International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Monitoring Bonnard Rock Glacier under the effect of climate change

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Abstract

The purpose of this work is to examine the impact of climate change on the stability and movement of rock glaciers in the Alpine region, focusing on Bonnard one in Switzerland. Rock glaciers, significant indicators of permafrost and environmental shifts, are increasingly affected by rising temperatures, which amplify the deformation and melting of ice within their structure. The analysis is focused on its mechanical and morphological deformations from the data obtained over 11 years through environmental data analysis and geophysical methods namely GPS tracking: an evident acceleration of the surface material, namely rocks and boulders, is identified and the corresponding increase in slope instability, debris flows and movements of materials in general is highlighted especially through Pétérey torrent, posing heightened risks to downstream communities in Zinal village, located at the foot of the slope.
The findings underscore a need for ongoing monitoring and enhanced mitigation strategies to safeguard populated areas and infrastructure from potential hazards associated with periglacial dynamics and warming trends.

Keywords

Rock glacier, climate change, instability, acceleration, debris flows

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1 Introduction

The effects of climate change, particularly global warming, are linked with a significant increase in temperatures, with a mean of + 1.1°C higher than pre-industrial levels, in accordance with IPCC and UNEP reports, over the past century.

In high-mountain regions like the Alps, temperature rise more intensely than other areas (almost the double) and this causes visible effects specifically a reduction in the snow cover, melting ice, affecting the stability of debris slopes and glaciers, with movements becoming more rapid and frequent. The impact on permafrost — ground that remains frozen for at least two consecutive years — is particularly significant in periglacial environments, where temperatures dictate the flow and stability of rock glaciers.

Rock glaciers are not like traditional ones: they consist of ice mixed with rock, debris, water and mud forming a mass that flows downslope due to the gravity effect. This process (A. Kääb T. R., 2005), the so-called "conveyor belt effect" for which the material from the upper layers overrides the lower ones, then it is deposited in the front of the glacier and it is finally overridden by new material from upper layers, gives them their characteristic lobate shape together with surface deformations.

Bonnard glacier, located in Val d'Anniviers, Switzerland, between two moraines, covers an area of approximately 3 km^2 and dominates Zinal village, at 1670 m, just downstream Pétérey and Tracuit torrents which originate from it.

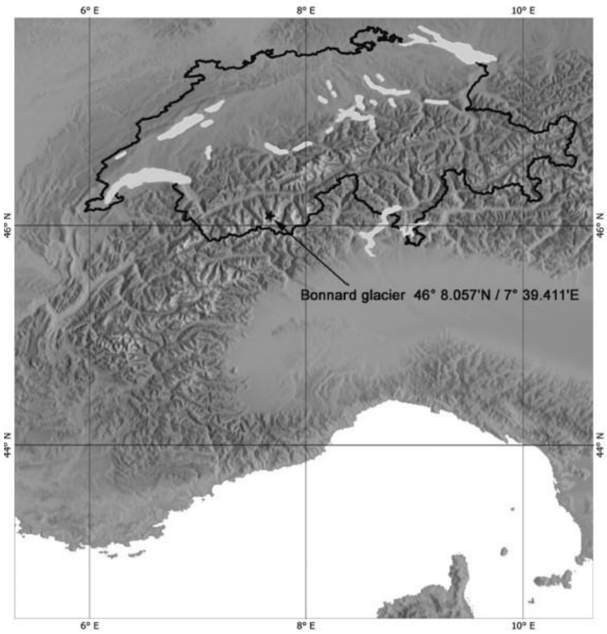

Fig. 1: Location of Bonnard rock glacier

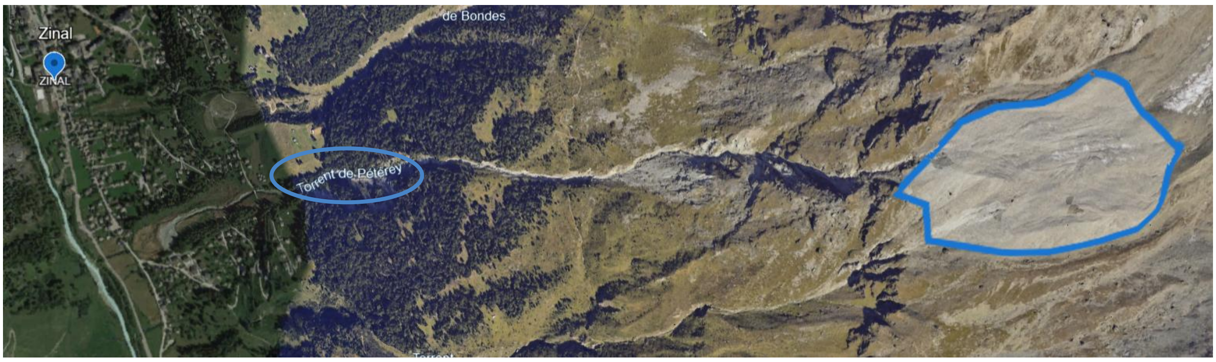

Fig. 2: Location of Zinal village with respect to the rock glacier and to Pétérey torrent, from Google Earth

Heavy rainfall events, strong glacier melting, but also warm periods without rainfall, related to the atmospheric warming, are linked to the many debris flows phenomena. As a result, water mainly feeds the northern part of the moraine, producing a mean of one to three of these events per year in the Pétérey torrent, where therefore the sedimentary activity results to be very important.

These phenomena are very powerful and destructive and they have been recorded through years for a total of 15 major events, which appears in literature.

Some research underline that the total volume of material that can be mobilised nowadays is 40 000 m^3 for Pétérey and the phenomenon is increasing because of climatic change: the movements of the glacier are not only due to the internal factors (geometrical, topographical, mechanical), but also to the external ones (thermal, hydrological and glaciological or related to possible overloading of rock glacier triggered by landslides or rock falls).

2 Meteorological and Environmental data analysis

Analysing mean temperature, precipitation and snowpack height trends is fundamental to understand the climatic influences on the glacier.

This kind of data is considered because of its relevance, knowing the important role of water and snow in the glacier's dynamic: water percolation implicates a loss of joints bonding and a reduction in hydraulic permeability and mechanical strength which alters the stress field, decreasing the safety factor of the slope and causing consequently destabilization, dislocation, debris flows and even collapse (P. Deline, 2015; M. Davies, 2001). In particular, temperature variations with a consequent transition from the frozen to the thaw state, have important effects on the related cohesion and friction angle of the soil (E. P. Howald, 2023). During the melting season or heavy rainfall events, rock glacier's advance increases and it can be summarized into four main processes: cohesion loss of sediments due to the thaw in the matrix, cohesion reduction due to creeping, spatio-temporal changes in water circulation and constant rejuvenation of sediments on the slope. (E. Bardou G. F.-B.-D., 2011).
Meteorological data are obtained, between 2007 and 2023, from three automatic weather stations, two owned by MeteoSwiss, the federal office of meteorology and climatology of Switzerland and the third by IMIS, (the Intercantonal Measurement and Information System).

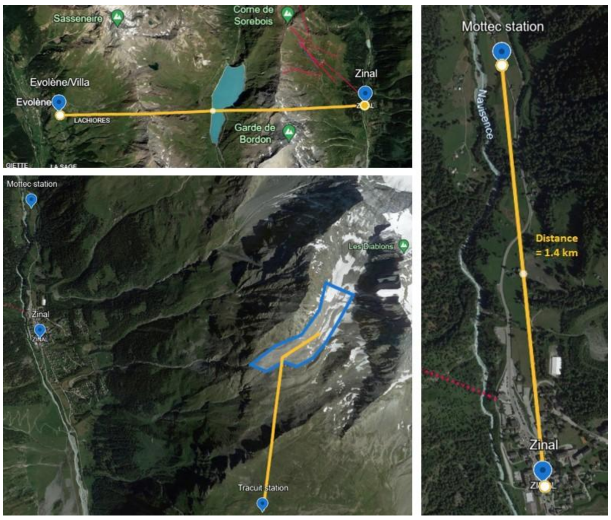

Fig. 3: The three station's location with respect to Bonnard rock glacier (blue perimeter)

The closest one is the “Mottec” station, located at 1580 m, 1.4 km upstream from Zinal, which belong to the hydroelectric plant standing in that zone: for this reason, only precipitation have been recorded during time.
The other is instead the “Evolène/Villa” station at 9 km in beeline from Zinal, around 300 m higher than the village (1825 m), so still representative for temperatures' analysis.
For a better investigation, timeseries are taken also from a third automatic station, the “Tracuit” one, at 2859 m, altitude closer to the one of interest and, in a straight line, between 1.4 and 2 km of distance.
Relevant data result to be in the specific air temperature [°C], snowpack height [cm], snow temperature at ground and at different depths [°C], available from January 1998 until December 2023, recorded every 30 minutes for every day of the years. For that reason, daily, then monthly and annual averages have been performed in order to be able to analyse them in the proper way.
Temperatures (of air, surface and snow) are increasing in an important way, while ground ones are more stable because the response of the system is delayed in time: in 16 years it is not possible to already see the effects of the important increment of the air temperature, which can be surely, appreciate in a few years.

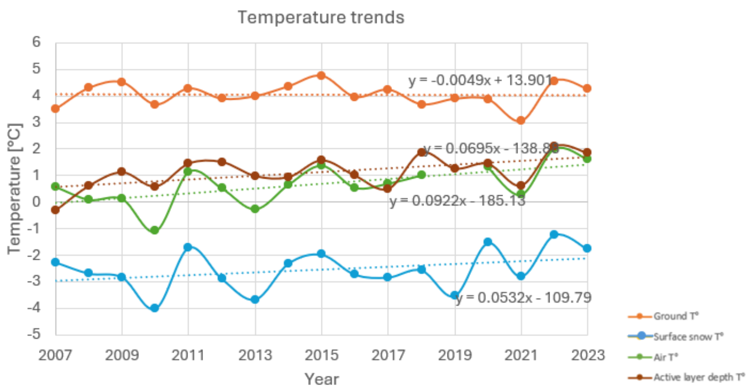

Fig. 4: Temperature trends respectively of ground, active layer, air and snow surface at Tracuit station

Also at this elevation, at around 3000 m, the mean value since 2014 is no more below 0°C during the year, meaning that the soil is not frozen, so the ice, which has a cement action, is not always present. Please notice that air temperature were not recorded in 2019.

It is interesting to consider also different monthly temperature variations over the years, which show an evident vertical shift, on average positive indicating a huge increment in only 16 years: in blue the mean trend for the first recorded year (2007) with a linear coefficient of 0.17, while for the grey one (2023) is 0.63.

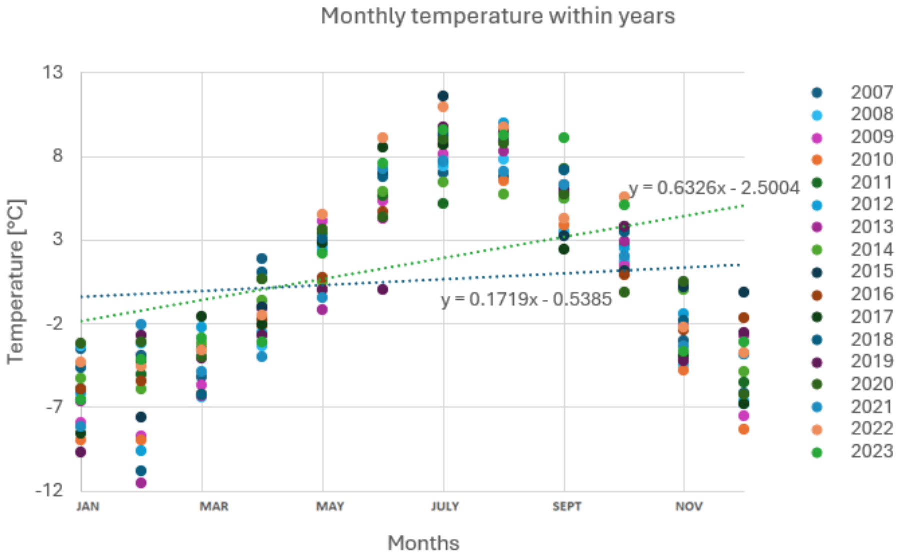

Fig. 5: Air temperature variations through years with mean trends calculated for 2007 and 2023

3 GPS system analysis

Moving to the other type of conducted analysis, situated on the studied area, GPS monitoring system was installed in 2007 and their advance has been measured until 2018; pay attention to the fact that a time jump exists between 2012 and 2015, because data for the years 2013 and 2014 are not available.

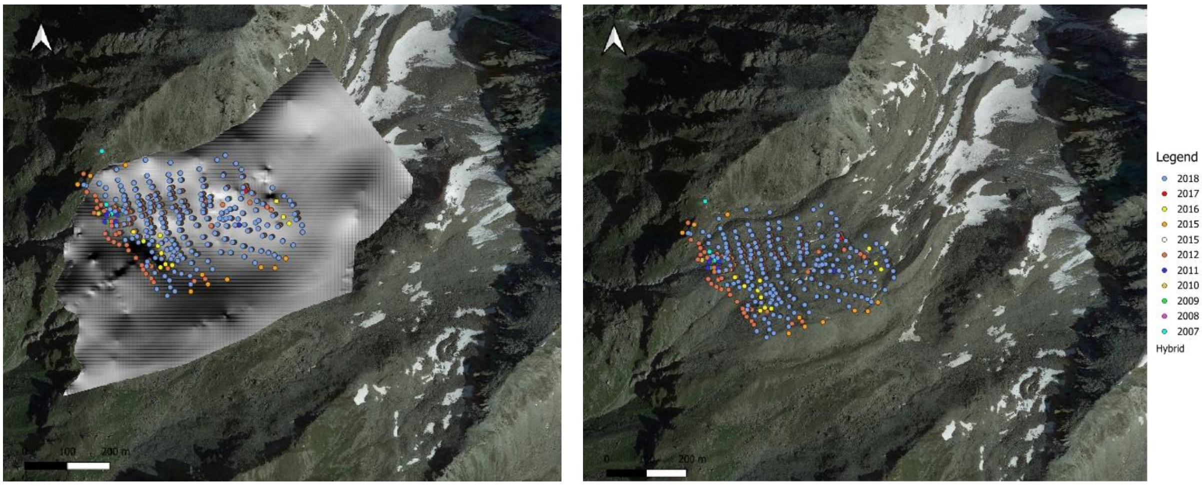

Fig. 6: Location of GPS points

In *Fig. 6* , the position of all the points is shown with and without the reference bedrock roof model: this has been created from the monitoring activity between years 2010 and 2014 using the seismic refraction method. Specifically, different drillings have been performed to better observe the terrain, then those data, together with a topographic analysis, allowed to create the final 3D model. It gives the information about the altitude of the analysed area, the one more subject to important movements: it ranges from 2700 to 3100 m.
Taking advantage of *QGIS* software, it is possible to quantify what is the actual displacement of the rock glacier in this specific time span: considering the same GPS points, it results that both their coordinates on the plane X, Y changed, but also the Z one, so in the vertical direction.
For the first case, it is sufficient to zoom in on the surface to appreciate the motion:

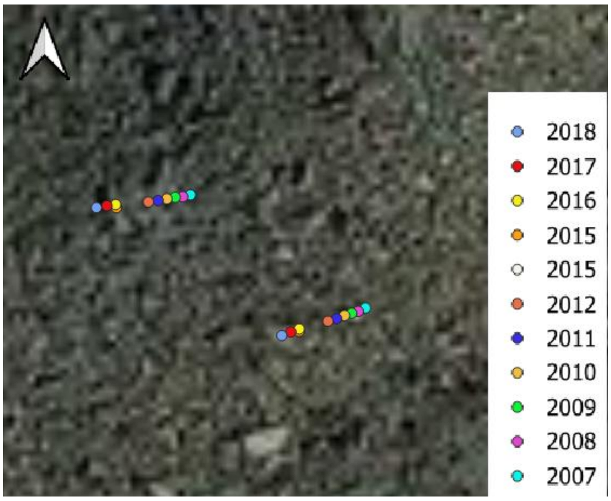

Fig. 7 : Example of GPS points' motion from 2007 to 2018

For the example shown in *Fig. 7*, a roughly estimation of the distance between points from 2007 to 2018 has been measured, obtaining a value of about 11 m, which means more or less a displacement of 1 m per year on average; moreover, the temporal gap from 2012 and 2015 can be appreciated because the distance between points is bigger. Moreover, taking advantage of *Fmeworkbench* software, it results that, on average, the displacement occurred mainly towards the South-West direction.
Considering Z coordinate, which indicates the elevation of each GPS station, instead, it is possible to calculate the variation of the mean depth of the active layer (the upper one) in time, over the area under analysis. Its thickness changes of several meters because the unconsolidated boulders, that predominantly composed it, move on the surface of the glacier, especially for two main reasons:

- on one side, the increment of temperature, responsible for the melting of the permafrost layer, which facilitates the sliding of the material;
- on the other side, the decrement of the snowpack height, which as seen is able to maintain all the structure more compact and to avoid rock falls or debris flows.

But in order to obtain consistent result, this kind of work has been performed only for the points for which measures have been repeated throughout all the period (2007-2018). So, after a filtering

procedure, finally the total number of points which contribute to this estimation has been found to be equal to 80.
Firstly, the mean elevation has been plotted and, as it can be noticed, it decreases while time passes:

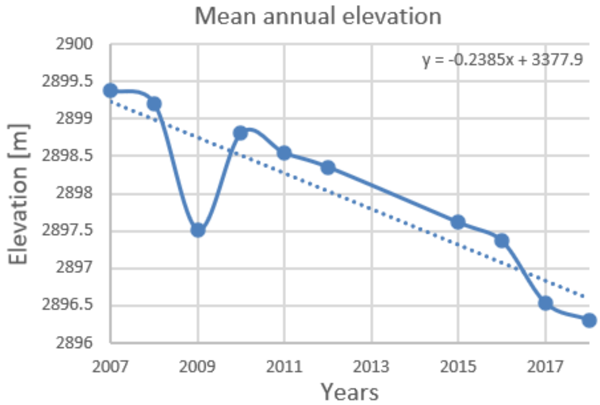

Fig. 8: 80 points mean elevation

Then, making the difference between the Z coordinate and the elevation of the bedrock's roof for each specific point, using *SAGA* software, as said, also the thickness of the active layer has been calculated for each of them; an almost linear decrement can be observed from the maximum depth in 2007 (20.3 m) to the minimum in 2018 (18.9m), with an average of 19.7 m:

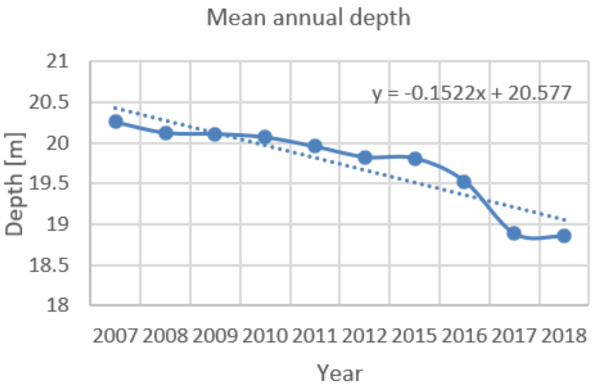

Fig. 9: Depth of material in motion with the relative variation in depth from one year to another

3.1 Fixed GPS analysis

Moreover, data regarding the total movements of two GPS, installed at specific and fixed locations, in the lower part of the rock glacier, are analysed between 2010 and 2023: daily displacements were recorded and data are provided in a cumulative way, in [m]: the absolute value can be obtained, with an average yearly displacement which is different for the two cases.

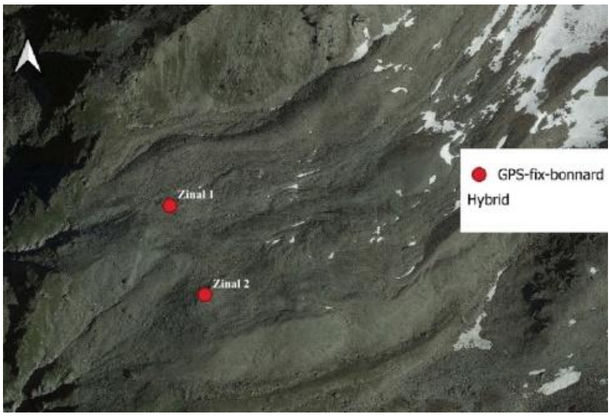

Fig. 10: Location of the 2 fixed GPS

It results to be of 0.004 m for GPS1, where an increasing trend can be noted, and of 0.002 m for GPS2 (about the half), where instead the linear coefficient is negative but small, so much small that it can be considered as stable through time. This can be explained by the fact that, as known following some specific soil and matrix analyses on site, GPS1 is above a quite thick layer of permafrost, so it is subject to its thawing and freezing because very sensitive to temperature variations, while GPS2 is not, so clearly results are at the end different, as it can be appreciated in the following graph:

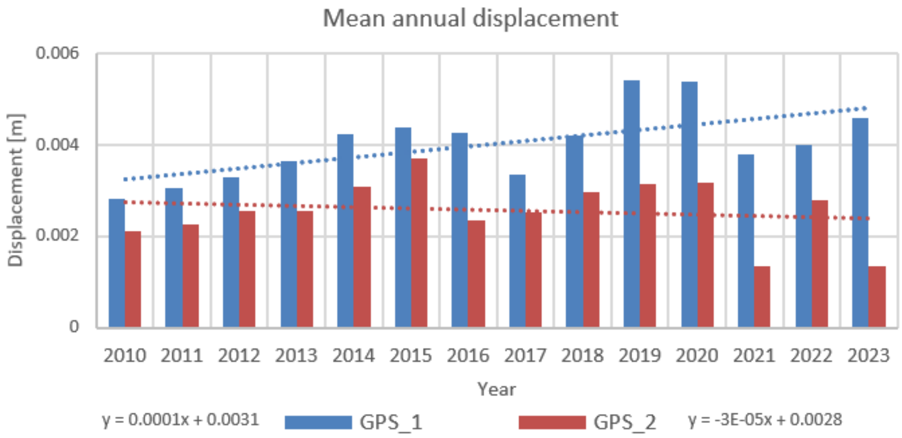

Fig. 11: Annual displacement of fixed GPS

In order to better understand the complete dynamic of the glacier, a focus on winter and on summer months (January, February and March for the first category are considered and July, August and September for the second one) is performed, putting in relation meteorological and displacement data. The main increasing trend is discovered during summer months when temperature are higher and so the snowpack height decreases, decreasing both strength and cohesion of the surface materials, triggering the motion of rocks, boulders and debris flows.

It results that for both GPS, trends of movements are positive meaning that inevitably high temperature have a concrete and direct impact on the main deformations occurring at the surface, because their raise is significant. In the specific, if under GPS1 is the layer of permafrost which is melting and so it is mainly responsible of its motion, GPS2 can be considered more stable, with movements which can be associated to water percolation coming from other upstream areas, or due to extreme precipitation events more intense and so impactful. When such events occur, water has no time to infiltrate and so it increases the runoff phenomenon, which can be another cause of boulders' motion and also the cause of the formation of mud and its flow.

For a complete overview, to better visualize these results, graphs with the comparisons between winter and summer are shown in the following, for both instruments:

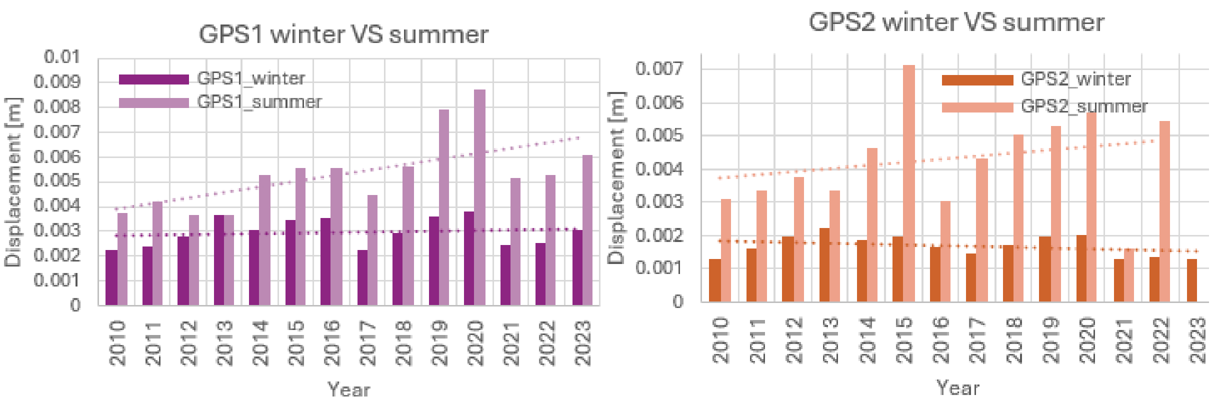

Fig. 12: Mean displacements in winter and in summer

It can be appreciated a huge difference between winter and summer, as expected, but also between years, with displacements ranging from more than 0.002 m to nearly 0.004 m for GPS1 and from 0.001 m to 0.002 for GPS2 during winter months and between 0.004 m and 0.009 m and 0.002 m and 0.007 m respectively during summer, basically indicating almost a doubling of the acceleration of rocks and debris.

4 Velocity analysis

At this point, it is interesting to focus on the areas that move more, localising them with respect to the entire rock glacier.

Answers come from GPS data: from their coordinates, velocities of the 80 points, for which all records are available, as explained, can be calculated from one year to the other, as the ratio between distances of the three coordinates and time. Then, the 3D velocity, again for each point, is obtained through the formula:

$$V = \sqrt{v_x^2 + v_y^2 + v_z^2}, \qquad (1)$$

where V total velocity
v_x velocity along x direction
v_y velocity along y direction
v_z velocity along z direction

which is applied separately for the negative and the positive values, indicating respectively deceleration and acceleration. Then, the average between these two results is performed and, at the end, the mean final speed of the surface values is obtained; as it can be appreciated in the following plot, it shows a positive trend.

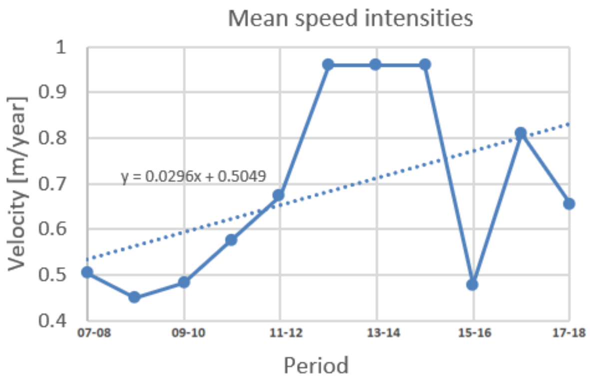

Fig. 13: Mean velocity of the area coinciding to the bedrock's roof

Actually, the peak joined in 2015 is followed by a decrement which can be explained, in part, by the huge amount of snow fallen especially during the winter of 2016, which was recorded higher than the mean over the period. In addition, this together with lower air temperature recorded during 2017 and especially during the summer period, fact which helped the snowpack to remain more at soil and to give stability to the area.

4.1 General velocity's maps overview

Then, based on the available GPS measurements, so georeferenced with their own coordinates, series of maps (available from 2007 to 2017) representing velocities' variations between two years were created by Eric Bardou and his team and dates available for this study; this using *Isatis*, a specific software designed for the use of geostatistics, which from data, produces high-quality maps and models.

Due to the fact that a degraded network is the result of the available GPS points, maps were obtained by resorting to the collocated cokriging technique, to rely on other information available at higher density and well correlated to the target variable, to reduce overall the uncertainties in the results (E. Bardou G. F.-B., 2015).

In general, stable parts are more visible on the edges, while the central part is the one which moves more and it is in acceleration with the two lobes which characterize the rock glacier which are clearly visible. The principal hotspot is located in the lower left part and coloured in red, in correspondence of the left lobe and of GPS1. Moreover, the general speed is increasing in time overall the considered surface, as the scaled bars and the maximum reached values indicate.

In the following, a comparison of the results of 2007 and 2018 are shown:

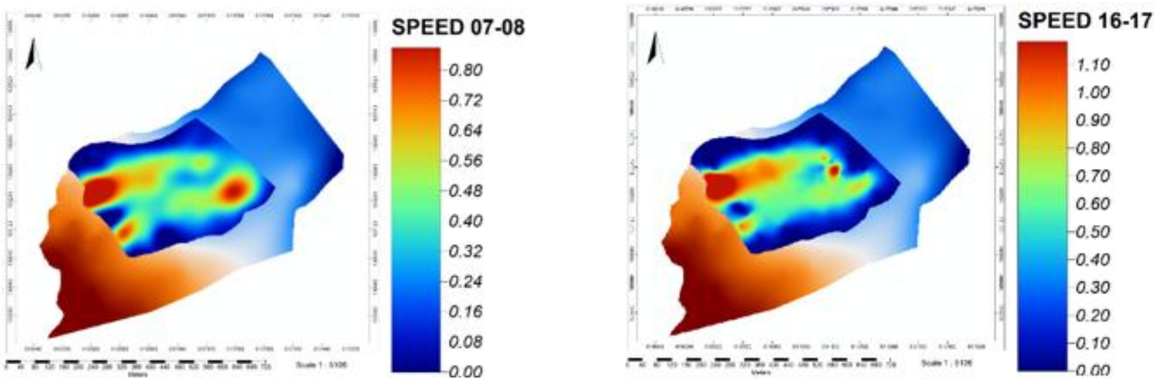

Figure 14: Differences in the speed maps between the beginning and the end of the monitoring period

It is clear that lobe 1 is the most dangerous area: it is the one which accelerates mostly and moreover it is exactly the source of Pétérey torrent, the most affected by debris flows.
An estimation of the total unstable volume can be carried out taking into account the fact that the rate of sediment which can reach the foot of the rock glacier depends on mainly four factors: (R. Lugon, 2010)

- mass-transfer rates produced by the rock glacier creeping;
- volume of ice and voids in the moving rock glacier section;
- rate of non-consolidated material accumulations due to active layer failures triggered by debris flows;
- permafrost ice lenses exposed at the surface.

These aspects are summarized in the following formula, which gives as result the volume V:

$$V = \frac{1}{2} * (v * W * D) = \frac{1}{2} * (118 * 70 * 15) \sim 62\,000\ m^3, \qquad (2)$$

where v creep velocity [cm year^{-1}]
W width of the interested area [m]
D depth of the shear zone [m].

The calculated value is not so far from the predicted volume of more or less 40 000 m^3 of dangerous material looming over Zinal which can derived from Pétérey torrent: the resulting discrepancy is mainly due to the presence of voids and ice in the rock glacier body, which needs to be taken into account, adding also the fact that when the ice melts, the deriving water occupy a lower total volume. This amount is different for each glacier because clearly dependent on its composition, sediment production rate, morphological characteristics: for Bonnard glacier, this factor is estimated to be around 1.55.
Finally, it is clear that the order of magnitude of the potential unstable material is significant and for that, due to the fact that the environmental trends are unfortunately now well delineated, the only possibility turns out to be the implementation of more mitigation and adaptation actions, in order to be able to protect the village together with the ski areas.

Conclusions

In conclusion, this study highlights the increasing instability and accelerated movement of Bonnard rock glacier, driven by climate change. Rising temperatures are significantly impacting its dynamics, amplifying the deformations and the occurrence of hazardous debris flows, which pose risks to the downstream communities. Continued monitoring, along with effective mitigation strategies such as the construction and the enhancement of some containment walls (the so called “dépotoirs”), is essential to safeguard these areas from periglacial hazards, to protect vulnerable populations and infrastructure in the face of ongoing climate-driven environmental changes.

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