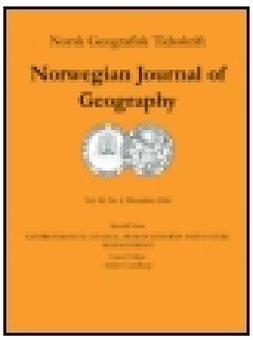

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Access routes to high mountain huts facing climate-induced environmental changes and adaptive strategies in the Western Alps since the 1990s

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ABSTRACT

In the European Alps, high mountain environments are subject to major impacts resulting from climate change, which strongly affect human activities such as mountaineering. The purpose of the study was to examine changes in access routes to 30 high mountain huts in the Western Alps since the 1990s. Data were derived from the use of two different methods, geo-historical studies and a questionnaire, and were used to identify both the climate-related processes affecting the climbing routes and the strategies implemented by public entities, Alpine clubs, guide companies, and hut keepers to maintain acceptable safety and technical conditions. The case studies revealed issues affecting three access routes and the results from the questionnaire showed that the main processes affecting access routes were loss of ice thickness and retreat from the front of the glaciated areas. Commonly, in situ equipment was installed to facilitate access for mountaineers and/or a part of a route was relocated to a safer area. The authors conclude that in most cases, the measures were effective but they were limited by financial, ethical and legal issues, especially in protected or classified areas that could jeopardise their durability and effectiveness.

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Introduction

High mountain areas such as the European Alps are particularly sensitive to climate change (Beniston 2005). The average temperature in the European Alps increased by 2 °C between the end of the 19th century and the early 21st century (Beniston 2005; Auer et al. 2007), and there has been a strong acceleration in the rate of warming since the 1990s (IPCC 2019). In this context, high mountain environments have been subject to major changes due to the widespread occurrence of glaciers and permafrost, which has rendered them highly sensitive to climate change.

Many scholars have discussed the possible consequences of climate warming on winter mountain tourism and outdoor recreation, especially on skiing activities, in the European Alps (Scott & McBoyle 2007; Koenig & Abegg 2010; Rixen et al. 2011; Scott et al. 2012). However, relatively few scholars have documented and discussed the effects of climate change on summer mountain tourism and outdoor recreation (Serquet & Rebetez 2011; Pröbstl-Haider et al. 2015; Welling et al. 2015), especially activities conditioned by high mountain environments, such as mountaineering. Mountaineering is a significant socio-economic activity and part of the cultural heritage in the European Alps (Modica 2015). The activity was originally developed in the Western Alps, especially in the Mont Blanc massif (between France and Italy) at the end of the 18th century (Hoibian 2008), and evolved as technical issues (Duez 2009) and cultural and ideological issues were addressed (Hoibian & Defrance 2002; Bourdeau 2007). Today, mountaineering remains an 'iconic' activity in the highest altitudes of the European Alps. This is reflected in the fact that in 2018 both Chamonix (France) and

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Courmayeur (Italy) were candidates for mountaineering to be included in UNESCO's list of Intangible World Heritage.

Mountaineering in the European Alps is highly structured according to the network of mountain huts, which are essential for mountaineers whose objective is to access high altitudes from the valley floor or from the top of a cable car or cog railway. However, warmer climates are leading to major changes in the European Alps and access to high mountain environments may be jeopardised by the consequent changes to the geomorphic settings. Few studies have investigated this issue in the Eastern Alps (Behm et al. 2006). Ritter et al. (2012) have compiled a relatively exhaustive inventory of all the geomorphological processes resulting from climate change that can affect a high mountain trail in the Austrian Alps.

Our research focused on three massifs in the Western Alps: Écrins, Mont Blanc and the Valais Alps (Fig. 1). First, we wanted to address the question of how access routes to high mountain huts and their conditions of frequentation had been affected by the climate since the 1990s. Second, we explored how the mountaineering routes had been adapted in order to maintain good safety and technical conditions. We used two different methods to gather qualitative and quantitative data: (1) geo-historical studies (for detailed information, see Mourey & Ravanel 2017), and (2) a questionnaire. Data obtained by both methods were used to address the following questions:

- What climate-related changes are affecting the access route?
- Are changes associated with global warming responsible for the deterioration of the safety conditions?
- What measures have been taken to restore acceptable safety conditions?
- Who financed the measures and who pays for the maintenance work?

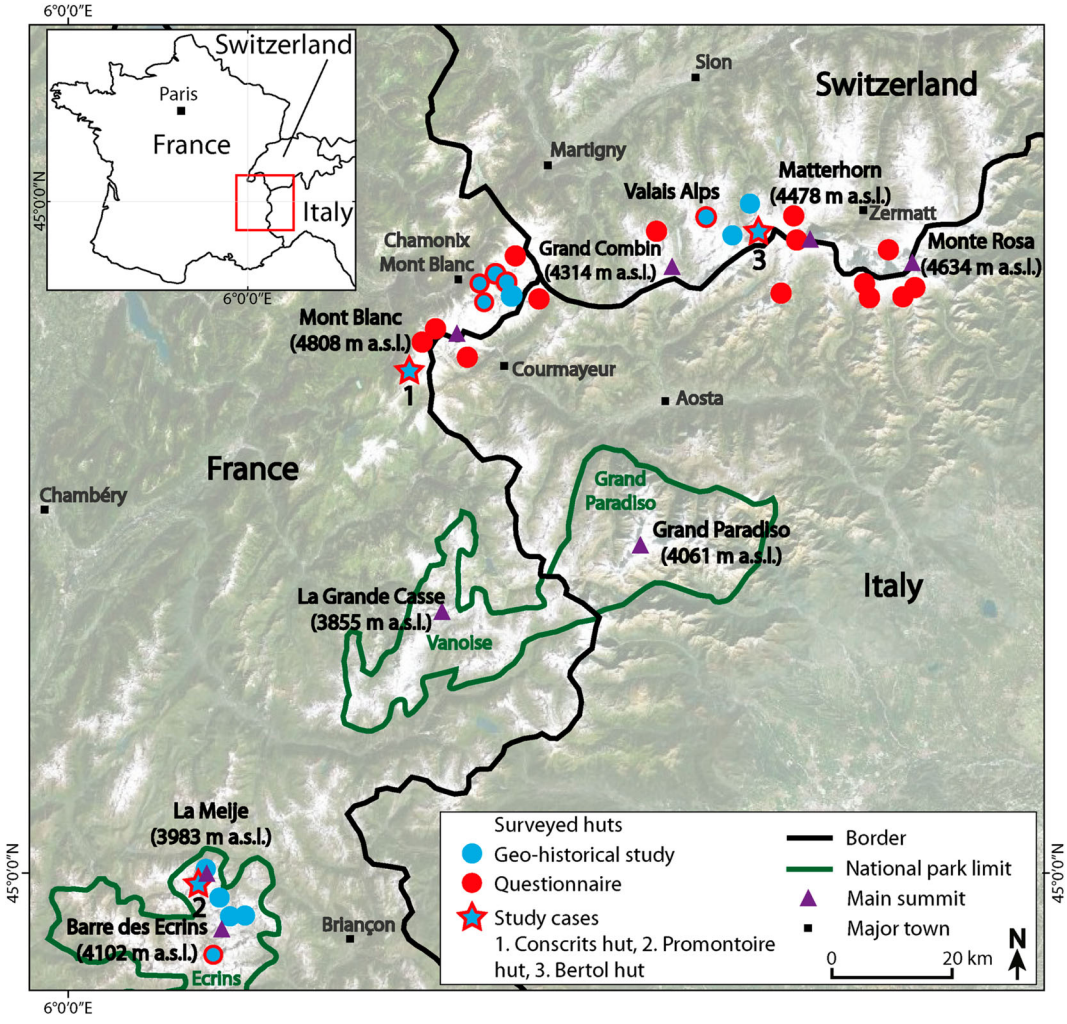

Fig. 1. Location of the 30 huts included in the study conducted in the Écrins massif, Mont-Blanc massif and Valais Alps (main map accessed from IGN (Institut national de l'information geographique et forestièr) in 2017)

Effects of climate change on high mountain environments in the Western Alps

Given that large parts of their surfaces are covered in ice or affected by permafrost, the European Alps are highly vulnerable to changing environmental conditions (e.g. warmer air temperatures and decreases in solid precipitation). In the European Alps, the surface areas of glaciers were reduced by half between 1900 and 2012, from 3350 km^2 to 1900 km^2 (Huss 2012). The mean glacier mass balance was -0.31 ± 0.04 m water equivalent annual (w.e.a.)$^{-1}$ in the period 1900–2011 and -1 m w.e.a.$^{-1}$ in the years 2001–2011 (Huss 2012), which illustrates the acceleration in melting due to warmer temperatures. Additionally, the loss of ice thickness has been significant. The Argentière Glacier (Mont Blanc massif, France), lost on average 80 m of ice at 1900m a.s.l. between 1994 and 2013.[1] The rate of ice thinning on the Mer de Glace (Mont Blanc massif, France) increased from 1 metres annual (m.a.)$^{-1}$ in the period 1979–1994 to more than 4 m.a.$^{-1}$ in the period 2000–2008 (Berthier & Vincent 2012). At the front of the Mer de Glace (1500 m a.s.l.), the loss in ice thickness was up to 60 m during the period 1979–2003 (Berthier et al. 2005). In the Écrins massif, 12.8 m of ice was lost on average from the surfaces of the Glacier Blanc (the largest glacier in the Southern Alps) between 2000 and 2017.[2]

Glacier fronts in the European Alps retreated significantly since c.1900: 366 m between 1994 and 2007 in the case of the Mer de Glace, 370 m between 2002 and 2015 in the case of the Glacier Blanc, and up to 2400 m between 1890 and 2000 in the case of Aletsch Glacier in the Valais Alps (Vincent 2010). In some cases, glacier retreat has led to more frequent ice avalanches from hanging fronts of warm-based and cold-based glaciers (Fischer et al. 2006; 2011). In the Mont Blanc massif, ice avalanching mainly occurs in the warmest periods of the year, and after the 1940s the avalanching occurred during or at the end of the warmest periods (Deline et al. 2012).

Thus, paraglacial processes are intensifying. Ballantyne (2002, 4) defines paraglacial processes as 'the non-glacial processes at the surface of the Earth … which are directly conditioned by the glaciations and the deglaciations'. A paraglacial period starts as a direct reaction to deglaciation and ends when all consequent glacial sediments have been eroded or otherwise stabilised (Church & Ryder 1972; Ballantyne 2002). In high mountain environments, paraglacial processes refer mainly to the erosion of moraines through rockfalls and landslides (McColl 2012; Deline et al. 2015; Draebing & Eichel 2018; Eichel et al. 2018), illustrated by the gullying of the inner flank of lateral moraines due to very steep slopes of up to 80 degrees (Lukas et al. 2012). As an example, on the Gentiane moraine located on the west side of the Tortin Glacier (Valais Alps, Switzerland), 3650 ± 175 m^3 of glacial materials (tills) destabilised between 2007 and 2014 (Ravanel et al. 2018).

Periglacial environments and processes (French 2007) in alpine environments are mainly characterised by frost action and permafrost (i.e. lithosphere materials that remain at or below 0 °C for at least two consecutive years). When the climate is warming, frost action is reduced and permafrost is degraded (Haeberli & Gruber 2009). This, in turn, increases both the frequency and volume of rockfalls (Harris et al. 2001; 2009; Geertsema et al. 2006; Ravanel & Deline 2011; Ravanel et al. 2013; 2017). On the Mont Blanc massif, more than 550 rockfalls ($V > 100\ m^3$) due to permafrost degradation occurred between 2007 and 2015 (Ravanel & Deline 2015).

Methods

We used the following three parameters when selecting mountain huts for our study: (1) huts that were open also during the summer season, (2) huts that supported the mountaineering activities and (3) huts for which the access route had been modified due to the effects of climate warming. All huts were located in the Western Alps, on the Mont Blanc massif (extending into France, Italy and Switzerland), the Écrins massif (France), and the Valais Alps (Switzerland) massif (Fig. 1), at 3020 m a.s.l. on average. However, the list of selected huts that matched the three parameters for the three massifs considered in this article was not exhaustive. Although 43 huts in the Western Alps matched the three parameters, we excluded 13 of them due to lack of data: 5 huts on the Mont Blanc massif and 8 in the Valais Alps. Thus, we considered the large majority (70%, 30 huts) of the original sample.

Initially, we conducted geo-historical studies of 16 huts (Fig. 1). The huts were chosen primarily because of the marked changes to the access routes to the huts that we had observed and that were due to the effects of climate change. The geo-historical studies were carried out using a 3-step method (for details of the method, see Mourey & Ravanel 2017):

1. a diachronic comparison of maps and photographs to enable the main evolutionary phases of the access routes to be dated
2. the analysis and comparison of guide books and articles on climbing published by publishers that specialise in mountaineering-related literature

3. interviews with hut keepers, high mountain guides and trail maintenance workers.

The method enabled us to determine the geomorphological processes at work, their effects on safety, and the solution designed to adapt the routes. Three of the case studies are presented to highlight how global warming affected the access routes to the high mountain huts, and to analyse the main solutions applied.

Due to time constraints, it was not possible to conduct geo-historical studies of all of the high mountain huts in the Western Alps. Therefore, in order to collect data for as large a number of access routes as possible and to study the largest number of huts located on the three study massifs, a questionnaire was drafted, based on information acquired during the geo-historical studies. The questionnaire was structured in three sections: (1) eight questions on the main features of the hut, (2) five questions about the access route and the geomorphological processes that affect it, and (3) eight questions about adaptive solutions applied (nature of the work, cost and contractors) and the maintenance work (entities in charge and annual cost). In 2015, the questionnaire was distributed in person to 23 keepers of high mountain huts that matched the above-mentioned three parameters (Fig. 1). In most cases, a researcher was present to answer potential questions while the hut keeper completed the questionnaire. In total, 9 of the 16 huts had previously been studied in detail by three of the co-authors of this article, which had allowed us to validate the questionnaire and its efficiency, and to check whether the questionnaire answers corresponded to the data gathered in the detailed studies, especially concerning the geomorphological processes affecting the access route. The data collected using the questionnaire were analysed using SphinxIQ software. Thereafter, in order to make the questionnaire easier and quicker to complete, most of the questions were either closed or multiple choice.

Some of the hut keepers in the Alps regularly moved from one hut to another and thus were able to assess the changes in the access route over a relatively short period. Nevertheless, together with the long-term hut keepers, they were interesting resource persons for our study. Part of the keeper's work is to be aware of and warn mountaineers about any dangers that may affect their access route to the hut, and they gather much information from the previous hut keeper, the local guides company or Alpine Club that owns the hut, and mountaineers who have experience of using the access route, sometimes over many years. The inclusion of different sources of information provided a sound basis for establishing knowledge about the evolution of the access routes and the related geomorphological changes, particularly since the 1990s.

To eliminate the possibility of misinterpreting the exact origin and/or type of geomorphological processes, particularly those identified by the few hut keepers who did not fill out the questionnaire in the presence of one of the authors, the latter hut keepers were contacted again to verify the information they had provided. Naturally occurring erosion processes such as rockfalls or serac falls (Pralong & Funk 2006; Allen et al. 2011) may be misinterpreted as the result of permafrost degradation or glacial shrinkage.

Results

In the following, we describe in detail the issues affecting mountaineers' access routes to three different huts, based on data obtained from the geo-historical studies and the completed questionnaires. The three case studies respectively represent three classic types of adaptation work carried out on access routes and their variability according to specific local conditions: (1) route modification and major infrastructure installation (Conscrits hut case), (2) provision of equipment to facilitate access (Promontoire hut case), (3) route modification and provision of equipment to facilitate access (Bertol hut case).

Case 1: Conscrits hut (2602 m a.s.l., Mont Blanc massif)

New access needed due to glacier shrinkage and paraglacial processes

The access to the Conscrits hut (90 beds, 4000 overnight visits per summer season in the period 2000–2018) on the south-western part of the Mont Blanc massif has dramatically changed since the 1990s (Fig. 2). The former access route was along the Trè-la-Tête Glacier, for c.1.5 km between the Mauvais Pas and the Trè-la-Grande seracs, leading to rock slopes on the north bank of the glacier and then to the hut (Fig. 2A and 2B). However, this route has been almost entirely transformed by the recent shrinkage of the Trè-la-Tête Glacier.

In the late 1980s, the loss of ice thickness on the Mauvais Pas (Fig. 2C) caused more frequent rockfalls due to the erosion of the morainic veneer. This in turn led to several accidents. Then, all ice disappeared from the descent route between 2005 and 2008.[3] The subsequent proglacial torrent sometimes proved difficult to cross, depending on its flow rate and location.

At the Trè-la-Grande seracs, it was once possible to reach the rock slope from the glacier before following a ramp to reach the Conscrits hut. However, in the early

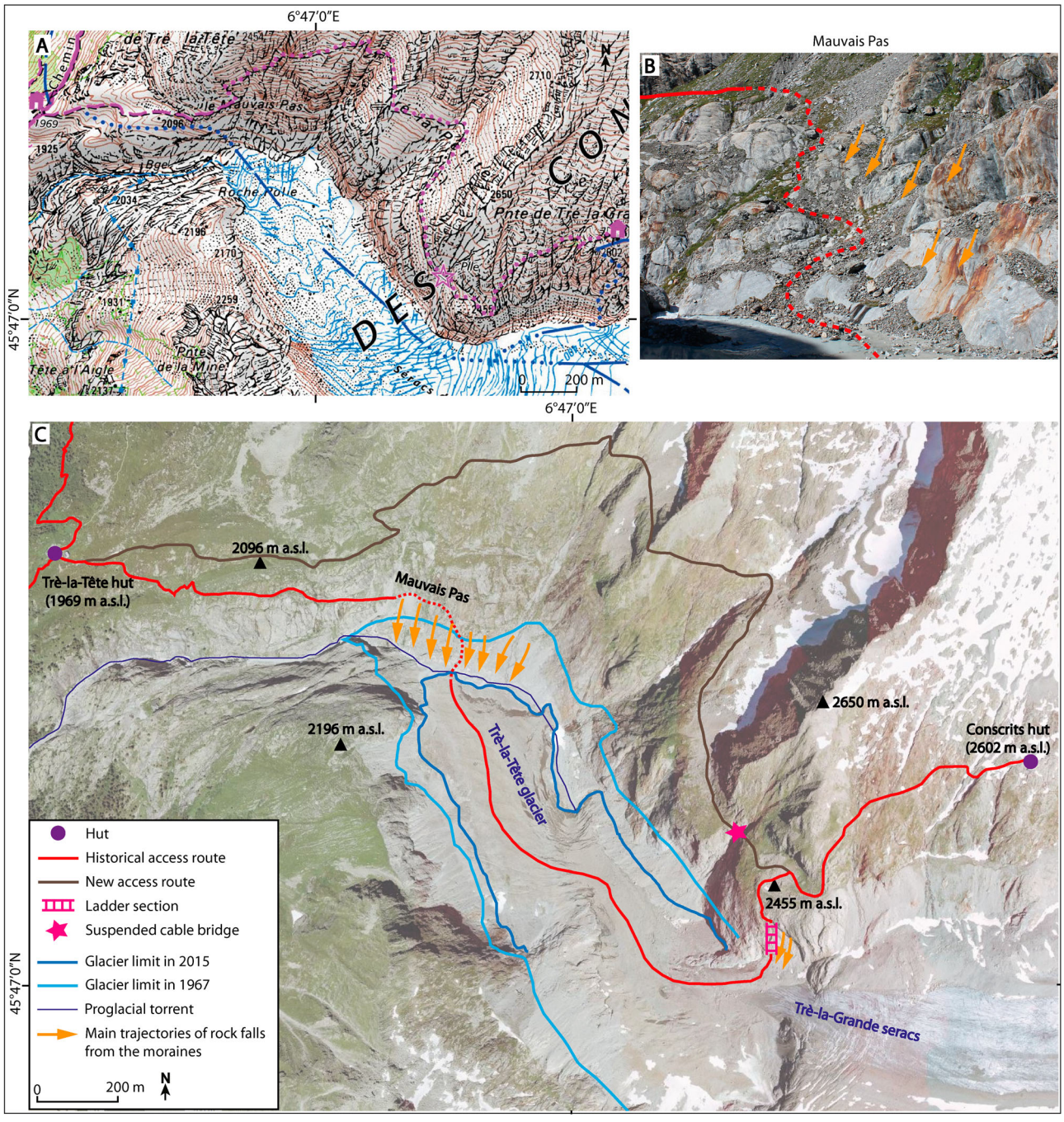

Fig. 2. Change in the access route to the Conscrits hut since the 1990s: A. Conscrits hut sector (map accessed from IGN (Institut national de l'information geographique et forestièr) in 2017); B. the Mauvais Pas in 2015 (Photo: Jacques Mourey, 2015); C. Location of the old and new access routes to the Conscrits hut (map accessed from IGN in 2017)

21st century, a ladder had to be installed to maintain the access due to of the loss of ice thickness: c.80 m was lost in that area between 1990 and 2015 (see note 3). The rate of ice loss is accelerating, which means that new sections with ladders have had to be added at regular intervals. In 2015, a total length of 70 m on the route was accessed by ladders (O. Beguin, high mountain guide responsible for the maintenance of the route, personal communication 2015). In addition, the moraine slope formed at the bottom of the ladders grew steeper and longer as the loss of ice thickness continued, which increased the risk of rockfalls and landslides.

Conscrits hut – adaptations in response to change

Starting in the 1990s, two sections of the access route became more difficult and dangerous. Based on an assumption that the glacier would continue to retreat in both length and thickness, local mountain guides

and the hut keeper suggested a new route. The new route is longer and involves more ascents, adding 45 minutes to the time required to reach the hut, and it has been necessary to build a 60 m footbridge across a gorge. However, the new route avoids the difficult and dangerous sections on the glacier. It was opened in September 2012, following an investment of EUR 130,000, which was mainly provided by the EU-funded ALCOTRA project Eco Innovation en Altitude. The route now requires regular and costly maintenance (EUR 4000 per year), which is carried out by the local mountain guides and Les Contamines Montjoie Municipality. As the route avoids the glacier and ladder sections, not only mountaineers but also hikers can reach the hut, and the footbridge serves as a visitor attraction that boosts trips to the hut to eat lunch served by the hut keeper.

Case 2: Promontoire hut (3082 m a.s.l., Écrins massif)

Difficult and dangerous access due to retreating ice and snow covert

The Promontoire hut (30 beds, 1980 overnight visits per summer season in the period 2000–2018) is accessible from two different valleys. One access route crosses a narrow col, the Brèche de la Meije (Fig. 3). The approach ascends the north side of the mountain before descending down to the hut on south-facing slopes below the col. Historically, this passage was snow-covered all year long and therefore the route was relatively easy to cross both ways. However, since 1999, the ice and snow cover has been melting earlier in the summer before disappearing completely each year. The southern slope beneath the col is often completely free of snow from mid-July onwards, in which case mountaineers have to climb down 40-degree slabs on a loose rock over a distance of 70 m (Fig. 3). This section of the route is therefore much more difficult and dangerous than in the past, especially since rockfalls are now frequent across the whole area.

Promontoire hut – adaptations in response to change

In order to reduce the danger to mountaineers from rockfalls, four bolts were installed on the southern side of the col in 2004. These function as anchors from which mountaineers can belay down to a path and if a mountaineer were hit by a rockfall, his or her fall should be stopped. However, such equipment cannot prevent accidents in which mountaineers are hit by rockfalls triggered by other mountaineers above them. In 2011, local mountain guides and rescue workers installed additional equipment on the south side of the col: two abseil stations, 25 m apart, were installed to facilitate the descent (Fig. 3) and the whole area was cleared of loose rocks to reduce the risk of rockfalls. Despite the further work, the same section of the approach route remains exposed to rockfalls and is much more dangerous than it used to be.

Case 3: Bertol hut (3311 m a.s.l., Valais Alps)

Glacier shrinkage and increased rockfall activity on the access route

The Bertol hut is located near Sion (Valais Alps), on the popular high-altitude route linking Chamonix and Zermatt (Fig. 1, Fig. 4, and Fig. 4A). It was built on a rock ridge between 1896 and 1898 (Fig. 4B). Since the end of the 19th century, the access route has been affected by glacier shrinkage, which has led to an increase in rockfalls, especially at the upper end of the route. The trail starts at Arolla, a small village 6 km north of the Bertol hut, and thereafter passes over moraine deposits dating from the Little Ice Age before crossing the small Bertol Glacier (Fig. 4A). The Bertol Glacier has shrunk dramatically: our diachronic comparison of maps showed that the glacier front retreated 400 m between 1909 and 2010. Near the Bertol Pass, the loss in ice thickness has made the slope much steeper (Fig. 4B). After the snow disappears in summer, it is dangerous to walk across this crevassed sector of the glacier. The last section of the route climbs a steep rock wall immediately below the hut. Cables and ladders have been installed to allow mountaineers to ascend this 50 m section.

The main hazards are due to increased rockfalls from the Clocher de Bertol, which poses a threat to the route across the glacier (Fig. 4C). Major rockfalls ($V > 100\ m^3$) occurred in 2006 ($V = c.150\ m^3$) and 2009. Rockfall activity has increased directly below the hut, and destroyed a bridge in 2009. It is probable that the permafrost warming in the rock face is responsible for the increase in rockfall frequency, although no supporting data are available.

Bertol hut – adaptations in response to change

To avoid the hazardous route below the Clocher de Bertol, in 2008 a via ferrata was installed on an outcrop that had emerged from the glacier since the 1980s (Fig. 4D). However, the solution is not optimal because several sections are loose and therefore rockfalls can be triggered by mountaineers themselves. In the final section of the route, the destruction of the bridge in 2009 prompted the owner of the Bertol hut to move the route from the south-east face of the Clocher de Bertol to the south-west face, which is more stable (Fig. 4B).

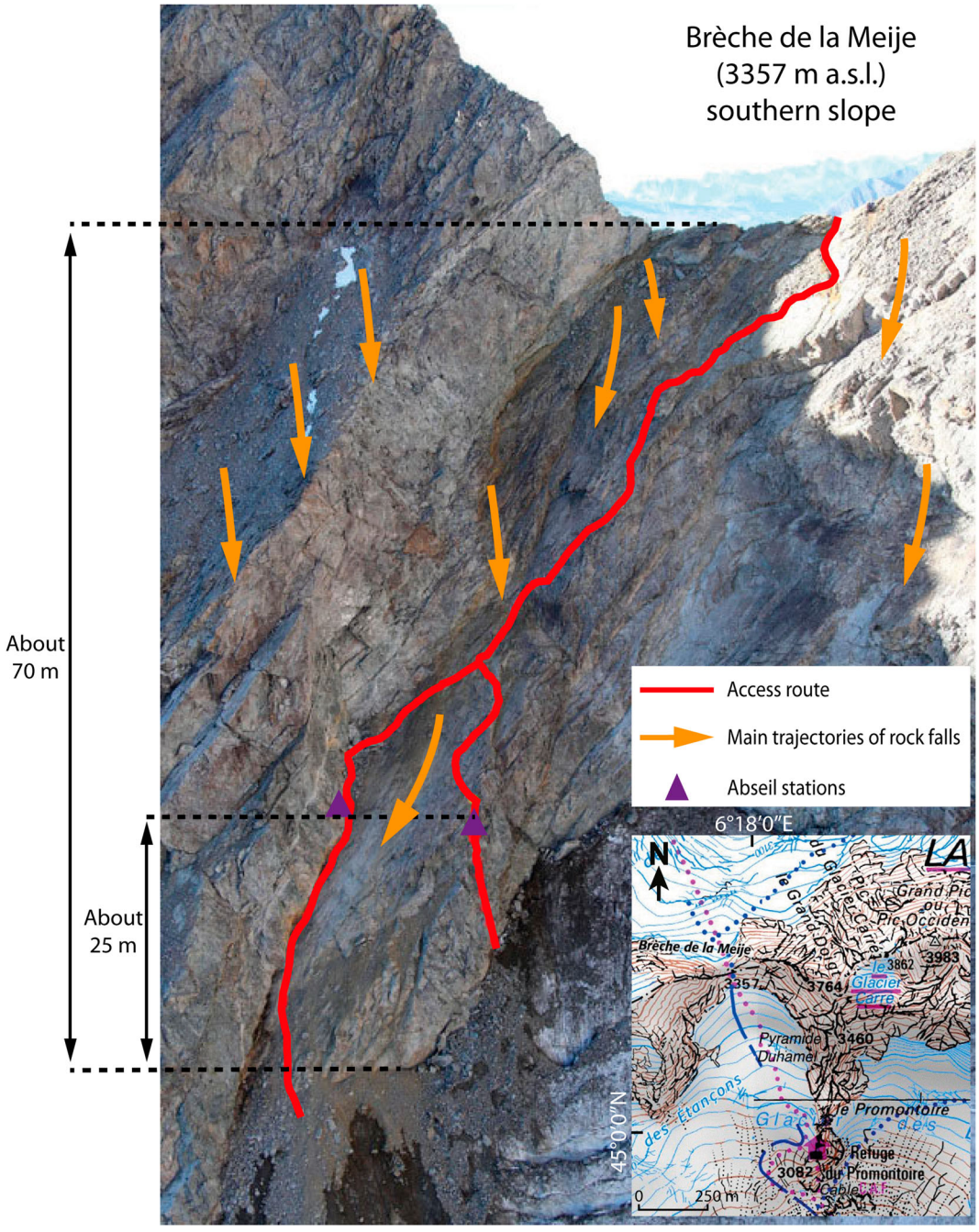

Fig. 3. The southern side of the Brèche de la Meije (3357 m a.s.l.) (photo: Parc national des ecrins, 2012; location of the Brèche de la Meije shown in the inset map (accessed from IGN (Institut national de l'information geographique et forestièr) in 2018)

Effects of warming on high mountain huts – questionnaire survey results

Numerous access routes to high mountain huts are affected by the effects of climate change. The questionnaire survey enabled us to complete the geo-historical studies and conduct our further work on a regional scale. We also identified the processes that affected most of the access routes, as well as the most frequent solutions applied to restore safety and technical conditions (Fig. 5).

Most of the studied access routes affected by glacier shrinkage

According to the keepers of the 30 studied huts, the geomorphological processes – some of them interdependent (Fig. 5A) – that affected the access routes included the following: glacier shrinkage (loss of ice thickness and retreat of the glacier front) in 80% (24) of cases; permafrost degradation (40%) (12); paraglacial processes (32%) (10); ice avalanche due to glacial retreat (6%) (2); decrease in ice and/or snow cover due to melting (6%) (2); and

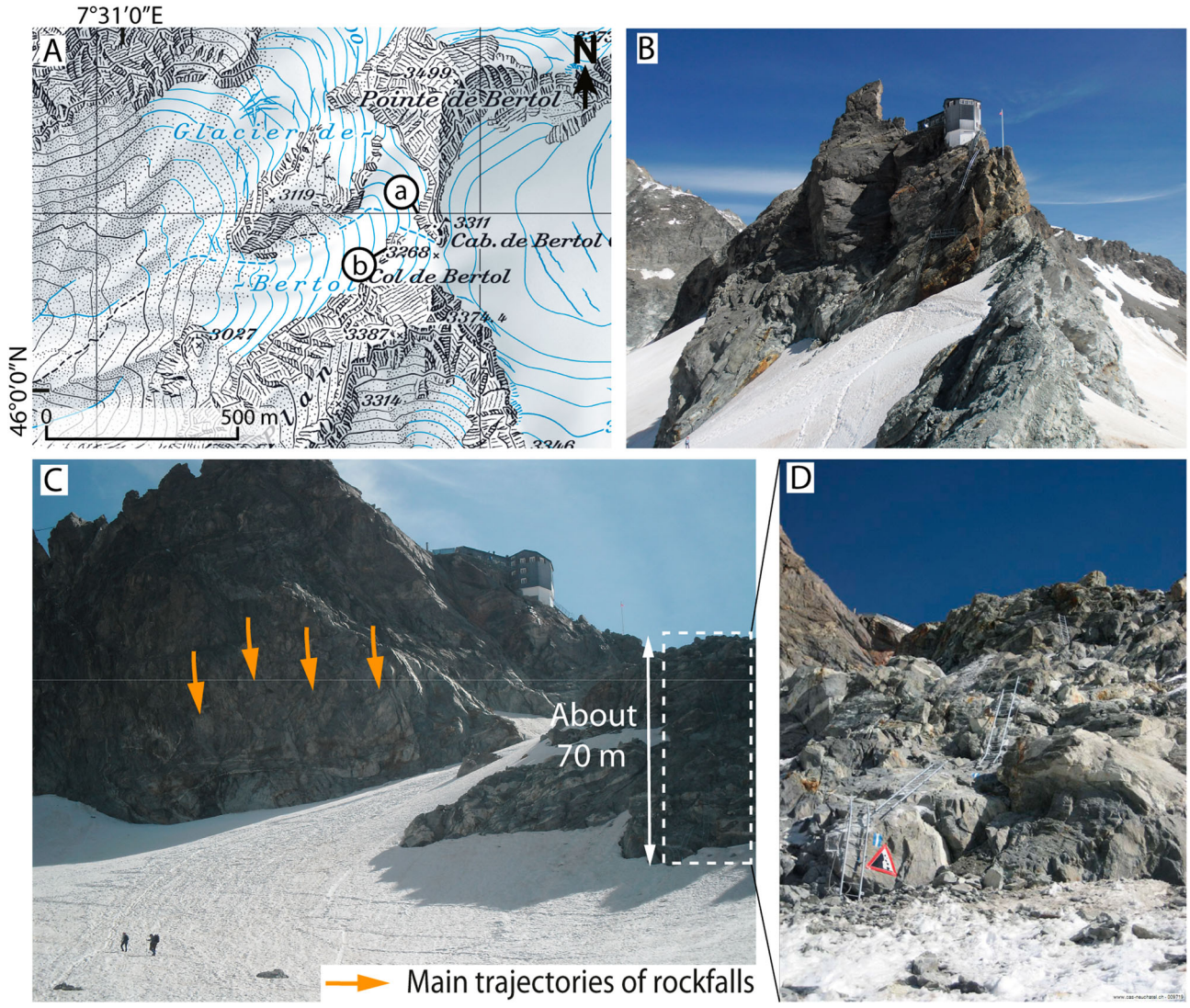

Fig. 4. Change in the access route to the Bertol hut since the 1990s: A. The Bertol hut sector (source: Swisstopo (Swiss Federal Office of Topography), 2017) – a = location of photo in 4C; b = location of photo in 4D; B. View of the hut, with the new location of the ladders and the recently deglaciated pass (Photo: Joël Strecker, 2014); C. The route towards the hut, threatened by rockfall from the Clocher de Bertol (Photo: Joël Strecker, 2014); D. The via ferrata established on the recently emerged outcrop (Photo: CAS Neuchatel, 2008)

torrential floods (6%) (2). It is interesting to note that there is a link – although not statistically tested – between the average altitude of the huts and the processes that affected their access route. The access routes affected by glacier shrinkage and the associated paraglacial processes, which occur on the rock slopes on both sides of the glaciers in the ablation zone (i.e. below 3250 m a.s.l.) (Rabatel et al. 2013), led to the huts located at the lowest altitudes (24 huts, located at 2820 m a.s.l. on average). The access routes mainly affected by processes due to permafrost degradation (Ravanel et al. 2017) led to the huts located at higher altitudes (12 huts, located at 3110 m a.s.l. on average).

The 30 huts in the study were located at 3020 m a.s.l. on average. Hence, their access routes were mainly situated in the glacier ablation zone, where ice shrinkage was most intense and affected the largest areas, especially compared with processes more related to local permafrost degradation.

Three main solutions implemented to restore safety conditions

All 30 hut keepers reported that the access routes were becoming more dangerous due to geomorphological evolutions. Therefore, in order to restore acceptable safety and technical conditions, three different solutions were applied (Fig. 5B): (1) provision of equipment (e.g. ladders, handrails and steps), (2) relocation of all or part of the route, and (3) installation of major infrastructure. Equipment was installed in 67% (20) of the access

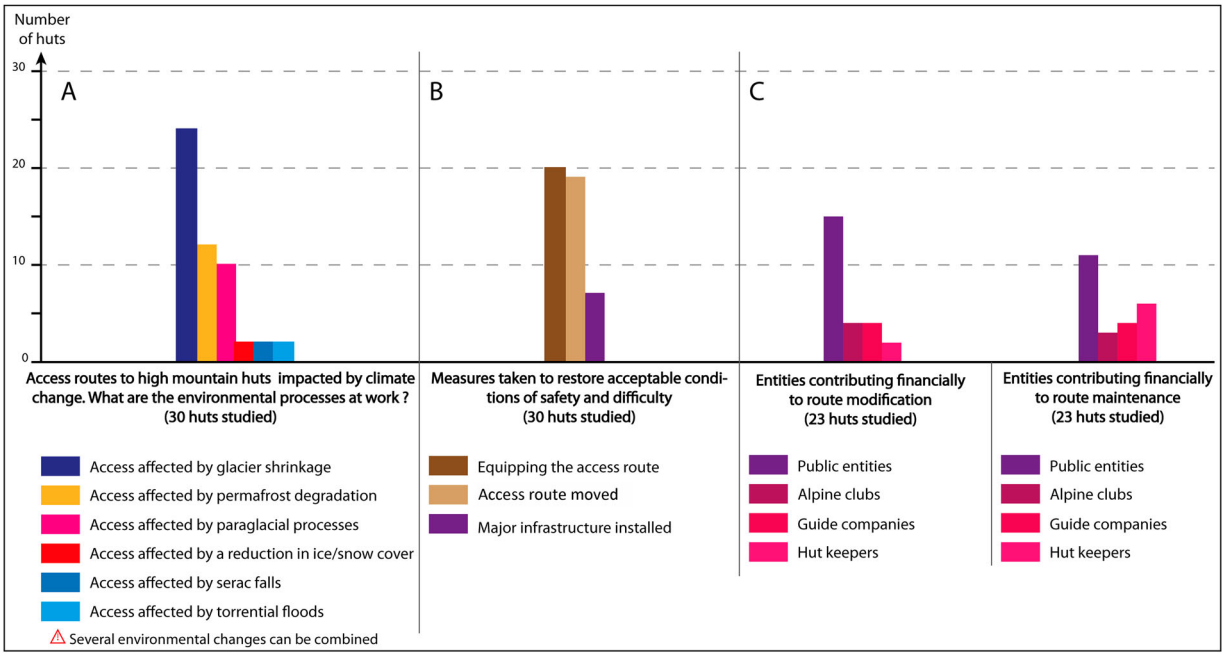

Fig. 5. Access routes to high mountain huts affected by climate change between the 1990s and 2018: A. Processes due to climate change affecting the access routes; B. Modifications carried out to restore acceptable levels of safety and difficulty; C. Organisations that have funded modification and maintenance work for access routes to mountain huts

routes, the routes were partially moved in 63% (19) of the cases, and major infrastructure such as footbridges were installed in 22% (7) of the cases. According to the hut keepers and the Peloton de Gendarmerie de Haute Montagne (PGHM) in charge of rescue missions in the French high mountain areas, the adaptations had made the access routes safer and helped to reduce the number of accidents. However, several hut keepers also reported that the new equipment required a higher level of monitoring, which implied higher maintenance costs.

In the case of the Goûter hut (Mont Blanc massif), which is on the most common route to the very popular Mont Blanc (4808 m a.s.l.), the keeper reported that the equipment has improved safety, but paradoxically increased the number of accidents (for an explanation of the increase, see Mourey et al. 2018). As the route was made safer, more people attempted the route and/or they were less careful, which led to more accidents.

Adaptation work financed by several entities

Concerning the financial implications of the adaptation work on the access routes to the huts (i.e. provision of equipment, route modifications, and installation of major infrastructure), 65% (15) of the projects were financed by public entities, 17% (4) by local mountain guides companies, 17% (4) by national alpine clubs, and 9% (2) by the hut keepers (Fig. 5C). In 12% (3) of the cases, projects were financed by several entities. The situation differed between France, Italy and Switzerland. In France and Italy, public funding was used in most cases (respectively 67% (7) and 82% (6) of the projects); in Switzerland, the Swiss Alpine Club was involved in 60% (3) of cases.

The above entities were involved in the general maintenance of the access routes (usually annual small-scale work as refastening or replacing ropes and ladders), but the numbers differed (Fig. 5C). Public funding was used to maintain access routes in only 47% (11) of the study cases and the hut keepers were involved in 26% (6) of the cases. In the remaining cases, maintenance was carried out either by mountain guide companies or by local sections of national alpine clubs. Furthermore, the general maintenance situation differed from one country to another: in Italy, hut keepers generally took care of the maintenance work on the access route to the hut they managed (67%) (5 of the cases); in France, the work was primarily done by the public entities (73%) (7); and in Switzerland, the work was done by the national alpine club (60%) (3).

Modification of access routes is often very expensive. The average cost of the adaptive solutions is not known but, as an example, work carried out to equip the access route to the Pannossière hut (2641 m a.s.l., Valais Alps) in 2014 cost EUR 350,000 and the equipping of a new access route to the Charpoua hut (2841 m a.s.l.,

Mont Blanc massif) in 2015 cost EUR 150,000. The average cost of the maintenance work per hut in the summer season was in the range of EUR 1000–10,000 (E. Henry Amar, Communauté de Communes de la Vallée de Chamonix-Mont-Blanc (CCVCMB) trail maintenance service, personal communication 2015).

Discussion

The results of our research confirm and complement the research done by Ritter et al. (2012). While many types of geomorphological process (22 according to Ritter et al. 2012) can affect access routes to high mountain huts, the loss of ice thickness from glaciers and the retreat of the glacier fronts are the two main disruptive processes (80% (24) of the cases). Both gravitational processes associated with permafrost degradation and paraglacial processes arising from slope deglaciation affected less than one-third of the access routes included in the study: permafrost degradation affected 40% (12) cases; paraglacial processes affected 32% (10) cases.

Compared with other processes identified (Fig. 5A), the above-mentioned gravitational processes and paraglacial processes were more localised in time and space, and it was difficult to detect them and measure their effects on the access routes with precision. Moreover, the link between geomorphological processes and safety could not be fully established from our data set. Nevertheless, we can hypothesise that glacial shrinkage affected most of the access routes, which would thus signal a need for them to be adapted. The gravitational processes associated with permafrost degradation suggest that the safety levels of the routes deteriorated. While only a limited number of route modifications were made in response to the processes, the role such processes play in the deterioration of access routes' safety must not be underestimated.

In the future, climate change will continue to accelerate (Christidis et al. 2015), especially in mountain areas (IPCC 2019). Therefore, glacial shrinkage (Vincent et al. 2017) and associated paraglacial processes will continue (Zemp et al. 2006) along with permafrost degradation (Harris et al. 2001; Haeberli & Gruber 2009). It has been estimated that by 2040, 54–60% of the glaciated surfaces will no longer have ice (Huss 2012). We can postulate that the evolution of access routes in the Western Alps will continue and even intensify in the coming decades. Projects to modify the routes in order to maintain acceptable levels of safety and difficulty will have to be more frequent and extensive. However, the extent to which the routes can be modified will have to be addressed in the future.

Differences in funding and maintenance possibilities between massifs and between countries

The fact that adaptation and maintenance work on access routes in high mountain areas are not financed by the same entities from one country to another means there are different contexts of management and therefore different adaptation possibilities. Equipping and maintaining access routes to mountain huts in the present context of climate change is expensive. The costs are mainly due to the difficulty of reaching the affected areas; often helicopters are needed to transport equipment and workers. In addition, the ladders, cables, and other equipment used on the routes are expensive. It is therefore increasingly harder for small organisations to fund projects for the installation of equipment. The CCVCMB's annual maintenance budget for the access routes to its seven high mountain huts is approximately EUR 50,000. The costs are associated with hiring qualified workers (EUR 10,000–20,000), necessary equipment (e.g. ladders, nets, and handrails) (EUR 12,000), helicopter transportation (EUR 17,000), and technical equipment (e.g. harnesses, ropes and drills) (EUR 2000) (E. Henry Amar, CCVCMB trail maintenance service, personal communication 2015). It is important to note that although the CCVMB can afford the investments, not all mountain municipalities have the same financial resources available for maintaining access routes to high mountain huts. The latter point is illustrated by the Conscrits hut case, for which European funds were necessary to finance the new access route.

Furthermore, in some areas of the Western Alps, environmental regulations limit the amount of work that can be done on access routes to high mountain huts. For example, the Mont Blanc massif is a protected site (*site classé*) where any infrastructure that could modify the state and/or appearance of the site is subject to legal authorisation. However, no specific authorisation is required if the activity and the equipment will only slightly modify the state and/or appearance of the site (Choay & Merlin 2005). Therefore, the equipment on access routes to mountain huts does not require legal authorisation unless the associated infrastructure required is particularly intrusive (e.g. a bridge). The current policy of the CCVCMB is to maintain and equip the access routes to huts in order to maintain acceptable safety conditions for mountaineers, without the use of major new infrastructure such as footbridges (E. Henry Amar, CCVCMB trail maintenance service, personal communication 2015).

Since 1991, all new infrastructure in Écrins National Park is subject to approval by the steering committee

of the Convention Alpinisme et Escalade (mountaineering and climbing convention) (Écrins National Park 2012). The objective of the convention is to limit infrastructure to certain popular areas. However, the convention has led to fierce debates between park managers, mountain guides, and hut keepers who have equipped routes without authorisation.[4] Some parties do not agree on what is an acceptable level of infrastructure, and have divergent economic interests and different opinions on heritage and ethics, which have fuelled their debates (see note 3). The following questions have been raised in the debates: Should the use of fixed equipment be encouraged to maintain a strong economic activity, with the risk of damaging the environment? Does modifying the environment go against the principles of mountaineering? Are the access routes to mountain huts part of the mountain heritage that should be preserved? Thus, the extent of the adaptation solutions is called into question and as the rate of global warming accelerates, the question of up to what point will funding be made available to maintain the access routes will need to be addressed. We will address all of these issues in future studies.

The effectiveness and sustainability of adaptive strategies

In some cases, due to financial, ethical and legal constraints, adaptive strategies or high mountain access routes are organised differently and therefore present different levels of effectiveness and sustainability. Annual maintenance work is often essential to maintain access to a mountain hut with acceptable levels of safety and difficulty. However, it is expensive and not always a viable long-term solution when the effects of climate change on high mountain environments are taken into consideration (e.g. glacier retreat). As an example, the access route to the Mer de Glace Glacier (Mont Blanc massif) from the Montenvers railway station (located 4 km east of Chamonix) and hence to the five huts in this area of the Mont Blanc massif has been moved twice since 2000 and several metres of new ladders have been needed every year to compensate for the ice loss (Mourey & Ravanel 2017). At the end of summer in 2018, there were 95 m of ladders in place compared with only 30 m in 2001.

As temperatures continue to rise, the front of the Mer de Glace Glacier is expected to retreat by c.1200 m by 2040 (Vincent et al. 2014). This would imply a reduction in thickness of 160 m compared with the 2010 level, which was 1649 m a.s.l: the section would require ladders c.250 m high and the surrounding area would be very dangerous for mountaineers (e.g. due to large gravitational processes from the moraines). Therefore, even if access were maintained by annual work, the route would become more dangerous and more difficult, thus decreasing the effectiveness of the strategy. New major infrastructure, such as footbridges, might provide a long-term solution but would be limited by several factors: in the case of bridges, the local topography does not always allow for their installation, they are expensive, and they are difficult to justify in protected areas for ethical reasons. The CCVCMB has already considered the possibility of stopping all maintenance of access routes and dismantling existing infrastructure if it becomes too difficult to guarantee acceptable levels of safety and technical conditions (E. Henry Amar, CCVCMB, trail maintenance service, personal communication 2015). If that were to happen, it would be very hard to access the Mer de Glace and five huts would have to close.

The above-described example of the Mer de Glace Glacier suggests that current strategies are based on a reactive stance (Amelung & Nicholls 2014). Furthermore, they are possibly an inadequate response to climate change in a long-term perspective, since many local elements have to be taken into account in order to develop sustainable and effective strategies.

Vulnerability of high mountain based tourism compared with nature-based tourism

Many scholars have examined the specificities of mountain tourism (Nepal & Chipeniuk 2005) and the impacts of climate change on mountain outdoor recreation and tourism (for a review, see Hewer & Gough 2017). Our findings are consistent with those of previous international studies that focused on high altitude and high latitude activities, and from which the authors conclude that the effects of climate change lead to an increase in dangerous conditions to mountaineers, due to more intense and frequent climate-related processes (Purdie et al. 2015; Temme 2015; Pröbstl-Haider et al. 2016). As a result, the mountaineering season in the Western Alps is shortening and shifting toward spring by more than three or four weeks compared to in the 1980s (see note 3).

However, we note that in general the impacts of climate change on nature-based tourism (Peter 1992) do not correspond to mountaineering activity. Several studies have shown that global warming will have a positive effect on some types of nature-based tourism. For example, Jones & Scott (2006) predict an increase of more than 10–40% in visits to national parks in Canada by the end of the 21st century, due to increases in daily maximum temperatures. Additionally, Wall et al. (1986) predict that the length of the camping season in

eight of the Ontario's provincial parks will increase by 40 days by 2050. Similar positive effects are also expected in the European Alps, due to an increase in the number days with sunshine (Pröbstl-Haider et al. 2015). However, such findings are not relevant for high mountain activities, for which the season is shortening and periods of warm temperatures are leading to increasingly dangerous conditions for mountaineers. Therefore, it seems that high mountain activities are not subject to the same dynamics as nature-based tourism in general.

Conclusions

In broad terms, the results of our research add to the literature on the effects of climate change on mountain tourism and contribute to fill in the knowledge gap identified by several studies (Scott et al. 2012; Welling et al. 2015; Hewer & Gough 2017). This is mainly a consequence of our cross-area analysis of adaptation strategies applied to access routes to high mountains huts in the Western Alps. Our results should lead to a better understanding of how the effects of global warming may jeopardise accessibility to high mountain environments and more generally may jeopardise mountaineering activities. They should also contribute to shape transformation towards a more sustainable situation by increasing the awareness and the understanding of the issues reported in this article.

Of all of the effects of climate change on high mountain environments, the main processes affecting the access routes to high mountain huts in the Western Alps are the loss of ice thickness and the retreat of glacier fronts. Consequently, access routes are becoming more dangerous for mountaineers and therefore measures to restore acceptable safety conditions are needed. In general, the standard practice has been to install equipment and/or to relocate routes. It has been less common to install major infrastructure. In most cases, the modifications have been effective: they have allowed access to be maintained, improved safety, and made the routes less difficult to use to access the high mountain huts (e.g. the Bertol, Promontoire and Conscrits huts).

However, the development of adaptive strategies, usually based on a reactive stance, is variable and can be limited by the ethical, legal and especially financial issues that have to be taken into account by stakeholders. The strategies are costly and imply expensive maintenance works that are difficult for the entities in charge to afford (guide companies, alpine clubs and hut keepers), which usually have limited resources. Moreover, climate change will continue to accelerate and degrade the high mountain environment.

Our conclusions and perspectives lead us to ask what the future might be for huts at high elevations and high altitudes, and more generally for the practice of mountaineering. Will the degradation of access routes cause a decrease in the number of hut visits and jeopardise the economic viability of those huts?

Notes

1. GLACIOCLIM programme, unpublished data, 2019
2. M. Bonnefoy-Demongeot and E. Thibert, unpublished data, 2019
3. Research report by L. Moreau, titled 'Glacier de Très la Tête (Massif du Mont-Blanc), Bilan de masse année 2015', prepared for ASTERS & Glaciolab.
4. Research report by P. Bourdeau, titled 'Effets du changement climatique sur l'alpinisme et nouvelles interactions avec la gestion des espaces protégés en haute montagne: Le cas du Parc National des Ecrins', prepared at the University of Grenoble for Écrins National Park.

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