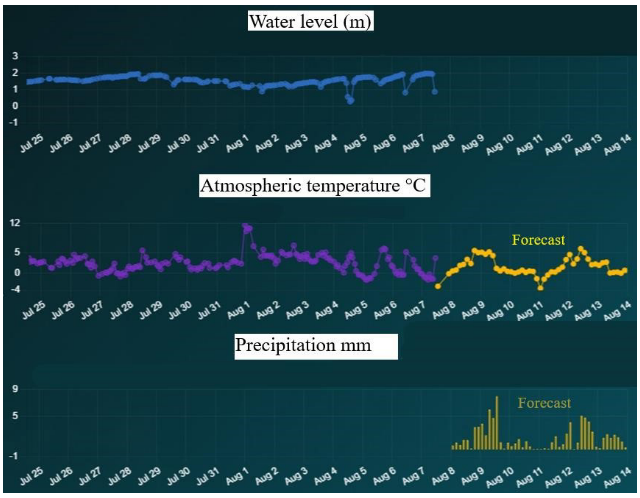

Figure 7. Series with data obtained at the Laguna de los Témpanos station of the Steffen Glacier (Table 2) up to August 7, 2024 and their respective meteorological forecasts up to August 14, 2024.

In the next phase of the project some of the outline stations will be re-installed with improved setups, including better protection of underwater sensors (against icebergs) and more robust power supply systems. Also, new locations will be searched in collaboration of DGA. The postulation for fresh funds for the new phase aiming to re-installing more robust station setups and the development of the predictive model will take place in 2025.

Figure 8. SAGAZ monitoring station in the Laguna Frías superior with a prototype lake level sensor with GNSS-IR technology (Photo by Camilo Rada).

## 5. Conclusions

The first phase of implementation of the SAGAZ system was successfully completed thanks to the design and construction of low-cost and lightweight stations, with robust *off the shelf* components, which allow the equipment to remain operational in adverse logistical and meteorological Patagonian conditions. During this phase, a network of 11 stations was installed to continuously measure air temperature, precipitation and water level in the studied lakes. The collected data are transmitted in real time to online servers that feed a web page (www.sagaz.org) where the variations of each variable and the weather forecasts for each site are visualized on an hourly basis. Despite the robustness of the implemented system, improvements are still needed. Only 6 of the installed stations are currently operational, due to several electronic component failures, power supplies disconnections and the lack of frequent structural maintenance. The next stage of the project, subject to funding expected to be obtained in 2025, will aim to complete the modeling that will allow the prediction of GLOF events and the activation of the early warning system. Also, in this new phase we plan to re-install damaged stations, improving sensors protective designs, a better selection of sites and a more frequent number of field campaigns enabling checking operational conditions and eventually, repairing the damaged installations.

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