Author Response

We are grateful to the the referees for the constructive and overall positive comments that acknowledge the novelty, relevance and potential of the proposed method. Thanks to their comments, the clarity of our paper should now be substantially ameliorated. Both reviews enable to clarify and strengthen our work.
In a nutshell, following their comments, we changed (i) the title and modified the abstract, (ii) clarified the discussion and the interpretation, and (iii) removed the terms exogeneous/ endogenous which were confusing.

Reviewer 1

The authors present an interesting study assessing the potential of the co-detection of elastic waves emanating from micro-cracks within a moving mass of soil or rock for slope stability early warning purposes. The results are discussed considering monitoring data from a network of 6 geophones distributed near the tongue of the an active rock glacier. Although the experimental data are limited, as the data have been collected in the test area for just a few months, the analysis of the monitoring data show results that are worth to be published. My overall recommendation is that the manuscript should be accepted subject to minor revisions (see following comments).

MAIN COMMENTS The title and the Abstract should be modified to better fit the content of the manuscript. In particular, they should emphasize that the research findings only refer to an active rock glacier (not to all "gravitational slope failures") and that the extend of the monitoring data does not allow a generalization of the results.

Author Response (A.R.):
We agree, the experimental study was focused on an active rock glacier. However, the strategy used here (co-detection) is theoretically valid for all types of failure, i.e. all gravitational slope failures (Faillettaz et al. 2016).
This study is also a first step towards a generalization of the results as steep glacier tongues are steep slope of natural heterogeneous material sharing all relevant properties of gravitational slope failures. We therefore adjusted the title to include the application to a rock glacier: "Towards early warning of gravitational slope failure with co-detection of micro seismic activity: the case of an active rock glacier".

In the Introduction, references to currently adopted monitoring strategies for local landslide early warning systems are missing and must be added. To this aim, a simple google scholar search would be useful to find the most recent references on this topic.

A.R: *We clarified the text on this point, and introduced local landslide early warning systems and their monitoring strategies. We added the following references: Pecoraro et al. (2018), Chae (2017), Stahli (2015), Petley (2012), Lacasse et al (2009), Petley et al (2005).*
See page 1 line 18 and page 2, lines 3-10.

In section 3.2 the Authors introduce "detection thresholds" and they write "the numbers given - 500 to 2000 - are arbitrary, without unit". This statement is not sufficient to understand the meaning of the parameter used to define the thresholds. Is it the sum of the (0.1s-long) short periods? If yes, it would be better define a time-length parameter(i.e. the used number divided by 10) having time units (e.g., seconds). If not, what is it? Please clarify.

A.R.: *No, the threshold is simply based on the maximal recorded amplitude of the signal. As the signal is digitalized using a 12-bits ADC, its recorded amplitude varies from -2048 to 2048. We adjusted and clarified the text in section 3.2 lines 5-10.*

The terms “exogenous failure” and “endogenous failure” are not used in slope stability practice. When they are first introduced, their meaning should be clearly defined. To this aim, significantly expand the initial sentence in Section 3.3.

A.R.: *We changed these terms to internally and externally driven events.*
For more details see reviewer 2.

FIGURES Figure 2 can be extended in width (full page with) for clarity.
A.R.: *OK*

Figure 5. What is the meaning of the numbers shown in the two comparisons? In other words, what is the parameter being monitored? Add parameter in the figure above the legend bar. Modify caption to clarify.
A.R.: *OK see new caption.*

Figure 6. The precipitation record does not show anything and the reader can be confused by seeing the rain legend and the caption mentioning the precipitation record. I understand that when there is no rain the white color is indicative of this condition, yet it would be more appropriate in this case to either: i)delete the rain/precipitation part of figure and caption from this figure; or ii) write “no rainfall recorded” in the figure where the color-scheme items were supposed to appear.
A.R.: *OK, we changed according to this comment and add “no rainfall recorded”. See new figure.*

Reviewer 2

The analysis and presentation of the micro-seismic data (e.g. multiple detection thresholds, joint time-frequency analysis) is rigorous and of high quality.
The reviewer's main concerns relate the authors interpretation of the slope mechanisms and behaviour, which consequently means revisions to the interpretation of seismic data are required. The terms 'exogenous failure' and 'endogenous failure' are not appropriate in the context of slope stability. All discussion and interpretation of slope behaviour should be set within the scientific literature on the topic, using well-established terminology and understanding. For example, there is currently no reference to pore pressures, mobilised shearing resistance, effective stress, applied shear stress, etc. Much of the analysis is underpinned by an assumption that micro-seismic signatures generated by 'exogenous' means should be different to 'endogenous' means; however, this is not appropriately justified and linked to physical understanding.

A.R.: *As demonstrated in this manuscript, we showed that the micro-seismic activity exhibits two quite different behaviours prior failure (either short and high energetic signals with high number of co-detections, or long and low energetic signal with high micro-seismic activity but with low number of co-detections).*
Thanks to the meteorological measurements, we showed that rainfalls generate high seismic activity (see inset figure 3), and the analysis of all detected event showed that the second behaviour occurs systematically during periods of rainfalls (as explained in section 3.3 page 10 line 1-10)
We never assumed that the micro-seismic signatures should be different if generated by exogeneous or endogenous means.
However, we interpret/attribute this change in behaviour to the different triggering mechanism.
We use the terms exogeneous and endogeneous in analogy with complex system theory, referring to Sornette, D., & Helmstetter, A. (2003). Endogenous versus exogenous shocks in systems with memory. Physica A: Statistical Mechanics and its Applications, 318(3-4), 577-591.
We changed these terms and replaced them by internally-driven (e.g. increasing damage) event and externally-driven (e.g. rainfall, climatic) event.

We first did not refer to pore pressure, effective stress, applied shear stress because we do not have any measurements of these quantities.
However, we added a small paragraph in the discussion on this issue and indirect observations related to such quantities (e.g. water outflow):
"Infiltration of liquid water in the rock glacier causes elevated pore pressure which reduces effective stress and hence shearing resistance. causing slope movement and its possible destabilization. Note that during the short peak velocity that occurred between 10-13 August, seismic activity and co-detection number stay at a very low level (Fig. 4), indicating aseismic displacement of the glacier. This period corresponds also to the appearance of an active stream at the tongue (see Fig. 2), indicating that the material is fully saturated.
Strictly speaking, our system does not record any slope movements but only the resulting seismic activity. If the slope is simply sliding over a soft layered interface, no seismic waves are expected to be generated, resulting in an aseismic behavior. This might be the case here, in a fully saturated rock glacier.", page 13, lines 7-13.

The authors categorise rainfall as 'external forcing' (exogenous failure);however, infiltration of rainfall causes elevated pore pressures, which reduces effective stress and hence shearing resistance – this is what causes a reduction in stability and the slope to move.

A.R.: *Totally agree, infiltration of rainfall causes slope to move. However the initial forcing is still external. We showed that the resulting microseismic activity is different in this case (Fig. 7). We clarify this point by rephrasing and adding in section 3.3:"*
In general, a combination of dynamical and quasi-static processes can lead to the change of one of these components: an initial change in the external forcing (e.g. rainfall, meltwater, earthquakes, etc.) and from internal changes (e.g. increase in internal damage, leading to a decrease in resisting stress)." page 8, line 1-4

In addition to the above comments, the paper needs a subsection on back-ground/environmental/extraneous noise. The geophones monitor low frequencies(«1kHz) and hence measurements will constantly be contaminated by noise.

A.R.: *As explained in the paper, higher frequencies are so attenuated that they can only be detected in the vicinity of the sensors, typically at meter scale, which discards our method.*
This was also evidenced in Fig. 8 and in the text:"Moreover, the analysis of the spectrograms shows a clear difference in the frequency content of these events: whereas internally-driven event exhibits a dominant frequency around 20-40 Hz (highlighted in red in Fig. 8), externally-driven events are less energetic, with only a few isolated frequency bands containing with substantial energy, apparently linked to each sensor location (Fig. 8).
We also added a paragraph of discussion on noise in section 4, page 10 lines 15-22.

Why are the authors confident that what they are measuring is in fact slope movements (or pre-curser deformations)?

A.R.: *We are not measuring the slope movements. We are measuring the seismic waves generated by the slope. If the slope is simply sliding over a soft layered interface, no seismic waves are expected to be generated, resulting in an aseismic behaviour. In this case, we do not measure anything. We clarified this point in section 4: "Strictly speaking, our system does not record any slope movements but only the resulting seismic activity. If the slope is simply sliding over a soft layered interface, no seismic waves are expected to be generated, resulting in an aseismic behavior. This might be the case here, in a fully saturated rock glacier.", page 13, lines 7-13.*

This needs to be clearly explained. Statements are included about the geophones being covered by 'large stones' but this is not sufficient justification to exclude noise as a potential source.

A.R.: *Covering geophones by large stones avoids to detect the direct impact of the rain drop on the sensors, limiting thus the noise produced by the direct impact of the rain drops. However, another type of noise can perturb our analysis. The core of our method is to co-detect seismic signals. As by definition, a co-detection occurs only if the signal corresponds to the same source, uncorrelated noise is naturally filtered out, or at least does not change the long-term evolution of the number of co-detections. On the contrary, a large landslide or rockfall occurring in the vicinity of our experimental site could, in principle, result in a high number of co-detections as, in this case, the seismic signals are generated by a unique external source which has nothing to do with micro-cracks with the slope. However, this is highly unlikely and this should not produce seismic precursors.*
Moreover, our analysis is based on the temporal evolution of the number of co-detection, implying that the stationary noise is naturally filtered out (e.g. streams, flows)
We added a paragraph in the discussion on this issue page 10, lines 15-22.

The only independent measurements presented to compare with the micro-seismic records are daily surface GPS measurements and periodic photographs: neither of these allow micro-seismic events to be conclusively attributed to slope movements (or pre-curser deformations)
A.R.: *Considering both discussed "exogenous" examples, it appears that the time lapse photographs evidenced the occurrence of a landslide at the tongue. During these periods, the seismic activity was low except during the period shown in Fig. 6. We clearly already state this: "During these periods, the recorded seismic activity was low with almost no co-detections except during short periods", section 3.3, page 8, line 12.*

Abstract: The system is claimed to be low-cost, robust and autonomous. However, as stated in the conclusions, this is an area for future work. These claims should therefore be removed from the abstract as they are not a contribution of this paper.
A.R.: *OK. This was rather meant as working towards such robust systems, so we deleted this part of the sentence and rephrased it as:"This new strategy being theoretically valid for all types of failures, it constitutes a first step towards the development of a new early warning system for gravitational slope failure."*

Page 3: The measurement system should be explained in sufficient detail for readers to be able to replicate the work. For example, what pre-amplifiers were used, what gain settings, was filtering applied to the measurements?
A.R.: *We added further details to this:*
"The seismic experimental setup is composed of six geophones (Ion SM-6, one channel with a natural frequency of 10 Hz) directly wired to a central data acquisition unit (Fig. 1, right inset), ensuring a good time synchronization.
Each sensor is also embedded in a waterproof casing specially designed for these sensors (Fig. 1) . A pre-amplifier (Micro-Power Precision Operational Amplifiers - OPA 333 from Texas Instruments - with a gain of -57) was also installed to mitigate attenuation effects in the 20 meters cables (for more technical details, see appendix A).
A data acquisition unit was built and designed specially for this experiment. The analog signal is first amplified (OPA 4330 from TI, gain of 10) and filtered, then converted to a digital signal with an analog-to-digital converter (ADC) of 12 bits resolution. A mini computer Arduino records and stores on a SD card signal amplitude (0 +- 2048) of the 6 sensors at a sampling rate of 250 Hz. "
in the section 2.2 (page 4 line 4-12)

We also added a supplement with all the details (in a new Appendix A)
"
1) Preamplifiers at Geophone:
Micro-Power Precision Operational Amplifiers (OPA 333, or OPA244 from Texas Instruments) configured as inverting amplifier with capacitive coupling to Geophone, and pseudo balanced output.
Gain (fix): -57
High pass (1st order): 1.94Hz
Low pass (1st order): 720.48Hz
2) Input Amplifiers at Mainboard (Peli Case):
Micro-Power, Precision, Zero Drift CMOS Operational Amplifiers (OPA4330 from TI) configured as differential input amplifiers with capacitive coupling.
Gain (fix): 10
High pass (1st order): 1.59Hz
Low pass (1st order): 338.63Hz
3) Filter before ADC (same OPAmps as above):

Gain (fix): 2
Low pass (3rd order): 153.92Hz
4) Microcontroller ADC:
The A/D converter has a resolution of 12Bit.
Since the circuit is running on a single supply (3.3V, referenced to Ground), we have introduced a pseudo ground at 1.65V. In this way, when no geophone's signal is recorded, there is 1.65 V at the last filter stage, representing 2048 in the digital domain.
The maximal swing is therefore 2048 +/- 2047 (ADC values: 0.4095)
"

Page 12, line 2: 'water lubricates...'. As stated above, water elevates pore pressures which reduces shearing resistance.
A.R.: *We added a small paragraph in the discussion on this issue and indirect observations related to such quantities (e.g. water outflow):*
"Infiltration of liquid water in the rock glacier causes elevated pore pressure which reduces effective stress and hence shearing resistance. causing slope movement and its possible destabilization. Note that during the short peak velocity that occurred between 10-13 August, seismic activity and co-detection number stay at a very low level (Fig. 4), indicating aseismic displacement of the glacier. This period corresponds also to the appearance of an active stream at the tongue (see Fig. 2), indicating that the material is fully saturated.
Strictly speaking, our system does not record any slope movements but only the resulting seismic activity. If the slope is simply sliding over a soft layered interface, no seismic waves are expected to be generated, resulting in an aseismic behavior. This might be the case here, in a fully saturated rock glacier.", page 13, lines 7-13.

Page 12, lines 15 to 19: "analysing the spatial distribution of the sensors detecting this precursory seismic activity provides a rough estimate of the location of the potentially unstable zone" – This has not been addressed sufficiently in the manuscript; for example, no discussion has been included regarding the variable/heterogeneous nature of the subsurface and hence parameters needed for estimating wave propagation, e.g. Young's modulus, Poisson's ratio, density, are highly uncertain.

A.R.: *This is right. We have no clue about all these parameters. But as explained in the co-detection method, attenuation phenomenon affects the amplitude of seismic wave and only the sensors located closed to the source can detect a signal (i.e. amplitude of the signal higher than the RDT, see section3.2, page 7, lines 5-12). In this way, even without knowing all these parameters, the rough location of the source can be determined. This is in agreement with the two internally-driven events, where the sensors located closed to the event are actively detecting a seismic activity. We clarify this point in the text:*
"In both events shown in Fig. 6, the closest sensors to each event were mostly active prior to failure: sensors 2 and 3 before the July 20 event; sensor 1 and 6 before July 21 event.", section 4, page 14, lines 10-11.

Towards early warning of gravitational slope failure with co-detection of micro seismic activity: the case of an active rock glacier

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Abstract.

We developed a new strategy for Disaster Risk Reduction for gravitational slope failure: We propose to validate on a case study a simple method for real-time early warning of gravity-driven failures that considers and exploits both the heterogeneity of natural media and characteristics of acoustic emissions attenuation. This method capitalizes on co-detection of elastic waves emanating from micro-cracks by a network of multiple and spatially distributed sensors. Event co-detection is considered as surrogate for large event size with more frequent co-detected events marking imminence of catastrophic failure. In this study we apply this general method to a steep rock glacier / debris slope active rock glacier, a natural heterogeneous material sharing all relevant properties of gravitational slope failure, and demonstrate the potential of this simple strategy for real world cases, i.e. at slope scale. This low cost, robust and autonomous system provides a well adapted alternative/complementary solution for Early Warning Systems. new strategy being theoretically valid for all types of failures, it constitutes a first step towards the development of a new early warning system for gravitational slope failure.

1 Introduction

Slope and rock instabilities due to permafrost degradation, rockfalls, landslides, snow avalanches or avalanching glacier instabilities are common in high mountain areas. These gravity-driven rupture phenomena occurring in natural heterogeneous media are rare, but have a potential to cause major disasters, especially when they are at the origin of a chain of processes involving other materials such as snow (snow avalanche), water (flood) and/or debris (mudflow) (Gill and Malamud, 2014). They potentially endanger mountain communities or real estate development and are at the origin of huge human fatalities and economic costs (Petley et al., 2005; Sidle and Ochiai, 2006)(Petley et al., 2005; Sidle and Ochiai, 2006; Lacasse et al., 2009; Petley, 2012) . In the context of climate warming, degradation of permafrost is expected to further promote slope destabilization in high mountains and thus increase the occurrence of such natural disasters (Gruber et al., 2004). Because of the potential magnitude of such catastrophic phenomena, a reliable forecasting combined with a timely evacuation of the endangered areas is often the most effective way to cope with such natural hazards. However, the nonlinear nature of geological material failure hampered by inherent heterogeneity, unknown initial mechanical state, and complex load application (rainfall, temperature, etc.) hinder predictability.

Slope stability assessment is often based on monitoring In the last decades, landslide hazard analysis and risk assessment have become a major subject in landslide studies, leading to recent advances in local landslide early warning systems (Chae et al., 2017) . Such systems are based on different monitoring strategies (ground-based or remote sensing) (Chae et al., 2017), as well as on a variety of methods and techniques (for a review, see Pecoraro et al., 2019), possibly involving long-term monitoring of event precursors (Stähli et al., 2015). In general slope stability assessment (and prediction of slope failures) are based on the long-term monitoring and analysis of the temporal evolution of external parameters such as geometry, surface displacement (or surface velocity) as well as on the observation of external forcing such as meteorological/climatic conditions (e.g., rainfall duration and intensity, temperature, wind, snow accumulation,...).

On the basis of a theoretical/modeling study, Faillettaz et al. (2016) recently proposed a new method to investigate natural slope stability based on continuous monitoring and interpretation of seismic waves generated by the potential instability before the failure - i.e. an internal parameter. This method capitalizes on both heterogeneity and attenuation properties of natural media for developing a new strategy for early warning systems: As heterogeneous materials breaks gradually, with their weakest parts breaking first, they produce precursory "micro-cracks" with associated elastic waves traveling in the material. Therefore the monitoring of such micro-seismic activity offers valuable information concerning the progression of damage and imminence of global failure (Michlmayr et al., 2012)(Michlmayr et al., 2012; Faillettaz and Or, 2015). Such monitoring are providing new insights into the imminence of break-off and in some cases it has been applied to natural gravity-driven instabilities such as cliff collapse (Amitrano et al., 2005), slope instabilities (Dixon et al., 2003; Kolesnikov et al., 2003; Dixon and Spriggs, 2007), glacier break-off (Faillettaz et al., 2011) or failure in snow pack (Van Herwijnen and Schweizer, 2011; Reiweger et al., 2015). However, as elastic waves travel in the material, their amplitudes decay with distance from the source. Due to attenuation of propagating acoustic/seismic signals (elastic waves), an event (i.e., a crack formation in the material) may also be observed and recorded differently by an acoustic/seismic sensor depending on its location. Theoretical considerations based on simple numerical modeling suggest that, although statistical properties of attenuated signals amplitude could lead to misleading results, detecting emergence of large events announcing impeding failure (precursors) is possible even with attenuated signals (Faillettaz et al., 2016). It requires a network of (seismic/acoustic) sensors on a potential unstable slope and and the detection of events in real time. Real-time processing of measured events that are detected concurrently on more than one sensor (co-detected) enables then to easily access their initial magnitude as well as their approximate initial location. This simple method based on co-detection of elastic waves traveling through natural media provides a simple means to access characteristics and temporal evolution of surrogate variables linked to hillslope damage and mechanical state. For this method to function, temporal synchronization between sensors must be sufficiently accurate to reliably classify events detected simultaneously by multiple sensors, therefore the sensor network needs to be precisely synchronized. Preliminary application to acoustic emissions during failure of snow samples at lab scale has confirmed the potential usefulness of co-detection as indicator for imminent failure.

To demonstrate the application potential of this simple strategy for Early Warning Systems to real cases, i.e. at slope scale, we designed and built an experimental system composed of a network of six seismic sensors wired to a data acquisition unit, ensuring an interleaved sampling time synchronization between sensors. This experimental setup was installed and tested on the steep tongue of the Dirru rock glacier, a location where small scale slope instabilities were highly probable. Note that the steep slope is composed of an highly heterogeneous material consisting of a mixture of ice, rock, fine sediment, air and water. In this study, we show the first results of the analysis of the seismic activity generated by the steep tongue during summer 2017. Thanks to a meteorological station located closed to the rock glacier and L1 Differential GPS unit on the rock glacier (Wirz et al., 2013), we were able to investigate the relation between seismic activity, surface displacement and external forcing (rainfall, temperature). Using additional webcam images with a time interval of 30 minutes, we identified three small scale failure events (of approximately 10 cubic meters each) and analyze the associated number and temporal evolution of co-detection prior to to failure. This co-detection analysis showed typical patterns of precursory events prior failure, demonstrating thus the potential of this method for real world applications in early warning. Moreover, this seismic method provides new insights on the rock glacier dynamics, especially the short term peaks of velocity in relation to external forcing.

The motivations of this study are twofold: First, it aims at testing the applicability of the co-detection method at the slope scale and thus at demonstrating its application potential in the context of natural slope stability assessment. Second, as our experiment was deployed on a fast moving rock glacier, we had the opportunity to investigate, for the first time, the seismic activity emitted by the glacier tongue and its link to complex rock glacier dynamics.

The paper is organized as follow: After describing the study site and the experimental setup, we performed the analysis of the co-detection method and demonstrate its potential applicability to early warning of gravity driven geofailure. Comparing results with all available data, ranging from surface displacement to meteorological data, complex rock glaciers dynamics is discussed in the light of these new observations.

2 Study site and experimental setup

2.1 Study site

The study site is located in the area of the Dirruhorn in the Matter Valley, above Herbriggen/Randa, Switzerland. The mainly westerly exposed slopes range from 2600 to 4000 m a.s.l.. Permafrost is abundant in this area (Delaloye et al., 2010). The field area includes various cryosphere-related slope movements: e. g. exceptionally fast and potentially dangerous rock glaciers moving up to 10 m/a (Delaloye et al., 2010). The rock glacier Dirru is composed of various lobes and fronts, originating from different rock glacier generations. The currently active lobe, which is located on the orographic right side of Dirrugrat, has a total length of more than 1 km, is about 60 to 120 m wide, and is approximately 20 m thick (Wirz et al., 2016b). It has a convex profile and slope angles increase from about 15^o in the upper part to more than 30^o in the lower part towards its front. Since the 1970/80s this steep frontal part (tongue) has progressively accelerated and reached surface velocities above 5 $\mathrm{m.a}^{-1}$, potentially indicating a phase of destabilization (Delaloye et al., 2013). Its front already collapsed in some parts in the recent past. At this front, water emerges occasionally in spring and summer. Based on past photographs, it was found that the actual acceleration phase of its frontal part started progressively during 1970s and 1980s and that the origin of the destabilization of the entire rock glacier seems to be older (Delaloye et al., 2013; Wirz et al., 2016b).

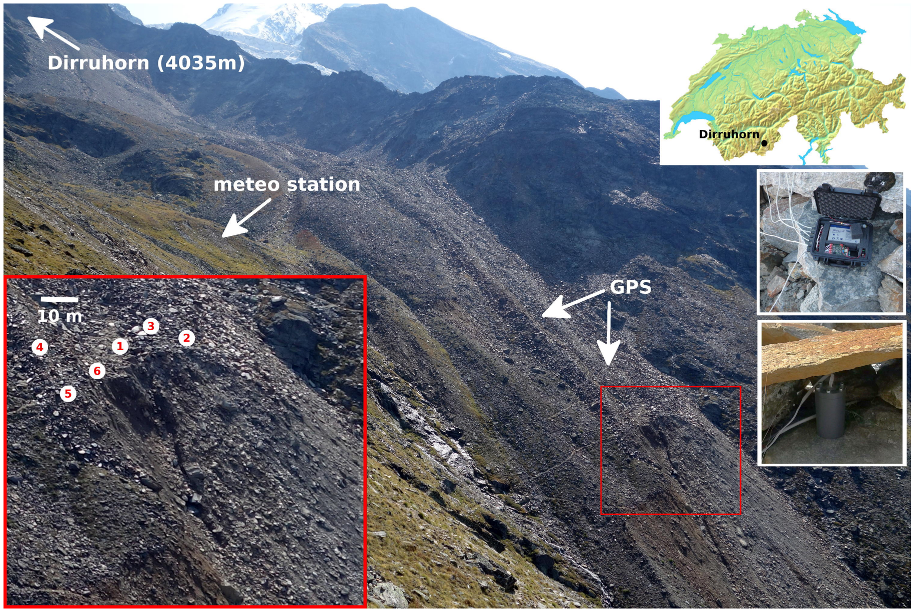

Figure 1. General view of the Dirru rock glacier. White arrows indicate the location of the GPS and meteo stations installed on the rock glacier and analyzed in this study. Bottom left inset: Location and associated number of each sensor installed near the steep tongue of the Dirru rock glacier. Top right inset: General location of Diru glacier. Middle right inset: View of the central data acquisition unit, each sensor being wired to this unit. Bottom right inset: View of a sensor installed on the field with a large rock sheltering it.

2.2 Field experiment setup

The seismic experimental setup is composed of six geophones (Ion SM-6, one channel with a natural frequency of 10 Hz) directly wired to a central data acquisition unit (Fig. 1, right inset), ensuring a good time synchronization. Each sensor is also embedded in a waterproof casing specially designed for these sensors (Fig. 1) . A pre-amplifier (Micro-Power Precision Operational Amplifiers - OPA 333 from Texas Instruments - with a gain of -57) was also installed to mitigate attenuation effects in the 20 meters cables (for more technical details, see appendix A). A data acquisition unit was built and designed specially for this experiment. ~~It is composed of a~~ The analog signal is first amplified (OPA 4330 from TI, gain of 10) and filtered, then converted to a digital signal with an analog-to-digital converter (ADC) of 12 bits resolution. A mini computer Arduino ~~able to record and store~~ records and stores on a SD card signal amplitude (0± 2048) of the 6 sensors at a sampling rate of 250 Hz.

The procedure for recording data is the following: As soon as a signal with an amplitude higher than a preset threshold is detected, the ~~Analog to Digital Converter (ADC)~~ ADC is powered on and data is recorded from all sensors for one second. If, during this period, one of these sensors records an amplitude higher than the preset threshold, the whole array continues to record for another whole second. If the activity is high, this procedure could result in a single long record. During the monitoring period (11 July - 5 September 2017) the maximum duration of a signal was around 500 seconds.

Besides the highly probable occurrence of failure events during summer, this site was also selected for a pilot experimental study because of the proximity to other concurrent measurements setup during the Xsense I and II projects (Wirz et al., 2016a, b) . During this period, air temperature and precipitations were monitored (from the ~~meteo~~ meteorological station installed few hundreds meters from the tongue, see Fig. 1) along with a webcam that took images from the tongue at a 30 minutes interval (Fig. 1). These images provide valuable information on the timing, the location and the rough magnitude of failure events occurring at the the tongue. Events ranging from single rockfalls/rockslides to large slides were detected. Analyzing the seismic activity during these short periods provides a unique way to investigate the seismic signature of each event, and thus to characterize the potential precursory seismic signals associated with each event. During bad weather conditions the webcam images were obscured by fog, but this only occurred a few days during the observation period in summer (<7 days). Two differential L1-GPS sensors permanently installed on the fast moving part of the rock glacier were also monitoring surface displacement (Fig. 1).

3 Results and analysis

3.1 General overview of meteorological conditions and rock glacier dynamics

Fig. 2 shows temperature, precipitation and surface velocity of the rock glacier at two different locations (Fig. 1), over the monitoring period in summer 2017. As already observed for earlier years by Wirz et al. (2016a), rock glacier movement shows a seasonal pattern with an increase starting with the snow melt and reaching maximum flow in late summer/early autumn. In addition to these seasonal variations, short-term peaks in surface velocity are also recorded, in agreement with previous observations ~~(Wirz et al., 2016b)~~(Wirz et al., 2016a, b). During such peaks, velocity approximately double over a period of a few days to speeds of a few centimeters per days (2 to 5 cm.d^{-1}) and drop rapidly to their initial value. These peaks seem to be related to the presence of large amounts of liquid water within the glacier. Indeed they appear after intense precipitation events or during the snowmelt period. Moreover, a stream spilling out of the tongue, indicating substantial flux of liquid water within the rock glacier, was observed four times in the summer period (May to September) and once during the monitoring period, i.e. 11 July - 5 September 2017 (indicated with a red band on Fig. 2). Note that the occurrence of such water outflow is also concomitant to such short-term speed-up events.

Fig. 3 shows the hourly seismic activity (seismic hit probability) emanating from the rock glacier tongue during the monitoring period. Seismic activity shows a clear correlation with air temperature: The number of seismic events is increasing during the day, reaching its maximum concurrently to the maximum in air temperature. Further, the seismic activity is shown to be clearly higher during periods when liquid precipitations occurred (Fig. 3 inset). As a result, the seismic activity generated by the steep rock glacier tongue appears to be strongly correlated with both air temperature and the presence of liquid water (rainfall or snowmelt).

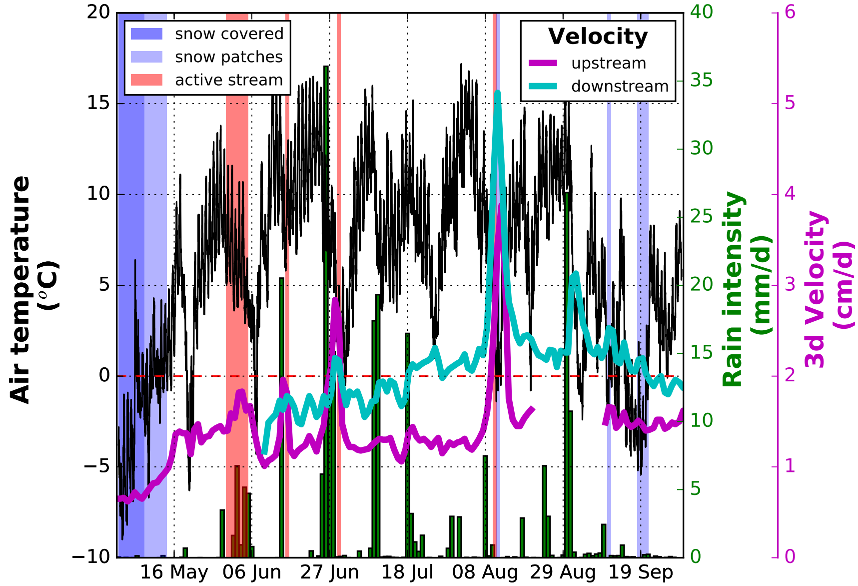

Figure 2. Temperature (black line), precipitations (green bars) and surface velocity (blue and magenta line) of the rock glacier during summer 2017. Upstream and downstream velocities refers to the velocities of two differential L1 GPS stations located in the upper and lower part of the rock glacier tongue, respectively. Red bars in background indicate periods when a stream was spilling out the rock glacier tongue, dark blue period when snow fully covered the rock glacier and light blue periods when snow only partially covered the rock glacier.

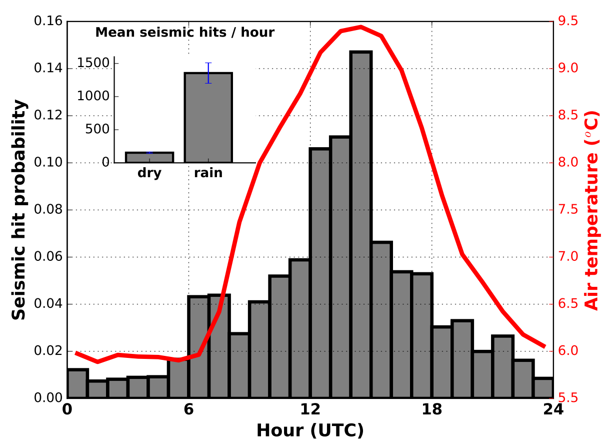

Figure 3. Mean hourly seismic activity (expressed in hits per hour) during the seismic monitoring period (11 July - 5 September 2017). The inset shows the difference in seismic activity between wet (i.e. when liquid precipitations occurred) and dry days.

3.2 Co-detection

The number of co-detection is defined as the number of sensors that detect an event emanating from the same source (i.e., the signal amplitude is larger than a predefined threshold). In practice, we counted the number of sensors detecting a signal within a short period (here 0.1 second), this time window being evaluated according to the sensor spacing and the signal propagation in the medium. Although the real detection threshold (RDT) is given by the properties of the sensors and the setup, it could be increased enhance during the post analysis, as the full waveforms of the seismic signals are concurrently recorded and the trigger threshold in the original setup set sufficiently low. Fig. 4 shows (a) the number of co-detection as a function of time using different detection thresholdspost analysis detection thresholds (PADT) based on the amplitude of the recorded digital amplitude of the waveforms (ranging from -2048 to 2048), the larger the thresholdPADT, the less sensitive the detection (the numbers given - 500 to 2000 - are arbitrary, without unit, corresponding to the amplitude of recorded digital signal), (b) which sensor is detecting an event, (c) the daily seismic hits, the mean daily velocity from two different locations and (d) the air temperature and precipitation during the monitoring period.

In general, the number of co-detections exhibits similar trend as the seismic activity (total number of seismic events detected by the network, independently of their amplitudes or energy, third panel of Fig. 4): During the monitoring period, three periods with high seismic activity and high number of co-detection can be highlighted (17-21 July, 8-11 August and 1-4 September). The initiation of these active seismic phases occurred after wet periods (rainfall event or snow melt event, i.e periods of high air temperatures). Whereas surface velocity exhibits a slightly increasing trend (except few velocity peaks shortly after or close to enhaced seismic activity), the seismic activity or the number of co-detection show a different temporal variation pattern during the monitoring period and even a calm period (e.g. 13-20 August, Fig. 4c), indicating that glacier dynamics and seismic activity are not directly correlated.

As already shown in Fig. 3, a rainfall event (i.e., a direct addition of liquid water on the rock glacier) increases seismic activity at the tongue, but Fig. 4 shows that the response is not linear: Low precipitation rates are sometimes related to high activity (e.g. 7^{th} August), whereas during large rainfall events only a small increase in seismic activity is recorded (e.g. 17^{th} July).

The sensors 2 and 3, located closed to the steep left-side front, are detecting more seismic events than the others, whereas sensor 4, located few tens of meter upstream the front, detects substantially less events. Even if these sensors are not located that far apart (less than 50 meters), the recorded seismic activity is substantially different, demonstrating thus that the attenuation phenomenon has a huge influence on seismic monitoring.

3.3 Destabilization process and associated seismic precursors:

In general, slope destabilization can result either from dynamical or Classically failure of infinite slopes is described by an equation (called factor of safety) that balances the downslope component of (gravitational) driving stress against the resisting stress (due to basal Coulomb friction, mediated by pore water pressure). In this concept slope destabilization results either due to an increase in the driving stress or to a decrease in the resisting stress. In general, a combination of dynamical and

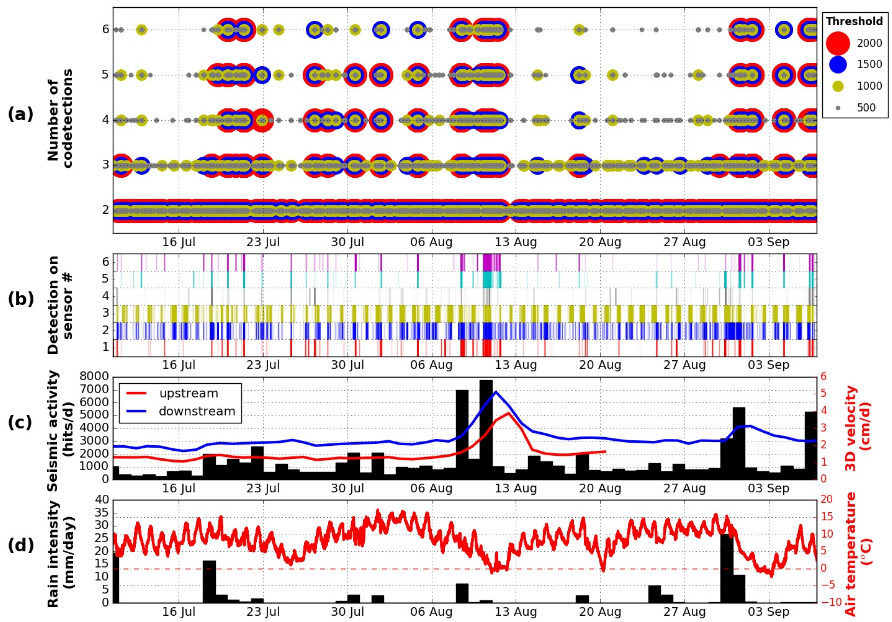

Figure 4. (a) Number of co-detections as a function of time using different detection thresholds (colored different sized circles), the larger the threshold, the less sensitive the detection (the numbers given - 500 to 2000 - are arbitrary, without unit), (b) Event detection per sensors number, each vertical line represents a detected seismic event (c) Daily seismic hits (bars) and mean daily velocity from two different GPS locations (blue and red lines), (d) Air temperature (red line) and liquid precipitations (black bars) recorded at the meteorological station located few hundreds of meters from the tongue (see Fig. 1). The seismic monitoring period ranges from 10 July to 5 September.

quasi-static processes, respectively from a processes can lead to the change of one of these components: an initial change in the external forcing (i.e.exogenous failure) or e.g. rainfall, meltwater, earthquakes, etc.) and from internal changes (i.e., endogenous failure). Resulting seismic signatures of such types of failure are expected to thus be different. The different type e.g. increase in internal damage, leading to a decrease in resisting stress).

The different types of data from our field experiment allows to identifyand analyze both exogenous and endogenous failures allow to identify, isolate and analyze carefully both processes during the monitoring period. Failure events were detected using the webcam images with a temporal resolution of 30 minutes (when usable). Results are shown in Fig. 6 and 7.

During the monitoring period, we identified two clear failure events corresponding to endogenous (internal) failures internally-driven events (Fig. 6): Differences between consecutive usable webcam images show undoubtedly small "landslide"-type events (3-10 m^3) occurring at the tongue during dry periods. According to the webcam images, such confirmed debris-slides occurred (i) between July 19 at 19:40 and July 20 at 06:10 (a long time interval because of night) and (ii) on July 21 between 09:40 and 10:10. During these periods, the recorded seismic activity was low with almost no co-detections except during short periods,

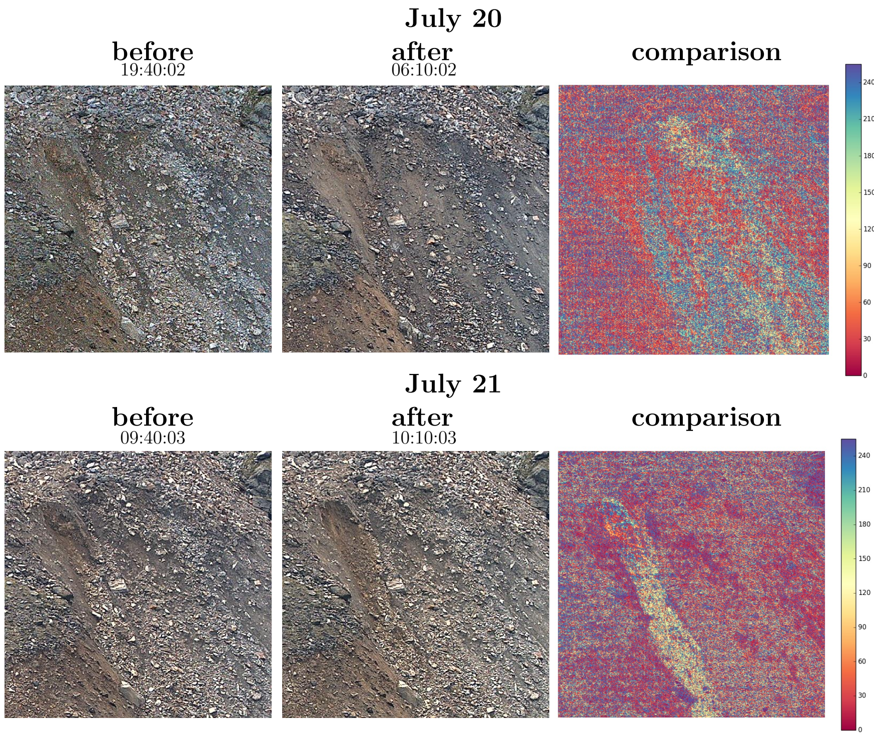

Figure 5. Close-up images (800 * 800 pixels) taken from the webcam during the ~~endogenous failures~~ internally-driven events of 20th July and 21st July 2017. First column shows the last exploitable image (with its exact timing) before the associated event, the second column the first exploitable image after the event. The third column shows the differences ~~,~~ between the two images using a heatmap (arbitrary ranging between 0 and 256) where yellow and blue colors highlight locations experiencing the larger mismatch between images. These differences are evaluated for each pixel as the maximum of the absolute difference on each channel (red, green and blue) separately.

i.e. on 20 July at 00:45 and on 21 July at 09:45 (Fig. 5). As landslide-type events release high seismic energy generating large seismic waves (e.g. shocks between rolling blocks), these high numbers of co-detection might correspond to the exact timing of the occurrence of the instabilities. As no rainfall occurred during and in the 2 days preceding these events, the destabilization was not directly triggered by changes in external forcing, and could thus be attributed to an ~~endogenous failure~~internally-driven event. The detailed analysis of the co-detection monitoring of two of these periods is shown on Fig. 6. These ~~endogenous~~ internally-driven events exhibit strong similarities: (1) a clear increase in seismic activity and increasing number of co-detection about 45 minutes prior to the failure event (a pattern as expected by (Faillettaz et al., 2016)), (2) the occurrence of a precursory event 10 to 15 minutes prior the main failure, (3) a strong increase in the number of detection of the sensors located close to the final event, allowing to some degree to locate the final event (event 20 July between sensor 2 and 3, 21 July between 1 and 6 and 31 August near 2).

Table 1. The different types of failure and their associated behavior

Failure type	Seismic activity	Co-detection number	Precursor	Power spectral density
exogenous externally-driven	high	low	no	low
endogenousinternally-driven	high	high + increasing	yes, 10-15 minutes	high

Exogenous failures (externally driven) Externally-driven events were also identified from the webcam images during large rainfalls. The detailed analysis for two typical events is shown in Fig. 7. In such cases, a different seismic activity has been recorded: Although the seismic activity is very high, there is only a few co-detections, indicating that such seismic events have low amplitudes. In contrast to endogenous failureinternally-driven events, no clear precursors can be found. Moreover, the analysis of the spectrograms shows a clear difference in the frequency content of these events: whereas endogenous failure internally-driven event exhibits a dominant frequency around 20-40 Hz (highlighted in red in Fig. 8), exogenous event externally-driven events are less energetic, with only a few isolated frequency bands containing with substantial energy, apparently linked to each sensor location (Fig. 8).

4 Discussion

Seismic waves captured by our geophone-network system can be produced by the initiation or propagation of internal cracks, by the landslide event itself but also by surface activity, i.e. small rock sliding and rolling on the steep tongue, or rearrangement of the larger blocks located at the surface of the rock glacier. The direct impact of rainfall on the geophone can also create seismic signals (noise), but, as we sheltered the sensors by large stones (Fig. 1), we will excluded this process as a potential source of seismic activity.

However, other types of noise (background/environmental/extraneous) can perturb our analysis. The core of our method is to co-detect seismic signals. As by definition, a co-detection only occurs if the signal corresponds to the same source, uncorrelated noise will be naturally filtered out (although each sensor can individually detect noise). On the contrary, a large landslide or rockfall occurring far outside our experimental site could, in principle, produce a high number of co-detections: in this case, the micro-cracks activity resulting from the evolution of internal slope damage is too far away to be detected whereas the slide will generated co-detected seismic signals (a unique remote extraneous source). However, we did not observe any of these highly unlikely events during this study. Moreover, our analysis is based on the temporal evolution of the number of co-detections, implying that the stationary / constant noise will not perturb our results.

During periods with external forcing (i.e. rainfall, snow melt periods), it appears that exogenous seismic activity is rather distributed along all the sensors, indicating an homogeneous distribution of seismic events over the rock glacier (Fig. 4b). Movements in unconsolidated materials (or over a pre-exisiting pre-existing failure plan) or progressive melting under large superficial blocks are not expected to produce seismic waves. Moreover, such exogenic externally-driven events appear to be less energetic with longer duration (Fig. 8) than the endogenous internally-driven events (Fig. 6 and 7). This suggests that the

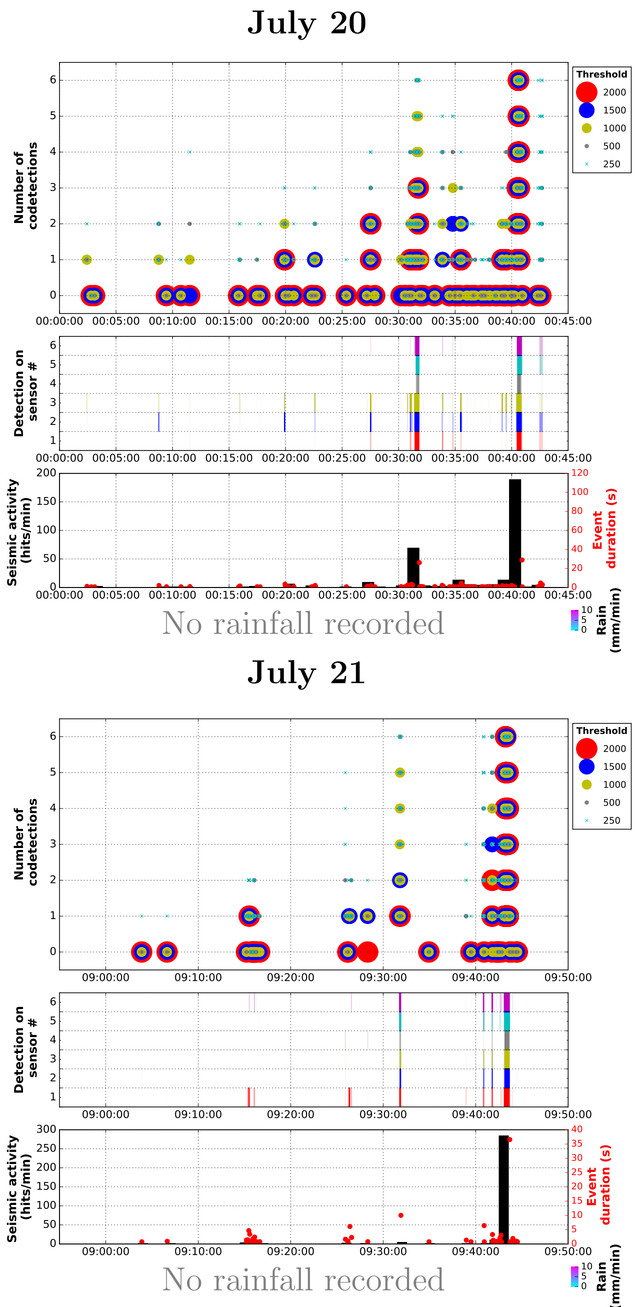

Figure 6. ~~Endogenic failure~~ Internally-driven event (top panel: 20 July, bottom: 21 July): Number of co-detection using different thresholds (same arbitrary unit as in Fig. 4), their associated detecting sensors, the corresponding seismic activity (and event duration) and the precipitation record during this period.

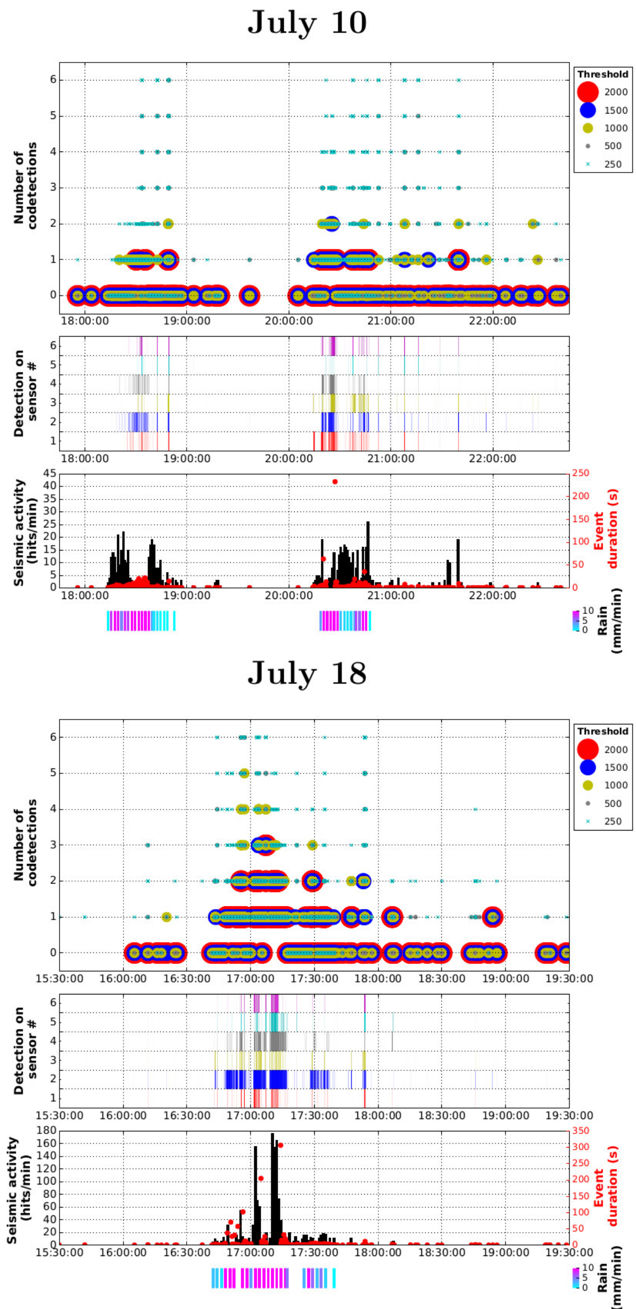

Figure 7. ~~Exogenic failure~~ Externally-driven event (top panel: 10 July, bottom: 18 July): Number of co-detection using different thresholds, their associated detecting sensors (same arbitrary unit as in Fig. 4), the corresponding seismic activity (and event duration) and the precipitation record during this period.

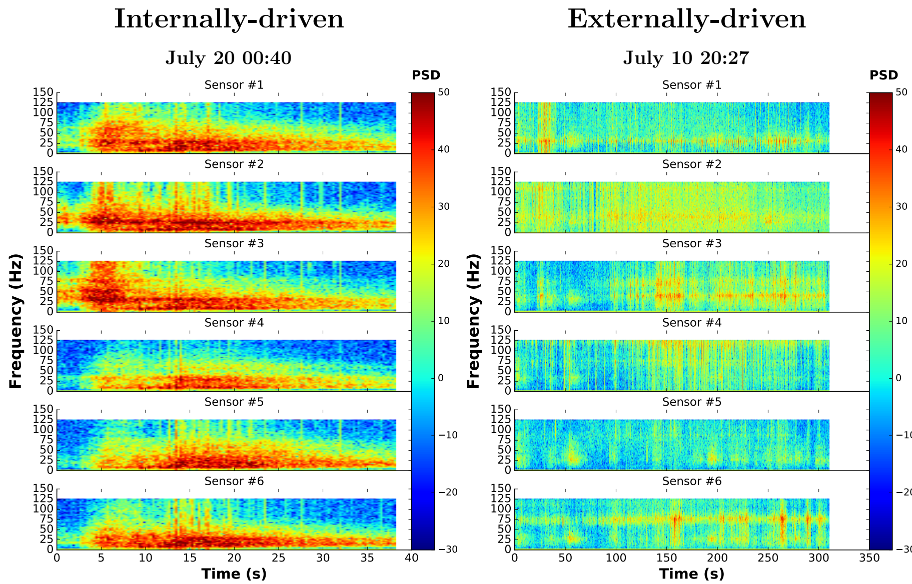

Figure 8. Typical power spectral densities (i.e. spectrograms) associated with ~~endogenic~~ internally and ~~exogenic~~ externally-driven events, plotted with the same scale. Frequency domains are colored from red for high power to blue for low power.

~~exogenous~~ externally-driven seismic activity is mainly produced by the sudden rearrangement of the superficial blocks of the rock glacier: As the rock glacier experiences superficial acceleration, the blocks located at the surface can be moved to unstable positions. Rainfall events can then trigger sudden readjustment of superficial blocks, as water lubricates the contacts between the larger blocks and thus reduces friction. Of course, blocks located near to the steepest part of the tongue might also slide and roll, thus explaining the slight increase in seismic activity detected close to the tongue. ~~No precursory signs of failure is thus expected for exogenous failures~~

Infiltration of liquid water in the rock glacier causes elevated pore pressure which reduces effective stress and hence shearing resistance. causing slope movement and its possible destabilization. Note that during the short peak velocity that occurred between 10-13 August, seismic activity and co-detection number stay at a very low level (Fig. 4), indicating aseismic displacement of the glacier. This period corresponds also to the appearance of an active stream at the tongue (see Fig. 2), indicating that the material is fully saturated. Strictly speaking, our system does not record any slope movements but only the resulting seismic activity. If the slope is simply sliding over a soft layered interface, no seismic waves are expected to be generated, resulting in an aseismic behavior. This might be the case here, in a fully saturated rock glacier.

As our co-detection strategy makes possible to separate ~~endogenous from exogenous~~ externally and internally-driven activity, periods, timing and locations of debris release can be quantified and, hence, rough estimates of debris delivery from the tongue can potentially be derived. Such information is needed for debris flow modeling, as the initial volume of unstable debris is a key parameter to model debris flow runout.

We analyzed different "landslide"-type events based on our new strategy and concurrently analyzed the variations of glacier velocity during this period. In this particular experiment, two ~~endogenous~~ internally-driven events (on 20 and 21 July) occurred during relative "slow" periods (1-3 cm/d, see Fig. 4) and a low seismic activity emanating from the tongue. In contrast, the co-detection analysis combining different post analysis thresholds showed a clear increase before each event, thus indicating that the proposed strategy has for this particular example a better potential application to prediction of failure than seismic activity or even surface displacement. The co-detection method provides also another metric helping experts to assess slope stability, this metric being related to the ongoing destabilization of the rock glacier.

In this pilot study we were able to find precursory signs announcing the impeding failure for small landslides. Moreover, analyzing the spatial distribution of the sensors detecting this precursory seismic activity provides a rough estimate of the location of the potentially unstable zone. In both events shown in Fig. 6, the closest sensors to each event were mostly active prior to failure: sensors 2 and 3 before the July 20 event; sensor 1 and 6 before July 21 event. The existence of precursors to catastrophic failure highly depends on the nature of the rupture process (Faillettaz and Or, 2015). For ductile-like rupture, a lot of precursors are expected to occur, suggesting thus a high potential for Early Warning perspectives. In contrast, for brittle-like rupture, even if precursors exist, they are seldom (Faillettaz and Or, 2015). In this case, the ongoing destabilization is expected to be more difficult to detect in advance. However, the proposed method has clear potential to assess the general type of rupture by studying the effect of external forcing (rainfall for example) on the generated seismic activity. As Faillettaz and Or (2015) proposed with their universal global failure criterion (damage weighted stress), a sudden change in external forcing may directly imply an enhanced production of seismic waves for ductile-like failure. In contrast, for brittle-like failure, the external forcing is not expected to produce any additional seismic activity. Studying the seismic response to a change in the external forcing would then offer a direct characterization of the nature of the rupture at stake on a particular slope. In this way, even if no seismic activity is recorded during a change in external forcing, the system might also provide new insights on the nature of the studied instability. "Listening to silence" in combination with observing external forcing might also be as relevant as capturing seismic events.

To really assess efficiently slope stability, a long term monitoring is needed. As every slope is different (composed of different materials, having different external forcing,...), their behavior will differ. Therefore, the instantaneous seismic activity emanating from the slope does not provide conclusive information for stability assessment purposes. Continuous monitoring of the seismic activity over a long period will allow to establish a reference state enabling then to detect potential changes and trends in behavior, and therefore to estimate/assess the state of stability.

We demonstrated that the sudden increase of co-detected events is a good indicator of slope destabilization, providing more insights than seismic activity. However, defining a suitable criterion based on the number of co-detections for assessing slope stability and provide early warning perspectives still needs to be determined. Analyzing concurrently the same set of data (waveforms) using different post-analyzed detection threshold allows to better characterize the size and location of the precursory events. However, it is not clear if such analysis is able to determine such a robust threshold criteria for co-detection, the maximum co-detection number, i.e. the number of sensors, being too small (six) to characterize an increase. Moreover, different metrics can be used to define a criterion suitable for early warning: Such criterion could be based on (i) an absolute number of co-detected events which would be easy to be implement in real-time, but, as every slope is different, such type of criterion might depend on the overall background noise and number and spatial arrangement of the sensors; (ii) on the differences in the temporal evolution of co-detections for different detection thresholds; or on (iii) the statistics of "record breaking" events, in the same way as in the mean field model of fracture Danku and Kun (2014). Records are bursts (i.e. seismic events) which have the largest size since the beginning of the time series, hence their behavior involves extreme values statistics. Danku and Kun (2014) showed that, thanks to such analysis, two regimes of the failure process can be identified, one dominated by the disorder of the material (corresponding to a relative slowdown of the records dynamics) and another dominated by the enhanced triggering of events towards failure (characterized by a temporal acceleration of the record dynamics). Performing such type of co-detection analysis would provide a direct way to assess the time of the failure, even if the initial state is not known.

5 Conclusions

In order to demonstrate the application potential of this simple co-detection strategy for Early Warning Systems to real cases, i.e. at slope scale, we designed and built an experimental system composed of a network of six geophones wired to a central recording unit, ensuring thus a perfect time synchronization between the sensors. This experimental setup was installed and tested on the steep tongue of the Dirru rock glacier, a location where small scale slope instabilities were highly likely. To our knowledge, this constitutes the first detailed seismic study on a rock glacier. Note that the steep slope is composed of an highly heterogeneous material resulting from a mixture of ice, rock, fine sediment, air and water. In this study, we present the first results and analysis of the seismic activity generated by the steep tongue during summer 2017. Using additional data from a meteorological station and GPS located on the rock glacier, we were able to investigate the relation between seismic activity, surface displacement and external forcing (rainfall, temperature). Using an additional webcam taking images at a time interval of 30 minutes, we could identify three small-scale failure events (of approximately 10 cubic meters) and analyzed the associated number of co-detected events prior to failure. This detailed analysis allowed us to detect typical patterns of precursory events prior slide events, demonstrating the potential of this method for a real word applications. Moreover, such a seismic method provides new insights on the rock glacier dynamics, especially on the short term peaks of velocity in relation with external forcing. Additionally, as this simple strategy filters out the small seismic events (generally produced by ~~exogenous failure~~externally-driven event), only the information relevant for slope stability assessment is delivered and analyzed.

As a next step we propose to develop low-cost tightly integrated sensors that can communicate the relevant seismic data in a wireless manner and in real time with a sufficient time synchronization (less than 0.1 s). As the principle of this method is quite general and is virtually applicable to all gravity-driven instabilities, potential applications are numerous ranging from natural hazard prevention and warning of snow avalanches, rockfall, landslides, debris flow, moraine stability, glacier break-of to glacier lake outburst,.... Thanks to its simplicity and its robustness, this new strategy would (a) reduce the amount of data to be processed (as only the precise detection time is needed, not the waveform), (b) simplify data analysis and thus enable on-site real time analysis, (c) provide low energy monitoring solution and (d) have low production cost. This new system - that tracks the in situ evolution of a potential unstable slope in real time- would provide a low cost, robust and simple simple and complementary alternative to the existing Early Warning Systems.

Author contributions. Jérome Faillettaz designed the field experiment. Jérome Faillettaz prepared the data, performed all the data analysis and made the figures in Python 3 with input and advice from the other authors. Jérome Faillettaz prepared the manuscript with critical revision and final approval from all co-authors.

Competing interests. There is no conflict of interest

Appendix A: Complete technical specifications of the measurement system

1) Preamplifiers at Geophone:

Micro-Power Precision Operational Amplifiers (OPA 333 from Texas Instruments) configured as inverting amplifier with capacitive coupling to Geophone, and pseudo balanced output.

- Gain (fix): -57
- High pass (1st order): 1.94 Hz
- Low pass (1st order): 720.48 Hz

2) Input Amplifiers at Mainboard (Peli Case):

Micro-Power, Precision, Zero Drift CMOS Operational Amplifiers (OPA 4330 from TI) configured as differential input amplifiers with capacitive coupling.

- Gain (fix): 10
- High pass (1st order): 1.59 Hz
- Low pass (1st order): 338.63 Hz

3) Filter before ADC (same OPAmps as above):

- Gain (fix): 2
- Low pass (3rd order): 153.92 Hz

4) Microcontroller ADC:

The AD converter has a resolution of 12 Bit. Since the circuit is running on a single supply (3.3 V, referenced to Ground), we have introduced a pseudo ground at 1.65 V. In this way, when no geophone's signal is recorded, there is 1.65 V at the last filter stage, representing 2048 in the digital domain. The maximal swing is therefore 2048 +/- 2047 (ADC values: 0.4095).

Acknowledgements. This work was partly supported by the project X-Sense2 funded by the nano-tera.ch. The authors thank Diego Wasser for handling the technical development of this pilot field experiment and Pr. Reynald Delaloye (Univerty of Fribourg, Switzerland) for providing the webcam images.

References

Amitrano, D., Grasso, J. R.~~Grasso, and G. Senfaute(2005), ~~, and Senfaute, G.: Seismic precursory patterns before a cliff collapse and critical point phenomena, ~~*Geophys. Res. Lett.*, ~~Geophys. Res. Lett., 32, https://doi.org/10.1029/2004GL022270~~.~~, http://dx.doi.org/10.1029/2004GL022270, 2005.

Chae, B.-G., Park, H.-J., Catani, F., Simoni, A., and Berti, M.: Landslide prediction, monitoring and early warning: a concise review of state-of-the-art, Geosciences Journal, 21, 1033–1070, https://doi.org/10.1007/s12303-017-0034-4, https://doi.org/10.1007/s12303-017-0034-4, 2017.

Danku, Z. ~~, and F. Kun(2014), ~~and Kun, F.: Record breaking bursts in a fiber bundle model of creep rupture, ~~*Front. Physics*, 2~~Front. Physics, 2, 8, https://doi.org/10.3389/fphy.2014.00008~~.~~, http://journal.frontiersin.org/article/10.3389/fphy.2014.00008, 2014.

Delaloye, R., ~~C. Lambiel, and I. ~~Lambiel, C., and Gärtner-Roer~~(2010), ~~, I.: Overview of rock glacier kinematics research in the ~~swiss alps, *Geographica Helvetica*, ~~Swiss Alps, Geographica Helvetica, 65, 135–145, https://doi.org/10.5194/gh-65-135-2010~~.~~, https://www.geogr-helv.net/65/135/2010/, 2010.

Delaloye, R., ~~S. Morard~~Morard, S., Barboux, C.~~ Barboux~~, Abbet, D.~~ Abbet~~, Gruber, V.~~ Gruber~~, Riedo, M.~~ Riedo, and S. Gachet(2013), ~~, and Gachet, S.: Rapidly moving rock glaciers in ~~mattertal, *Mattertal–ein Tal in Bewegung, edited by: Graf, C., Publikation zur Jahrestagung der Schweizerischen Geomorphologischen Gesellschaft*, 29, 21–31.~~Mattertal, Mattertal–ein Tal in Bewegung, edited by: Graf, C., Publikation zur Jahrestagung der Schweizerischen Geomorphologischen Gesellschaft, 29, 21–31, 2013.

Dixon, N. ~~, and M. Spriggs(2007), ~~and Spriggs, M.: Quantification of slope displacement rates using acoustic emission monitoring, ~~*Can. Geotech. J.*, ~~Can. Geotech. J., 44, 966–976~~.~~, 2007.

Dixon, N., ~~R. Hill, and J. Kavanagh(2003), ~~Hill, R., and Kavanagh, J.: Acoustic emission monitoring of slope instability: development of an active waveguide system, ~~*ICE - Geotechnical Engineering*, ~~ICE - Geotechnical Engineering, 156, 83–95, https://doi.org/10.1680/geng.2003.156.2.83~~.~~, 2003.

Faillettaz, J. ~~, and D. Or(2015), ~~and Or, D.: Failure criterion for materials with spatially correlated mechanical properties, ~~*Phys. Rev. E*, *91*~~Phys. Rev. E, 91, 032~~,~~134, https://doi.org/10.1103/PhysRevE.91.032134~~.~~, http://link.aps.org/doi/10.1103/PhysRevE.91.032134, 2015.

Faillettaz, J., ~~D. Or, and I. Reiweger(2016), ~~Funk, M., and Sornette, D.: Icequakes coupled with surface displacements for predicting glacier break-off, J. Glaciol., 57, 453–460, https://doi.org/10.3189/002214311796905668, http://www.ingentaconnect.com/content/igsoc/jog/2011/00000057/00000203/art00007, 2011.

Faillettaz, J., Or, D., and Reiweger, I.: Codetection of acoustic emissions during failure of heterogeneous media: New perspectives for natural hazard early warning, ~~*Geophys. Res. Lett.*, ~~Geophys. Res. Lett., 43, 1075–1083, https://doi.org/10.1002/2015GL067435, http://dx.doi.org/10.1002/2015GL067435, 2015GL067435~~.~~, 2016.

Gill, J. C. ~~, and ~~and Malamud, B. D.~~Malamud (2014), ~~: Reviewing and visualizing the interactions of natural hazards, ~~*RG*, ~~RG, 52, 680–722, https://doi.org/10.1002/2013RG000445, http://dx.doi.org/10.1002/2013RG000445, 2013RG000445~~.~~, 2014.

Gruber, S., ~~M. Hoelzle, and W. Haeberli(2004), ~~Hoelzle, M., and Haeberli, W.: Permafrost thaw and destabilization of ~~alpine ~~Alpine rock walls in the hot summer of 2003, ~~*Geophysical Research Letters*, ~~Geophysical Research Letters, 31, https://doi.org/10.1029/2004GL020051~~.~~, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004GL020051, 2004.

Kolesnikov, Y. I., Nemirovich-Danchenko, M. M.~~Nemirovich-Danchenko~~, Goldin, S. V.~~Goldin, and~~ , and Seleznev, V. S.~~Seleznev (2003),~~ : Slope stability monitoring from microseismic field using polarization methodology, ~~*Nat. Hazard Earth Sys.*,~~ Nat. Hazard Earth Sys., 3, 515–521, https://doi.org/10.5194/nhess-3-515-2003~~.~~, http://www.nat-hazards-earth-syst-sci.net/3/515/2003/, 2003.

Lacasse, S., Nadim, F., Lacasse, S., and Nadim, F.: Landslide Risk Assessment and Mitigation Strategy, pp. 31–61, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-540-69970-5_3, https://doi.org/10.1007/978-3-540-69970-5_3, 2009.

Michlmayr, G., ~~D. Cohen, and D. Or(2012),~~ Cohen, D., and Or, D.: Sources and characteristics of acoustic emissions from mechanically stressed geologic granular media – ~~a review, *Earth-Sci Rev.*,~~ A review, Earth-Sci Rev., 112, 97 – 114, https://doi.org/10.1016/j.earscirev.2012.02.009~~.~~, http://www.sciencedirect.com/science/article/pii/S0012825212000293, 2012.

Pecoraro, G., Calvello, M., and Piciullo, L.: Monitoring strategies for local landslide early warning systems, Landslides, 16, 213–231, https://doi.org/10.1007/s10346-018-1068-z, https://doi.org/10.1007/s10346-018-1068-z, 2019.

Petley, D.: Global patterns of loss of life from landslides, Geology, 40, 927–930, https://doi.org/10.1130/G33217.1, https://doi.org/10.1130/G33217.1, 2012.

Petley, D. N., Dunning, S. A.~~Dunning, and~~ , and Rosser, N. J.~~Rosser (2005), *The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities*~~: The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities, pp. 367–374, Taylor & Francis~~.~~, 2005.

Reiweger, I., ~~K.~~ Mayer, K.~~ Steiner, J. Dual, and J. Schweizer(2015),~~ , Steiner, K., Dual, J., and Schweizer, J.: Measuring and localizing acoustic emission events in snow prior to fracture, ~~*Cold Reg. Sci. Technol.*,~~ Cold Reg. Sci. Technol., 110, 160 – 169, https://doi.org/http://dx.doi.org/10.1016/j.coldregions.2014.12.002~~.~~, http://www.sciencedirect.com/science/article/pii/S0165232X14002183, 2015.

Sidle, R. C. ~~, and H. Ochiai (2006), *Landslides: processes, prediction, and land use*~~and Ochiai, H.: Landslides: processes, prediction, and land use, vol. 18, American Geophysical Union~~.~~, 2006.

Stähli, M., Sättele, M., Huggel, C., McArdell, B. W., Lehmann, P., Van Herwijnen, A., ~~and J. Schweizer (2011),~~ Berne, A., Schleiss, M., Ferrari, A., Kos, A., Or, D., and Springman, S. M.: Monitoring and prediction in early warning systems for rapid mass movements, Natural Hazards and Earth System Sciences, 15, 905–917, https://doi.org/10.5194/nhess-15-905-2015, https://www.nat-hazards-earth-syst-sci.net/15/905/2015/, 2015.

Van Herwijnen, A. and Schweizer, J.: Seismic sensor array for monitoring an avalanche start zone: design, deployment and preliminary results, ~~*J. Glaciol.*,~~ J. Glaciol., 57, 267–276, https://doi.org/doi:10.3189/002214311796405933~~.~~, http://www.ingentaconnect.com/content/igsoc/jog/2011/00000057/00000202/art00008, 2011.

Wirz, V., ~~J. Beutel~~Beutel, J., Buchli, B.~~ Buchli~~, Gruber, S.~~ Gruber, and P. Limpach(2013),~~ , and Limpach, P.: Temporal characteristics of different cryosphere-related slope movements in high mountains, in~~*Landslide Science and Practice*~~: Landslide Science and Practice, vol. 4, pp. 383–390, Springer, https://doi.org/10.1007/978-3-642-31337-0–49~~.~~, 2013.

Wirz, V., ~~S. Gruber,~~ Geertsema, M., Gruber, S., and Purves, R. S.~~Purves~~: Temporal variability of diverse mountain permafrost slope movements derived from multi-year daily GPS data, Mattertal, Switzerland, Landslides, 13, ~~J. Beutel~~67–83, ~~I. Gärtner-Roer~~https://doi.org/10.1007/s10346-014-0544-3, https://doi.org/10.1007/s10346-014-0544-3, ~~S. Gubler, and A. Vieli(~~2016a~~)~~, .

Wirz, V., Gruber, S., Purves, R. S., Beutel, J., Gärtner-Roer, I., Gubler, S., and Vieli, A.: Short-term velocity variations at three rock glaciers and their relationship with meteorological conditions, ~~*Earth Surface Dynamics*,~~ Earth Surface Dynamics, 4, 103–123, https://doi.org/10.5194/esurf-4-103-2016~~.~~

~~Wirz, V., M. Geertsema, S. Gruber, and R. S. Purves (~~, https://www.earth-surf-dynam.net/4/103/2016/, 2016b~~), Temporal variability of diverse mountain permafrost slope movements derived from multi-year daily gps data, mattertal, switzerland, *Landslides*, , 67–83,~~ .