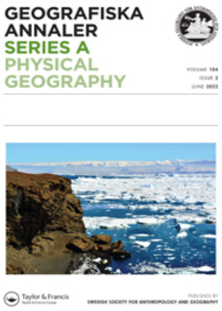

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Climate change related processes affecting mountaineering itineraries, mapping and application to the Valais Alps (Switzerland)

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ABSTRACT

Climate change leads to deep modifications of high Alpine environments. Those modifications have significant consequences on mountaineering itineraries and make them technically more difficult and more dangerous. Although a growing number of studies have recently documented this issue, they only list the processes affecting the itineraries and do not document their characteristics. Therefore, the acquired data lack relevance to be spread and for prevention making among climbers. In the present study, on the basis of the processes identified in previous studies in the Mont Blanc massif, we developed a legend in order to map the processes related to climate change that affect the itineraries and modify their climbing parameters. Following the UNIL geomorphological legend and using the same color code, 21 symbols were defined to map 23 processes. In order to evaluate the applicability and interest of the legend proposed, we present a first application in the Valais Alps (Switzerland), based on 21 semi-structured interviews with local Alpine guides and hut keepers. The map then allowed to list the processes affecting each of the 36 itineraries studied. On average, an itinerary is affected by 9 different processes and 25% of the itineraries have greatly evolved, which means their ascent in summer cannot be recommended anymore because of climate change. More generally, this legend would provide a common methodological basis, destined to be completed within future studies and to be relevant beyond the European Alps. This basis would also ease the comparability and compilation of results from different future studies.

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Introduction

Climate change leads to deep modifications of high Alpine environments (Beniston et al. 2018; IPCC 2019), especially because of shrinking glaciers (Shannon et al. 2019; Hock and Huss 2021; Hugonnet et al. 2021) and permafrost degradation (Harris et al. 2001; Etzelmüller et al. 2020; Marcer et al. 2021). This implies a series of processes such as the retreat of glacier fronts (GLAMOS 2020), the loss of ice thickness (Fischer et al. 2014), the erosion of moraines (Lukas

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et al. 2012), an increase in the frequency of rockfalls (Ravanel et al. 2017), etc. All these glaciological and geomorphological processes have significant consequences on recreational mountain activities and especially on mountaineering (Ritter et al. 2011; Temme 2015; Purdie and Kerr 2018; Mourey, Marcuzzi, et al. 2019a; Mourey, Ravanel, et al. 2019b), which has recently been inscribed by UNESCO on the Representative List of the Intangible Cultural Heritage of Humanity (Debarbieux 2020).

Ritter et al. (2011) proposed a list of 22 processes related to climate change that affects mountaineering and trekking itineraries in the Austrian Alps, and showed that they have numerous impacts on the itineraries such as an increase in danger, technical difficulty and the period when they can be climbed in fairly good conditions. However, they only identified these processes but did not analyze in detail the evolution of a sample of itineraries and therefore did not identify the processes that most affect the itineraries or that are the most determinant for the practice. Temme (2015) proposed a comparison of guidebooks from different periods and showed that the rockfall frequency in mountaineering itineraries has increased since 2000 in the Bernese Alps. Purdie and Kerr (2018) made a detailed analysis of the modification of the classic itinerary to climb Mount Cook (3724 m a.s.l.) in the Southern Alps of New Zealand, and showed that the itinerary is mainly affected by the loss of ice thickness of the Tasman glacier in its lower part, while it becomes steeper because of the melting of the Linda hanging glacier in its upper part. It results in an increase of the technical difficulty of the itinerary and a decrease by half of the length of the favorable period to climb it.

On a similar methodological approach as Purdie and Kerr (2018), Mourey, Marcuzzi, et al. (2019a) studied the modification of the mountaineering itineraries described in G. Rébuffat's iconic guidebook *The Mont Blanc Massif: the 100 Finest Routes* (1973). The authors identified 25 geomorphological and glaciological processes related to climate change affecting the itineraries in the Mont Blanc massif (MBM, European Alps) and modifying their climbing parameters (level of exposure to objective dangers, technical difficulty and the optimal period for climbing – i.e. when the number/intensity of processes affecting the itinerary is the lowest). On average, each of the 95 itineraries studied is affected by 9 different processes such as rockfall, glacier slope angle increase, ice apron retreat, appearance of smooth slabs of bedrock or serac fall. In other words, a climber attempting to climb one of these itineraries has to consider and potentially adapt his behavior to, on average, nine different processes related to climate change. As a result, 36% of the itineraries have become more dangerous and difficult and are unclimbable during certain periods of the year, particularly in summer and during/following heat waves – which are increasingly common (Della-Marta et al. 2007) – while 27% are no longer climbable in summer, as the processes affecting them lead to an excessive level of danger and/or technical difficulty. Finally, 3% of the itineraries have already disappeared, either due to glacial retreat or rockfalls. For example, the Bonatti pillar on the west face of the Drus (3754 m a.s.l.), disappeared in 2005 because of a 700 m high and 292 680 m^3 rock avalanche (Ravanel and Deline 2008; Guerin et al. 2017). In such a context, mountaineers must consider these changes – which are increasingly constraining – and must adapt their behavior to continue the practice of mountaineering and limit their risk-taking (Pröbstl-Haider et al. 2016; Mourey et al. 2020).

While the study by Mourey, Marcuzzi, et al. (2019a) is probably the most thorough that has been realized up to now, it only lists the processes affecting each itinerary and does not document their characteristics or location. Thus, the acquired data lack relevance to be spread and for prevention making among climbers who need to know the characteristics of the processes and where they are affecting the itineraries. Adding spatial information to the type of process affecting each itinerary would therefore help to reduce these limitations and to better document the changes that affect high mountain environments. Therefore, the main objective of the present study is to develop a legend to map the processes related to climate change that affect mountaineering itineraries and modify their climbing parameters. Such a legend should (i) ease data collection, (ii) make the data analysis simpler, (iii) favor the knowledge transfer to the mountaineer's community and (iv) participate in improving knowledge on processes related to climate change in high mountains.

More generally, this legend would provide a common methodological basis, destined to be completed within future studies and to be relevant beyond the European Alps. It would also enable the comparability and compilation of results from different researches.

In order to evaluate the applicability and interest of the legend proposed, we thus present a first application in the Valais Alps (Switzerland), allowing to assess the modification of mountaineering itineraries for this Alpine region, following the scheme of the previous study carried out in the MBM. A comparison of the results between these two massifs is also carried out.

Study area

The Valais Alps, the 100 finest routes as the reference sample

The Valais Alps are located on the orographic left side of the Rhone River (Figure 1). The high-altitude study area includes many summits above 3500 m a.s.l., 5 summits above 4000 m a.s.l. and 27 glaciers. It belongs mainly to the Dent Blanche nappe (Austroalpine unit), where orthogneisses of the Arolla series (Arolla gneiss) are dominant, with the exception of the Aiguilles Rouges d'Arolla, that belong to the Tsaté nappe (Upper Penninic unit) and are composed of metagabbros. Climatically, the Valais Alps are under the influence of a semi-continental climate of intra-Alpine shelter. The mean annual air temperatures and precipitations at 2800 m a.s.l. are around −1°C and 1200 mm/yr according to MeteoSwiss data (Évolène weather station, 1825 m a.s.l.).

Using the same general approach as the study conducted on the MBM by Mourey, Marcuzzi, et al. (2019a), the present study focused on the itineraries presented in M. Vaucher's guidebook (1979) – The Valais Alps, the 100 finest routes – whose series was directed by G. Rébuffat. It presents all kinds of itineraries (rock, snow and mixed) in an increasing order of difficulty from F-facile – easy – to ED-extrêmement difficile – extremely difficult – (see Cox and Fulsaas 2006). This makes this guidebook a relevant and representative sample of popular itineraries in this massif, at least at the date of publication.

The 100 itineraries presented in the guidebook dedicated to the Valais Alps are spread over a very large area (3000 km^2), extending from the Grand-Saint-Bernard pass (2469 m a.s.l.) to the Simplon pass (2106 m a.s.l.). In this work, we have only studied the itineraries present in the Bagnes, Hérémence, Hérens and Anniviers valleys (Figure 1). This represents a region of 750 km^2 in the French-speaking part of the Valais Alps and 36 different itineraries are described (Figure 1). Each itinerary was divided into four parts: (i) the access to the refuge, which starts down in the valley, (ii) the approach, which starts at the refuge and ends either at the foot of the rockwall to be climbed or at the bergschrund (crevasse between moving glacier ice and stationary ice or firn or rockwall above); (iii) the route itself and its continuation to the summit and (iv) the descent, which starts at the summit and ends in the valley.

For some cases, the guidebook proposes several different routes for the same itinerary number. If the orientation and the type (rock, snow, or mixed) of the routes presented for the same itinerary are different and if they are far away from each other, they have been analyzed as different itineraries. It is the case for itineraries 62 and 25 (see Appendix). For the itinerary 62, the guidebook proposes three routes to climb the Mont Blanc de Cheilon (3870 m a.s.l.): the north face, the Gallet ridge and the Jenkins ridge. Since the three routes have a different orientation, are of different types (one 'snow' and two 'rock') and relatively separated in space, they have been analyzed separately. We did the same for the itinerary 25, which presents three different routes to climb the Pointes de Mourti (3564 m a.s.l.): the north face, the south face and the west face. On the contrary, when the routes have the same orientation, are of the same type, and are close to each other, they have been analyzed as a single route. It is the case for the itineraries

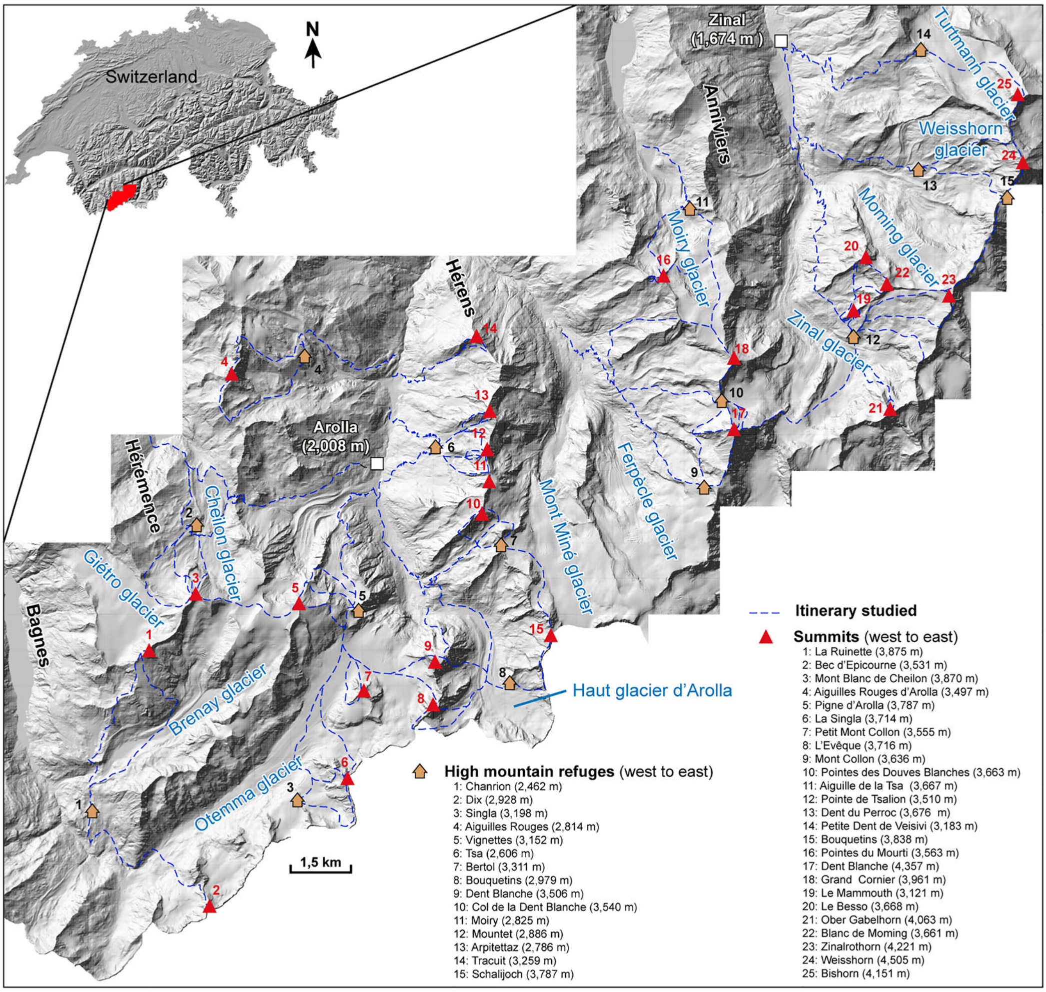

Figure 1. Location map of the Bagnes, Hérémence, Herens and Anniviers valleys in the Valais Alps (Switzerland). The 36 itineraries studied are represented with the summits they reach and the refuges concerned (alt. are in m a.s.l.). DTM SwissTopo.

4 (Le Mammouth, 3215 m a.s.l.), 9 (Pointe de Tsalion, 3512 m a.s.l.) and 61 (Dent de Perroc, 3676 m a.s.l.). Accordingly, a total of 36 different itineraries were studied, 7 of them are 'snow' routes, 24 'rock' and 5 'mixed'.

The Alpine environments in the context of climate change

In the current context of climate change, the study area undergoes deep modifications. Since the end of the Little Ice Age (LIA), there has been a clear decrease in the number of snowfall days relative to the total precipitation days in the Alps (Serquet et al. 2011), together with earlier snow melting (Klein et al. 2016). In the Swiss Alps between 1139 and 2540 m a.s.l., snow cover duration shortened by 8.9 days/decades during the period 1970–2015, with a snow season starting 12 days later and ending 26 days earlier than in 1970 (Klein et al. 2016). This decrease is dependent on the altitude and therefore less significant at high altitudes.

Glacierized areas in the Swiss Alps have decreased by 28% between 1973 and 2010 (Fischer et al. 2014) with an acceleration of the melting since the 1990s (Huss 2012; Vincent et al. 2017). Between 1900 and 2011, glacier volume in the Alps decreased by 49% (Huss 2012). In the study area, the

Giétro, Breney and Otemma glaciers have lost respectively 43%, 61% and 63% of their mass between 1850 and 2009 (Lambiel and Talon 2019) and the Haut glacier d'Arolla has lost 40 (±5) × 10^6 m^3 of ice volume between 1999 and 2005, associated with a vertical loss of 35 m in the tongue area (Dadic et al. 2008). At the same time, glacier fronts retreated dramatically, as for example, the Zinal glacier for which the front retreat reached 400 m between 1990 and 2018 (Glamos 2020).

Another consequence of climate change on glaciers is a decrease in snow cover on glaciers, both in area and depth, in relation with a 170 m rise of the glacier equilibrium line (ELA) altitude between 1984 and 2010 in the western Alps (Rabatel et al. 2013) and a reduction in winter snow accumulations (Beniston et al. 2018). As a consequence, crevasses masked by snow in winter appear higher in altitude and earlier in spring and areas of bare ice, technically difficult to cross for a climber in steep terrain, are more extended, even above 3000 m a.s.l.

The decrease in snow cover on glacier, combined with a decrease in the frost frequency (Pohl et al. 2019) and a rise in altitude of the 0°C isotherm in summer (167 m increase in the MBM since 1960; *Météo France* and Snow Research Center data, analysis by the Research Center for Alpine Ecosystems) probably leads to an earlier weakening of snow bridges in spring or during heat waves. Moreover, the retreat of steep hanging glaciers may imply an increase in the frequency of ice avalanches, as evidenced locally by Fischer et al. (2006). On annual and secular time scales, they are occurring especially during the warmest periods (Deline et al. 2012). Glacial shrinkage also leads to an increase in the surface and/or thickness of supraglacial debris covers for some glaciers (Gomez and Small 2018; Scherler et al. 2018).

In response to the melting of glaciers, the Alps are currently in a paraglacial period (Church and Ryder 1972; Ballantyne 2002; McColl, 2012). As a consequence, paraglacial processes – defined by Ballantyne (2002) as 'the non-glacial earth-surface processes, sediment accumulations, landforms, landsystems and landscapes that are directly conditioned by glaciation and deglaciation' – are intensifying. In the Alps, the main paraglacial processes at work are rockfalls, debris slides and slumping due to the erosion of recently deglaciated moraines (McColl 2012; Deline et al. 2015; Draebing and Eichel 2018; Eichel et al. 2018; Ravanel et al. 2018) and rockfalls from recently deglaciated rock slopes (Hartmeyer et al. 2020).

At the same time, permafrost undergoes accelerated degradation (Haeberli and Gruber 2009; Biskaborn et al. 2019), which results in more frequent and voluminous rock slope movements (rockfalls, rock slides) (Harris et al. 2001, 2009; Ravanel and Deline 2011; Ravanel et al. 2017). However, one must be careful not to consider every rockfall as due to permafrost degradation, since it is a natural erosion process in high mountain environments.

Methods

Construction of the legend and mapping of the processes affecting the itineraries

The method used to map the processes affecting the itineraries is divided in 4 steps (Figure 2):

(1) A legend was developed on the basis of the 25 processes identified in the MBM (Mourey, Marcuzzi, et al. 2019a). Following the UNIL geomorphological legend (Schoeneich 1993; Lambiel et al. 2016) and using the same color code, 21 symbols were defined to map 23 processes (Figure 2). The processes 'Weakening of snow bridges' and 'Less frequent night freezing', identified in the MBM, have not been considered in this work as they are impossible to map at the scale of a mountaineering itinerary and the two processes 'Glaciers surface more often in bare ice' and 'Glaciers slope angle increase' are almost always associated and are therefore represented using the same symbol. The same applies for the two processes 'Ice aprons surface more often in bare ice' and 'Ice aprons slope angle increase.' The processes were classified according to the terrain in which they take place: (i) glacier margins, (ii) glaciers, (iii) unglaciated and/or permafrost affected rock slopes and (iv) ice aprons, hanging glaciers and snow ridges.

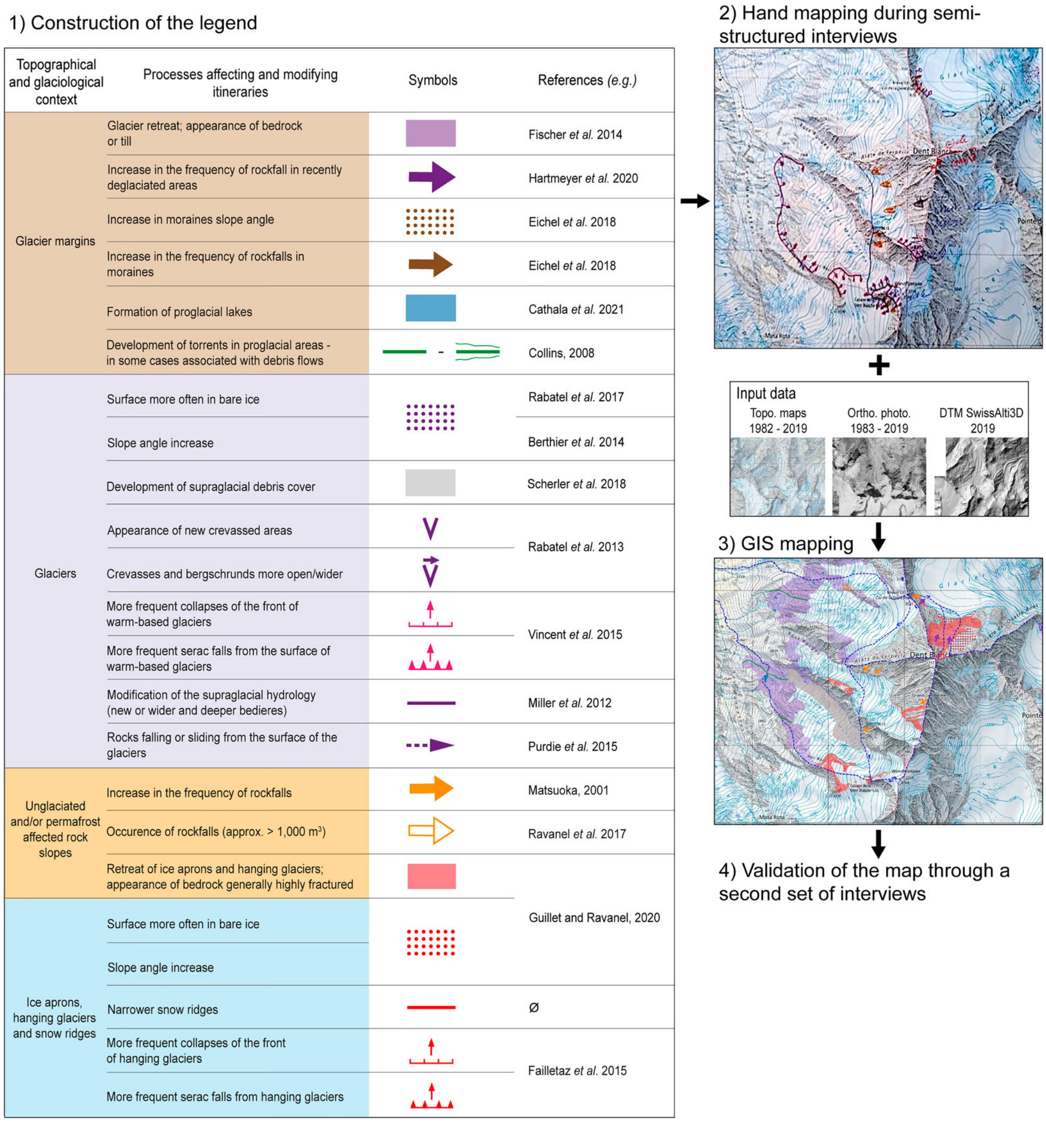

Figure 2. The four steps of the mapping work of the climate-related processes affecting mountaineering itineraries.

(2) In a first set of semi-structured interviews (16 interviews lasting 1–2 hours) carried out by the same researcher, local mountain guides and refuge keepers were asked to draw on the most recent topographic map available, with the help of the legend, the long-term modifications of the itineraries (since the 1980s) they are able to identify. At the same time the interviewer took notes to complete and clarify the mapped processes.

(3) The changes mapped during the interviews were then remapped using the Geographic Information System (GIS) *QGIS*. This information was completed by a diachronic analysis of aerial images from 1982 to 1983 and 2019 to 2020, together with the analysis of topographic maps and the SwissAlti3D digital elevation model (DTM) of *Swisstopo* (2 m resolution) (Figure 2). The latest aerial images allowed to accurately digitize the difference in ice surfaces related to the shrinkage of glaciers and ice aprons, the development of debris covers on glaciers, the newly formed proglacial lakes, the development of torrents in proglacial areas and the changes in supra-glacial hydrology such as the formation/widening of bedieres and moulins. Overall,

only the processes affecting the itineraries studied – or in the direct proximity with them – were mapped. The digitization was carried out at a scale between 1:1000 and 1:5000. The scale of the final map (Appendix 1) is 1:25,000, in accordance with the scale of the topographic map used. A few days of field work were also needed to confirm some observations, as for example the limits of debris-covered glacier, which are difficult to identify from aerial images.

(4) Finally, an evaluation of the map was completed through a second set of five interviews with some other local mountain guides and refuge keepers, not interviewed during the first set. They were asked to confirm/precise or invalidate the processes mapped if necessary.

From the final map, all the processes affecting each of the itineraries could be listed and organized in a database (Appendix 2), cross-referencing each of the itineraries with the 23 geomorphological and glaciological processes. A cross analysis between the number of processes that affect each itinerary, their type, their level of modification, their orientation, etc., could then be performed.

During step 2, the identification by the interviewees of the processes affecting the itineraries was generally influenced by the conditions encountered during their last ascent and/or their clients. The interviewees identified in priority the processes that are the most relevant for their ascent, without necessarily considering the season and the climate-related evolutions. For example, an alpine guide will be more prone to notice a change such as a steeper glacier if he is with clients of a rather low technical level. It was the interviewers' role to encourage interviewees to identify only long-term processes rather than focusing on their last ascent. For this reason, each of the itineraries was studied during at least two different interviews.

Change in the climbing parameters for each itinerary

The interviewees were asked to evaluate the level of change of the climbing parameters for each itinerary, according to the 5-level scale used in the MBM (Mourey, Marcuzzi, et al. 2019a):

- Level 0: the itinerary is not affected by any process related to climate change. There is no change in its climbing parameters.
- Level 1: the itinerary is affected by a few processes related to climate change, but they only affect a small part of the itinerary and do not imply an increase in danger or in technical difficulty.
- Level 2: the itinerary is affected by processes related to climate change that imply a moderate increase in danger and/or technical difficulty; as a result, the itinerary may not be climbable all the summer long and the most favorable period to climb it shifts to spring and/or fall, sometimes winter.
- Level 3: the itinerary is affected by processes related to climate change that imply a strong increase in danger and/or technical difficulty; the itinerary is thus generally no longer climbable in summer.
- Level 4: the itinerary is affected by processes related to climate change that led to the disappearance of a large part of the itinerary (e.g. massive rockfall). It can no longer be climbed.

Results

Map of the climate-induced processes affecting mountaineering itineraries

The general map (Appendix 1) shows the glaciological and geomorphological processes related to climate change that affect the 36 itineraries studied and an example is given in Figure 3. This map was then used to list the processes affecting each of them and to perform a statistical analysis (Appendix 2). For example, according to the local map extracted for the Cheilon glacier area (Figure 3), the itinerary 62 – the 'Gallet ridge' on the *Mont Blanc de Cheilon* (3870 m a.s.l.) – is affected by 12 different types of processes.

On average, an itinerary is affected by nine different processes. Eight processes are affecting more than half of the itineraries: (i) glacial retreat and the appearance of bedrock or till (34 itineraries affected

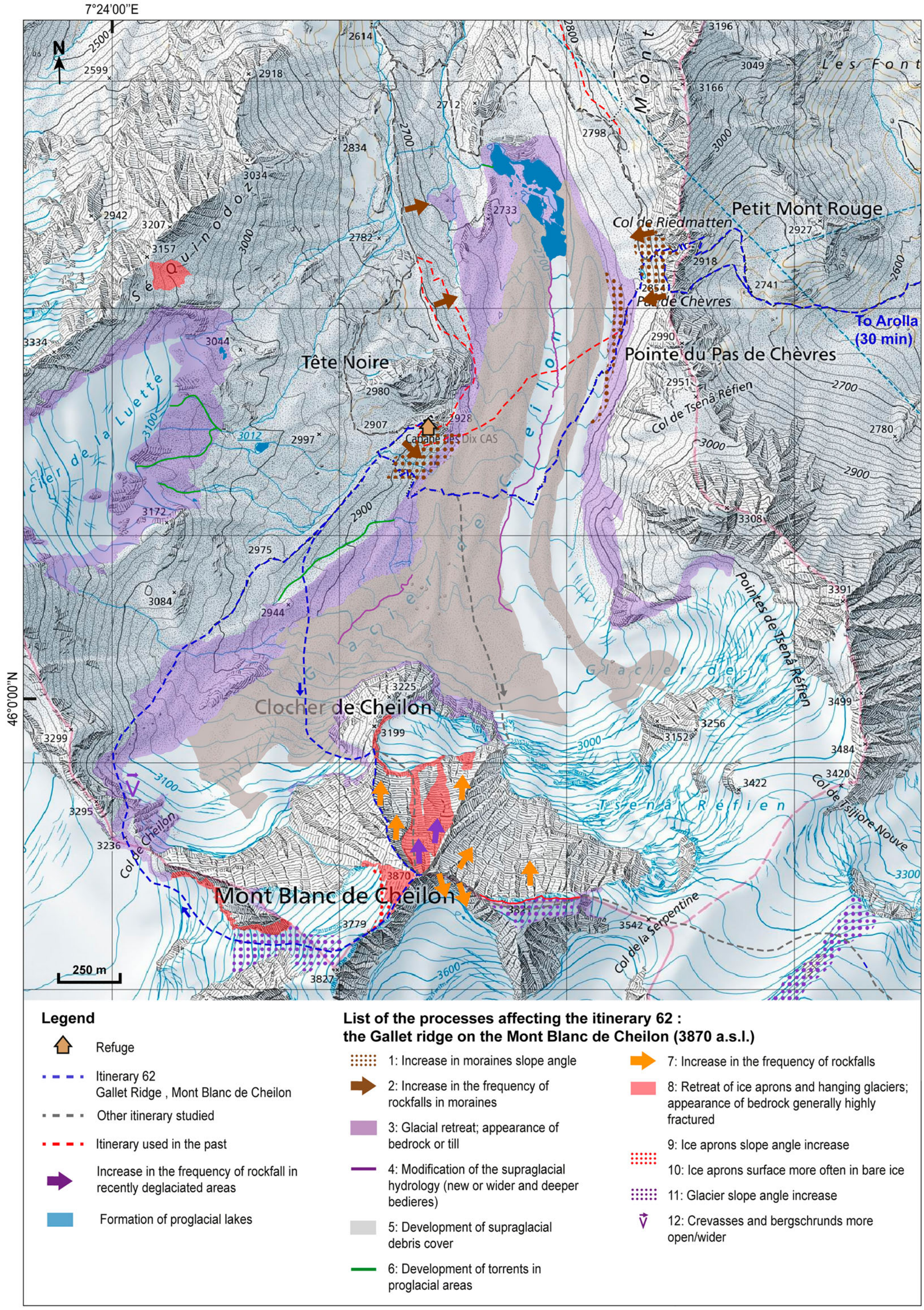

Figure 3. Extract of the general map of the climate-related processes affecting mountaineering itineraries: the Cheilon glacier area (Hérémence valley). Twelve processes are affecting the itinerary 62, the 'Gallet ridge' on the Mont Blanc de Cheilon.

out of 36 = 94%), (ii) the retreat of ice aprons and hanging glaciers and the appearance of bedrock, generally highly fractured (33/36 = 92%), (iii) the development of a supraglacial debris cover (26/36 = 72%), (iv) the increase in the frequency of rockfalls in unglaciated rock slopes (26/36 = 72%), (v) steeper ice aprons and hanging glaciers (24/36 = 67%), (vi) ice aprons more often in bare ice (24/36 = 67%), (vii) the development of torrents in proglacial areas – in some cases associated with debris flows (23/36 = 64%) and (viii) the increase in the frequency of rockfall in recently deglaciated areas (19/36 = 53%). Overall, these processes cause an increase in danger and technical difficulty for climbers.

Altitudinal distribution of the climate-induced processes affecting the itineraries

The different parts of the itineraries (refuge access, approach, route and descent) are not affected by the same processes (Figure 4) which are generally altitudinally distributed.

Refuge accesses are affected by 15 different processes occurring mainly in glacier margins. Glacier retreat and the appearance of bedrock or till is the process that mostly affects the refuge accesses (23 over 36–64%). This observation is consistent with the fact that the 15 refuges concerned

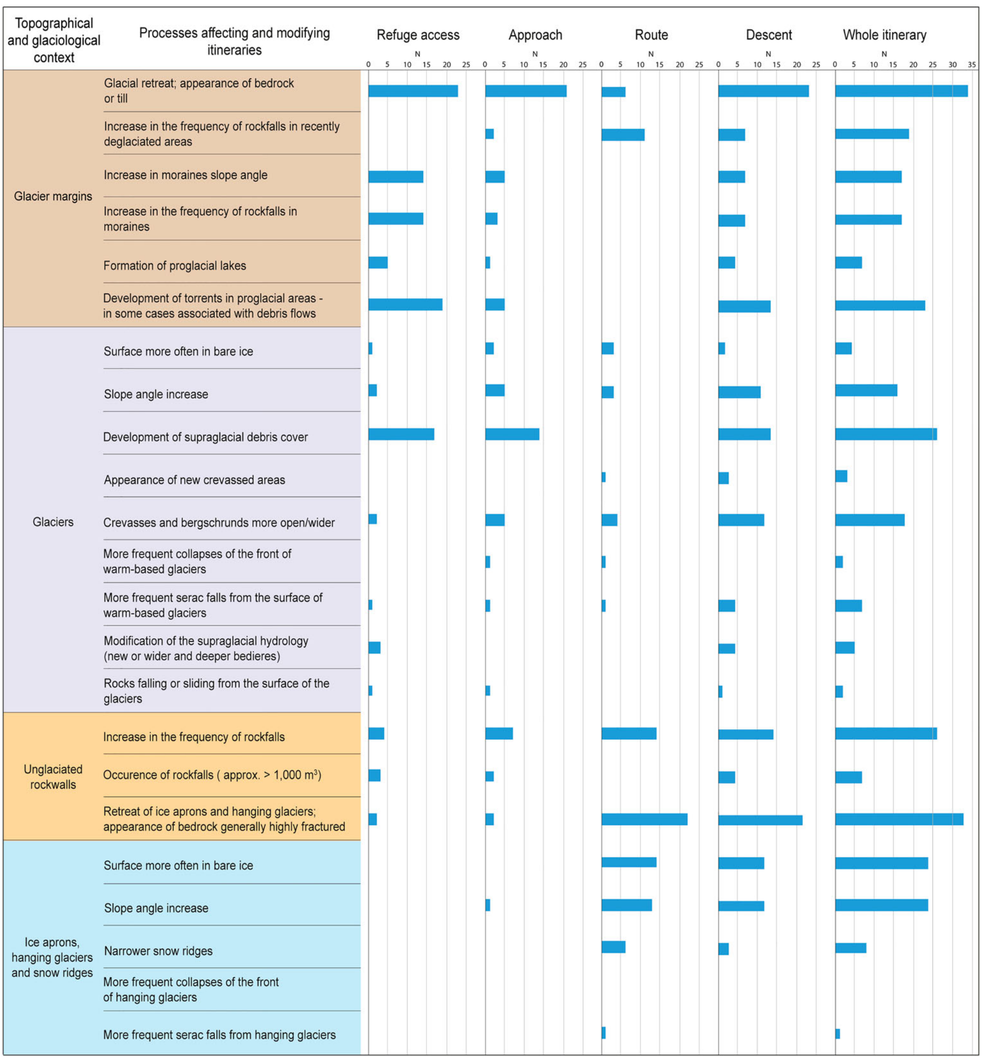

Figure 4. Number of refuge access, approach, route and descent affected by each process.

are located at a mean altitude of 3069 m a.s.l. (min.: 2462 m a.s.l.; max.: 3787 m a.s.l.; med.: 2954 m a.s.l.), i.e. below the ELA. Their access follows and/or crosses glacier tongues, where the melting is the highest (Berthier et al. 2014). This finding is in agreement with other studies carried out on climate-related evolution of the accesses to high mountain refuges in the Alps (Mourey and Ravanel 2017; Mourey, Ravanel, et al. 2019b).

The approach to the route start is the part of the itinerary affected by the highest number of processes (17/23) and is also mainly affected by the glacier retreat and the appearance of bedrock or till (23/36–64%). However, as they are located a little higher in altitude than the accesses to the refuges, they are less affected by paraglacial processes and they are more affected by processes occurring in unglaciated rock slopes such as the increase in the frequency of rockfalls (Figure 4).

The route itself is the part of the itinerary that is affected by the lowest number of processes (14/23) as their environment is generally monotype (rock, snow or mixed), but these processes largely define the level of change of the climbing parameters of the entire itinerary. Indeed, the route being in general the steepest and the most technically difficult part of the whole itinerary, the slightest modification of the environment quickly leads to a modification of its climbing parameters. The process that mostly affects the routes is the retreat of ice aprons and hanging glaciers and the appearance of bedrock, generally highly fractured (22/36–61%).

Level of change of the climbing parameters of the itineraries

The climbing parameters have not evolved for only 1 (3%) of the itineraries studied: the *Traversée des Petites Dents de Veisivi* (3184 m a.s.l.; itinerary 34), located relatively low in altitude and without glaciers. They have slightly evolved (level 1) for 12 (33%) of the itineraries, moderately evolved (level 2) for 14 (39%) and strongly evolved (level 3) for 9 (25%). None of the studied itineraries are at a level 4 of change.

Overall, snow and mixed itineraries are more affected by climate change, with an average level of change of 2.5 and 2 respectively, than rock itineraries (1.6). North-oriented routes have the highest average level of change (2.5) compared to the south-oriented routes (1.3). The samples of west- and east-oriented routes are very limited (3 routes for each; Table 1) so they have not been considered in the later analysis.

Table 1. Comparison of the samples of itineraries studied in the Valais Alps and the MBM according to their type, orientation, technical difficulty and level of change of their climbing parameters.

	Valais Alps		Mont Blanc massif	
	N	%	*N*	%
Type of itinerary				
Snow	7	19	24	25
Mixed	5	14	22	23
Rock	24	67	50	53
Orientation				
N	15	42	29	31
S	15	42	39	41
E	3	8	10	11
O	3	8	16	17
Technical difficulty				
Somewhat difficult	2	5	9	10
Fairly difficult	15	41	15	16
Difficult	12	32	30	32
Very difficult	8	22	33	35
Extremely difficult	0	0	7	7
Level of evolution				
0	1	3	2	2
1	12	33	30	32
2	14	39	34	36
3	9	25	26	27
4	0	0	3	3

Moreover, there is a link between the number of geomorphic changes affecting an itinerary and its level of change. On average, for level 1, 7.5 changes were affecting the itineraries, 9.4 for level 2 and 11.2 for level 3.

Eight of the nine itineraries with a modification level of 3 show the same pattern of change. For these 8 itineraries, the routes located on north faces are unclimbable during most of the summer period due to the melting of ice aprons. The laters re-form during winter and melt earlier in spring, leading to the appearance of generally highly fractured bedrock and related frequent rockfalls.

In our sample of itineraries, the following north-facing routes are presenting this pattern of change and a level of change of 3: the *Pointes de Mourti* (3564 m a.s.l.; itinerary 25), the *Petit Mont Collon* (3538 m a.s.l.; itinerary 43), the *Pigne d'Arolla* (3796 m a.s.l.; itinerary 46), the *Mont Blanc de Cheilon* (Figure 3; 3869 m a.s.l.; itinerary 62), the *Ober Gabelhorn* (Figure 5; 4063 m a.s.l.; itinerary 84) and the *Dent Blanche* (4357 m a.s.l.; itinerary 99).

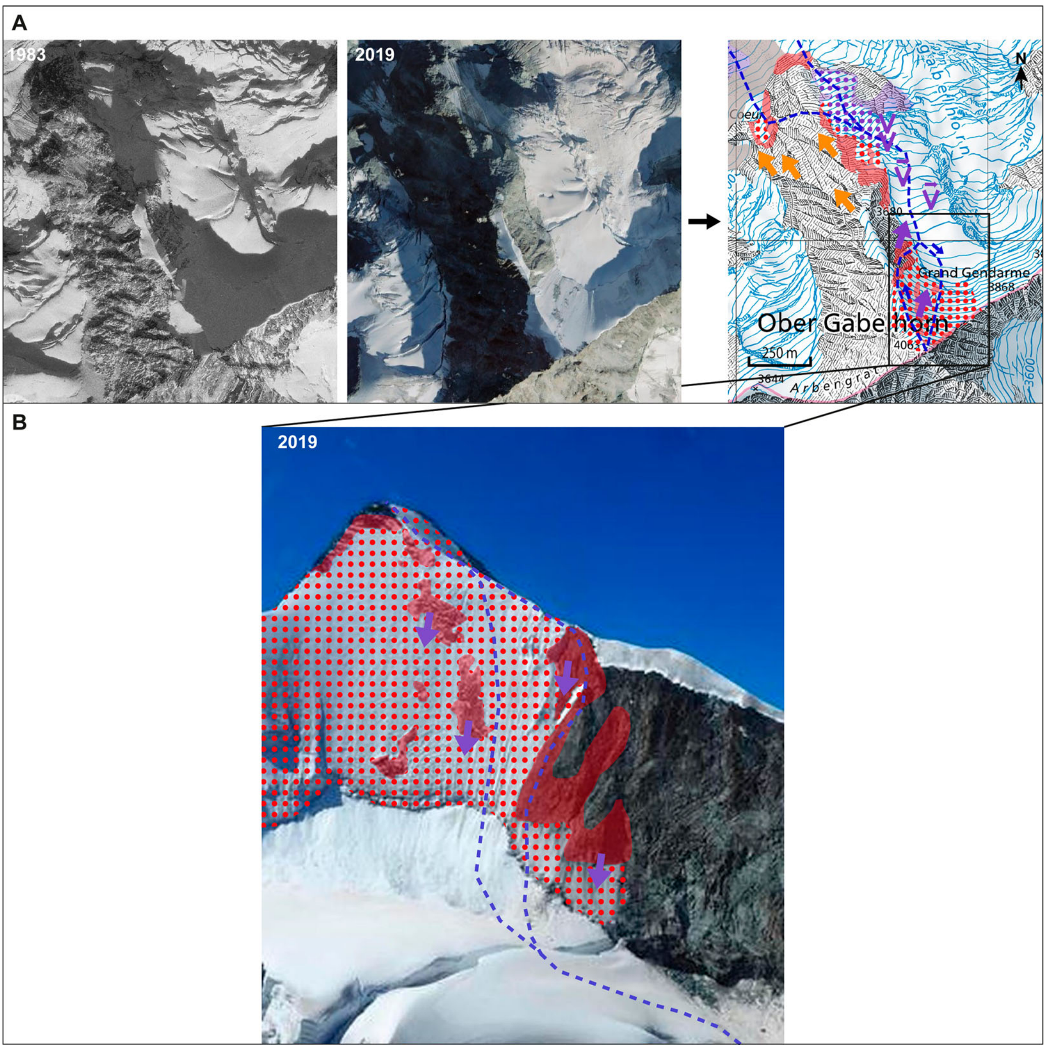

Figure 5. Evolution of the Ober Gabelhorn (4063 m a.s.l., itinerary 84; modification level: 3). (A) Comparison of aerial images from 1983 and 2019 (Swisstopo) to build the map on GIS. (B) The North Face in 2019 with the processes affecting the itinerary mapped (PoliceValais).

Discussion

Climate-related processes versus seasonality

In this paper, we identified the processes related to climate change that affect mountaineering itineraries on a climatic time scale (the last 40 years). In general, they lead to an increase in danger and technical difficulty of the itineraries and a modification in the most favorable and stable time of the year for mountaineering that tend to be more variable in summer and shift towards spring and fall. However, those consequences can be reduced or increased by seasonal and meteorological factors. The processes related to climate change identified in this work are generally less frequent and/or intense at the beginning of the season and on the contrary, they are more frequent and/or intense at the end of the summer season and/or during/following heat waves, which are becoming increasingly frequent and intense (Della-Marta et al. 2007). Thus, it is possible that at certain periods of the summer, depending on the conditions, the level of change of the climbing parameters of the studied itineraries may be less or more important than in the results presented above.

It is also important to note that some sections may also become easier thanks to changing conditions, notably in favor of a flatter and/or less crevassed glaciers. However, in the Valais Alps as well as in the MBM, this observation never applies to a whole itinerary. In all cases studied, the maximum technical level and/or the danger level has remained unchanged or increased.

Comparison between the Valais Alps and the MBM

Considering the main characteristics of the itineraries (type, orientation and technical difficulty), the samples studied in the MBM (see Mourey, Marcuzzi, et al. 2019a) and the Valais Alps are relatively similar (Table 1). Both have a majority of rock routes and a similar percentage of snow and mixed routes. Similarly, the proportion of routes for each orientation and technical level are of the same order (Table 1).

Results for the Valais Alps and the MBM are very similar. No new processes affecting and modifying the itineraries have been identified in the Valais Alps. On the contrary, no itinerary is affected by the process 'More frequent collapses of the front of hanging glaciers' in this region. In both massifs, the itineraries are affected by an average of nine climate-related processes. The level of change of the climbing parameters is also very similar (Table 1) with, in both massifs, a quarter of the itineraries with a level 3 of change. The main difference is that there are no itineraries with a level 4 of change in the sample studied in the Valais Alps. In both massifs, the process that mostly affects the itineraries is the glacial retreat and the appearance of bedrock or till. In contrast, the second and third processes in order of importance are not the same. In the Valais Alps, these are (i) the retreat of ice aprons and hanging glaciers and the appearance of bedrock generally highly fractured (33/36–91%), (ii) the development of supraglacial debris cover (26/36–72%) and (iii) the increase in the frequency of rock slope movements in unglaciated rock slopes (26/36–72%). In the MBM, these are: (i) more open crevasses and bergschrund (78/95–74%) and (ii) the increase in glacier slope angle (73/95–70%). These differences are probably related to the differences in the topographical, lithological and glaciological contexts between the two massifs. Indeed, compared to the Valais Alps, the MBM has a higher average altitude, a higher proportion of glaciated areas and a more humid climate. This explains that the processes that most affect the itineraries in the MBM are related to the evolution of glacial environments, whereas in the Valais Alps the processes are more diverse and also related to the evolution of unglaciated rock walls.

The differences in the identified processes may also be partly due to the two different methods used for each massif and in particular to the fact that diachronic analysis of aerial images was systematically used in the Valais Alps to draw the map.

In the MBM, three main patterns of itinerary change were identified: (i) snow routes made more difficult and dangerous, and sometimes unclimbable, by the melting of ice aprons, (ii) rock routes made inaccessible by the loss of glacier ice thickness and (iii) access to refuges made more difficult and dangerous by the melting of glacier tongues. In the Valais Alps, we find the same patterns concerning the snow routes and the access to the refuges. However, the pattern concerning the rock routes has not been identified. This difference is probably linked to the lithology. In the recently deglaciated areas of the MBM, the granite tends to form smooth rocky slabs that are particularly difficult to climb, whereas the fractured gneiss in the Valais Alps limits the formation of such unclimbable rocky slabs and instead produces ledges.

Finally, in both massifs, rock routes have the lowest average level of change (1.6 in both massifs) and conversely, snow and mixed routes have the highest level of change (2.5 in the Valais Alps and 2.4 in the MBM). This finding is not in accordance with the events that are generally reported in the press, which generally reports on events where climbers have been affected by rockfalls (examples of the Matterhorn were two climbers were killed by rockfalls on Wednesday 25th of July 2019; https://www.letemps.ch/suisse/canicule-accelere-lerosion-alpes-accentue-chutes-pierres). It is likely that the media focuses on these types of events because they are known by the general public, easy to illustrate and regularly at the origin of fatalities. However, our work shows that rockfalls, although very dangerous and spectacular, are not the process that most affect mountaineering itineraries.

Interest of the mapping

Mapping the climate-related processes affecting the mountaineering routes with the method presented here greatly facilitated the data acquisition and analysis, compared to the method used by Mourey, Marcuzzi, et al. (2019a) in the MBM. Indeed, it was easier for the interviewees to draw on a map the modifications they identified than to list them during an oral discussion without any physical support. The intellectual effort of visualizing the itinerary and identifying the processes affecting it is much greater without a map, while drawing the changes also avoided repetition between interviews and/or a too important focus on only one part of the itinerary. In addition, we chose to have several interviewees drawing on the same extract of map. Therefore, from one interview to the other, the interviewees could see the data already collected. This facilitated the validation of the mapped processes from one interview to the next, but this methodological choice may also imply a bias in the sense that an interviewee may be influenced by what he saw on the map. It was therefore the researcher's role to limit this bias during the interviews by asking each interviewee to have a critical look at the processes mapped during the previous interviews. In any case, the methodological approach used in this work, based on semi-structured interviews, necessarily implies a certain amount of subjectivity, as most of the information collected comes from the memories and appreciations of the interviewees.

The map also facilitates the analysis of the data. Once the map was made, it was easy to identify the processes (Figures 3–5) that affect each itinerary and then do a statistical treatment as presented in the results. In addition, the map will make the update of the data easier compared to a table that lists the processes for each route.

The use of topographic maps at the scale 1:25,000 is convenient and easy in Switzerland where maps have a high level of accuracy and are freely available. Moreover, Swiss Alpine guides and refuge keepers are used to read this type of document. However, in other parts of the world where maps are not necessarily accessible and/or of lower quality and the resource persons not used to reading maps, it might be necessary to use another type of support. One possibility could be to map on ground-based photographs as in Figure 5(B). However, this method would require a potentially large bank of images, depending on the size of the study area, and would not necessarily be easy to collect.

Mapping the climate-related processes affecting mountaineering itineraries also allows to produce documents that promote the transfer of knowledge to mountaineers. The 1:25,000 topographic map is a tool classically used by mountaineers, on which we add information on the change of the itineraries. In order to encourage awareness about the effects of climate change and the adaptation of mountaineers, these maps could, for example, be displayed for free in high mountain refuges. The map has a strong informative power for the users and should be a valuable planning and prevention tool in the future. Refuge keepers interviewed have already shown their interest for such initiative.

Limitations

The mapping method we propose here has however several limitations. Mapping processes in two dimensions is not optimal for representing elevation changes. For example, a glacier can lose several meters of ice thickness without any significant surface changes. In this case, no processes will be represented while the terrain and the climbing parameters of the itinerary have potentially deeply changed. This limitation can be balanced by applying the legend to ground-based photographs.

The legend we propose does not allow the mapping of all the processes that affect mountaineering itineraries. The fact that freezing is less frequent in high mountains (Pohl et al. 2019), with for example a projected decrease of 15–20% of the number of icy days (daily maximum temperature <0°C) between 2300–2700 m a.s.l. by 2030 (Cremonese et al. 2019) will have a significant effect on climbing parameters, but it is impossible to map. It is the same for the process 'Weakening of snow bridges'.

The snow conditions on the aerial images used during step 3 (GIS mapping) have necessarily conditioned the digitization of glaciers and ice aprons. The presence of snow can hide some changes. However, any process drawn on the map was identified in step 1 and confirmed in step 3.

The attribution of a process as a result of climate change is done by the interviewees and is subject to the appreciation of the researcher, especially during the stage 3 of the method. It is not the result of a quantitative measurement with therefore a part of uncertainty on the exact causes of each process. In order to limit this bias as much as possible, we insisted during interviews on the fact that the interviewees have to identify changes over a long period of time and not during particular events; anyway, there are some cases where the attribution of processes as a direct effect of the climate change remains uncertain. This is particularly true for rockfalls because they can be triggered by several factors possibly combined.

As for the MBM, the present work does not take into account any ice gullies, which are defined as seasonal (Faup 2003) 'concealed and narrow ice couloirs' (Jouty and Odier 1999). Those gullies started to be climbed thanks to improvements in mountaineering equipment, after the guidebooks used in the MBM and the present study were published. According to the interviewees those gullies are also affected by climate change and form less frequently, with a lower ice quality because of a diminution in winter and spring snowfalls and more intense melting of the ice/snow cover. It is likely that new symbols will have to be added to the legend when studying this type of routes.

There is also a bias related to the itinerary sectorization. The fact that the descents start at the summit and end at the bottom of the valley implies that they are statistically affected by a large number of processes.

Conclusions and perspectives

This study presents the first legend that enables to map the processes related to climate change that affect mountaineering itineraries and modify their climbing parameters. This study responds to one of the main limitations identified in several previous studies on this topic. It facilitates the acquisition, analysis and update of the data, through the precise localization and quantification of the processes related to climate change that affect mountaineering routes. Their modification and the evolution of the possibility to practice mountaineering because of climate change are therefore all the better documented.

Furthermore, the legend defines an analytical framework, which can be completed and reused in other regions of the world, allowing for a better comparability and compilation of results. As could be expected, the comparison of the results between the MBM and the Valais Alps shows very similar patterns with, in both massifs, (i) an average of nine processes affecting the itineraries, (ii) itineraries mainly affected by glacial retreat and the appearance of bedrock or till and (iii) a quarter of the itineraries that is no longer climbable in summer. This observation confirms the robustness of the methodology used. In the future, similar studies on other massifs of the world should be made. In this regard, a work by the authors on the Hurrungane massif and the Lynguen Alps in the Scandinavian Alps should start soon. Another perspective would be to quantify the processes mapped in particular by measuring at the scale of mountaineering itineraries ice surface evolution and carrying out diachronic analysis of DTMs (loss of ice surface/thickness, evolution of the slope angles, etc.) in GIS.

Finally, mapping makes it possible to produce documents that promote the transfer of information to mountaineers and their adaptation to the effects of the climate change. They can therefore be used in this sense on many occasions and in particular during the training of Alpine guides and conferences as well as being displayed in high mountain refuges.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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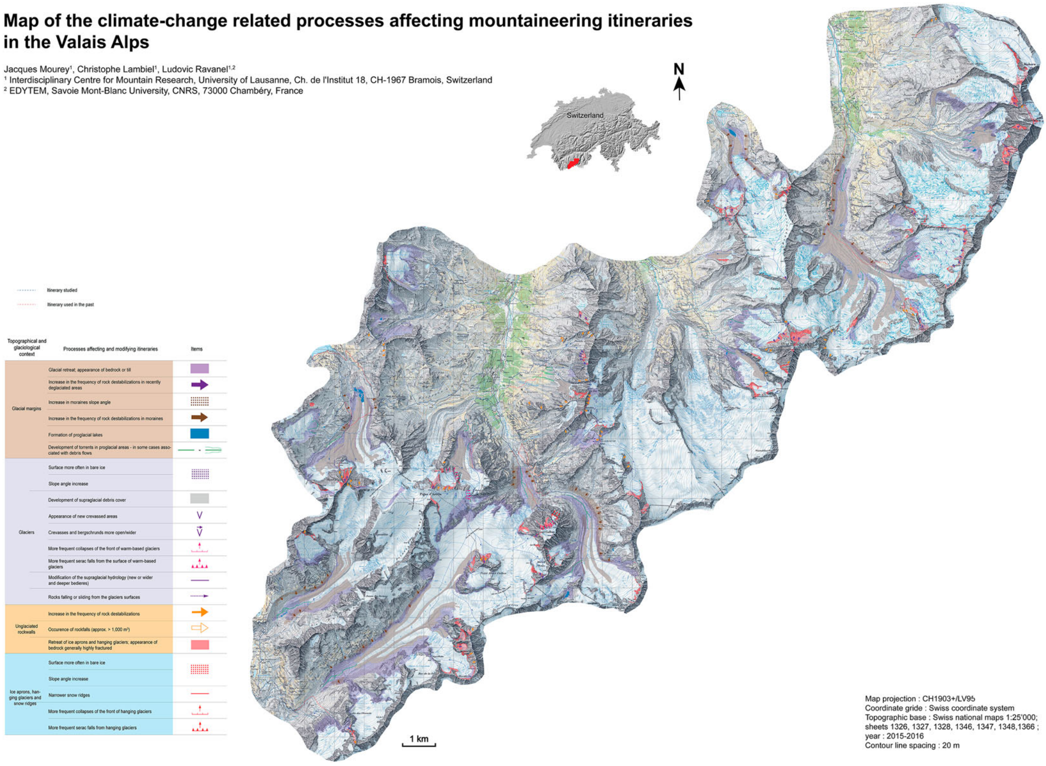
Appendices

Appendix 1



Appendix 2

Summit	Itinerary	Number	Altitude (m a.s.l.)	Max. difficulty	Orientation of the route	Type of route	Marges glaciaires / Glacier margins: Glacier retreat; appearance of bedrock or till	Increase in the frequency of rockfall in recently deglaciated areas	Increase in moraines slope angle	Increase in the frequency of rockfalls in moraines	Formation of proglacial lakes	Development of torrents in proglacial areas - in some cases associated with debris flows
Le Mammouth	SW ridge and S face	4	3215	AD	SW and S	Rock	X		X	X		
La Ruinette	SW ridge	5	3875	F	SW	Snow	X, X		X	X		X
Bec d'Epicoune	N ridge	8	3529	F	N	Snow	X	X				
Pointe de Tsalion	The Cabane ridge, The Pilier and the du Gendarme Rouge routes	9	3512	D	W	Rock	X	X				X
Pigne d'Arolla et Mont Blanc de Cheilon	Traverse	14	3796 - 3870	AD	E - W	Snow	X, X, X		X	X		X, X
L'eveque	SW ridge	19	3716	AD-	SW	Rock	X, X, X	X	X, X	X		X, X, X
Pointes de Mourti	N face	25	3564	AD	N	Snow	X, X	X	X	X		
Pointes de Mourti	S face	25	3564	AD	S	Rock	X, X					
Pointes de Mourti	W face	25	3564	AD	W	Rock	X, X					
Grand Cornier	S ridge	28	3962	AD+	S	Rock	X, X	X			X	X
Besso - Blanc de Moming	SW ridge and traverse	30	3668 - 3663	AD	S	Rock	X, X, X	X	X	X		
Petite dent de Veisivi	Traverse	34	3184	AD+	S	Rock						
Aiguille de la Tsa	W ridge	40	3668	AD	N	Rock	X	X				X
La Singla	Traverse	41	3714	D	S	Rock	X, X					X, X
Petit Mont Collon	N face	43	3538	D+	N	Snow	X, X, X	X				X, X
Aiguilles Rouges d'Arolla	N-S traverse	45	3646	D	N - S	Rock	X, X					
Pigne d'Arolla	N face	46	3796	D	N	Snow	X	X				X
Rothorn de Zinal	Rothorn ridge	53	4221	AD+	N - S	Rock	X, X, X	X	X, X	X, X		X
Dent Blanche	Classic route	56	4357	AD	S	Rock	X, X				X, X	X, X
Douves Blanches	SW ridge	58	3642	D	SW	Rock	X, X, X		X	X		
Dent de Perroc	SW promontory and The Carougeois route	61	3676	D - TD	SW	Rock						X
Mont Blanc de Cheilon	Jenkinx ridge	62	3869	AD+	N	Rock	X, X, X		X, X, X	X, X, X		X, X, X
Mont Blanc de Cheilon	Gallet ridge	62	3870	AD	N	Rock	X, X, X		X, X	X, X		X, X
Mont Blanc de Cheilon	N face	62	3870	TD	N	Mixed	X, X, X	X	X, X	X, X		X, X
Dent Blanche	Ferpècle ridge	68	4357	D+	W	Rock	X, X	X			X, X	X, X
Pointe de Moming - Schalihorn	Traverse	72	3975	AD	S - N	Mixed	X, X		X	X		
Weisshorn	Traverse	73	4505	D	S - N	Rock	X, X	X			X	
Weisshorn	Young ridge	77	4505	D	N	Rock	X, X	X				
Mont Collon	N face	79	3637	TD	N	Rock	X, X	X				X, X
Dent Blanche	The 4 Anes ridge	81	4357	D	E	Mixed	X, X, X		X	X	X	X
L'eveque	E face	83	3716	TD	E	Rock	X, X, X	X	X, X	X		X, X, X
Ober Gabelhorn	N face	84	4063	TD	N	Snow	X, X, X, X	X, X	X, X	X, X		
Mont Collon	SE promontory	86	3637	TD	S	Rock	X, X, X	X	X, X	X, X		X, X
Dent Blanche	N ridge	87	4357	TD	N	Mixed	X, X				X, X	X, X
Les Bouquetins	Traverse	94	3838	D	S	Rock	X, X, X		X, X	X, X		X
Dent Blanche	N face	99	4357	TD	N	Mixed	X, X	X, X			X, X	X, X
			Number of itineraries affected by each process				34	19	17	17	7	23
			Purcentage of itineraries affected by each process				94	53	47	47	19	64

Summit	Itinerary	Glaciers: Surface more often in bare ice	Slope angle increase	Development of supraglacial debris cover	Appearance of new crevassed areas	Crevasses and bergschrunds more open/wider	More frequent collapses of the front of warm-based glaciers	More frequent serac falls from the surface of warm-based glaciers	Modification of the supraglacial hydrology (new or wider and deeper bedieres)	Rocks falling or sliding from the surface of the glaciers
Le Mammouth	SW ridge and S face			X						
La Ruinette	SW ridge			X					X	
Bec d'Epicoune	N ridge									
Pointe de Tsalion	The Cabane ridge, The Pilier and the du Gendarme Rouge routes									
Pigne d'Arolla et Mont Blanc de Cheilon	Traverse	X, X	X, X	X, X		X, X		X	X	
L'eveque	SW ridge		X	X, X	X	X		X		
Pointes de Mourti	N face			X, X						
Pointes de Mourti	S face			X, X						
Pointes de Mourti	W face			X, X						
Grand Cornier	S ridge			X						
Besso - Blanc de Moming	SW ridge and traverse			X						
Petite dent de Veisivi	Traverse									
Aiguille de la Tsa	W ridge									
La Singla	Traverse	X	X, X	X, X		X, X		X, X		
Petit Mont Collon	N face	X	X, X, X	X, X		X, X		X		
Aiguilles Rouges d'Arolla	N-S traverse		X	X						
Pigne d'Arolla	N face			X		X	X			
Rothorn de Zinal	Rothorn ridge			X, X		X, X				
Dent Blanche	Classic route									
Douves Blanches	SW ridge	X, X	X, X, X			X, X, X				X, X
Dent de Perroc	SW promontory and The Carougeois route									
Mont Blanc de Cheilon	Jenkinx ridge		X	X, X, X		X			X, X	
Mont Blanc de Cheilon	Gallet ridge		X	X, X, X		X			X, X	
Mont Blanc de Cheilon	N face		X	X, X, X		X			X, X	
Dent Blanche	Ferpècle ridge			X						
Pointe de Moming - Schalihorn	Traverse			X		X				
Weisshorn	Traverse			X		X				
Weisshorn	Young ridge		X							
Mont Collon	N face		X	X, X		X	X	X		
Dent Blanche	The 4 Anes ridge		X	X, X		X				
L'eveque	E face		X	X, X	X	X		X		
Ober Gabelhorn	N face	X, X	X, X	X, X, X	X, X	X, X				
Mont Collon	SE promontory		X	X, X, X		X		X		
Dent Blanche	N ridge									
Les Bouquetins	Traverse		X	X		X				X
Dent Blanche	N face									
Number of itineraries affected by each process		4	16	26	3	18	2	7	5	2
Purcentage of itineraries affected by each process		11	44	72	8	50	6	19	14	6

Summit	Itinerary	Parois non englacées / Unglaciated and/or permafrost affected rock slopes: Increase in the frequency of rockfalls	Occurence of rockfalls (approx. > 1,000 m3)	Retreat of ice aprons and hanging glaciers; appearance of bedrock generally highly fractured	Couvertures glacio-nivales, glaciers suspendus et arêtes de neige / Ice aprons, hanging glaciers and snow ridges: Surface more often in bare ice	Slope angle increase	Narrower snow ridges	More frequent collapses of the front of hanging glaciers	More frequent serac falls from hanging glaciers	Level of evolution of the climbing parameters	Number of processes affecting the itineraries
Le Mammouth	SW ridge and S face									1	4
La Ruinette	SW ridge	X		X, X						2	8
Bec d'Epicoune	N ridge	X, X		X	X	X				2	6
Pointe de Tsalion	The Cabane ridge, The Pilier and the du Gendarme Rouge routes	X		X	X	X				2	7
Pigne d'Arolla et Mont Blanc de Cheilon	Traverse	X		X	X	X				2	14
L'eveque	SW ridge			X, X	X	X				2	13
Pointes de Mourti	N face	X	X	X, X	X	X				3	10
Pointes de Mourti	S face	X, X	X, X	X	X	X	X			1	8
Pointes de Mourti	W face	X, X	X, X	X	X	X	X			1	8
Grand Cornier	S ridge	X	X, X	X	X	X				2	10
Besso - Blanc de Moming	SW ridge and traverse		X, X	X, X	X	X				1	9
Petite dent de Veisivi	Traverse									0	0
Aiguille de la Tsa	W ridge	X, X		X	X	X				2	7
La Singla	Traverse	X		X, X	X	X				2	11
Petit Mont Collon	N face	X		X, X	X	X				3	12
Aiguilles Rouges d'Arolla	N-S traverse			X						1	4
Pigne d'Arolla	N face	X		X, X	X	X, X				3	10
Rothorn de Zinal	Rothorn ridge			X	X	X	X			2	11
Dent Blanche	Classic route	X, X		X, X, X						1	5
Douves Blanches	SW ridge	X, X, X, X		X, X						1	9
Dent de Perroc	SW promontory and The Carougeois route	X, X, X								2	3
Mont Blanc de Cheilon	Jenkinx ridge	X		X	X	X				3	12
Mont Blanc de Cheilon	Gallet ridge	X		X	X	X				3	12
Mont Blanc de Cheilon	N face	X		X, X	X, X	X				3	13
Dent Blanche	Ferpècle ridge	X, X, X		X, X						1	7
Pointe de Moming - Schalihorn	Traverse			X	X	X	X			1	9
Weisshorn	Traverse	X		X, X	X, X	X, X	X			2	10
Weisshorn	Young ridge	X, X		X, X	X, X	X, X	X, X			2	8
Mont Collon	N face			X, X					X	3	10
Dent Blanche	The 4 Anes ridge	X, X		X			X			2	11
L'eveque	E face			X	X	X				2	13
Ober Gabelhorn	N face	X, X		X, X	X, X	X, X				3	13
Mont Collon	SE promontory			X						1	10
Dent Blanche	N ridge	X	X	X						1	6
Les Bouquetins	Traverse	X		X, X	X	X				1	12
Dent Blanche	N face	X, X	X	X, X, X	X	X	X			3	10
Number of itineraries affected by each process		26	7	33	24	24	8		1		9
Purcentage of itineraries affected by each process		72	19	92	67	67	22	0	3		

Legend

Access to the refuge X
Approach X
Route X
Descent X

	French	English
F	*Facile*	Easy
AD	*Assez difficile*	Quite easy
D	*Difficile*	Difficult
TD	*Très difficile*	Very difficult