Multi-method monitoring of rockfall activity on the Mont Blanc (4,809 m a.s.l.) classic route to promote the adaptation of mountaineers

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Abstract. There are on average 35 fatal mountaineering accidents per summer in France. On average since 1990, 3.7 of them have occurred every summer in the *Grand Couloir du Goûter*, on the classic route up Mont Blanc (4,809 m a.s.l.). Rockfall is one of the main factors that explains this high accident rate and contributes in making it one of the most accident-prone areas in the Alps for mountaineers. In this particular context, the objective of this study is to document the rockfall activity and its triggering factors in the *Grand Couloir du Goûter* in order to disseminate the results to mountaineers and favor their adaptation to the local rockfall hazard. Using a multi-method monitoring system (5 seismic sensors, an automatic digital camera, 3 rock subsurface temperature sensors, a traffic sensor, a high-resolution topographical survey, 2 weather stations and a rain gauge), we acquired a continuous database on rockfalls over 68 days in 2019 and some of their potential triggering factors (precipitation, ground and air temperatures, snow cover, frequentation by climbers). At the seasonal scale, our results confirm previous studies showing that rockfalls are mostly frequent during the snowmelt period in permafrost-affected rockwalls. Furthermore, the unprecedented time precision and completeness of our rockfall database at high elevation thanks to seismic sensors allowed us to investigate the daily trigger of rockfalls. We found a clear correlation between rockfall frequency and air temperature with a 2-hours delay between peak air temperature and peak rockfall activity. A small amount of rockfalls seems to be triggered by the mountaineers. Our dataset shows that climbers are not aware of the variations in rockfall frequency and/or they cannot/won't adapt their behavior to this hazard. These results should help to define an adaptation strategy for climbers. Therefore, we disseminate our results in the mountaineering community, thanks to the full integration of our results into the management of the route by local actors. Knowledge built during this experiment has already been used for the definition and the implementation of management measures of the attendance for the summer 2020.

1 Introduction

Despite a growing body of scientific literature, several international entities such as the World Meteorological Organization (WMO), the Intergovernmental Panel on Climate Change (IPCC) or the Mountain Research Initiative (MRI) agreed on the profound lack of knowledge on the vulnerability of socio-economic activities to climate change in mountain areas. Echoing this observation, a review of studies by McDowell *et al.* (2019) on adaptation actions in glaciated mountain areas showed that the majority of the adaptation strategies are implemented in direct reaction to *stimuli* and do not respond to well thought-out plans, based on scientific knowledge and taking into account all the interacting socio-economic factors as well as the future effects of climate change. According to the authors, this results in a significant lack of medium- and long-term efficiency of the adaptation strategies.

Mountaineering is an emblematic activity, recently inscribed by UNESCO on the Representative List of the Intangible Cultural Heritage of Humanity (Debarbieux, 2020), strongly affected by climate change (Ritter *et al.* 2011; Temme, 2015; Probstl-Haider *et al.* 2016; Purdie and Kerr, 2018; Mourey *et al.* 2019). Mountaineers are now forced to adapt, in particular to growing hazards. The climbing parameters - technical difficulty, level of exposure to natural hazards and optimal periods for climbing - of the classic mountaineering route up Mont Blanc (4,809 m a.s.l., Mont Blanc massif – MBM – France), undoubtedly one of the most popular in the world (20,0000 passages per year; Mourey and Ravanel, 2017), have significantly changed because of the effects of climate change (Mourey *et al.* 2019). This evolution is mostly related to an increasing number of rockfalls in the west face of the *Aiguille du Goûter* (3,863 m a.s.l.), that includes the crossing of the *Grand Couloir du Goûter* and the ascent of the *Goûter* rock ridge ("*arête du Goûter*") leading to the *Goûter* refuge located at 3,835 m a.s.l. (Fig. 1). According to Magnin *et al.* (2015) this sector is located in a context of permafrost - any lithospheric materials with temperature remaining below or at 0°C for at least two years (NRCC, 1988; Van Everdingen, 1998; Fig. 1).

There are on average 35 fatal accidents per summer in mountaineering in France (Soulé *et al.* 2014). On average since 1997, 3.7 of those fatal accidents occurred in the *Grand Couloir du Goûter* (Mourey *et al.* 2018), hence its reputation in the media as the "couloir of death". Rockfalls directly explain 29 % of the accidents and are partly involved in 50 % of the accidents due to a fall of a climber in the couloir (Mourey *et al.* 2018). Rockfalls are therefore one of the main factors that explain this high accident rate and contribute in making it one of the most accident-prone areas in the Alps for mountaineers.

Despite the number of mountaineers and the high accident rate in the *Goûter* area, before the summer 2020, no management measures were initiated by the actors in charge of the route and only few scientific studies were carried out about the occurrence of rockfalls and their triggering factors. Based on 42 days of *in situ* visual observations during the day (8 am – 6 pm) in the summer 2011, Alpes-Ingé (2012) showed that a rockfall occurred on average every 28 minutes in summertime. However, this study has many limitations: rockfalls were not measured over the whole season nor during periods of bad weather (rain, fog, thunderstorms), nor at the end of the day, night and early morning. Lemarechal (2011) proposed, on the basis of a trajectography study, various possibilities for securing the crossing of the couloir such as purging of the face, installing block nets, protecting the crossing with a concrete structure or installing a footbridge. However, until now, no continuous observation of rockfalls was available to better characterize their occurrence and their triggering factors (temperature, rainfalls, snow cover, human activity).

Our study is motivated by the high number of accidents in the *Goûter* area and the fact that rockfalls are increasingly frequent (Mourey *et al.* 2019). Therefore, we aim at better characterizing the rockfall hazard and its origins in the *Goûter* area through an integrated approach of data acquisition and dissemination within the mountain community to promote the implementation of efficient adaptive behaviors and to avoid an increase in the number of accidents due to rockfalls, or even to reduce it. To meet our objective, we quantitatively documented the climbers traffic, the occurrence of rockfalls and their potential triggering factors in the *Grand Couloir du Goûter*. The comparison between rockfall occurrences and environmental parameters should enable us to identify the most favorable conditions for rockfall, while the analysis of the traffic will show if it is adapted to the local rockfall hazard or if a change in traffic is required.

In context of permafrost in high Alpine environments, rockfall occurrence is preconditioned by the structural and lithological characteristics of the rock (especially its degree of fracturing) and the topography of the rockwalls (Krautblatter *et al.* 2013; McColl and Draebing, 2019). Meteorological factors and ground characteristics such as the presence/absence of snow, precipitation, air and ground temperatures will initiate thermo-mechanical processes involved in the rockfall triggering. In a steep permafrost slope such as the west face of the *Aiguille du Goûter*, these processes can be operating and, depending on the conditions, can favor the stability or, on the contrary, the instability of the slope. Draebing *et al.* (2014) proposed a conceptual model to understand these interactions and their role. On a seasonal scale, two periods particularly conducive to rockfalls are identified: early summer and autumn. In early summer, the infiltration of liquid water from melting snow accelerates the deepening of the active layer - the subsurface horizon that thaws during the summer period - along the cracks (Gruber and Haeberli, 2007) and causes the melting of the ice in the cracks (Hasler *et al.* 2011). As a result, the shear strength of the rock is reduced by the thawing of the active layer while hydrostatic pressure increases, favoring the initiation of rockfalls (McColl and Draebing, 2019). In autumn, the cooling of the rock leads to the freezing of water and the increase of cryostatic pressure. Ravanel *et al.* (2017) also identify autumn as a favorable period for the occurrence of large-scale destabilizations ($V > 10,000$ m^3), as deep warming of the terrain reaches its maximum at this time of the year. Thus, the triggering processes of rockfalls in high alpine environments are relatively well identified on a seasonal scale. However, they are much less quantified on a daily and hourly scale due to the lack of data on rockfall activity at high altitudes at these fine temporal scales. Presently, only seismic measurements can be used to obtain a continuous record of the rockfall activity during days and nights, independently to the weather conditions (Helmstetter and Garambois, 2010; Hibert *et al.* 2011, 2017; DeRoin and McNutt, 2012; Dietze *et al.* 2017a, 2017b; Durand *et al.* 2018;). All these former studies however focused on un- or de-glaciated mountain areas. Some authors used seismic monitoring for the detection of large rockfalls at regional scales (Dussauge *et al.* 2003; Dammeier *et al.* 2011; Manconi *et al.* 2016; Hibert *et al.* 2019), thus not focusing on permafrost conditions. To our knowledge, only Guillemot *et al.* (2020) provided a rockfall database for a rock glacier area in Switzerland. At the daily scale, they showed a direct correlation between rockfall activity and air temperature, caused by increased melt water production.

In order to quantify the frequency of rockfalls and their triggering factors in the local context of the *Grand Couloir du Goûter*, a multi-method monitoring system was set up in 2016 and became fully operational in 2019. It is composed of (Fig. 1): (i) 5 seismic sensors to detect the impacts of rockfalls, day and night, independently of weather conditions, and to estimate their intensity ; (ii) an automatic digital camera to monitor the evolution of the snow-covered surfaces in the couloir; (iii) 3 subsurface temperature sensors installed 10 cm deep in the rock to analyze the presence/absence of the permafrost and its thermal regime; (iv) a pyroelectric sensor to record the number, time and direction of climbers crossing the couloir; (v) a high-resolution topographical survey by terrestrial laser scanning to define the topography of the couloir ; (vi) 2 weather stations measuring air temperature, one near the *Tête Rousse* glacier (3,126 m a.s.l.) and the other close to the *Goûter* refuge (3,817 m a.s.l.); and (vii) a rain gauge, positioned at the base of the couloir (3,270 m a.s.l.) measuring rainfalls. In this study, we present this experiment and the novel results obtained on the rockfall activity at the hourly and daily scale during the 2019 season, together with an analysis of the mountaineers behaviors toward the rockfall hazard.

2 Study site: *the Grand Couloir du Goûter*, on the classic route up Mont Blanc

The MBM is located in the north-western Alps, between Switzerland, Italy and France (Fig. 1) and covers ~550 km². About 30 % of its surface is covered with ice (Gardent *et al.* 2014) comprising 121 glaciers (Paul *et al.* 2020) including the Mer de Glace, the largest glacier in the French Alps with an area of 30 km². Twenty-eight summits exceed 4,000 m a.s.l., including the Mont Blanc (4,809 m a.s.l.), the highest summit of the European Alps. The *Grand Couloir du Goûter* (Fig. 1) is located on the west face of the *Aiguille du Goûter* (3863 m a.s.l.) located in the south-western part of the MBM. The classic route up Mont Blanc crosses this couloir in its lower part, at an altitude of 3,270 m a.s.l., over a horizontal distance of about 70 m. The route then follows the left side of the couloir over an elevation gain of almost 500 m up to its summit at 3,817 m a.s.l. This sector - the traverse of the couloir and the ascent of its left ridge - is one of the most difficult part of the route because of its steepness (slope angle between 45 and 60°), and also the most dangerous because of rockfalls which increased in frequency and volume during the recent decades (Mourey *et al.* 2019).

The ascent of Mont Blanc is classically done over two days (one night in a refuge) with two main possibilities in the choice of the refuge and the preferred time for crossing the *Grand Couloir du Goûter*. The first possibility is to spend the night at the *Tête Rousse* (3,187 m a.s.l.) or *Nid d'Aigle* (2,400 m a.s.l.) refuges located below the couloir (Fig.1). The climbers can then cross the couloir twice on the second day, first very early in the morning on the way up and again in the afternoon on the way down from the summit. The second possibility is to sleep at the *Goûter* refuge (3,830 m a.s.l.; located on the summit ridge of the *Aiguille du Goûter*, Fig 1). Climbers thus cross the couloir on the first day on the way up, generally at the end of the morning/beginning of the afternoon. They cross again the couloir on the way down from the summit, usually in the early afternoon. The timing of the crossing is therefore linked to the refuges and the climbing schedule chosen by the climbers and not according to the rockfall hazard.

In 2015, due to two heat waves during which rockfalls were particularly frequent, climbing the couloir was strongly discouraged and the *Goûter* refuge was closed by prefectural decree from 15 to 31 July and then from 06 to 19 August, corresponding to 23 % of the traditional opening period of the refuge. These closures resulted in a drop in the number of overnight stays of 17 % for the *Goûter* refuge and 39 % for the *Tête Rousse* refuge compared to the average for the three previous years.

The topographical and geological characteristics of the *Grand Couloir du Goûter* are particularly favourable to rockfalls. The sector is formed of highly fractured gneiss and micaschists (Mennessier, 1977), with a slope angle between 45 and 60° over an altitude difference of 700 m. Due to the fracturing of the rock in the area and previous rockfalls in the couloir, many rocks/blocks are susceptible to secondary fall. Moreover, the *Aiguille du Goûter* west face is located in the altitudinal range where permafrost is highly degrading with Mean Annual Rock Surface Temperatures (MARST) mostly between -1 and -4°C (Magnin *et al.*, 2015), which is the most favorable temperature range observed for the occurrence of rockfalls in the MBM due to permafrost degradation (Legay *et al.* 2021).

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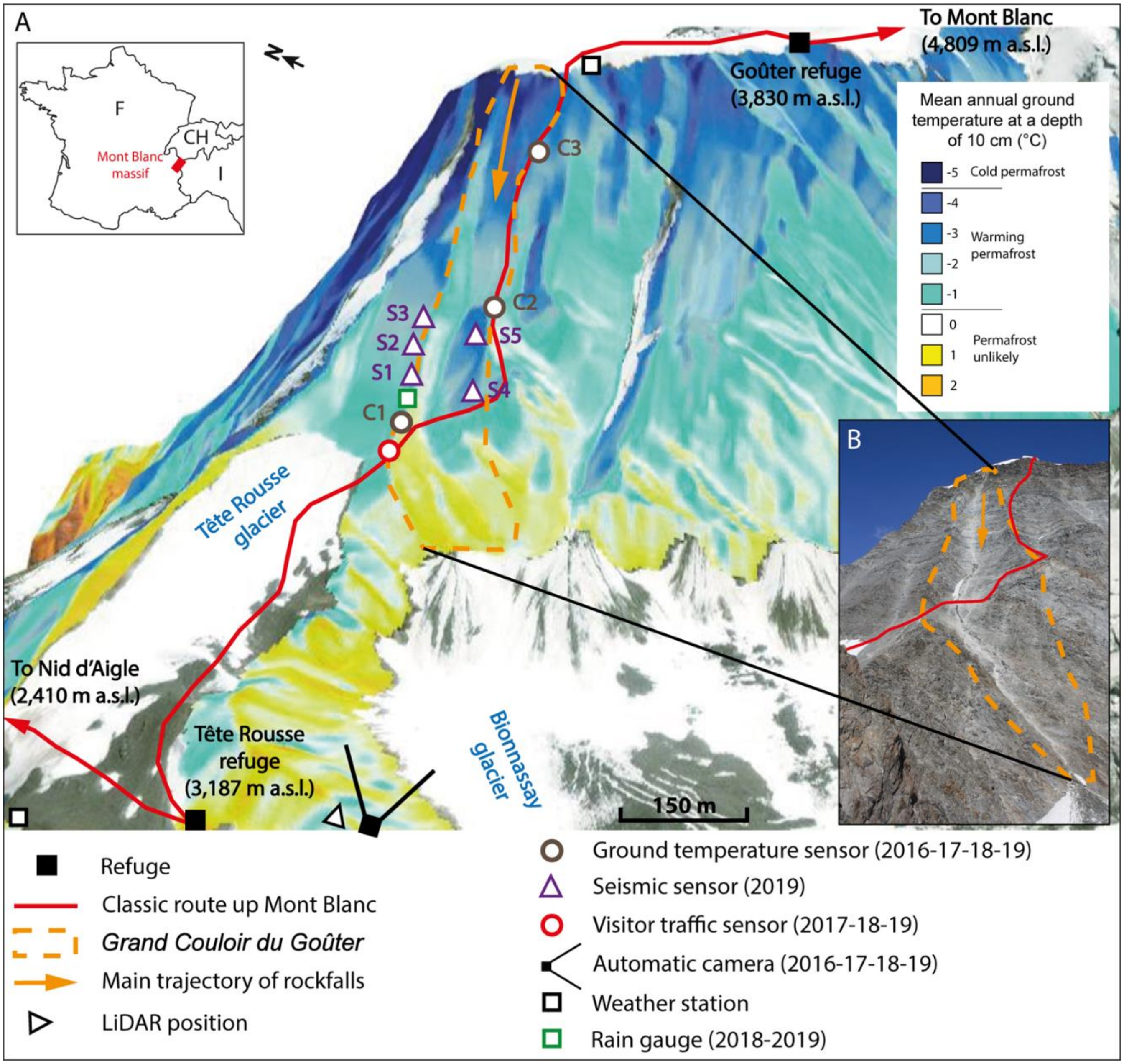

Figure 1: Study site and multi-method monitoring system at the *Grand Couloir du Goûter*. A. Permafrost map from the modelling of Magnin *et al.* (2015) (aerial photography, © Microsoft), location of the classic route up Mont Blanc on the west face of the *Aiguille du Goûter* (in red) and the set up instruments. Years indicate the presence of the different sensors. B. Picture of the couloir taken by the automatic camera (04 August 2019).

3 Methods

Several factors potentially responsible for the triggering of rockfalls were studied and quantified as well as the traffic on the route through a multi-method monitoring system.

3.1 Rockfall detection and characterization

Five autonomous seismic sensors (Zland3C nodes), short period with a sampling frequency of 250 Hz, were installed on both sides of the couloir (Fig. 1) from 29 June to 04 September 2019 (68 days). This seismic network was used for the detection of the seismic signals generated by rockfalls and to characterize their energy. The detection was carried out following the method developed by Helmstetter and Garambois (2010), by isolating peaks in the spectrograms stacked in the frequency band [1-30] Hz, with amplitudes greater than 4 times the noise level (calculated over 30 s at the onset of the records). All the peaks separated by less than 30 s are considered to be part of the same event. This method makes it possible to isolate a large number of signals, not all of which are rockfalls (earthquakes, anthropogenic noise including helicopters; Fig. 2). A visual expert analysis was then used to classify these signals and identify those due to rockfalls. The visual expertise was trained by field comparison done 2 times during 2 hours, once in July and once in August 2019. The rockfall signals in the couloir are characterized by many impacts, high frequency content, and long signals (Fig. 2.A., 2.B.). Some rockfall signals can be confused with serac falls in the Bionnassay North face, 800 m West to the couloir (Fig. 2.E.). However, the absence of high frequency content due to the attenuation of these "far" signals is a decisive criteria to reject them. Some rockfalls are also characterized by one or few (< 3) impacts, making them complex to identify and to separate them from local micro-quakes or anthropogenic noise from mountaineers in the couloir. Those signals correspond to the smallest rockfalls. Therefore, we decided to keep only the largest signals, *i.e.* when the rockfall origin was sure. This corresponds to about only 20 % of the detected signals. Consequently, the smallest rockfalls or those without marked impacts in the couloir – yet potentially fatal for climbers – are not necessarily detected in our study, which rejects all the signals of uncertain sources (~80 % of the total number of signals). The detection of the small rockfalls in the seismic records could be improved using machine learning algorithms (*e.g.* Hibert *et al.* 2017), trained on sample signals checked on the field.

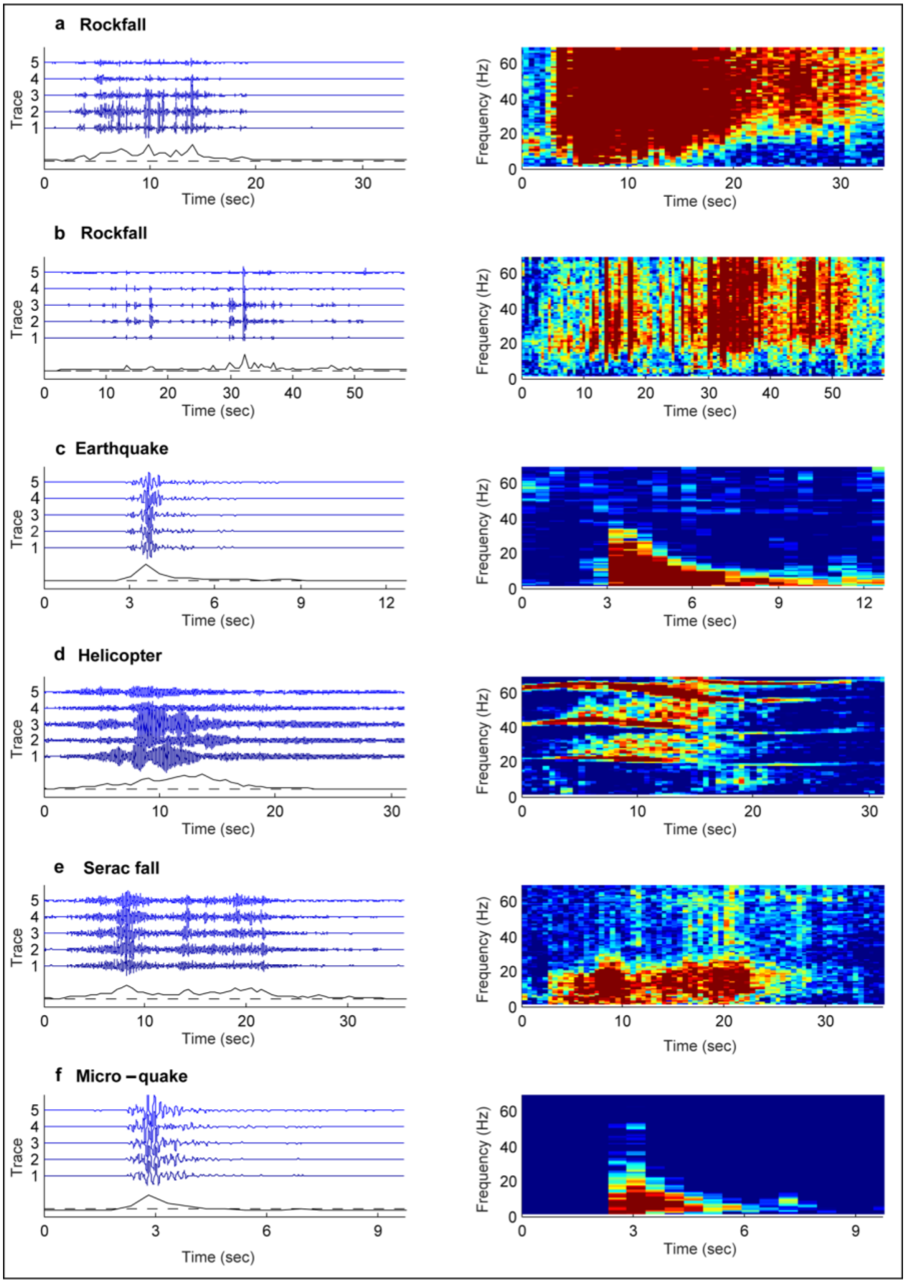

Figure 2: Example of typical signals recorded by the seismic network on June 28, 2019: two rockfalls in the *Grand Couloir du Goûter* (a, b), a local earthquake (c), an helicopter (d), and a serac fall from the Bionnassay North face (e). On the left, the seismic waveforms are represented in blue colors at each sensor (1 to 5) as well as the seismic envelope in black. The right panels represent the spectrograms at lower frequency (0-75 Hz) averaged over all the sensors. The red colors represent higher energy, compared to blue colors.

Finally, the most energetic peaks of each signal were located by a beam-forming method (Lacroix and Helmstetter, 2011) consisting in searching the source location and the mean seismic wave velocity in the media that maximizes the inter-trace correlation shifted in time by their respective source/sensor propagation time (Fig. 3). The signals with a majority of peaks located in the couloir were kept (Fig. 3). The others were considered as coming outside from the couloir. This strategy makes it possible to obtain a rockfall inventory in the couloir, precisely located in time. It must be noted that rockfall signals with low peaks, related either to small rocks/blocks that slide down without impacting the ground, or snow-damped rocks/blocks are thus not necessarily recorded. The results presented in the following sections therefore underestimate the amount of rockfalls, especially the smallest.

Each rockfall can be characterized by properties of its seismic signal: its duration, maximum amplitude, and its energy, which is obtained by integrating the mean seismic envelope between all traces over the whole signal duration. This energy is corrected from the gain of the seismic sensors. Volumes can be derived from these characteristics (Dietze *et al.* 2017b; Hibert *et al.* 2017; Le Roy *et al.* 2019), which are also a function of the distance to the source, the type of ground impacted (rock, soft soil, snow), or the drop height. That's why the quantification of volumes requires a calibration of the seismic data with an independent source (*e.g.*, a comparison of Digital Terrain Models - DTM - acquired two years apart; Durand *et al.* 2018). Such a calibration was not possible here, as only one DTM was acquired by Terrestrial Laser Scanning (TLS, LiDAR method for Light Detection And Ranging; see § 3.2). However, as the rockfall sources are all originating from similar locations, the signal energy can be considered, on a first order, proportional to the volume of the rockfall. It should also be noted that this volume will tend to be underestimated when there is snow in the couloir, which absorbs the impacts.

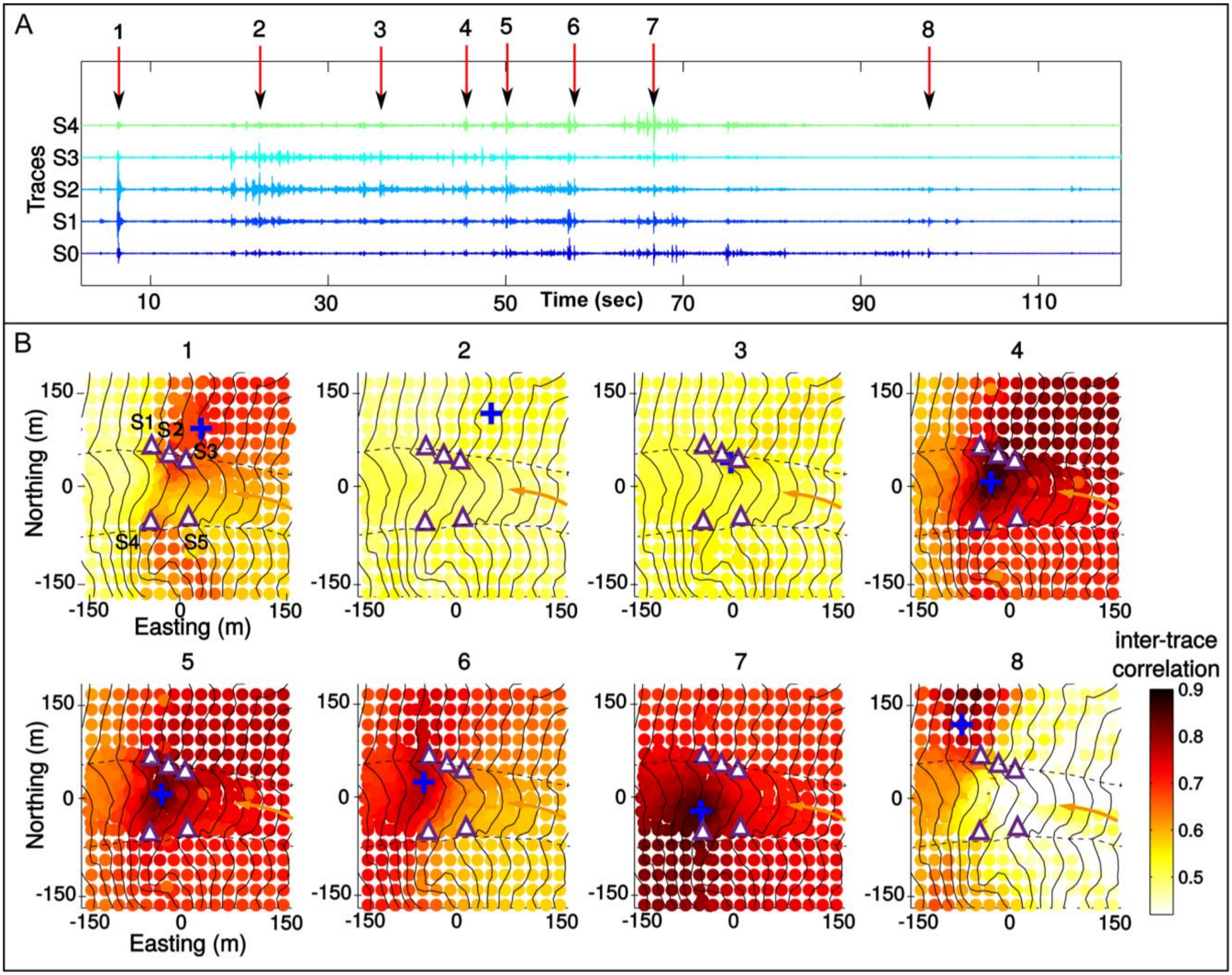

Figure 3: A. Seismic waveforms of a rockfall that occurred on 02 August 2019, recorded by the 5 sensors (noted S1 to S5 and located with triangles on the maps of subplots B). The main impacts (noted 1 to 8) are automatically located by the beam-forming method. B. Spatial distribution of the inter-trace correlation for each of the 8 impacts. The optimum location is indicated with a blue cross. The elevation iso-contours are displayed every 25 m. The yellow arrow indicates the downward propagation of the rockfalls in the couloir.

3.2 Photographic monitoring of the snow cover

In order to study the evolution of the snow cover in the couloir, an automatic camera (Canon EOS Digital Rebel XS, F/13, ISO 200) was installed in June 2016 (Fig. 1). It took 4 photos per day of the couloir over the whole summer period (photos from the camera are presented in Fig. 8). The photos were processed in 3 steps: i) manual selection of the images suitable for studying snow (absence of clouds, fog, or shadows); ii) on each photo, the pixels associated with snow are detected and isolated. The detection is automatic and based on the blue channel of the photo (Fedorov *et al.* 2016) in which the histogram of blue intensities presents two peaks. The first peak corresponds to snow-free pixels and the second peak to snow pixels. A threshold between the two peaks is calculated using the Isodata algorithm (Ridler and Calvard, 1978) and is used to segment the photo into two classes : snow pixels and snow-free pixels; iii) the snow pixels are then converted into an area in m^2 by a monoplotting technique: the camera intrinsic (sensor size, focal length, optical center, distortion) and extrinsic (position and orientation in space) parameters are estimated by a non-linear optimization based on 11 correspondences between real world coordinates and photo points (Hartley and Zisserman, 2003). Then a ray-tracing on a DTM is carried out for each pixel of the photos, in order to convert the snow pixel extension in meters (Flöry *et al.* 2020). The DTM was generated with the software CloudCompare (with 1 m accuracy) from a point cloud acquired on 12 September 2016 - with the couloir completely free of snow - by TLS using an ILRIS LR Optech, from the surroundings of the *Tête Rousse* refuge (Fig. 1).

The evolution of the snow cover in the couloir was only evaluated from snow-covered surface data. They give biased information on the quantity of liquid water available during melting. For a powdering of snow or a fall of several decimetres of snow on the whole couloir, the snow-covered surfaces will be very similar whereas the quantities of liquid water resulting from the melting are very different.

3.3 Characterization of the permafrost thermal state

Continuously measuring the rock surface temperature (RST) for at least one full year (Gruber *et al.*, 2004; Magnin *et al.* 2015) allows to verify the presence/absence of permafrost. Three Geoprecision PT100.0 sensors (C1, C2 and C3 on Fig. 1) with M-Log5W loggers recording temperature every 3 hours with a resolution of 0.01°C and an accuracy of +/- 0.1°C, were installed out of the sunlight, 10 cm deep in the rock, in July 2016. To ensure that there is no influence of the air temperature, a silicone seal ensures that there is no air circulation between the outside air and the hole in which the sensor is installed (Ravanel *et al.* 2017). The acquired data allow the analysis of the annual thermal regime of the subsurface and attest the presence/absence of permafrost (Table 1).

Sensors	Alt. m a.s.l.	Aspect	MARST (°C)	T°C Max.	T°C Min.
C1	3345	0.95° N	-1.2	13	-14.6
C2	3460	0.50° NW	-3	10.9	-16.5
C3	3665	30° NW	-3.4	10.6	-18.2

Table 1: Ground temperature sensors key information and data recorded between 01 September 2016 and 01 September 2019 (3 years records).

3.4 Continuous monitoring of the climbers traffic

The number of climbers following the route was continuously monitored from June to September in 2017, 2018 and 2019 using a pyroelectric sensor (Fig. 1; Mourey and Ravanel, 2017) installed on the side of the "trail" before the section that crosses the couloir. This type of sensor combines passive infrared technology with a high-precision lens to detect the heat emitted by the human body and determine the direction of travel, with the crucial advantage of not being influenced by weather conditions. Thus, the number of persons that passed the sensor and their direction of travel were recorded continuously, with a value produced in 15-minute sequences. This means that the number of climbers and their walking direction were known for each quarter of hour. The margin of error of the sensor was quantified by performing at least three manual counting sessions at the site each summer. It is important to point out that the sensor indicated the number of times a person has passed the sensor and not the number of individuals climbing the Mont Blanc: a climber who climbed up Mont Blanc and got back down was counted twice by the sensor. Moreover, some of the climbers come from other routes, in particular from the *Trois Mont-Blanc* route (*via* the *Aiguille du Midi* cable-car and the Cosmiques refuge), from the Italian side of Mont Blanc, or from the *Aiguille de Bionnassay* and use the *Goûter* route on the way down.

4 Results

The multi-method monitoring system implemented led to the construction of one of the few available continuous - with day and night and weather independent conditions - databases on rockfall activity in permafrost conditions associated with snowfall, precipitation, air and ground surface temperatures and climbers traffic. This database is continuous over 68 days from 29 June to 04 September 2019.

4.1 Rockfalls in the *Grand Couloir du Goûter* during the summer 2019

In 2019, 26,339 seismic signals were detected. 2,648 were classified as rockfalls located inside the couloir. It gives an average of 39 events per day. A rockfall is thus recorded every 37 minutes on average, indicating a significant geomorphic activity compared to other study sites in high Alpine environments (Ravanel *et al.* 2017; Hartmeyer *et al.* 2020). The number of events is lower in the second half of the season: 72 % of the events are recorded in July against 28 % in August.

The energy of an event measured in 2019 is 0.16 megajoules on average. 88 % of the events recorded have an energy lower than the average (Fig. 4). The 1 % of the most energetic events (26 events with an energy > 2.8 megajoules) mainly occurred at the end of the summer season. 19 events out of 26 occurred after 24 July, among which 14 occurred after 10 August (Fig. 4).

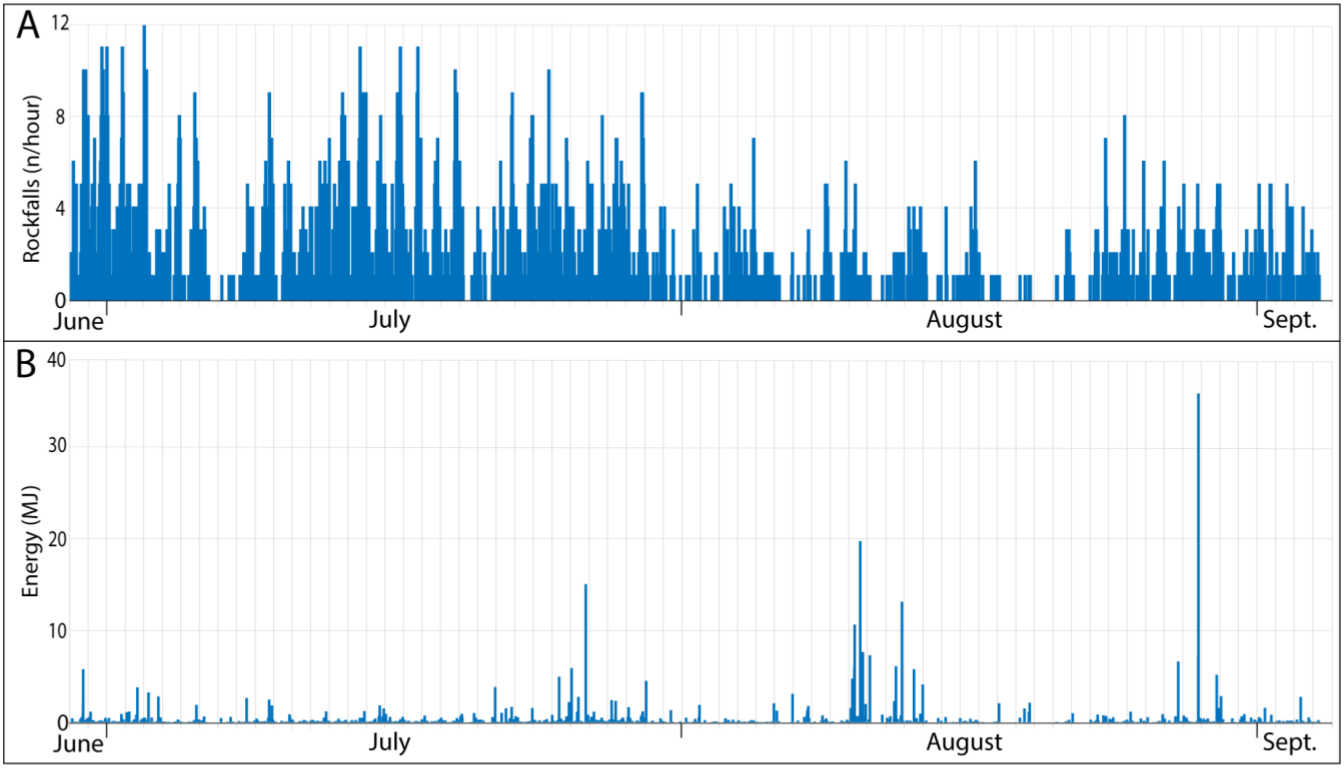

Figure 4: Seismic records in 2019. A. Number of rockfalls per hour. B. Maximum energy (Megajoules) of each rockfall.

On average, on a daily time-scale, rockfalls are distributed as follows (Fig. 5): the period with the lowest activity is in the morning between 2 and 12 pm (Local Time), with a minimum of hourly activity between 9 and 10 am (1 event every 85 min.). The activity then increases markedly between 12 and 8 pm with a maximum frequency between 6 and 7 pm (1 event every 17 min.). Then, the frequency decreases progressively, until 9 am. The most energetic rockfalls occur between 3 and 10 pm, when they are also the most frequent (Fig. 5).

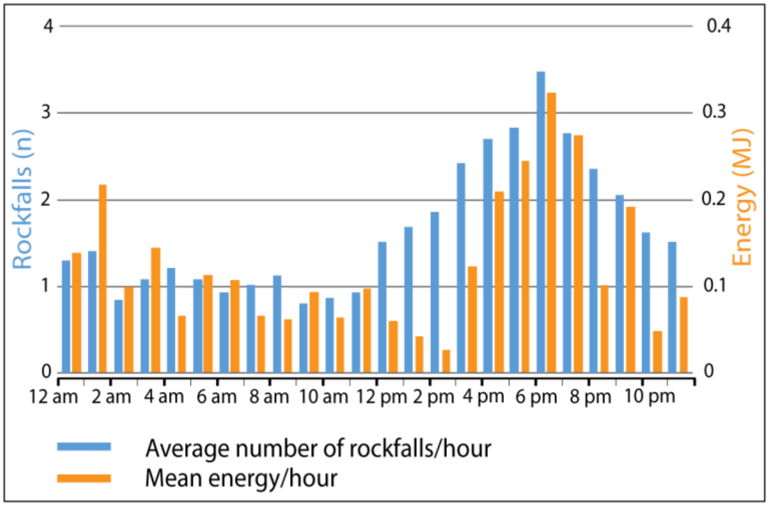

Figure 5: Evolution over 24 hours of (i) the average number of rockfalls per hour and (ii) the mean energy of a rockfall per hour.

4.2 Air temperature

According to semi-hourly measurements at the *Tête Rousse* meteorological station at 3,126 m a.s.l., the mean temperature over the period 29 June to 04 September was 5.8°C with a maximum at 15°C (24 July) and a minimum at -2.9°C (15 July). Over the whole period, there were only three short periods with negative air temperatures, one of 15 hours (15 July), another of 17 hours (13 August) and the last of 4 hours (13 August). At the top of the couloir, at the level of the *Goûter* refuge (3,817 m a.s.l.), over the same period, the average temperature was 0.2°C with a maximum of 9.9°C (25 July), and a minimum of -15.9°C (02 August).

4.3 Rock temperature evolution and permafrost distribution

In situ measurements of subsurface temperatures over two years (2018 and 2019) confirm the presence of permafrost in the *Grand Couloir du Goûter*. The lower part of the couloir is located near the lower permafrost limit with an annual mean temperature of -1.1°C (sensor C1; 3,345 m a.s.l.). The temperature is lower in the middle and upper parts of the couloir, with an annual mean temperature of -2.8°C at C2 (3,460 m a.s.l.) and -3.4°C at C3 (3,665 m a.s.l.).

Over the period of rockfall recordings, the number of effective freeze-thaw cycles (EFTC; Matsuoka, 1990; Seto, 2010) at 10 cm in the rock is very limited. Two EFTC were recorded by sensor C3 (upper part of the couloir; Fig. 6) and none with sensors C1 and C2 in the lower and middle parts of the couloir, respectively.

4.4 Evolution of the snow-covered areas

During the summer 2019, snow surfaces in the couloir were measured over the period 29 June to 04 September. They showed a progressive decrease between 29 June and 31 July. At this date, only a small residual snowpack was still present in the center of the couloir (Fig. 6). From 01 August to 04 September, the couloir was completely free of snow except for the period 20-25 August when ~5 cm of snow fell but completely melted in 5 days. On 08 August and 28 August, the upper part of the couloir was powdered with snow that melted in a few hours.

4.5 Climbers traffic

The results of the climbers traffic measurements are presented for the summer season 2019 between the 29 June and 04 September. Over this period, there were 17,768 (± 7.2 %) passages on the route, among which 41.5 % were on the way up and 58.5 % on the way down. The daily mean number of climbers is slightly higher in July (271) than in August (248). Over the whole season, the number of climbers is very dependent on the weather. When the weather deteriorates, the number of persons decreases. Conversely, a window of one or two days of good weather is enough to increase, sometimes significantly, the number of climbers again (Fig. 6). For example, on 12 August, the weather is rainy and there are only 44 passages in the couloir. Only two days after (14 August), in favor of the first sunny day following a period of bad weather, the maximum number of daily passages of the season (497) is reached.

On average, there are 261 passages per day, which are organized according to the time profile displayed on Figure 8. On the way up, there are two initial peaks in traffic at 2-3 and 5-6 am. These correspond to the two starts from the *Tête Rousse* refuge. Then, there is a main peak between 10 am and 3 pm, corresponding to all the climbers coming from the Mont Blanc tramway. The first train reaches the *Nid d'Aigle* (2,410 m a.s.l.) at 8.30 am at the earliest. Therefore, the first climbers reach the couloir at around 10 am. On the way down, there is a peak between 7 am and 3 pm, with a maximum between 9 and 10 am which corresponds to all the climbers coming down. As a result, the vast majority of climbers crosses the couloir between 10 am and 2 pm, with a peak between 12 am and 1 pm. In one hour, 12.7 % of the daily total of climbers cross the couloir.

5 Discussion

We can distinguish 3 main periods according to the daily occurrence of rockfalls (Fig. 8). Period 1 covers the first half of the season (29 June to 30 July, *i.e.* 32 days), characterized by the highest rockfall frequency (1916 events, *i.e.* 1 rockfall every 24 min.). Then, Period 2 (31 July to 22 August, *i.e.* 23 days) displays a clear decrease in the rockfall frequency with 353 events (*i.e.* 1 every 94 min.). Finally, Period 3 (23 August to 04 September, *i.e.* 13 days) shows a slight increase in the frequency (379 events measured, *i.e.* 1 every 49 min.). In this section, in order and easily designate a period of the season, the rockfall triggering factors will be discussed according to these 3 periods.

5.1 Rockfall triggering factors in the *Grand Couloir du Goûter*

On a seasonal scale, rockfalls are very numerous during the snow cover melting period (Fig. 6 - Period 1). Then, their frequency of occurrence sharply and rapidly decreases when snow disappears in the couloir or when only a small residual firn is still present in the lower part of the couloir, at the level of the traverse (Fig. 8 - Periods 2 and 3). Rockfalls were 2.6 times more frequent during Period 1 than during Period 2 and 3. This finding is in agreement with previous observations in high Alpine environments (Krautblatter *et al.* 2013; Draebing *et al.* 2014; Draebing *et al.* 2017; Weber *et al.* 2018) indicating that the first favourable period for rock instability after the cold season is the period of snowpack melt.

The most energetic rockfalls occur during the second part of the season (Periods 2 and 3; 16 out of 26 events; Fig. 4.B). The snow potentially dampened the impacts of the blocks in early July. However, as the majority of the couloir was not covered by snow, it can be estimated that a large-scale event would have been measured as such anyway. This finding is in agreement with previous studies on rockfalls in the Mont Blanc massif (*e.g.* Ravanel and Deline, 2010; Ravanel *et al.* 2017) indicating that active layer thaw leads to an increase in rockfall mobilizing large volumes (rock collapse type, $V > 100\ m^3$), mostly in sectors where the rock is highly fractured, and in particular at the end of the summer season when the penetration of the seasonal heat in the rock is already well advanced and the active layer is the deepest (Legay *et al.* 2021). According to these studies, the events mainly occur on slopes between 40 and 60°, between 3,400 and 3,500 m a.s.l., in an altitudinal range where the permafrost often reaches MAST between -2 and 0°C at a depth of 10 cm. Also, the *Grand Couloir du Goûter*, located between 3,200 and 3,800 m a.s.l. (the lower part of the couloir corresponds to the lower limit of the permafrost; Fig. 6.A), with a slope angle of 45 to 60°, constituted by highly fractured gneiss, and with an active layer that reaches its maximum thickness in September (Pogliotti *et al.* 2015; Magnin *et al.* 2017a) brings together conditions that are particularly prone to the occurrence of large rockfalls due to the active layer deepening. Moreover, the most energetic rockfalls occurred mostly (23 out of 26 events) during rainfall events or following on average 8.6 mm of precipitation in the last 24 hours. This suggests again the key role played by water infiltration in triggering rockfalls, including the largest ones. However, there is no correlation (0.03) between the rainfall quantity during the 24 hours before an event and its energy.

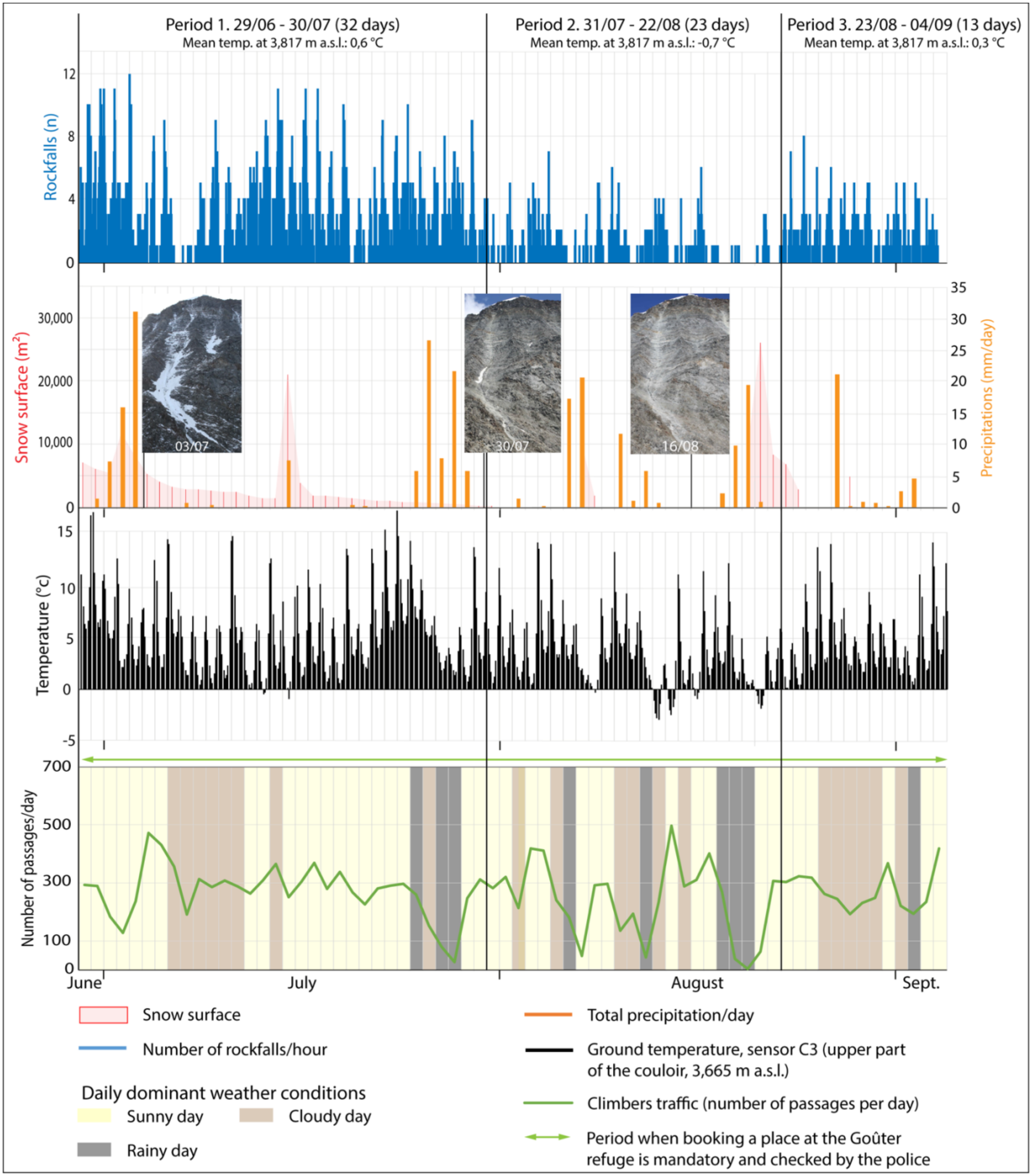
Period 1. 29/06 - 30/07 (32 days)
Mean temp. at 3,817 m a.s.l.: 0,6 °C
Period 2. 31/07 - 22/08 (23 days)
Mean temp. at 3,817 m a.s.l.: -0,7 °C
Period 3. 23/08 - 04/09 (13 days)
Mean temp. at 3,817 m a.s.l.: 0,3 °C
Rockfalls (n)
0
4
8
12
Snow surface (m²)
0
10,000
20,000
30,000
Precipitations (mm/day)
0
5
10
15
20
25
30
35
03/07
30/07
16/08
Temperature (°c)
-5
0
5
10
15
Number of passages/day
0
100
300
500
700
June
July
August
Sept.
Snow surface
Number of rockfalls/hour
Daily dominant weather conditions
Sunny day
Cloudy day
Rainy day
Total precipitation/day
Ground temperature, sensor C3 (upper part of the couloir, 3,665 m a.s.l.)
Climbers traffic (number of passages per day)
Period when booking a place at the Goûter refuge is mandatory and checked by the police

Figure 6: Comparison between the number of rockfalls per hour, the evolution of the snow-covered surfaces, precipitations, ground temperatures on the upper part of the couloir (sensor C3) and the daily variations of climbers traffic during the summers 2019. Pictures were taken with the automatic camera (§ 4.2.). They allow to study the evolution of the snow cover in the couloir.

In order to quantify the correlation between rockfalls and other parameters (rainfalls, temperatures, frequentation) on an hourly scale, we computed the cross-correlation function between hourly rockfall rates (R) and other parameters P at the hourly rate, defined by Equation (1), $Cr, P(t) = \sum(Pi\, R(ti)P(ti + t))$, *cf.* Helmstetter & Garambois, 2010. The correlation that mostly explains the rockfall rates at the hourly scale is the air temperature measured at the *Goûter* station (Fig. 9). The correlation is low (0.28), but significant (much higher than the peak of all the correlations). A time-delay of 2 h is found between the temperature time-series and the hourly rockfall rates. No clear correlation is found with precipitation at the hourly scale, showing that it is not the dominant mechanism during our period of measures. The few days with significant rainfalls show however a higher rockfall activity than on the previous days.

The number of rockfalls starts to increase on average 3h after the return of positive air temperatures at the top of the couloir with a maximum between 6 and 7 pm (Fig. 5). This maximum occurs on average, over the whole season, 6 hours after the warmest air temperature of the day at the top of the couloir and 2 hours after the warmest temperature at *Tête Rousse*. Conversely, the time of the day with the lowest rockfall frequency is between 9 am and 12 pm, after the coldest period of the day (between 11 pm and 7 am). There is therefore a time lag of several hours between the maximum/minimum air temperatures and the rockfalls, which is probably linked to the thermal inertia of the snow and the rock surface and the topographic shading. Moreover, the number of events starts to increase when the couloir gradually turns into the sun, between 12 and 1 pm at the beginning of the season, and between 1 and 2 pm at the end of the season. The number of rockfalls only starts to decrease after 8 pm, which corresponds to the moment when the air temperature at the top of the couloir falls below 0°C. The nightly cooling and the daytime thawing at the top of the couloir thus seem to have an effect on the rockfall triggering.

It is likely that nocturnal refreezing (indicated by air temperatures at the *Goûter* station and associated with radiative cooling of the surface) only has an impact on the first few centimetres below the rock surface. It probably leads to the cementation of the finest elements only, a halt in the melting of the snow present during Period 1 and the resulting processes, and thus reduces the frequency of rockfalls. On the contrary, the progressive increase in temperature during the morning reactivates the melting of the snow and all the associated thermo-mechanical processes and, in particular, the supply of liquid water into the cracks which implies an increase in the rockfall frequency. The clear link between air/rock temperatures and the rockfall frequency also suggests that some of the rockfalls may be triggered by conductive expansion of the rock during the warmest hours of the day (Collins and Stock, 2016; Draebing *et al.*, 2017).

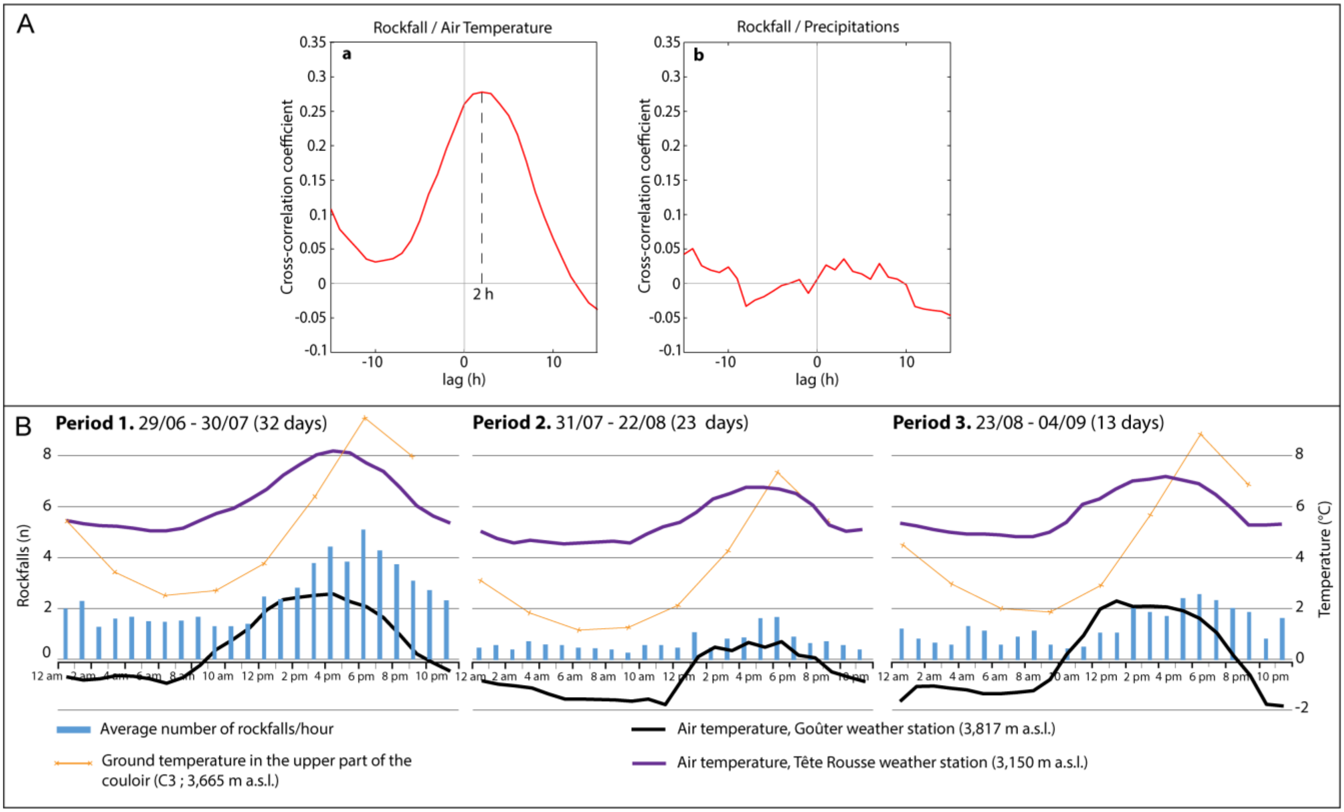

Figure 7: A. Cross-correlation function of the hourly rate of rockfalls and (a) the hourly temperature recorded at the *Goûter* refuge (3,809 m a.s.l.), and (b) the hourly precipitations. The blue dashed line highlights the time-delay of 2 h between the hourly temperature and the rockfall triggering. B. Evolution over 24 h, for the Periods 1, 2 and 3, of (i) the average number of rockfalls per hour, (ii) the mean hourly ground temperature in the upper part of the couloir (C3), and (iii) the mean hourly air temperature at the *Tête Rousse* and the *Goûter* weather stations.

According to our field observations, some rockfalls are triggered by the climbers themselves, from the upper left part of the couloir. The data acquired do not allow us to measure precisely the anthropogenic part of the rockfalls. However, there are two time periods when the number of rockfalls increases slightly: during the night, between 4 and 5 am, and in the morning, between 8 and 9 am, *i.e.* 2 or 3 hours after the first traffic peaks at the bottom of the couloir (at 2-3 am and 5-6 am, respectively; Fig. 8.A.). This time-delay of 2-3 hours between the peaks of traffic in the couloir and this rising rockfall frequency corresponds to the time needed for climbers to reach the upper part of the couloir from the traverse, where they are the most likely to trigger rockfalls. Thus, these slight increases in the number of events could be – at least partly – of an anthropogenic origin. The focus on specific days when no snow in the couloir nor precipitation trigger rockfalls support this observation. For instance, on 31 July, 7 rockfalls were recorded, corresponding clearly with the highest number of climbers, mostly in the morning when no other sources of trigger occur (Fig. 8.B.).

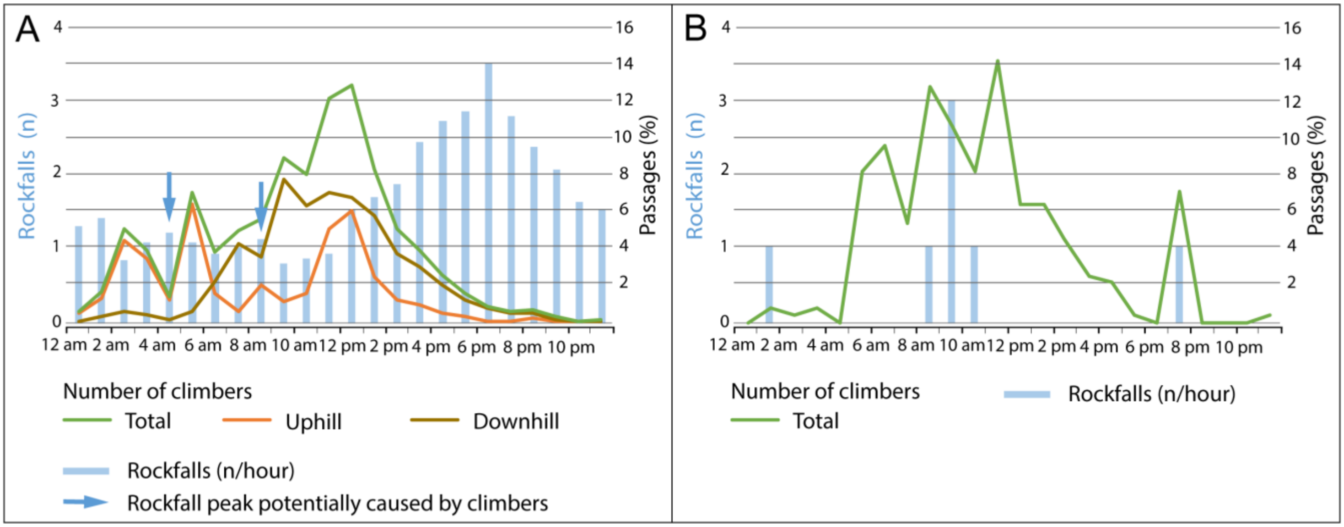

Figure 8: Hourly distribution of climber traffic and number of rockfalls per hour, (A) average over the whole period of measurement and (B) average specifically for 31 July.

5.2 Climbers traffic and rockfalls

The number of climbers following the route does not vary according to the frequency of rockfalls. On a seasonal scale, frequent or – conversely – very rare rockfalls do not lead to a change in the number of climbers. In 2019, for the same number of days with good weather, there were almost as many passages in July (8,408) as in August (7,708), whereas rockfalls were 2.6 times more frequent in July. The number of climbers is mainly determined by the weather and probably by other socio-economic factors and management of the route, such as the refuges booking procedures.

On an hourly scale, the traffic peak occurs between 11 am and 2 pm, just before that the number of rockfalls significantly increases (Fig. 8). However, climbers, mainly on the way down, continue to frequent the *Grand Couloir du Goûter* sector until 6 pm, which is the time of the day when rockfalls are the most frequent.

These observations, especially on the seasonal scale, imply that climbers are not aware of the variations in rockfall frequency and/or that they cannot/won't adapt their behavior to this hazard. This observation justifies: (i) the need to acquire knowledge on rockfalls and their triggering factors in the local context of the *Grand couloir du Goûter* and, (ii) to disseminate this knowledge to mountaineers in order to favor their adaptation.

5.3 Interest of the new acquired knowledge for mountaineers

The knowledge we have acquired thanks to this study about the periods of occurrence, the frequency and the rockfall triggering factors are key information for mountaineers to better take into account and adapt to the rockfall hazard in the *Grand couloir du Goûter*:

- Results confirm that the crossing of the *Grand Couloir du Goûter* and the ascent of its left ridge is particularly exposed to rockfalls with, in 2019, an event every 37 minutes on average and every 17 minutes during the peaks of activity between 7 and 8 pm. Special attention must therefore be paid to this hazard.
- The frequency of rockfalls increased on average 3 hours after temperatures became positive at the top of the couloir.
- Rockfalls are more frequent and larger when the couloir becomes exposed to the sun.
- The time of day when rockfalls are the least frequent is between 9 and 10 am.
- Rockfalls are the most frequent during periods of snow melt. The presence of snow in the couloir is not a guarantee of safety.
- The most voluminous rockfalls occur at the end of the summer season.
- The presence of liquid water is an important element to take into account to assess the rockfall hazard in the *Grand Couloir du Goûter* sector. The more liquid water, either from melting snow or from rainfalls, the more rockfalls are likely.

The knowledge acquired in this study therefore allows climbers to better prepare their ascent by choosing the most favorable period to cross the *Grand Couloir du Goûter* and, once on the field, to better evaluate the rockfall hazard. This information is sufficiently precise to help climbers to adapt, while remaining accessible to non-specialists. Moreover, this knowledge promotes effective adaptation based on scientific evidences, and not only on sensitive experience. We can thus formulate two main recommendations for mountaineers : (i) they have to cross the couloir as early as possible, if possible before midday when the west face of the *Aiguille du Goûter* is still in the shade, and not to wait until the end of the afternoon or the beginning of the evening - for air cooling - which is the most dangerous period of the day, as some climbers do, in order to avoid arriving too early at the refuge and (ii) although mountaineers consider periods when there is snow as the most favorable for the practice, the presence of snow is not a guarantee of safety in the local context of the *Grand Couloir du Goûter* especially during the melting periods.

In 2020, thanks to the initiative of the French Federation of Alpine and Mountain Clubs (FFCAM) which is the manager of the three refuges located on this route (*Goûter*, *Tête Rousse*, and *Nid d'Aigle*), web-cameras facing the couloir (one picture every minute) and air temperature sensors have been installed on the roofs of the *Goûter* and *Tête Rousse* refuges. The data are available live for free on the websites of the refuges and allow a better evaluation of the conditions in the couloir (https://montblanc.ffcam.fr/webcams-tete-rousse.html).

5.4 Dissemination of the acquired knowledge to the mountain community and implementation of management measures of the route

In order to promote a better knowledge and adaptation of mountaineers to the danger of rockfall in the *Grand Couloir du Goûter*, and consequently to try to reduce the number of accidents in this sector, we already have widely disseminated the knowledge acquired in the mountaineering community.

A study report has been published and is available for free in French and English on the *Petzl Foundation* website (https://www.petzl.com/fondation/projets/accidents-couloir-gouter?language=en). It was presented during a webinar organized by the *Petzl Foundation* in June 2020, notably to the press and mountain stakeholders (Mountaineering Federation, Unions of Alpine guides, Alpine Clubs, National School for Skiing and Mountaineering, journalists specialized in mountaineering, etc.; 70 people attended), which led to the publication of several papers. To accompany the publication of this report, a 4-minute film (https://www.petzl.com/fondation/projets/accidents-couloir-gouter?language=en) presenting the main results and recommendations to climbers and inviting them to better take into account and adapt to the local rockfall hazard was produced in collaboration with the *Petzl Foundation*. It was presented at the *Science and Mountain* festival in Grenoble (two broadcasting, 60 000 spectators in total) and, in addition, has been seen more than 600 000 times on the internet (written comm. *Petzl Foundation*).

Moreover, our results were used by local and regional authorities, the FFCAM and the military forces in charge of the rescue operations for the definition and the implementation of management measures of the attendance for the summer 2020. The objectives of these measures were, among others, to reduce the number of accidents in the *Grand Couloir du Goûter* and to favor the adaptation of mountaineers to the local rockfall hazard. These measures consist in mandatory reservations in the refuges in order to better distribute the number of climbers over the entire season and to encourage an ascent of Mont Blanc in three days instead of two which enables the climbers to cross the couloir very early in the morning on the way up and on the way down. The ascent in three days consists in spending the first night either at the refuge of *Tête Rousse* or at the *Nid d'Aigle* and crossing the couloir on the way up very early in the morning of the second day, then sleeping at the *Goûter* refuge on the way down from the summit and thus crossing the couloir on the way down very early in the morning of the third day. The knowledge acquired in this study is also taught during the formation of French and Italian Alpine guides.

At this point, it is impossible to know how effective our work has been in changing climber behavior and how effective the route management measures have been in reducing the number of accidents. However, the fact that our results have been widely downloaded, that they have received strong attention by the press, and that they have been used by the actors in charge of the management of the route shows that they respond to a need for knowledge and that they promote the implementation of concrete actions for adaptation. These adaptation measures are all the more important as it can be estimated that, in the future, climate change will lead to an increase in rockfall hazard in high Alpine environments.

6 Climate change and future projections

In the current socio-economic and cultural context, the Mont Blanc is likely to remain one of the most climbed peaks in the world. However, climate change is likely to lead to an increase in rockfall hazard, mainly due to the warming permafrost (Allen and Huggel, 2011; Ravanel and Deline, 2010) and glacial shrinkage (Hartmeyer *et al.* 2020). Indeed, in the Alps, it is estimated that the climate will warm by 3-4°C in winter and 3-7°C in summer by 2100 (IPCC, 2019; RCP 8.5 scenario). The 0°C isotherm is expected to rise by 400 m in summer (RCP 8.5 scenario), from 3,800 today to 4,200 m a.s.l. in 2050, leaving only a few areas of the MBM outside of the melt zone (Cremonese *et al.* 2019). In parallel, the freezing frequency will decrease by 4.5-5.0 % between 3,500 and 4,500 m a.s.l. by 2100 based on the RCP 8.5 scenario (Pohl *et al.* 2019). This will reduce the daily-scale frost weathering. Snowmelt will occur even earlier in the summer season and probably over a shorter period. As a result, a significant amount of liquid water will infiltrate into the cracks of the rock but over a shorter time period. Although precipitation does not show a decreasing trend in the Alps, the frequency of intense episodes of precipitation will increase (*Météo France* data - Drias-climat; http://www.drias-climat.fr). This implies that large quantities of liquid water could punctually infiltrate the cracks of the rock. It is therefore likely that rockfalls linked to liquid water infiltration and the resulting thermo-mechanical processes will be particularly frequent but possibly over shorter periods. Finally, the ongoing degradation of permafrost will continue and intensify (Magnin *et al.* 2017b; Biskaborn *et al.* 2019). It can therefore be estimated that the most voluminous rockfalls, that tend to occur at the end of the summer season or after heatwaves (which are also more frequent (Della-Marta *et al.* 2007)), will be enhanced with an active layer that will become increasingly deep.

7 Conclusions

The classic route up Mont Blanc (4,809 m a.s.l.) is very popular (20,000 climbers per summer season) but the accident rate in the *Grand Couloir du Goûter* is also very important (3.7 deaths per year since 1990). Rockfalls, which are increasingly frequent in the couloir (Mourey *et al.* 2019), are one of the main factors explaining this high accident rate. This particular context has justified this study which led to the acquisition of new knowledge on the rockfall activity and the triggering factors at this location which is useful for mountaineers to adapt to the local rockfall hazard. Our results confirm previous studies showing a seasonal time scale of rockfalls in permafrost-affected rockwall: events are more frequent during the snowmelt period. On a daily scale, there is a clear correlation between rockfall frequency and air temperature with a 2-hour delay between the peak of temperature and the peak of rockfall activity. Our data also confirmed the field observation that mountaineers can trigger rockfalls. These results are key information to identify the best moment to cross the couloir. On a seasonal time scale, it is particularly important to be wary of the periods of snow melt and, on a daily scale, it is important to try to cross the couloir at the end of the night and beginning of the morning, when rockfalls are less frequent.

However, our results also showed that climbers are not aware of the variations in rockfall frequency and/or that they cannot/won't adapt their behavior to this hazard. The results obtained have been disseminated to the mountain community and used to implement management measures of the route, which confirms the interest/necessity of the knowledge acquired to promote the adaptation of mountaineers. However, it is too early to assess how effective these management measures are, particularly in reducing the number of accidents.

This study is an example of the operational scope of scientific work and their capacity to promote adaptation behaviors. Similar case studies could be implemented on other sites with high stakes for mountaineering. One example is the emblematic and popular route of the Meije traverse (Écrins massif, Southern Alps), which has become very dangerous following a rock collapse in 2018 and the gradual melting of an ice apron. A better understanding of the occurrence of rockfalls and the future evolution of this sector, particularly in relation with the melting of the ice apron, is a major heritage and economic issue for the mountaineers in this sector. Another potential site should be the eastern ridge of the *Aiguille du Midi* (3,842 m a.s.l., MBM), which is one of the main accesses to the high mountains in the MBM.

Author contribution

JM, PL and PAD conceived the study. JM, PL and PAD realized most of the field missions and analyzed the data from different sensors (JM: weather stations and traffic sensor; PL: seismic sensors; PAD: ground temperature sensors and LiDAR processing). JM analyzed the full set of data and wrote the article with the analysis contributions of PL, PAD and LR. GM and MM participated in some of the field missions and made the analysis of the snow-covered surfaces. LR acquired the DTM on the field and contributed to fund the study. EM participated in most of the field missions, designed the automatic camera system and his technical skills were indispensable for the installation and maintenance of all the measurement systems and data storage.

Competing interests

The authors declare that they have no conflict of interest.

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