SWISS NETWORK OF AUTOMATED SNOW AND WEATHER STATIONS FOR AVALANCHE FORECASTING – SUCCESS FACTORS TO ITS ROBUSTNESS AND LONGEVITY

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ABSTRACT: The backbone of Swiss avalanche forecasting is a network of about 190 automated snow and weather stations located in the Swiss Alps. The network called IMIS (Intercantonal Measurement and Information System) is an almost 30-year success story. Launched in 1996, it still provides important information to local and regional avalanche services, the national avalanche service, and other data recipients such as engineering offices or researchers. Its design, continuous operation and evolution have been critical to the development and operation of downstream models, such as the SNOWPACK model, that are essential for modern avalanche forecasting. We describe the critical elements that have contributed to the IMIS network's robustness and longevity over the years. Among those is the close collaboration between various stakeholders, which has ensured that the network remains well coordinated and effectively managed. In addition, the uniformity in station design has been crucial, allowing for consistent data collection and enabling seamless integration of advanced sensor and software technologies across the entire network. For site selection, we have established processes that allow for selecting optimal locations for snow stations. Finally, the rigorous maintenance routines as well as network and data monitoring systems keep the stations operational even in harsh alpine conditions. By reviewing these elements, we aim to provide insights into the successful operation of IMIS, offering a model for the design, deployment, and maintenance of snow and weather station networks for avalanche forecasting worldwide.

KEYWORDS: automated snow and weather stations, measurement network, snow cover model, avalanche forecasting.

1. INTRODUCTION

Avalanche forecasting is a critical component of avalanche risk management in the Swiss Alps, where avalanches endanger both human lives and infrastructure. The backbone of the fore-casting system is the Intercantonal Measure-ment and Information System (IMIS), a network of approximately 190 automated snow and weather stations. Established in 1996, IMIS has evolved into a robust and reliable source of real-time data crucial for local and national ava-lanche services, engineering offices, and re-searchers. Its data feed several downstream models without which avalanche warning would no longer be possible.

We aim to examine the critical factors contributing to the IMIS network's robustness and longevity, highlighting the collaborative efforts between various stakeholders, the technological advancements in sensors and software, and the processes in place for site evaluations and maintenance. By delving into these aspects, we provide insights into the successful operation and continuous evolution of IMIS, which we believe is a model for snow and weather stations for avalanche forecasting worldwide.

2. FROM DATA TO MODEL

When planning the first IMIS stations started about 30 years ago, people may not have imagined that the data collected would one day be used by complex model chains to predict snowpack stability or the avalanche danger level. For more than 20 years now, the snow cover model SNOWPACK (Lehning et al., 2002) has been run at each snow station (Lehning et al., 1999), providing snow stratigraphy and its evolution. The main added value of the model is that parameters such as new snow height, stability indices (Lehning et al., 2004; Monti et al., 2016; Schweizer et al., 2006), the liquid water content index (Mitterer et al., 2013) and avalanche problem types (Reuter et al., 2022) can be derived. However, only recently, numerical avalanche prediction models have been developed that now run operationally (e.g., Hendrick et al., 2023; Mayer et al., 2022; Pérez-Guillén et al., 2022; Viallon-Galinier et al., 2023). These machine learning (ML) models are about to establish themselves as

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support tools for avalanche forecasters in the assessment of avalanche danger (Techel et al., 2024).

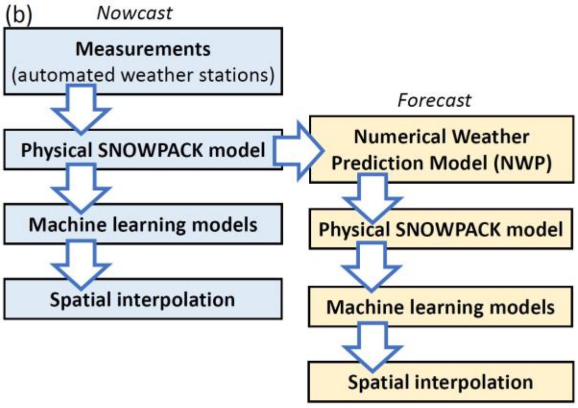

Figure 1: Model chain used in operational avalanche forecasting at SLF (Graphic by F. Techel).

This progress from manual data interpretation to ML models is attributable to several key decisions made during the planning of the measurement network.

Sensor selection
The parameters to be measured were chosen from the very beginning so that the relevant physical processes, the mass and energy balance, could be modeled (Bader and Weilenmann, 1992). Shortly after the first IMIS stations were constructed, the numerical snow cover model SNOWPACK was developed. It was designed such that the data collected at the IMIS stations could be exploited to run the model at the location of the IMIS stations (Lehning et al., 1999).

Uniform station design
The stations were designed to be as uniform as possible, with identical mechanics, electronics, and software. The sensors used were also identical across all stations from the very beginning, and importantly, the design was not changed to the present day. This allows to run the SNOWPACK model retrospectively on the entire dataset of all stations, allowing the downstream models to be trained on the complete historical SNOWPACK data. Hence, this uniformity of the stations positively impacts the development of machine learning models and now also allows exploiting the data for climatological studies.

Stakeholder involvement
All relevant stakeholders were involved from the start. In the confederal system of Switzerland, this included the Federal Office for the Environment, the mountain cantons, municipalities, and local avalanche services. The collaboration between the stakeholders and SLF, including data management, maintenance, and further developments, was formalized in 1997 in a written agreement. This ensured, among other things, that all stations built afterwards were implemented as standardized IMIS stations.

Site selection
Almost all snow stations were built in level and rather wind-protected terrain, considered as representative in terms of snow accumulation in the area to be assessed. Although stations in slopes may provide more meaningful data for evaluating a specific release area, flat-field stations are more suitable for assessing the avalanche situation in a particular area and for operating SNOWPACK.

3. DEVELOPMENT OF THE MEASUREMENT NETWORK

Before the IMIS measurement network was established, there was already an extensive network of about 75 manual observation stations, which still measure snow height and new snow once a day. However, most of these stations are located in mountain villages – often too low for assessing avalanche danger at higher elevations. At that time, there were only 11 automated pairs of stations (wind and snow) jointly operated by MeteoSwiss (Swiss Federal Office of Meteorology and Climatology) and SLF (MeteoSwiss, 1995); these so-called ENET stations were later incorporated into IMIS.

3.1 Measurement network concept

The IMIS network should provide weather and snow data with high temporal resolution from the elevations of avalanche starting zones across the Swiss Alps. The planning sought to balance local, regional, and national needs of avalanche forecasting. Ideally, each station should be relevant for assessing a local avalanche problem while also being representative of a broader region. Each station should include a wind station on a mountain top and a snow station on a rather flat, not wind-exposed site (Figure 2).

The snow stations should provide data on snow height, snow surface temperature, snow temperature, reflected short wave radiation, as well as air temperature, relative humidity, and wind speed and direction. At the wind stations, only the meteorological parameters are measured. The wind stations should help assess snow transport by wind. The sensors used are specified in Table 1.

Considerable effort was invested in selecting suitable locations (see also Section 4). Since the stations were intended to operate remotely, solar-powered electricity and radio-based data transmission were essential.

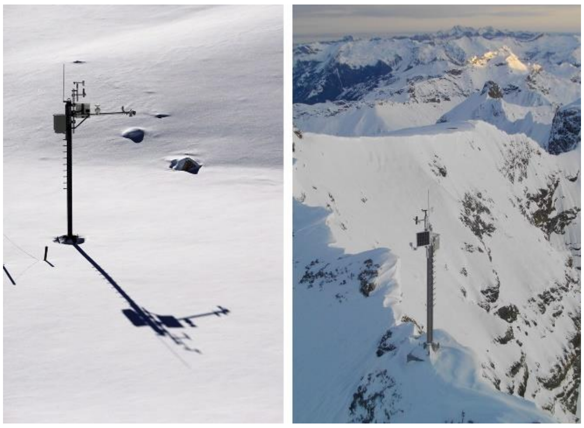

Figure 2: Left: Snow station ELA2 (Tschitta, 2726 m), Right: Wind station MUT1 (Ruchi, 3103 m).

Table 1: List of sensors used at the snow and wind stations. Sensors marked as (PA) are phase-out models. Some of the sensors are modified versions to meet the increased requirements in terms of failure rate and measurement accuracy in the harsh environmental conditions.

Measurement Parameter	Sensor
Wind Speed/ Wind Direction	R.M. Young 05103
Air Temperature/ Relative Humidity	Rotronic MP102H/HC2 (Snow Stations) Campbell Scientific CS215 (Wind Stations)
Snow Height	Campbell Scientific SnowVUE10 Campbell Scientific SR50a (PA)
Reflected Short Wave Radiation	Campbell Scientific CS300 Skye SKS1110 (PA)
Snow Surface Temperature	AlpuG SnowSurf SDI
Snow Temperatures	Campbell Scientific 107
Liquid Precipitation	Campbell Scientific ARG100

3.2 Historical development

In 1996, the construction and maintenance of the measurement network were publicly tendered. Three companies were given the opportunity to build a snow and a wind station according to specified requirements, with one company ultimately being awarded the contract to build the network and promptly starting to construct the stations.

Within the first three years, nearly 100 snow and wind stations were built. After the avalanche winter of 1999, the importance of the measurement network became even clearer, leading to further expansion of the network (Rhyner et al., 2002).By 2010 the network consisted of 186 stations. Since then, only a few stations have been added (2024: 191 stations). The evolution of the measurement network is illustrated in Figure 3.

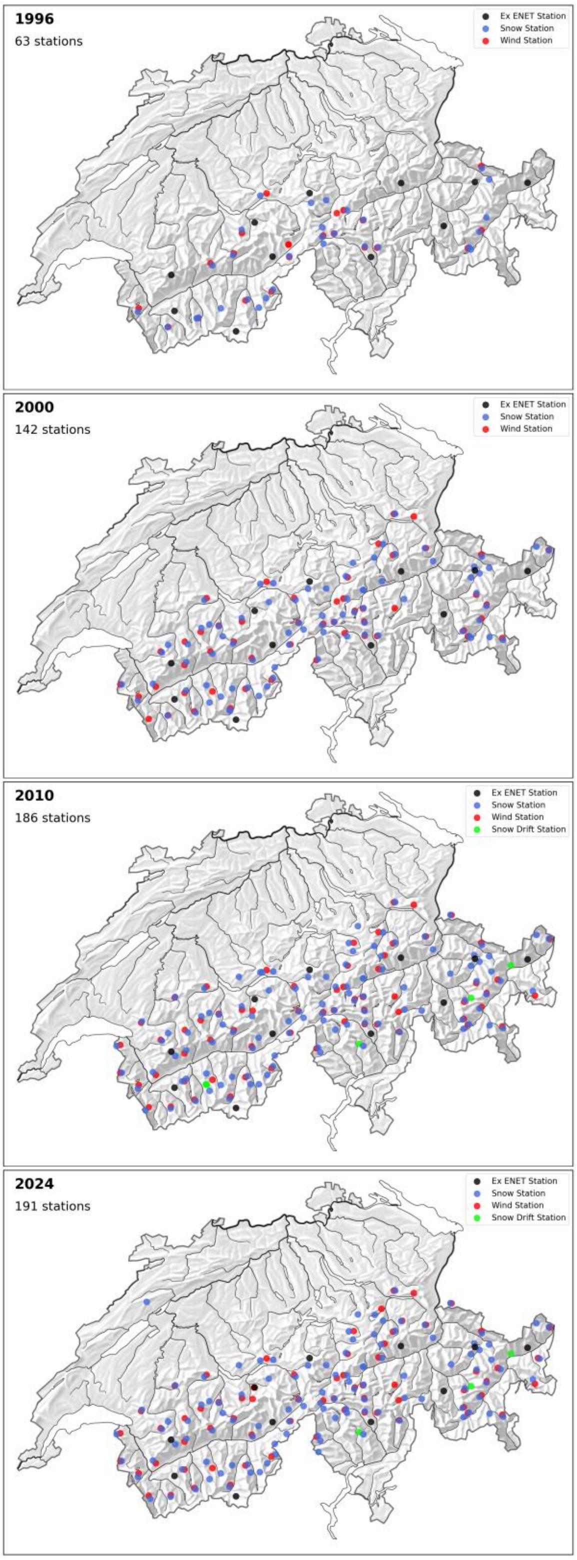

Figure 3: Development of the IMIS network over time. Before 1996 only the 11 automated ENET stations (black dots) existed.

4. SITE EVALUATIONS

4.1 *Snow stations*

For snow stations, selecting an appropriate location is crucial. Snow conditions and particularly snow depths can vary considerably over small areas. A station placed in an unsuitable location is effectively useless. The following criteria are essential for choosing the location of snow stations:

- Wind-protected and away from ridges
- Flat and safe from large and very large avalanches
- Uniform snow distribution around the snow depth measurement
- Representative snow depth for the area being assessed
- Located near and at the same elevation as the starting zones of the locally relevant avalanche paths to be assessed

In the early days, when many stations had to be planned and built in a short period of time, there was not as much effort invested in site evaluation as is the case today. Over time, it became apparent that the snow depth data from some stations were hardly of use or that some stations were frequently hit by avalanches.

Today, only about one new station is planned per year, or an alternative location is sought for a poorly positioned station. The current process for evaluating a suitable site involves:

- Identifying potential locations on maps by local experts and SLF
- Assessing the avalanche risk at proposed sites using RAMMS (Christen et al., 2010) to simulate 30-year avalanche events
- Conducting site visits in winter and performing manual snow depth measurements to assess local snow depth distribution
- Mapping snow depth by digital photogrammetry using a drone to create a snow depth model of the area (e.g., Bühler et al., 2016). This allows for the calculation of average snow depth and snow distribution in the surveyed area. Ideally, the snow depth at the chosen site should match the average snow depth in the surrounding area.
- Operating a test station at the most promising location during a winter season to assess snowfalls under different weather conditions and the impact of wind at the planned site
- Deciding on whether to construct the station based on the analysis of the data from the test station

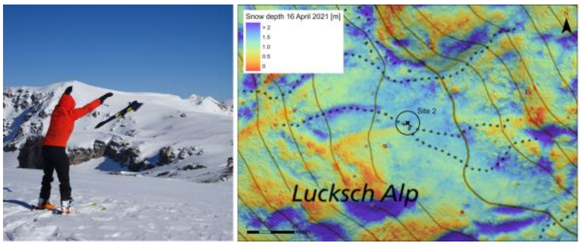

Figure 4: Left: Launching a drone to record photogrammetric data. Right: Generated snow height model around the location of a newly planned snow station at Büelenberg Davos, Switzerland.

4.2 *Wind stations*

The site selection for wind stations is somewhat simpler compared to snow stations. The goal is to measure wind as undisturbed as possible. Hence, wind stations should be placed on exposed ridges or peaks. Since ice formation on wind sensors is a major issue (see Section 6), it is important to select a site that is not highly prone to ice formation, although this is both difficult to assess and sometimes unavoidable.

5. MAINTENANCE AND CONTINUOUS IMPROVEMENT

5.1 *Maintenance*

A specialized company has been contracted to maintain the stations. Each station is serviced once a year in late summer. Failures during winter are repaired as soon as possible. The maintenance team still includes technicians who originally built the stations. Their long-term commitment has been and continues to be crucial for the continuous improvement of measurement technology, sensors, and software.

5.2 *Automated and manual data checks*

Various automated checks continuously monitor the timeliness of the data, the data connections to the stations, and the proper functioning of downstream services and models. Responsible personnel are alerted in case of malfunctions. Potentially faulty measurements are also detected using software tools.

During winter, the correct functioning of the measurement network is checked daily by SLF staff. Any malfunctions are reported to the maintenance companies so that errors can be promptly fixed.

5.3 *Continuous improvements in hardware and software*

Over the years, efforts have been made to identify and resolve weaknesses in the measurement network. Sensors have been modified to reduce failures or increase measurement accuracy. The software has also been continuously improved, leading to lower power consumption, more stable data transmission, and improved snow depth measurements, among other benefits.

One example of improved measurement accuracy is the optimization of the air temperature sensor. The goal was to reduce the radiation error of the unventilated sensor (see also section 6.3). The sensor probe was made smaller and placed in a way to maximize exposure to the natural airflow within the radiation shield. Figure 5 shows the errors in comparison to a ventilated high-quality meteorological air temperature sensor before and after the sensor optimization. With the optimized sensor the error was reduced by 30%. Still, during very calm (VW_{max} < 1 m/s) and sunny conditions (RSWR > 400 W/m^2) over a snow cover, the average deviation was 4.4 °C. Further sensor optimization is planned by using a helical radiation shield, which should further reduce the average error to 2.5 °C under the above conditions.

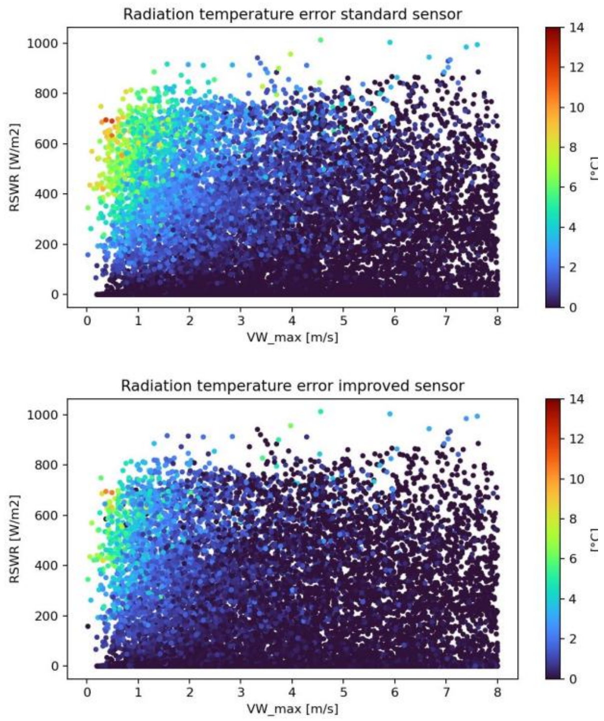

Figure 5: Error in air temperature of the unventilated sensor over a snow cover: standard sensor (above) and improved sensor (below) as a function of wind speed (VS) and reflected short-wave radiation (RSWR).

6. LIMITATONS

Operating weather stations and accurately measuring the desired parameters in a harsh environment with frequent extreme weather conditions is challenging. The fact that the stations are solar-powered does not make things easier. Therefore, the data quality cannot be compared with that of standard meteorological stations connected to the power grid and always easily accessible. The most significant limitations regarding data quality and availability are described below.

6.1 *Data availability*

In the event of technical problems or damage, which often occur during bad weather, immediate intervention is not possible because helicopter flights require good visibility. This results in data gaps or incorrect values being measured for a period after sensor failures occur.

6.2 *Iced wind sensors*

During winter storms, a significant number of the propeller anemometers (R.M. Young 05103) at the wind stations are subject to atmospheric icing, making wind data unavailable. Moreover, the sensors can be damaged by the weight of the ice. Approximately 15% of the wind sensors need to be repaired or replaced each year. Alternatives to the propeller anemometer have been sought for a long time, but the use of heated ultrasonic sensors is challenging with solar power. A reliable alternative has not been found yet.

6.3 *Radiation error in temperature measurement*

As mentioned in Section 5.3, significantly higher air temperatures are sometimes measured, particularly during spring with little wind and high radiation, because the air under the radiation shield heats up. Approaches to compensate for the error through post-processing have been examined but were not satisfactory. More promising is the use of a helical radiation shield, which creates air circulation around the temperature probe.

6.4 *Faulty historical data*

Until now, raw data were written directly into the database and published on the SLF website. Especially in the earlier years, measurement errors occurred more frequently, which is problematic for statistical analyses (extremes) or training machine learning models. Machine learning models are currently being developed to retrospectively correct or mark erroneous historical data (Svoboda et al., 2024).

7. CONCLUSIONS

The enduring success and robustness of the IMIS network for avalanche forecasting are attributed to careful planning, uniform station design, strategic positioning of the stations and thorough maintenance. Standardized sensors and software have facilitated consistent data collection, while the maintenance crew's long-term commitment has ensured ongoing improvements and high data availability.

Collaboration among municipalities, cantons, federal agencies, and industry partners has maintained the network's functionality. Consistently operating a numerical snow cover model provides a huge added value to the network and allows for the development of machine learning algorithms to support avalanche forecasting.

Despite challenges such as solar power dependency and sensor issues, continuous hardware and software improvements have mitigated many limitations. Elaborated site evaluations ensure the optimal positioning of new stations.

Overall, the success results from meticulous planning, dedicated maintenance, technological innovation, and effective collaboration providing a valuable model for similar systems worldwide.

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