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Climbing Mont Blanc (4808 m a.s.l.): What Are the Risks in the Grand Couloir Du Goûter and On the North Face of Mont Blanc Du Tacul?

Ludovic Ravel, Jacques Mourey, Lorig Tamian, Sébastien Ibanez, Didier Hantz, Pascal Lacroix and Pierre-Allain Duvillard

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Introduction

- 1 The risk of serious injury or even death while practising outdoor sports is well known, particularly in mountaineering, which takes place in challenging and ever-changing physical environments (Vanpouille *et al.*, 2021; Rushton and Ruddy, 2023). Effective prevention requires a thorough understanding of these environments, their evolution, and the geomorphological and glacial processes that shape them. Since 2019, mountaineering has been included in UNESCO's Representative List of the Intangible Cultural Heritage of Humanity (Debarbieux, 2019). Consequently, commitments have been made to promote the safety of mountaineering enthusiasts and to preserve the practice. This necessitates comprehensive prevention strategies grounded in an in-depth understanding of the environment, its evolution, and the geomorphological and

glacial processes that occur, along with a better understanding of the contexts and factors that contribute to accidents.

- 2 Mountaineering was born on the slopes of Mont Blanc (Hoibian, 2008) and the “roof of western Europe” (4808 m a.s.l.) remains a major objective for many mountaineers and neo-alpinists. There are many routes to the summit, but two “normal routes” are particularly popular. From Saint Gervais, the *Voie Royale* crosses the rocky Grand Couloir of Aiguille du Goûter (3863 m a.s.l.; hereinafter referred to as “Goûter”). From Chamonix, the *Trois Monts* route climbs the entirely glaciated NNW slope of Mont Blanc du Tacul (4248 m a.s.l.; hereinafter referred to as “Tacul”). As these two sections are regularly the scene of tragedies (Mourey *et al.*, 2018), this work aims to objectify the associated hazards and the risks taken by climbers. Thanks to innovative monitoring of the Grand Couloir during the summer of 2019 (Mourey *et al.*, 2022), the frequency and intensity of rockfalls were measured using a seismic device, while numbers of climbers were quantified using a pyroelectric sensor. At Tacul, five years of automatic photography (2016–2020) was used to determine the frequency and volume of serac falls (large blocks of ice) and to study the tracks left by climbers, as well as their dangerousness, and to quantify the number of climbers in summer 2017.
- 3 This is the first time that sections of mountaineering routes and their hazards are precisely studied, and that the risks experienced by mountaineers are quantified. To date, studies have mainly focused on changes in practice and routes due to global warming (*e.g.*, Ritter *et al.*, 2012; Temme, 2015; Purdie and Kerr, 2018; Mourey *et al.*, 2019, 2022). In addition to its societal dimension, this work tests two purely physical hypotheses: the close links between thermal conditions and rockfalls, and the absence of a direct link between air temperatures and serac falls. In other words, serac falls could occur at any time of the day and year, making it difficult to prevent the associated risks, while the daily and seasonal rhythms of rockfalls should enable climbers to reduce their risk-taking (see McDowell *et al.*, 2019).

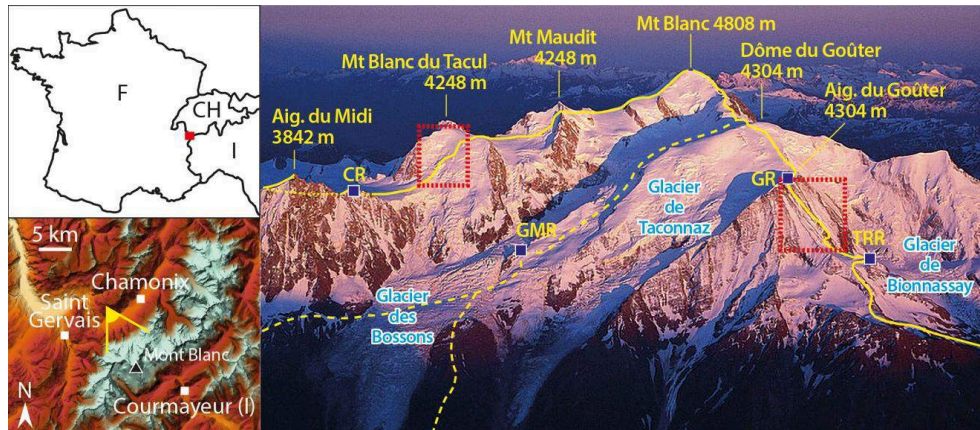
Two Study Sites on the Mont Blanc Normal Routes

Mont Blanc and its Massif

- 4 The Mont Blanc massif covers an area of 550 km² in the western European Alps (Fig. 1). It belongs to the outer crystalline Alps (von Raumer *et al.*, 1993). The massif has an extraordinary combination of peaks and ridges overlooking glaciers; many of its granite faces rise well above 3,000 m a.s.l., with steep rock faces ranging from 500 to more than 1,000 m in height (Deline *et al.*, 2012). 28 peaks exceed 4000 m a.s.l., including Mont Blanc on the French-Italian border, which is the highest peak in western Europe (4808 m a.s.l.). Its first ascent in 1786 marked a turning point in the history of mountaineering (Hoibian and Defrance, 2002). Mont-Blanc is one of the most glaciated massifs in the Alps. In 2019, the area covered by ice was 162 km², *i.e.*, 29.5% of the massif’s surface (Kaushik *et al.*, 2022). The massif is also largely affected by permafrost: it covers between 45 and 79% of the 86 km² of rock walls > 40°. Its presence is relatively continuous from 2600 m a.s.l. on the north face and 3000 m on the south face, but it covers all the rock faces above 3600 m (Magnin *et al.*, 2015a). These characteristics make the Mont-Blanc a highly favourable massif to slope morphodynamics (Deline *et al.*, 2012).

- 5 Thousands of climbers try to reach the summit of this iconic mountain every year. The easiest and most popular routes, considered as “normal routes”, are the *Voie Royale* (or Arête des Bosses, a route from Saint-Gervais via the Mont-Blanc tramway and the Goûter refuge; Fig. 1), and the *Trois Monts* (a route from Chamonix via the Aiguille du Midi cable car and the Cosmiques refuge; Fig. 1). This study focuses on the most dangerous sections of these two routes: the traverse of the Grand Couloir du Goûter and the ascent of the Tacul, respectively.

Figure 1: The Mont Blanc massif and the study sites (red dashed lines) on the *Trois Monts* (left) and *Voie Royale* (right) itineraries.



Yellow dashed line: route via the Grands Mulets. CR: Cosmiques refuge; GMR: Grands Mulets refuge; GR: Goûter refuge; TRR: Tête Rousse refuge. Altitudes are in m a.s.l.

From Saint-Gervais, the *Voie Royale*

- 6 The *Voie Royale* is the most popular route, as well as the main descent route, due to its modest difficulty compared with the other routes. Typically, would-be climbers reach Nid d'Aigle (2372 m a.s.l.) via the Mont-Blanc tramway before taking a steep path to the Tête Rousse refuge (3187 m). From the refuge, climbers ascend the Tête Rousse Glacier, then the slopes joining the right bank of the Grand Couloir before crossing it for 100 m at an altitude of 3270 m. They then climb the entire west face of the Aiguille du Goûter (3863 m) to reach the refuge du Goûter (3815 m), then the glacier slopes of the Dôme du Goûter (4304 m). They continue to the Vallot refuge (4362 m), follow the “arête des Bosses”, and reach the summit.
- 7 The crossing of the Grand Couloir is the most dangerous section of the route due to rockfalls. Their frequency and volume have increased over recent decades (Ravel and Deline, 2011; Ravel *et al.*, 2017; Mourey *et al.*, 2019). In France, the average annual number of mountaineering-related deaths was 41 between 2008 and 2018 (Vanpouille *et al.*, 2021). On average, since 1997, 3.7 of these deaths have occurred in the Grand Couloir (Mourey *et al.*, 2018). Rockfalls are directly responsible for 29% of accidents and are partly involved in 50% of accidents due to a climber falling in the couloir (Mourey *et al.*, 2018). Rockfalls (Fig. 2) are therefore one of the main factors behind the high accident rate, making this section of mountaineering route one of the most accident-prone in the Alps and probably in the world (Mourey *et al.*, 2019, 2022). In 2015, due to two heat waves which led to an increased rockfall frequency, crossing the couloir was strongly

advised against, and the Goûter refuge was closed by prefectural decree from 15 to 31 July, then from 6 to 19 August. This was also the case from 5 to 20 August 2022, again due to heat waves and an increased rockfall frequency (Fig. 2).

- 8 The topographical and geological characteristics of the Grand Couloir are particularly favourable to these destabilisations (Mourey *et al.*, 2022). The Goûter west face is made of highly fractured gneisses and micaschists, with a slope angle between 45 and 60° over a 700 m altitude difference. In addition, the slope is located at altitudes where permafrost degradation is most active, with mean annual surface temperatures between -1 and -4 °C (see Fig. 4A; Magnin *et al.*, 2015a), a temperature range that is highly conducive to rockfalls (Ravanel *et al.*, 2017; Legay *et al.*, 2021).
- 9 Until recently, the climb generally took two days (with one night in a refuge), with two options for choosing the refuge, which partly determine the time for crossing the Grand Couloir. When climbers stay at the Tête Rousse refuge, they cross the couloir twice on the second day, first very early in the morning on the way up, then on the way down in the afternoon. If they sleep at the Goûter refuge, they cross the couloir on the first day of their ascent, usually in the late morning/early afternoon, and cross it again the next day on the way down from the summit, usually in the early afternoon.

Figure 2: Rockfalls in the Grand Couloir du Goûter



A: July 2020 (Katarina C. S.; <https://youtu.be/xNRklmOHkb8>), B: 11 Aug. 2015 (E. Martin; https://youtu.be/_LHwYupe_WE), C: 15 July 2022 (P. Gianchandani; <https://youtu.be/P2-RMI29c7E>); D: 4 Aug. 2022 (unknown author); E: 8 Aug. 2015 (J. Goudin – PGHM; <https://youtu.be/JDbsq2EFjfU>).

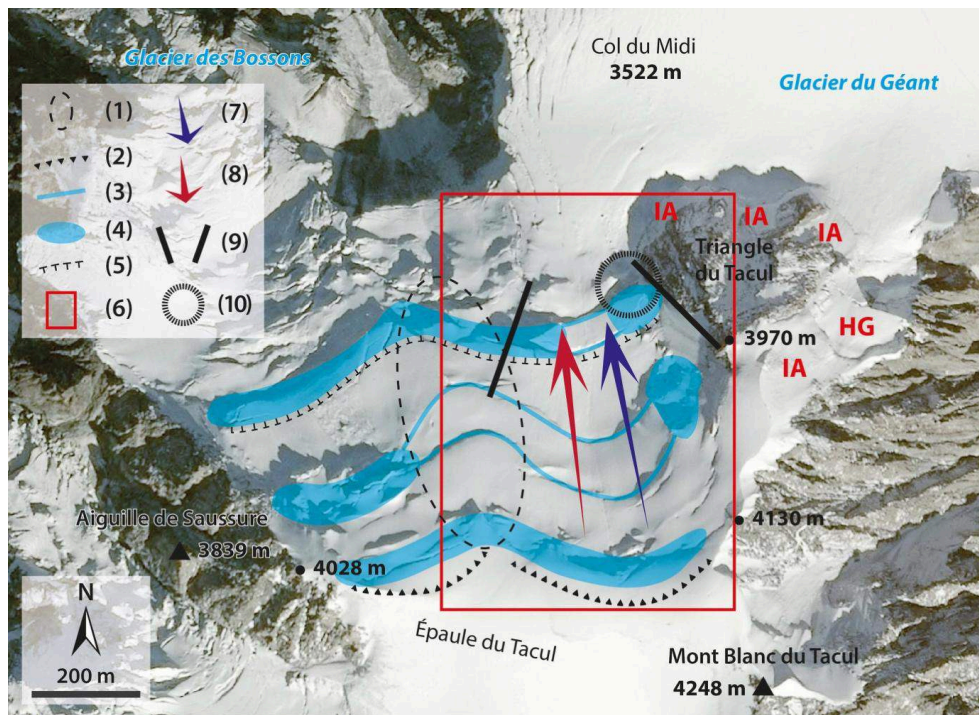
From Chamonix, the *Trois Monts* Route

- 10 Entirely ice/snow route, the ascent of Mont Blanc *via* the *Trois Monts* is more technical and less popular than the *Voie Royale*. From the Aiguille du Midi cable car (3842 m a.s.l.), climbers reach the Cosmiques refuge (3613 m). They then cross the Col du Midi (3522 m) before climbing the Tacul *via* its NNW slope (Fig. 3), whose serac falls have been the cause of several fatal avalanches in the last two decades (8 deaths in Aug. 2008, 2 in Aug. 2013, 3 in Aug. 2016, making a total of 13 deaths between 2000 and 2022), and climbing the “*épaule du Tacul*” (4187 m). The route passes over the Col Maudit (4029 m) then downstream of an accident-prone serac zone (*e.g.*, 9 deaths in July 2012, 3 deaths in Aug. 2016) before climbing the steep (45–50°) north face of Mont Maudit (4465 m), the Mur de la Côte and the slopes below the top of Mont Blanc.
- 11 The study area corresponds to the NNW slope of Tacul, climbed to ascend Mont Blanc *via* the *Trois Monts*, but it is also climbed to reach the top of Tacul itself (the first “4000”

for many climbers) and to return from Mont Blanc (although there are more descents *via the Voie Royale*), Tacul and many other routes. According to two generations of Cosmiques refuge keepers, between 65 and 70% of climbers using the refuge climb up and/or down the NNW side of Tacul (comm. L. Ravel and M. Marcuzzi, April 2023).

- 12 The entire north face of Tacul is characterised by different cold-based (*i.e.* negative temperature) slope glaciers, as suggested by the types of glaciers present, their altitude (3600–4150 m a.s.l.) and orientation (NNE, N and NNW) (Vincent *et al.*, 2012), confirmed by the presence of cold permafrost (≤ -2 °C) in the surrounding rock walls (Magnin *et al.*, 2015a), as well as by the dynamics of the glaciers (Gilbert and Vincent, 2014; Fig. 3). The eastern margin of the north face is occupied by a cold-based hanging glacier (Pralong and Funk, 2006). It is surmounted by an ice apron (Ravel *et al.*, 2023). Immediately to the West is the Triangle du Tacul (3970 m a.s.l.) with several ice aprons, particularly in its lower section (Guillet *et al.*, 2021). Most of the face (nearly 1000-m-wide), oriented NNW, is occupied by a slope glacier (Fig. 3) connected to another glacial system (Kaushik *et al.*, 2022), namely the Bossons and Géant glaciers. The area studied corresponds to the eastern half of this glacier (which feeds the Géant Glacier), over a 550 m drop, between 3600 and 4150 m a.s.l., with an average slope of 37°.
- 13 The dynamics of the glacier and its crevassing depend directly on its thickness, its slope angle, the subglacial topography, and its cold thermal regime, which means that the glacier is stuck to the rock, preventing it from sliding on the rock. The glacier therefore flows solely by creeping (*i.e.*, by deformation of the ice; Gilbert and Vincent, 2014).
- 14 Orthophotographs of the slope (Fig. 3) suggest that the central part of the slope glacier covers a rocky spur, more or less parallel to the rocky ridge around the Aiguille de Saussure to the West and to the rocky spur to the East, of which the Triangle du Tacul is the unglaciated part. This topography seems to separate two small glacial cirques, the western cirque feeding the Bossons Glacier and the eastern one (our study site) feeding the Géant Glacier. Overall, the two cirques have remarkably similar crevasses: 1) at the top of the slope, below the “*épaule du Tacul*”, a bar of seracs cuts horizontally across the entire glacier between 4050 m a.s.l. to the West and 4100 m to the East, 2) lower down, two crevasses cut horizontally across the glacier at around 3900 and 3980 m; on the lateral margins of the glacier, these crevasses join to form zones of seracs, 3) at the bottom of the slope, there is a long, very pronounced bar of seracs, at around 3730 m, probably linked to a break in the topography of the bedrock which, as earlier on the slope, leads to breaks in the ice under the effect of tensile stress (Faillettaz and Funk, 2013). These cuts in the glacier form crevasses. Seracs can detach from their upper side. The crevasses therefore generally form in the same place and evolve as the ice creeps, partly as a function of the subglacial topography (Schäfer, 2007).
- 15 The thickness of the seracs, the size of the crevasses and the general shape of the glacier seem to indicate an increasing thickness of ice from upstream to downstream, which, helped by the slope, tends to accelerate the glacier movement as it flows down the slope (Fig. 3; Gilbert and Vincent, 2014). An area of very high stress is found against the Triangle du Tacul. It contains the most striking seracs in the eastern cirque.

Figure 3: Glaciological functioning envisaged for the slope glacier (type “connected to another glacial system”) on the north face of Tacul



A subglacial rocky spur (1) seems to separate two glacial cirques (2) with crevasses (3) and bars of seracs (4) associated with slope breaks in the bedrock, one of which is the main (5). In the study area (6), the increase in thickness towards the bottom (7) and the increase in flow rates (8), coupled with a funnel effect (9), seem to have created a zone that is particularly conducive to serac falls (10). IA: ice apron; HG: hanging glacier.

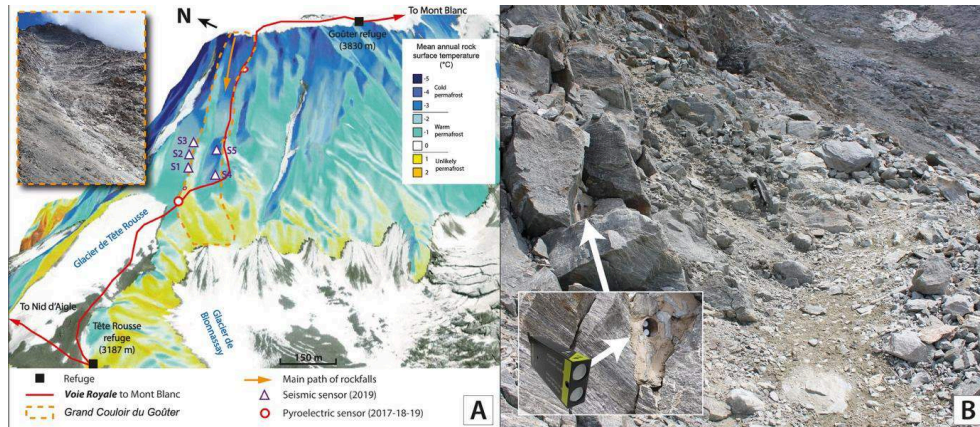
Methods

Quantifying Number of Climbers and Documenting Rockfalls at Gôûter

- 16 The number and direction of climbers crossing the Grand Couloir were measured continuously from June to September 2017, 2018 and 2019 using a pyroelectric *Éco-compteur* Pyro sensor (Mourey and Ravel, 2017; Mourey *et al.*, 2022; Fig. 4) installed in a cleft in the rock before crossing the couloir.
- 17 Five autonomous seismic sensors (nodes Zland3C; Fig. 4) were installed on the banks of the Grand Couloir from 29 June to 4 September 2019 (68 days). This seismic network was used to detect the seismic signals generated by rockfalls and to characterise their energy, using the method developed by Helmstetter and Garambois (2010). The signals show amplitude peaks corresponding to block impacts. Only signals with a minimum of three peaks have been selected, which excludes a large proportion of individual rockfalls (around 80%) in order to only include rockfalls from boulder accumulations. This method ensures that individual rockfalls are not confused with signals of other origins (anthropogenic, micro-earthquakes). In addition, each signal was located using a beam-forming method (Lacroix and Helmstetter, 2011) applied to each peak of the seismic signal, which means that only rockfalls that actually occurred in the couloir are

considered (Mourey *et al.*, 2022). Given that the majority of rockfalls originate from the same area, the energy of the signals was considered to be proportional to the rockfall volumes.

Figure 4: Monitoring in the Grand Couloir du Gôûter



A: Position of the seismic sensors and the counting system (Mourey *et al.*, 2022, modified) on permafrost distribution map. B: The pyroelectric passage sensor on the right bank of the Grand Couloir (Mourey and Ravel, 2017, modified).

Estimating the Number of Climbers and Documenting Serac Falls at Tacul

- 18 Automatic photography is the main source of data for this study. It was carried out by *La Chamoniarde* (Chamonix Mountain Safety and Rescue) between June 2016 and September 2020 from the terrace of the Cosmiques refuge (time step: 1 min, 24h/24). These data, whose series is discontinuous, have been supplemented by acquisitions from the *Panomax* of Aiguille du Midi (*Compagnie du Mont-Blanc*), which operated from March 2016 to July 2021 (time step: 10 min, from 7 a.m. to 7 p.m.). The summer periods selected for the study of the tracks of mountaineers extend from 15 June to 15 September for the years 2016 to 2020, and throughout the year for the documentation of serac falls.
- 19 The aim of analysing and comparing the photos is threefold. 1) To reconstruct the evolution of the position of the tracks left on the slope by climbers as a function of the constraints of the terrain. 2) To document serac falls by indicating the date and location and estimating the volume of the falls. The time of occurrence is defined in three 8-hour periods: morning (5–13 h), afternoon (13–21 h) and night (21–5 h). The volumes of ice involved are quantified on the basis of before-and-after photos of a serac fall and length measurements taken on *Géoportail* of rocky elements in the Triangle du Tacul and transferred to the glacier. This quantification is carried out here as it is done in rocky context (Ravel and Deline, 2013). The associated uncertainty varies between 15 and 50%. A zoning of the slope was created from an initial assessment of the position of the tracks and the structure of the glacier in order to situate these different elements. The data was compiled in a table for analysis. 3) To extract data related to daily use of the slope by manually counting climbers ascending and descending from

the photographs (summer 2017 only). The number of night-time climbers is considered thanks to the climbers' headlamps, which are visible in the photos.

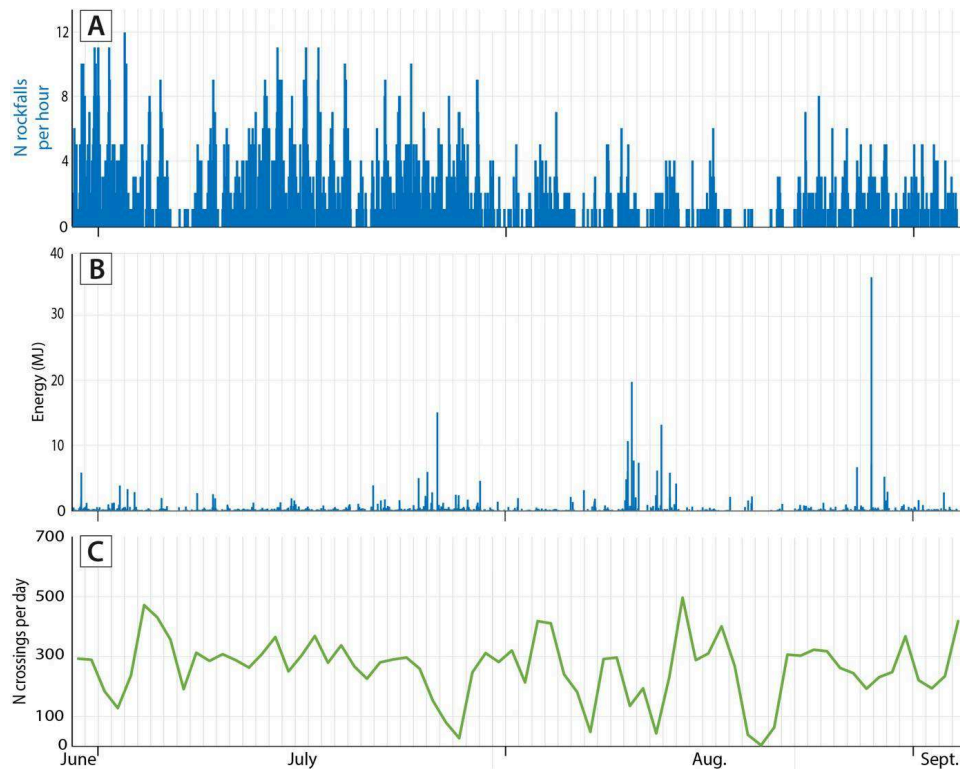
- 20 Another aim is to determine the risk to which climbers are exposed depending on the track they choose. By analysing data on areas of deposits of serac falls, it is possible to estimate the probability of being in such an area. Assuming that it takes around 30 minutes to cross a zone on the way up, the probability of fall in half an hour is calculated for each zone; this corresponds to the hazard. As these probabilities are low, we can consider that the sum of the hazards for each section of track constitutes the value of the hazard linked to serac falls for the entire route.

Results

Number of Climbers and Rockfalls at Goûter in 2019

- 21 During the period from 29 June to 4 September 2019, 17,768 passages ($\pm 7.2\%$) were recorded on the right bank of the Grand Couloir (Fig. 5), with 7,374 ascents and 10,394 descents. The average daily number of climbers was slightly higher in July (271) than in August (248). The daily number is highly dependent on weather conditions. In 2019, for an equivalent number of days of good weather, there were almost as many passages in July (8,408) as in August (7,708), while rockfalls were 2.6 times more frequent in July.
- 22 During the summer of 2019, 26,339 seismic signals were detected. Among these, 2,648 were classified as being related to fairly large rockfalls affecting the Grand Couloir (Fig. 5), giving an average of 39 events per day (Mourey *et al.*, 2022). On average, a fairly large rockfall is recorded every 37 minutes. The number of events is lower in the second half of the summer season, while they are more voluminous. The 1% of events with the most energy and therefore the greatest volume (26 events with an energy > 2.8 megajoules) occurred mainly at the end of the summer season. 19 of these 26 events occurred after 24 July, including 14 after 10 August (Mourey *et al.*, 2022).
- 23 On a daily scale, the period during which the frequency of rockfalls is lowest is the morning, between 2 and 12 a.m., with a minimum of activity between 9 and 10 a.m. (1 event every 85 minutes). Activity then increases sharply between 12 a.m. and 8 p.m., with a peak between 6 and 7 p.m. (1 event every 17 minutes). The frequency then gradually decreases until 9 a.m. The most voluminous destabilisations occur between 3 and 10 p.m. when they are also the most frequent.

Figure 5

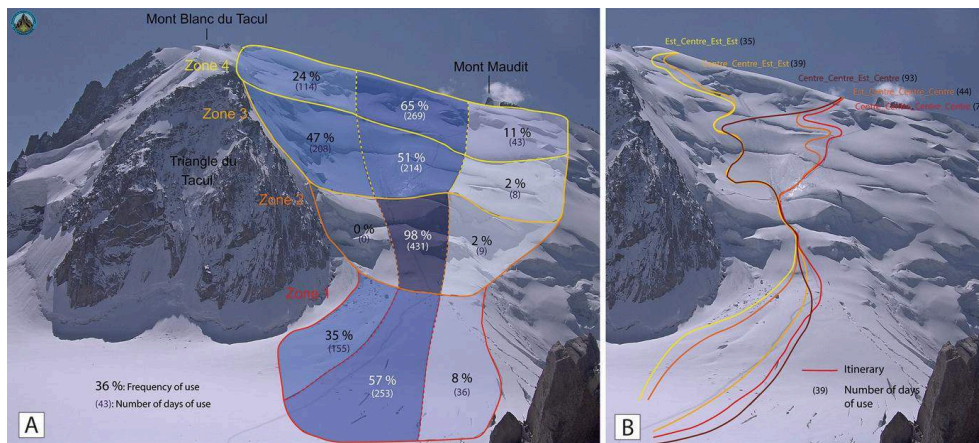


Number of rockfalls per hour (A), maximum energy of each rockfall (B), and number of climber passages per day in the Grand Couloir du Goûter during the summer of 2019 (C) (Mourey *et al.*, 2022, modified).

Number of Climbers and Serac Falls at Tacul

- 24 Between 15 June and 15 September 2017, 6,770 passages ($\pm 10\%$) were counted at Tacul, of which 50.8% (3,437) were on the ascent and 49.2% (3,333) on the descent. This corresponds to an average of 75 passages per day, with a maximum of 210 on 6 July.
- 25 By analysing the number of days each sector is used, we can identify the sectors most frequently used by climbers in the four zones of the face. These frequencies are represented as a percentage within the same zone and in terms of the number of days the route was used for the summers of 2016 to 2020 (Fig. 6A). At the start of the ascent, in Zone 1, the majority of the tracks pass through the Centre of the zone; this is the most direct route between the refuge and the bottom of the face. However, 35% of the tracks pass through the Eastern sector of Zone 1. In Zone 2, almost all the tracks are made in the Centre of the zone, between two large serac bars. The frequency of use is almost the same between the Centre and East passages of Zone 3, with 51% and 47% of the tracks respectively. In Zone 4, most of the tracks lead to the Centre of the face, with 65% being used. It is also possible to identify the “complete” routes most frequently used during the 4 seasons studied (Fig. 6B): *Centre_Centre_Est_Centre*.

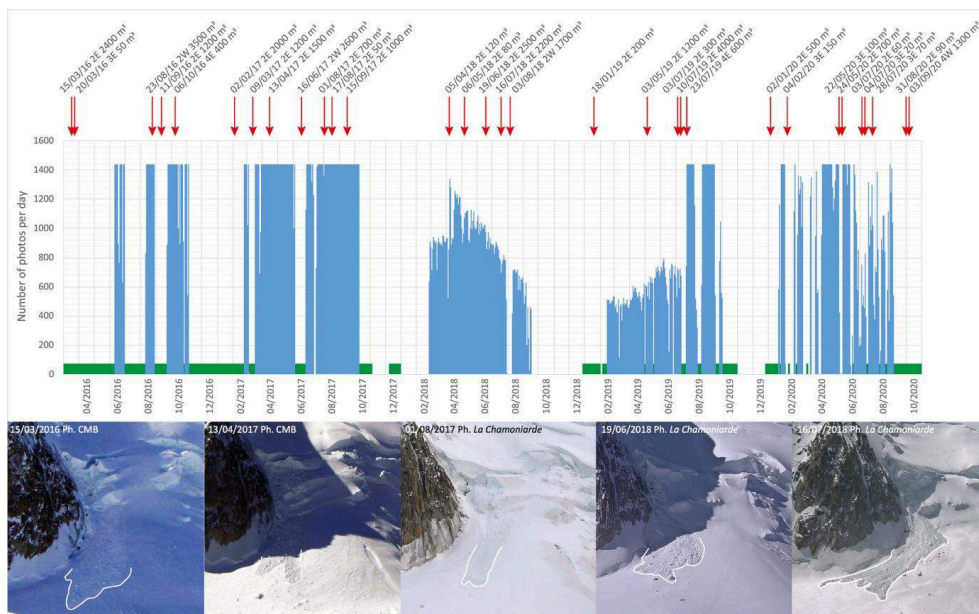
Figure 6: Tracks at Tacul



A: Most used sectors in percentage (100% for each zone) and number of days of use (background: ph. 23 Aug. 2019). B: The five most used routes over the 4 summer seasons 2016–2020.

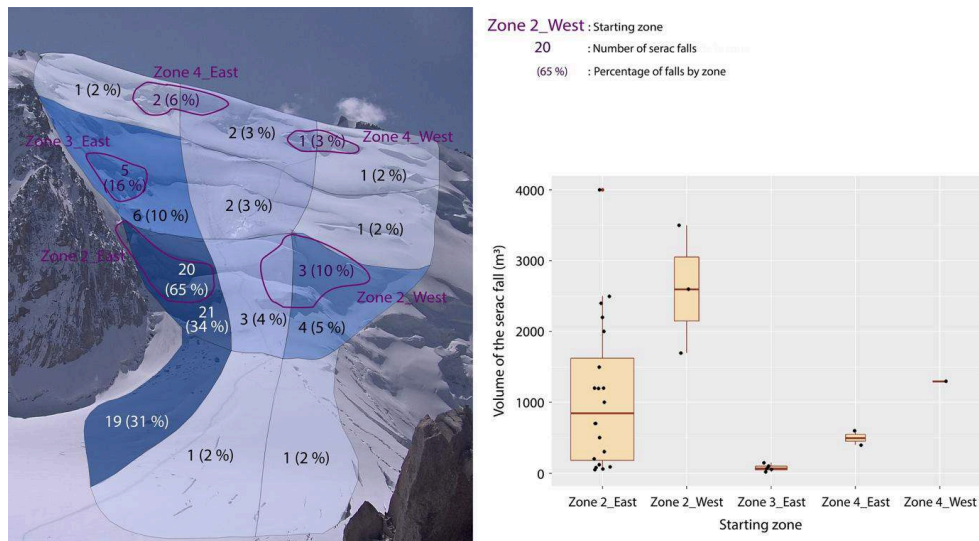
- 26 31 serac falls were recorded over the 4 years of the study (Fig. 7), with volumes ranging from 50 ± 10 to $4,000 \pm 600$ m³ (tot.: $35,500 \pm 6,850$ m³, avg.: 1,050 m³, med.: 700 m³). Five zones were identified as the source of these falls (Fig. 8): two in Zone 1 at the level of the highest serac bar on the slope, one in Zone 2 near the Triangle du Tacul, and two in Zone 3, including the one located against the Triangle du Tacul, which accounts for 65% of the total, with 20 destabilisations recorded (Fig. 8). This zone also has the greatest diversity in the volumes of ice mobilised (between 50 and 4,000 m³). Serac falls from Zone 4 (the top of the slope) are infrequent, but the associated avalanches generally affect the entire glacier, making them particularly dangerous (8 deaths on 24 Aug. 2008). Seracs can fall at any time of the day or night (11 in the morning, 6 in the afternoon and 15 at night).

Figure 7



Two discontinuous sources of photographs (in blue the automatic camera of *La Chamoniarde*, in green the *CMB Panomax* at Aiguille du Midi) to document serac falls (red arrows with date, sector affected and estimated volume). Below: examples of related deposits.

Figure 8



Position of the 5 zones at the origin of serac falls on the NNW face of Tacul and associated avalanche transit/deposit frequencies for each sector (left) and frequency/volume of serac falls as a function of source sectors (right).

Discussion

Hazards and Number of Climbers

- 27 The physical processes affecting the Grand Couloir du Goûter and the NNW face of Tacul differ in nature and frequency of occurrence. At Goûter, the frequency of events varies during the summer season: 72% of events are recorded in July, when the snow melts in the couloir, causing hydraulic pressure in the cracks which triggers numerous small-volume events (Krautblatter *et al.*, 2013; Weber *et al.*, 2018). 28 % occur in August, when increased permafrost degradation stimulated by global warming (Magnin *et al.*, 2015b; Ravanel *et al.*, 2017); it triggers less frequent but larger events (Fig. 5). The variability is also daily, with a maximum frequency in the late afternoon. Rock destabilisation at Goûter is therefore highly dependent on the air/rock thermal conditions and humidity levels in the soil rock (Mourey *et al.*, 2020, 2022). Serac falls (avg.: 0.018 events per day) are less predictable than rockfalls at Goûter because they can occur at any time of year (Fig. 7) and day. They are likely not linked to thermal conditions but to the mechanical conditions of the moving glacier as is the case for other cold glaciers at high elevation (Vincent *et al.*, 2015; Faillettaz *et al.*, 2016).
- 28 Summer climber numbers on the two routes also show significant contrasts, with an average of 265 persons per day (41.5% ascents and 58.5% descents) at Goûter in 2019 and 74 at Tacul in 2017 (equivalent numbers of ascents and descents). This means that the Grand Couloir du Goûter is around 3.6 times busier than Tacul during the summer. This difference can be explained by the technical level of the routes: the *Voie Royale*, which is rated PD- (a little difficult -), is much more accessible for beginners or less experienced climbers, and is highly publicised in the media. In addition, because it is less difficult, it is often chosen as descent route, which explains the imbalance between the number of ascents and descents. On the other hand, the figures are more balanced

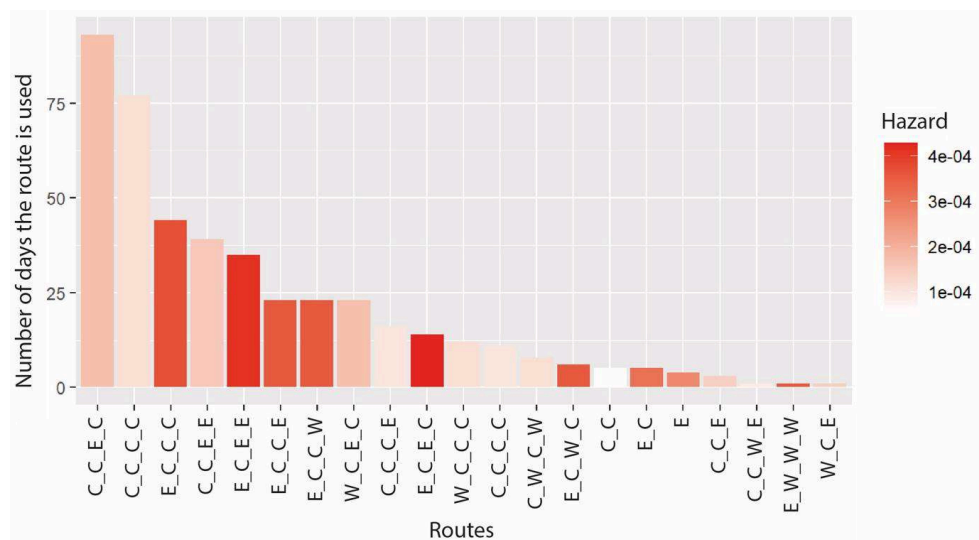
at Tacul, because the number of climbers who do the traverse of Mont Blanc (descending *via* the *Voie Royale*) is counterbalanced by the number of descents from other routes on Mont Blanc du Tacul and Mont Maudit.

What Are the Risks for Mountaineers?

- 29 The numbers of climbers, combined with much more frequent processes at Goûter, are the cause of a much higher accident rate at Goûter than at Tacul, even though the time of exposure to risk is very different. At Goûter, the average collective risk of death linked to rockfall is 3.7 deaths per year (Mourey *et al.*, 2018), despite the fact that crossing the Grand Couloir only takes a few minutes. This route is probably the deadliest in the Alps in terms of societal risk, but it is also almost certainly the most frequented. To assess the individual risk (the probability of death for a climber using this route), we need to divide the annual number of deaths by the number of passages on the route (Hantz *et al.*, 2020). With an average annual number of 21,350 passages (Mourey *et al.*, 2020), the individual risk of death per passage is therefore 1.7×10^{-4} . At Tacul, 13 deaths in 23 years is equivalent to an average of 0.6 deaths per year, even though it takes several tens of minutes (or even several hours) to climb up or down Tacul. The individual risk at Tacul is 8.3×10^{-5} , twice as low as at Goûter.
- 30 It seems interesting to compare these risks with the individual risks currently accepted or tolerated by society. The *International Technical Committee on Landslides* (JTC1 - *Joint Technical Committee on Natural Slopes and Landslides*) defines the concepts of acceptable and tolerable geomorphological risk (Leroi *et al.*, 2005; Fell *et al.*, 2008). Acceptable risk is a risk for which society is prepared to accept as it is with no regard to its management. Tolerable risk is that which society can live with, deriving some benefit from it, but trying to reduce it if possible. In France, regulations on natural hazards do not define any limit of acceptability. In Switzerland (PLANAT 2015), experts tend to agree that an annual risk of death due to natural hazards of less than 10^{-5} is acceptable, and less than 10^{-3} is tolerable. By way of comparison, the annual road traffic mortality rate in France in 2019 was 4.8×10^{-5} .
- 31 This rate at Goûter is around three times higher than the road mortality rate, which means that an average mountaineer is as likely to die in a single trip there as he is to die on the road in three years of normal use of his car. If we look at the annual mortality rate in France in 2017 (INED data), we can see that an average 45-year-old French person who climbs this route has a probability of dying 10 times lower than his “normal” annual probability of death, whereas a child under the age of 15 would double it, as would a 45-year-old mountaineer who climbs this route 10 times a year (high mountain guides, for example).
- 32 At Goûter, the new knowledge acquired should enable climbers to choose a date and/or time that reduces the risk. So far, the number of climbers doesn't seem to vary according to the frequency of rockfalls. The number of climbers seems to be determined mainly by the weather and probably by other socio-economic factors and route management, such as booking procedures for refuges.
- 33 As far as individual risk management at Tacul is concerned, since it is very difficult to anticipate serac falls beyond paying attention to possible warning signs (small ice falls, cracking noises, etc.), it is important to pay attention to the morphology of the slope (“reading the terrain”) in order to identify the most unfavourable geometries for seracs

(highly fractured zones, for example) and to favour the routes least exposed to the risk of serac falls (Fig. 9), such as *Centre-Centre-West-Centre*. Zone 1 East in particular, located beneath the most active serac bar, should be avoided.

Figure 9: Use of the 21 routes observed on the NNW slope of Tacul (some do not reach the summit and therefore do not cover the four zones) and associated hazard



The latter correspond to the sum of the probabilities of serac falls in half an hour for each zone, assuming a travel time of 30 minutes for each zone.

Conclusions

- 34 Mont Blanc is one of the most popular summits for mountaineers from all over the world. The two main normal ascent routes are distinguished by their different physical contexts (a highly fractured rock slope at Goûter and a cold-based slope glacier at Tacul), by the associated hazards (rockfalls and serac falls) and by the number of summer climbers (around 2.5 times higher at Goûter).
- 35 Although other sections should be studied to obtain an overall estimate of the risk of death on the two routes as a whole, in particular the north face of Mont Maudit on the *Trois Monts* route, this work is the first to attempt to quantify the risk on two particularly accident-prone sections. The results obtained indicate that the risk of death is 1.7×10^{-4} in the Grand Couloir du Goûter and 8.3×10^{-5} on the NNW slope of Tacul, *i.e.*, half as high in the latter case. In both cases, this risk could be considered “tolerable” for a climber aged over 45 if he only makes one ascent a year. At Goûter, an analysis of the temporal variability of the hazard allows us to put in place a strategy to reduce the risk, *i.e.*, crossing the Grand Couloir in the early morning. At Tacul, analysis of the spatial variability of the hazard makes it possible to distinguish the areas most exposed to serac falls, in particular the part of the glacier adjacent to the Triangle du Tacul.
- 36 Finally, particular attention must be paid to the evolution of conditions in the context of climate change, as the degradation of the permafrost on the west face of Goûter will inexorably accelerate in the coming years, while the warming of the ice on Tacul could

accelerate the creep of the glacier and therefore increase crevassing and the risks associated with serac falls.

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ABSTRACTS

Mountaineering is a sport highly dependent on the conditions of the physical environments in which it takes place. As a result, mountaineers have to deal with major glacial and periglacial hazards, such as those affecting the two main routes used to climb Mont Blanc (4808 m a.s.l.; Western European Alps): rockfalls in the Grand Couloir du Goûter on the *Voie Royale* and serac

falls on the NNW slope of Mont Blanc du Tacul on the *Trois Monts* route. Hazards in these two sectors and the number of climbers were measured using a multi-sensor system and automatic photographic acquisition, respectively. On the first site, which has a very high accident rate with an average of 3.7 deaths per year, 17,768 passages were recorded during the summer of 2019 and 2,648 seismic signals were classified as rockfalls affecting the Grand Couloir. The average risk of death associated with these rockfalls, the frequency of which depends on temperatures and the presence of liquid water in the ground, is estimated at 1.7×10^{-4} . At Tacul, where an average of 0.6 deaths occur each year, 6,770 passages were recorded during the summer of 2017, as well as 31 serac falls unrelated to temperatures. The risk of death is 8.3×10^{-5} . The risk is also quantified for each track made on the glacier. The results obtained makes it possible to specify the risks experienced by climbers and to promote risk reduction strategies.

INDEX

Keywords: Mountaineering, serac fall, rockfall, risks, Mont Blanc

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