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Effects of Climate Change on High Alpine Mountain Environments

Evolution of Mountaineering Routes in the Mont Blanc Massif over 50 Years

In high Alpine environments, glacial shrinkage and permafrost warming due to climate change are having significant consequences on mountaineering routes. Few research projects have studied the relationship between climate change and mountaineering; this study attempts to characterise and explain this evolution over the past 40 years of routes described in *The Mont Blanc Massif: The 100 Finest Routes*, Gaston Rébuffat's emblematic selected guidebook, first published in 1973.The main elements studied were geomorphic and cryospheric changes and their impacts, determining the manner and possibility for each route to be climbed. Thirty-one interviews and comparison with other guidebooks led to the identification of 25 distinctive geomorphic and cryospheric changes related to climate change affecting mountaineering itineraries. On average, each itinerary has been affected by nine changes. Among the 95 itineraries studied, 93 have been affected by the effects of climate change; 26 of them have been greatly affected; and three no longer exist. Moreover, periods during which these itineraries can be climbed in good conditions in summer have tended to become less predictable and periods of optimal conditions have shifted toward spring and autumn, because the itineraries have become more dangerous and technically more challenging.

Introduction

Climate change led to a temperature increase of 2°C in the Alps between the end of the 19th century and the beginning of the 21st with a strong acceleration in warming since the 1990s. In this context, and being very sensitive to climate variations, high Alpine environments have undergone major change. The total surface area of Alpine glaciers decreased by half between 1900 and 2012 while rock faces experienced an increase in the frequency and volume of rock fall. These changes raise the question of what the effects might be on recreational mountain activities, and especially on mountaineering. Mountaineers climbing during the summer months are undeniably noticing important changes to the environment to which they must adapt by modifying their techniques. Although awareness of this issue dates back to the 2000s, only a few studies have been conducted to confirm it. As such, the evolution of mountaineering itineraries due to climate change remains poorly documented.

This article aims to describe and explain the evolution over nearly half a century of mountaineering itineraries in the Mont Blanc massif (MBM), the birthplace of mountaineering and still a major mountaineering destination. It is impossible to document all mountaineering itineraries as several thousand have been climbed in the MBM. The 1975 Vallot guidebook alone includes 747 itineraries. Thus, our study focuses on itineraries in Gaston Rébuffat's famous guidebook, *The Mont Blanc Massif: The 100 Finest Routes*. Using recent guidebooks and interviews, the itineraries described by Rébuffat in 1973 were compared with their current state. First, the geomorphic and cryospheric changes that have affected the area were identified. Then, for each itinerary, the specific changes that have affected it were established and also the degree to which these changes have changed the route's technical level and danger. The evolution of the manner in which mountaineers tackle these routes due to the effects of climate change is then be discussed, along with the consequences for the popularity of mountaineering.

Mont Blanc Massif

Mountaineering originally developed in the western Alps, and especially in the MBM, at the end of the 18th century. Since then, it has evolved considerably through technical, cultural and ideological changes. The Golden Age of mountaineering was marked by a series of important first ascents, notably those made by Edward Whymper and his guides in the MBM, as well as the Matterhorn. In 2018 Chamonix and Courmayeur applied for mountaineering to be included on UNESCO's Intangible Cultural Heritage Lists. Over the past 200 years, the evolution of mountaineering has been mainly due to socio-cultural reasons. However, current changes to the high mountain environment due to climate change are challenging accepted mountaineering practices. The MBM (*Figure 1, overleaf*) is located in the north-west Alps between Switzerland, Italy and France, and covers 550km^2. About 30% of its surface is covered with ice with some 100 glaciers, including the Mer de Glace, the largest glacier in the French Alps with an area of 30km^2. A dozen peaks exceed the altitude of 4,000m, including Mont Blanc, the highest summit of the Alps (4809m).

The MBM presents a cross-range asymmetry. Six of the largest glaciers of the massif are located on its north-west aspect, where slopes are gentler than on its very steep south-east aspect, which is characterised by small glaciers bounded by high near-vertical rock walls. This asymmetry implies different climatic contexts. In Chamonix (1044m), the mean annual air temperature (MAAT) is 7.2°C, while in Courmayeur (1223m), it is 10.4°C. At the Aiguille du Midi (3842m), the MAAT is -8.2°C (reference period: 2008-10, Météo-France data). In Chamonix, MAAT increased by 1.7°C between 1934 and 2009. It is important to note this warming mainly affects winter temperatures; these increased by 2.8°C compared to summer temperatures, which increased by 1.5°C (Météo-France data). Moreover, MAAT

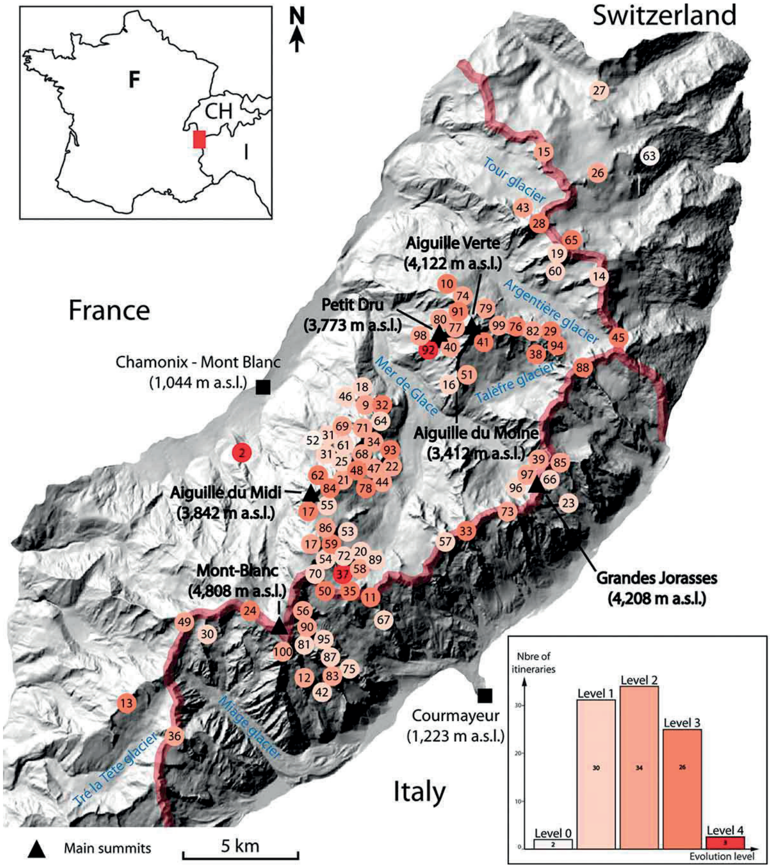


Figure 1 Location of the Mont Blanc massif, the itineraries studied and their level of evolution.

increased four times faster over the period 1970-2009 than during the period 1934-70. MAAT also increased at high elevations: above 4,000m, it increased by 1.4°C between 1990 and 2014. Since 1990, the MBM has experienced seven summer heat waves, four of them in the last decade. In France, summer 2018 was the second hottest summer since 1900. Only summer 2003 was hotter. In Chamonix, average annual precipitation is 1,288mm. In Courmayeur, it is 854 mm. At 3,500m, precipitation is three times higher than in the town of Chamonix. Since the end of the Little Ice Age (LIA), precipitation levels have experienced little change; however, there has been a clear decrease in snowfall days relative to total precipitation days and there is more frequent and intense melting. Consequently, in the Swiss Alps between 1,139m and 2,540m, snow-cover duration shortened by 8.9 days/decades^{-1} during the period 1970-2015, with a snow season starting 12 days later and ending 26 days earlier than in 1970. While these changes in snow cover are elevation dependent and less pronounced at higher altitudes, snow quantity at high altitude is also decreasing. With higher and faster warming at high altitudes than the global average, climate change is causing substantial change to high mountain environments. In the MBM, the glacial surface area decreased by 24% between the end of the LIA and 2008 with a considerable increase in the acceleration of melting since the 1990s. Mean glacier mass balance in the European Alps was -0.31m ± 0.04m wea^{-1} [*Editor's note:* wea^{-1} means 'water equivalent per year'] during the period 1900-2011 and -1m wea^{-1} during the first decade of the 2000s, which illustrates the acceleration of glacial shrinkage. In the MBM, the region-wide mean mass balance was -1.04 ± 0.23m wea^{-1} between 2003 and 2012; the Argentière glacier mean mass balance over the same period was -1.46 ± 0.4m wea^{-1}. The loss of ice thickness is also significant. At 1,900m, between 1994 and 2013, the Argentière glacier lost 80m of ice depth. On the Mer de Glace, the rate of glacial thickness loss increased from 1m per year (1979-1994) to more than 4m. The Mer de Glace loss in thickness was up to 60m at its front (1500m) during the period 1979-2003. At the same time, glacier fronts retreated dramatically: 366m between 1994 and 2007 for the Mer de Glace, with a particularly rapid period of shrinkage of 40m/y between 1998 and 2005. Glacial shrinkage affects high elevations, above the glacier equilibrium line altitude (ELA) that separates the accumulation and ablation zones. Between the 1960s and 2008, the glacier surface areas on the French side of the MBM decreased by 16% between 2,200m and 2,600 m, 11% at 2,600 to 3,000 m, 6% at 3,000, to 3,500 m and 3% at 3,500m to 4,000m. For example, the surface of the Talèfre glacier lowered by 5m to 10 m between 3,000m and 3,500m over the period 1979-2003. At 3,613m, the Géant glacier surface lowered by 20m between 1992 and 2012.

Glacial shrinkage coincides with a rise of the ELA of 170m between 1984 and 2010 in the western Alps. Also, combined with a decrease in winter snow accumulation, the snow cover on the glacier surfaces tends to decrease both in area and thickness. As a result, crevasses appear earlier in spring and areas of bare ice increase in summer. The decrease in snow cover on glaciers also results in an increase in the number of open crevasses, while snow bridges may be getting more fragile. The fragility of snow bridges is probably increasing as the average altitude of the 0°C isotherm has risen by 400m since 1980 and frost frequency has decreased. The snowpack does not refreeze and consolidate, especially during the night. As such, snow bridges are probably weakening earlier in spring and during heat waves.

In some cases, glacier retreat leads to more frequent serac fall from the hanging fronts of warm and cold-based glaciers. [*Editor's note:* Cold-based glaciers are at freezing where they meet the ground, warm-based glaciers are not.] In the MBM, serac fall mainly occurs during the warmest periods of the year and, at the secular scale, during or at the end of the warmest periods.

Due to glacial shrinkage, para-glacial processes – meaning non-glacial earth-surface processes, sediment accumulations, landforms, land-systems and landscapes that are directly conditioned by glaciation and de-glaciation – are intensifying. A para-glacial period starts as a direct reaction to de-glaciation and ends when all glacial sediments have been removed or stabilized. In this study, para-glacial processes refer mainly to the erosion of moraines through rock fall and landslides, illustrated by the gullying of the inner flank of lateral moraines due to steep slopes up to 80°.

At the same time, permafrost – ground that remains permanently at or below 0°C for at least two consecutive years – tends to warm and degrade. Even if all rock falls cannot be attributed to permafrost warming, as it is a natural erosion process in high mountain environments, its degradation results in more frequent and voluminous slope instabilities. In the MBM, more than 850 rock falls greater than 100m^3 occurred between 2007 and 2018. Permafrost is continuously present above 3,000m on average on north faces and above 3,600m on south faces.

The change in the high mountain environment raises the question of how mountaineering itineraries have been affected and what effect this has had on their popularity.

Rébuffat as Reference Sample

Rébuffat's selected guidebook has for several decades been a major source of information for alpinists. It was the first guidebook to offer a selection of routes based on their quality, unlike guidebooks of the same period, such as the Vallot series, that drew up more exhaustive lists of all the routes of a region. It also arranges routes by increasing difficulty, from *Facile* to *Extrêmement Difficile* as well as commitment, so can be used as a reference for progression. All types of routes are covered – rock, snow, ice and mixed – and they have been chosen from throughout the massif (*Figure 1*), making it this selection both relevant and representative of all mountaineering itineraries in the MBM.

Not all the itineraries in Rébuffat were included in this study: itineraries one and three to eight were ruled out because they are located outside the MBM. On the other hand, several itineraries are presented together in the book, as they can by climbed the same day or on the same trip into the mountains, but these have been treated separately for this study. Itinerary 17 is an example: Rébuffat recommends combining the normal route on Mont Blanc du Tacul (4248m) with the Cosmiques ridge on the Aiguille du Midi (3842 m) in a single day. Altogether, 95 itineraries were analysed. In some cases, several descents are possible; only the most classic were chosen.

Methodology

Our study is structured according to two main data collection methodologies. First, semi-structured interviews were carried out with alpine guides, including instructors at the National School of Skiing and Mountaineering (ENSA), hut-keepers, employees in charge of trail management, first ascentionists and guidebook editors. In total, 31 people were interviewed. These people all have a good knowledge of mountaineering itineraries and 19 of

Main effects of climate change on high alpine environments		Geomorphic changes affecting and modifying mountaineering itineraries	Number of itineraries affected (XX/95 - YY %)	Part(s) of the itinerary affected the most	Effects on the climbing parameters	References
Permafrost degradation		1. Rockfalls	55 - 52	Route	Increase in danger	Matsuoka and Sakai, 1999; Matsuoka, 2001
		2. Rock collapse	30 - 31	Route	Increase in danger	Gruber and Haeberli, 2007; Ravanel *et al.*, 2017
Melting of ice/snow covers and evolution of snow ridges		3. Surface of ice/snow covers in bare ice earlier in the season (or almost permanently)	58 - 55	Route	Increase in technical difficulty	Galibert, 1960 Delaloye, 2008
		4. Slope angle increase	53 - 50	Route	Increase in technical difficulty	
		5. Retreat of ice/snow covers; apparition of the bedrock in general very fractured	53 - 50	Route	Increase in danger	
		6. Snow ridges becoming narrower	25 - 24	Route	Increase in technical difficulty	
Glacial shrinkage	Paraglacial processes	7. Appearance of moraines and increase of their height	47 - 45	Approach, Descent	Increase in technical difficulty; Lengthening and greater drudgery of the way	Mortara and Chiarle, 2005
		8. Increase of the moraines slope angle	47 - 45	Approach, Descent	Increase in technical difficulty	Luckas *et al.*, 2012; Ravanel and Lambiel, 2013
		9. Destabilization of rocks (rockfalls, landslides) in the moraines	47 - 45	Approach, Descent	Increase in danger	Deline, 2008; McColl, 2012; Eichel *et al.*, 2018
		10. Development of torrent on proglacial zones	3 - 3	Approach, Descent	Increase in technical difficulty	Collins, 2008
		11. Appearance of smooth slabs of bedrock	77 - 73	Route	Increase in technical difficulty	Berthier *et al.*, 2014
		12. Appearance of destructured bedrock	30 - 28	Route	Increase in danger; Increase in technical difficulty	Ravanel *et al.*, 2013
		13. Appearance of new crevassed area	47 - 45	Approach, Descent	Increase in danger; Increase in technical difficulty	Ogier *et al.*, 2017
		14. Wider crevasses and bergschrunds	78 - 74	Approach, Route, Descent	Increase in danger; Increase in technical difficulty	
		15. Weakening of snow bridges			Increase in danger	
		16. Collapse of the front of cold-based glaciers	4 - 4	Descent	Increase in danger	Margreth *et al.*, 2011; Faillettaz *et al.*, 2015
		17. Serac falls from the front of cold-based glaciers	12 - 11	Route	Increase in danger	
		18. Serac falls from glaciers surfaces	23 - 22	Descent	Increase in danger	Le Meur and Vincent, 2006; Vincent *et al.*, 2015
		19. Collapse of the front of warm-based glaciers	7 - 7	Descent	Increase in danger	
		20. Modification of the supraglacial hydrology (drainage channels more frequent, wider and deeper)	4 - 4	Approach, Descent	Lengthening and greater drudgery of the way; Increase in technical difficulty	Miller *et al.*, 2012
		21. Glacier slope angle increase	73 - 70	Descent	Increase in technical difficulty	Berthier *et al.*, 2014
		22. Glaciers surfaces more often in bare ice	49 - 47	Approach, Route, Descent	Increase in technical difficulty	Rabatel *et al.*, 2013
		23. Development of supraglacial debris covers	24 - 23	Approach, Descent	Lengthening and greater drudgery of the way	Deline, 2005
		24. Rocks falling and sliding from the glaciers surfaces	11 - 10	Approach, Descent	Increase in danger	Purdie *et al.*, 2015
		25. Less frequent night freezing			Increase in danger	Böhm *et al.*, 2010; Pohl *et al.*, 2019

Approach — Route — Descent

Increase in danger — Increase in technical difficulty — Lengthening and greater drudgery of the way

Table 1 Climate-related geomorphic and cryospheric changes affecting mountaineering itineraries and their climbing parameters.

them have been active in the MBM since the 1980s, but only four senior Alpine guides who have frequented the range since the 1970s were interviewed. The two main questions were: 'What are the ongoing long-term changes on these itineraries since the 1970s?'; and 'How have these itineraries changed with regards to technical difficulty, objective dangers, and optimal periods for making an ascent?' The interviewees were only asked to report long-term changes. Attribution of climate-related changes was carried out by two researchers both familiar with the MBM and their results were compared afterwards. In some cases, to confirm the information collected during the interviews, descriptions of itineraries from Rébuffat's guidebook were compared with those from recent guidebooks.

Two sets of interviews were conducted in fall 2017. The first set led to the identification of the climate-related changes that have affected the itineraries (*Table 1*). Some of these have been the subject of scientific research, which has enabled us to confirm their existence and describe them more accurately. A second set of interviews was conducted in order to list the geomorphic and cryospheric changes affecting each of the 95 itineraries studied. At least 10 itineraries were considered per interview, which thus tended to be relatively long: up to three hours. The studied itineraries varied from one interview to another, depending on the memories of the interviewees. In the end, each of the 95 itineraries was studied during at least two different interviews. The database was formalised as a table, cross-referencing each of the 95 itineraries with the 25 geomorphic and cryospheric changes. This was completed during the interviews. The results are presented in *Table 1*. However, one of the limits of this method of data formalisation is that the location and the intensity of each of the changes identified were not recorded. Each itinerary was divided into three parts: the approach, which begins in the valley or at the top of a cable car and ends either at the foot of the rock wall to be climbed or at the bergschrund; the route and its continuation to the summit; and the descent, which begins at the summit and ends in the valley or at the top of a lift.

During this second set of interviews, a five-level scale was developed to evaluate the evolution of the climbing parameters of each itinerary. The climbing parameters considered are: itinerary type (ice, snow, mixed or rock), technical difficulty, level of exposure to objective dangers, and any changes to the optimal period for making an ascent, i.e. when the number or intensity of changes affecting it are lowest.

- *Level 0* The itinerary and the parameters determining the way the route is climbed have not changed.
- *Level 1* The itinerary and its climbing parameters have slightly evolved. Only a short section of the itinerary is affected by geomorphic and cryospheric changes, and this does not result in a significant increase in objective dangers and/or in technical difficulty.
- *Level 2* The itinerary and its climbing parameters have moderately evolved. The optimal periods for making an ascent have become rare or unpredictable in summer and shifted toward spring and sometimes autumn. Objective dangers and technical difficulty are increasing and mountaineers have to adapt their technique.
- *Level 3* The itinerary and its climbing parameters have greatly evolved. Generally, the itinerary can no longer be climbed in summer. Objective dangers and technical difficulty have greatly increased due to the number and intensity of the geomorphic changes affecting it. Mountaineers have had to fundamentally change the manner in which they climb the route.
- *Level 4* The itinerary has completely disappeared: it can no longer be climbed.

The identification of the changes affecting a mountaineering itinerary varied greatly from one person to another depending on the climbing circumstances encountered during the ascent (i.e. the occurrence or absence and the intensity of the changes previously identified), the technical level and number of clients and their personal perception. Changes identified were not always the same, nor assessed to the same degree. As an example, at the end of the summer season when the glacier surface is icy, any increase in steepness is more significant and easier to identify compared to the beginning of the season when the glacier surface is still covered with snow. Moreover, interviewees tended to underestimate the number of changes affecting an itinerary. Indeed, it seems individuals usually noticed only the changes that are relevant when making an ascent, without necessarily taking into account the season and high-mountain climate-related evolution. It was the interviewers' role to encourage interviewees to identify only long-term changes rather than focusing on their last ascent. For this reason, a great number of interviews were conducted in order to validate data collected.

Results

Twenty-five geomorphic and cryospheric changes were identified (*Table 1*). They result from glacial shrinkage, a reduction of ice-snow cover, changes in the structure of snow ridges, and permafrost warming. For each geomorphic change, its impact on climbing parameters was identified (*Table 1*): increase in objective dangers, technical difficulty and commitment, lengthening of the itinerary and any increase in the effort required to climb it.

All the types of changes that have affected each route between the 1970s and today were listed. On average, an itinerary has been affected by nine geomorphic changes. The appearance of bedrock (85 itineraries affected), wider crevasses and bergschrunds (78) and steeper glaciers (73) are the three most commonly observed changes. They cause an increase in the level of danger and technical difficulty. Alpine guides interviewed all had to deal with thinner and weaker snow bridges, while crevasses that were never or rarely observed now appear more often.

Finally, regarding the scale used to evaluate changes to the itineraries studied from a mountaineering point of view (*Figure 1*), two had not evolved (level 0), 30 had slightly evolved (level 1), 34 had moderately evolved (level 2), 26 had greatly evolved (level 3), and three had disappeared (level 4). Four examples are described here to better illustrate those evolutions and the implications for mountaineering. Moreover, there is a direct correlation between the number of geomorphic changes affecting an itinerary and its level of evolution. On average, for level 1, 7.4 changes were affecting the itineraries, 10 for level 2, 11.5 for level 3 and 12.5 for level 4. It is also important to note that during the summer of 2018, the evolution levels of three itineraries changed: from 1 to 3 (Cosmiques ridge: itinerary 17), 1 to 4 (Lépiney route: itinerary 37) and 1 to 2 (Rébuffat-Bacquet route: itinerary 55). The geomorphic changes responsible for those three evolutions have been identified thanks to a network of observers, mainly guides and hut-keepers, developed to study geomorphic changes in the MBM.

Patterns of Change

The first example is the disappearance of a rock route because of massive rock fall: the Petit Dru (3733m) west face. The *Bonatti* route, itinerary 92 in Rébuffat, was Walter Bonatti's emblematic rock climb first climbed in 1955. However, most of the route disappeared after a 700m pillar collapsed in 2005. This route has a level 4 evolution: see *Figure 2*.

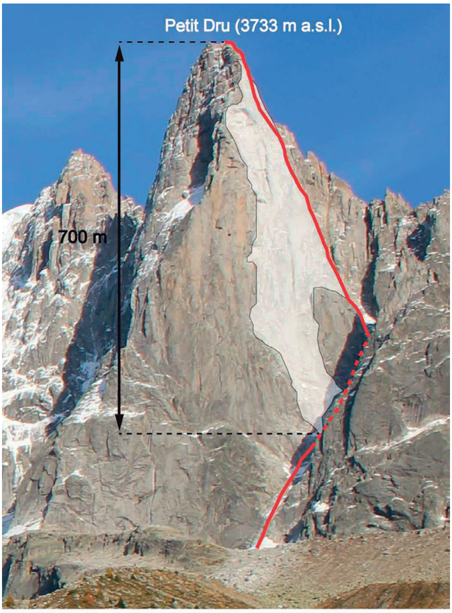


Figure 2 The Petit Dru west face, October 2017. A major part of the *Bonatti* route has disappeared because of a rock collapse in 2005 and a further rock fall in 2011 (292,000m^3).

An example of a snow and mixed route that can no longer be climbed in summer because of ice-snow cover melting early is the *Whymper* couloir on the Aiguille Verte (4122m), itinerary 41 and the line of the Verte's first ascent in 1865.

In 1973, Rébuffat classified this classic itinerary as a snow climb. Today, the ice-snow cover necessary for an ascent of the couloir has been significantly reduced (*Figure 3*). Indeed, it completely melts out early in summer and fractured bedrock is exposed. Rock fall is consequently frequent. In addition, the bergschrund at the bottom of the couloir becomes very wide and difficult to cross. Rock fall is observed frequently and a 22,000m^3 rock fall occurred on the right bank of the couloir in August 2015. These environmental changes have led to an increase in technical difficulty and inherent danger of the route and it is now possible to climb it only very early in summer. The change applied to this itinerary is Level 3.

Two instances of a rock route whose approach has been affected are the south face of the Aiguille du Midi (3842m) and the east face of the Aiguille du Moine (3412m). The *Rébuffat-Bacquet* route (itinerary 55), climbed in 1956 on the south face of the Aiguille du Midi, is a classic rock climb that sees a lot of traffic in summer. Apart from a small rock fall, it has not yet been directly affected by climate change, but the approach to the original starting point of the route has become more difficult because of two factors. First, the east ridge of the Aiguille du Midi that leads to the bottom of the face is becoming narrower. It is oriented west-east, meaning melting is much more significant on its south side than on its north. This makes it steeper, and it tends to become icy earlier in summer. Crevasses also now appear. Second, because the Géant glacier at the foot of the face has lost over 25m in depth over the past 30 years, the route's historic starting point is now difficult to reach (*Figure 4*). Climbers now have to follow the start of the *Contamine* route, which is technically more difficult, graded F6b instead of F6a, than any pitches on the Rébuffat-Bacquet. These environmental changes have led to an increase in the technical difficulty and commitment needed to reach the start of the route. The level of evolution applied to

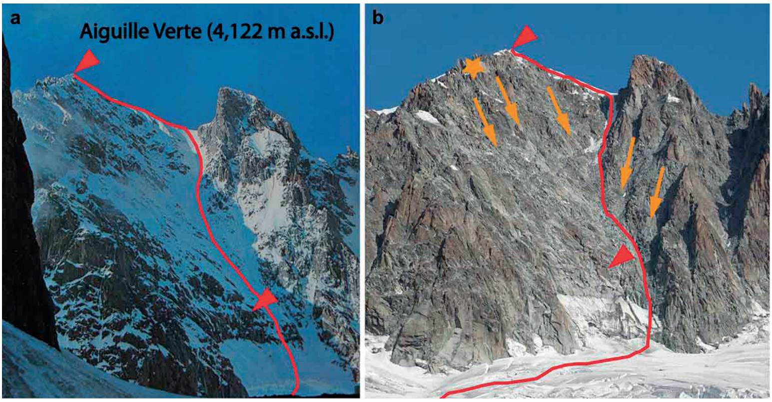
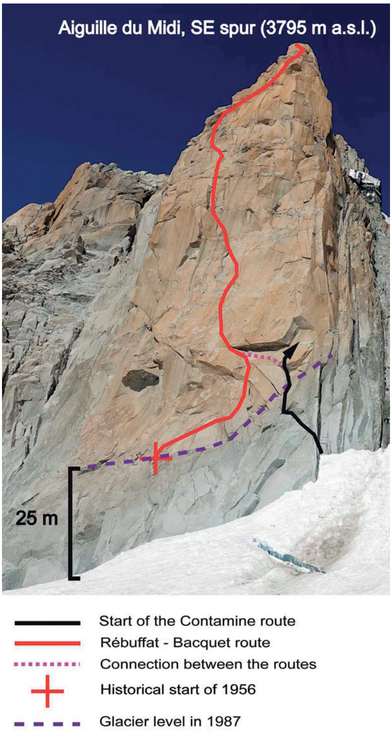


Figure 3 The *Whymper* couloir on the south face of the Aiguille Verte (4122m). The route is marked in red. A: situation at the end of the 1960s (picture from the guidebook). B: situation at the end of August 2017 (C Lelièvre). The ice-snow cover in the couloir has undergone a significant reduction, exposing fractured bedrock, leading to frequent rock falls (orange arrows). The orange star indicates the point where a 22,000m^3 rock fall released in 2015. The red triangles indicate similar features.



Right: *Figure 4* Aiguille du Midi south face, September 2018. The original start to the Rébuffat-Bacquet route (1956) is no longer accessible directly. The lower part of another route must be climbed to join it.

this itinerary is 2. Because the surface of the Géant glacier lowered greatly during the 2018 heat wave, the route was not accessible at the end of the summer period. A very difficult climbing section has appeared. This situation is identical for the majority of rock routes but the increase in difficulty varies depending on the extent of ice-thickness loss and the nature of the terrain exposed. In some cases, the route may lose its intrinsic logic and aesthetic if sections of climbing appear that are much more difficult than the rest of the route. This is the case for the *Labrunie-Contamine* route (itinerary 51) on the Aiguille du Moine (3412m) east face. A 15m section of F6c climbing is now exposed at the

Evolution level	Ice	Mixt	Snow	Rock
	Itineraries types			
0	0.0%	0.0%	0.0%	100.0%
1	0.0%	10.3%	6.9%	82.8%
2	8.6%	22.9%	14.3%	54.3%
3	15.4%	46.2%	26.9%	11.5%
4	33.3%	0.0%	0.0%	66.7%
Total	8.4%	24.2%	14.7%	52.6%

Evol. level/Itineraries types
p = <0,01 ; Khi2 = 33.93 ; ddl = 12 (VS)

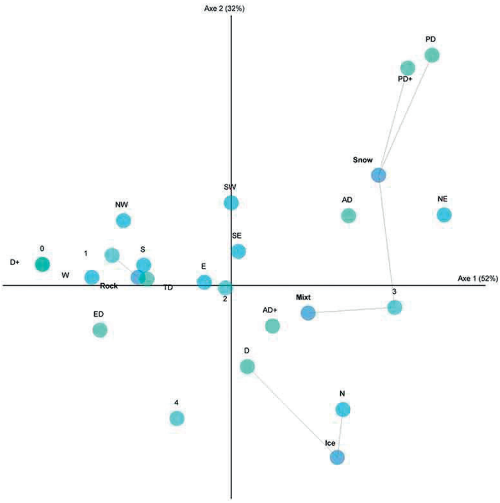


Figure 5 Cross-tabulation and graphical representation of the relationships between the level of evolution of a route for mountaineering purposes and its nature (rock, snow, ice and mixed), difficulty and aspect. The closer the circles are, the more meaningful their relations are. The statistically strongest relationships are underlined.

start of the route because of the lowered surface of the Talèfre glacier. The rest of the route is graded F6a maximum. This short, difficult section has made the route less attractive, and it is now climbed less frequently than before. The level of evolution applied to this itinerary is 2.

Another category is a rock route whose descent is more difficult and dangerous because of glacial shrinkage, an example being the Aiguille de l'M (2844m). The mountain's north ridge (itinerary 18) is a very popular rock route. The approach and route are not affected by geomorphic or cryospheric changes, notably because of its lower altitude. However, the way down follows a south-facing couloir to reach the Nantillons glacier at 2,500m. Because of the lowering of the glacier surface, the couloir is becoming steeper and exposed to rock fall coming from the lateral moraine of the glacier. In order to reduce the danger and technical difficulty, abseils and ladders have been installed in the couloir. Therefore, the itinerary can be climbed all summer and the descent is now less technically difficult. The level of evolution applied to this itinerary is 1.

Discussion

In general, snow, ice and mixed itineraries have been more affected by climate change, with a 2.4 average level of evolution, compared to rock routes with a 1.6 average level of evolution. This finding is confirmed by a correspondence factor analysis (CFA) linking the level of evolution of the itineraries with their type (rocky, snow, ice and mixed), difficulty, and orientation: see *Figure 5*. Itineraries undergoing level 3 evolution are mainly mixed and snow routes (46.2% and 26.9%, respectively) graded *Assez Difficile* or *Peu Difficile* and facing north-east. On the other hand, rock routes are statistically underrepresented (11.5%) in this evolutionary scale. The routes undergoing level 0, 1 and 2 changes are mostly rock routes (100%, 82.8% and 54.3%, respectively) for the highest level of difficulty *Extrêmement Difficile* and *Très Difficile*. Variable aspects are represented. In the 0 level of evolution, ice routes are statistically underrepresented (0%). We can conclude that climate change affects rock routes less than snow, ice and mixed routes.

Not all the geomorphic changes identified in this work affect the itineraries in the same way. Approaches are mainly affected by: wider crevasses and bergschrunds (53 of 95), para-glacial processes (41) and the appearance of new crevassed areas (27). The changes most affecting rock routes are: the appearance of smooth slabs or unstable bedrock (77) and all changes related to the disappearance of ice-snow cover and the evolution of snow ridges (52). Finally, the changes predominantly affecting descents are a steepening of glaciated slopes (63), wider crevasses and bergschrunds (59), and para-glacial processes (41). There is also a correlation between some changes and the orientation of the routes. For 39 routes located on southern slopes 23 are affected by processes due to permafrost degradation and 22 by the appearance of smooth slabs or fractured bedrock. On the other hand, changes in serac fall and the appearance of bare ice mainly affect north-facing routes. Other changes, such as the reduction in ice-snow cover, equally affect routes on southern and northern aspects.

Seasonal Changes

It is difficult to measure the effects of one or several changes on the climbing parameters of a route. In general, changes identified imply an increase in technical difficulty, danger and commitment of these itineraries in summer but seasonality must also be addressed.

The evolution of mountaineering itineraries is conditioned on two different timescales. The main timescale addressed in this study is climate-related and covers the period from the 1970s to 2018. However, deterioration of climbing parameters can be reduced or increased by seasonal factors. Changes are usually less impactful at the beginning of the summer season, when the winter snowpack has not yet melted out, even if snowpack in general is decreasing both in quantity and duration, and they increase at the end of the summer season or during heat waves, which are becoming more frequent and intense due to climate change. Itineraries in an optimal period for making an ascent – more and more commonly outside the summer period – are not necessarily any more difficult or dangerous than before. For this reason, windows for mountaineering tend to be more variable in summer and are shifting toward spring, autumn, as temperatures start to drop and new snowfalls occur and even winter, especially for snow, ice and mixed routes. Depending on the nature of the itinerary, much more attention must be paid to changing climbing conditions. According to the interviewees, the summer mountaineering season has shifted by three weeks toward spring compared with the 1980s. This confirms work done in the Écrins massif.

There isn't necessarily a direct link between the level of change of an itinerary and its popularity. A notable example is the classic route to the summit of Mont Blanc (itinerary 24). It has been greatly affected by climate change, with an increase in technical difficulty and especially in its level of danger. Rock fall is increasingly frequent in the Grand Couloir du Goûter and causes a significant number of accidents. Between 1990 and 2017, there were an average of 3.7 deaths and 8.5 injuries per summer on the crossing of the couloir and the climb to the Goûter ridge, mainly due to human error and rock fall. In addition, large crevasses, which are difficult to cross, are appearing even at high altitude above 4,000m, while the summit ridge is becoming narrower. The descent described by Rébuffat is no longer used in summer, as it has become too crevassed. Even though the level of change applied to this itinerary is 3, it is still one of the busiest mountaineering itineraries in the world because of the prestige of climbing the highest summit in the Alps.

On the other hand, some itineraries that have only been slightly affected by climate change are much less popular than in the past. To explain this, other socio-economic factors and the evolution of mountaineering itself must be considered. Today, mountaineers tend to limit their risk-taking and exposure to objective dangers such as rock and serac fall. Other itineraries are no longer popular because the approach is long or the in situ equipment is old. As an example, according to the guides interviewed, the north face of the Aiguille de Bionnassay (4052m), itinerary 49, was a classic ascent during the 1980s. Today, it is no longer climbed in summer despite a relatively low level of change (2) because of the danger of serac fall. This danger was also present 40 years ago.

In some cases, the evolution of mountaineering itineraries due to the effects of climate change leads to an increase in popularity. This is the case for the traverse of the Dômes de Miage (3673m), itinerary 13, a famous and beautiful snow climb. During the summer of 2015, a crevasse opened on the summit ridge, which itself had become narrower and icier. In addition, a rock fall occurred on the route, making it more technically difficult and exposing it to further rock fall. The ridgeline was no longer being traversed, with climbers choosing to descend by the ascent route. This made the itinerary less aesthetically pleasing and the number of people staying at the Conscrits hut (2602m), which gives access to the route, fell by 25% that summer. The same situation occurred in 2016 and 2017, with significant economic consequences for the hut-keeper. The Couvercle hut (2679m) is facing the same situation, with climbing parameters on most routes deteriorating earlier in the summer season. According to the former two hut-keepers, the steady decline in the number of overnight stays, 35% over the last 15 years, has been accentuated by the evolution of mountain itineraries, perhaps concurrently with socio-economic factors.

Is the aesthetic quality of high mountain areas deteriorating? Geomorphic and cryospheric changes result in significant changes to the landscape. The general drying of high mountain environments leads to the appearance of more and more rocky terrain as glacial surfaces decrease. With snow cover on glacier surfaces melting out faster and at higher altitudes, more bare ice appears, and debris cover is increasing as rock falls form more continuous deposits. All the interviews carried out indicate that high mountain landscapes no longer conform to the classic representation of blue ice and 'eternal snow'. The motivation of some mountaineers to go into the high mountains is thus reduced. 'I note there is less interest to go on glaciers […] that are dirty, with a dull colour; they are less attractive in a certain way,' the guide B Pelissier said in October 2017.

The Limits of Rébuffat

Because Rébuffat's guidebook dates from the 1970s, it does not feature any steep, narrow ice climbs, like the *Supercouloir* on Mont Blanc du Tacul, which appeared after Rébuffat's book thanks to improving equipment. According to the guides interviewed, the formation of ice gullies is becoming increasingly less frequent and the quality of ice is often lower. During the winters of 2016 and 2017, almost no such ice gullies formed in the MBM. It seems the main factors explaining the disappearance of these routes are the lack of winter and spring snowfall and the more rapid melting of the ice-snow cover. This phenomenon seems to be very recent and is due largely to an increase in the frequency of winter warm spells since the beginning of the 2000s.

Another factor limiting our methodology must also be highlighted. Because some itineraries have the same approach and descent, some changes have been overrepresented. This is particularly the case for para-glacial processes affecting approaches and descents in the Mer de Glace basin. One way of limiting this bias would have been to consider only the routes themselves, and not the approaches and descents but this method would not have given an accurate representation of the difficulties mountaineers are facing throughout the whole itinerary.

Moreover, it is not possible to objectively compare the grade of itineraries between the 1970s and today, as the grading system, equipment and technical level have changed considerably. Finally, because rock slope instabilities resulting from post-glacial decompression are relatively uncommon in the MBM and difficult to differentiate from the many rock falls resulting from permafrost degradation, they have not been considered in this study.

Conclusion

The impact of climate change on high mountain environments has altered mountaineering itineraries. This study presents an exhaustive list of 25 geomorphic and cryospheric changes related to climate change affecting a typical mountaineering itinerary. On average, an itinerary in the MBM is affected by nine of these changes. Moreover, the impacts of each of these changes have been documented and quantified for the first time. The exposure of bedrock, the widening of crevasses and bergschrunds, and steepening of glaciated slopes are the main changes.

The impact of these changes on mountaineering has been quantified for 95 itineraries. Only two routes have not changed, 30 have slightly, 34 moderately, 26 strongly and three have disappeared altogether. As a result, mountaineering itineraries tend to be more technically difficult and more dangerous. Optimal periods during summer months have become rarer and more unpredictable, resulting in progressive reduction in terrain available for mountaineers as the summer season progresses and good periods are now more likely to occur in spring, autumn and even winter on some itineraries. Changes in a mountaineering itinerary due to the effects of climate change may lead to a significant decrease in its popularity, but socio-economic factors must also be considered.

Climate change is expected to accelerate during the coming decades and this will lead to ever-increasing changes to the highly sensitive high-mountain environment. Changes to mountaineering itineraries described in this article are expected to continue and increase. This perspective may have significant consequences for mountaineering and the ability of mountain professionals, such as guides and hut-keepers, to adapt.

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For reasons of length, the extensive referencing for this article has been omitted. All references are available with the full paper online at *https://www.tandfonline.com/doi/full/10.1080/15230430.2019.1612216?scroll=top&needAccess=true*