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Emmanuel Salim, Laura Mabboux, Ludovic Ravel, Philip Deline, Christophe Gauchon. A history of tourism at the Mer de Glace: Adaptations of glacier tourism to glacier fluctuations since 1741. *Journal of Mountain Science*, 2021, 18 (8), pp.1977-1994. 10.1007/s11629-021-6723-5 . halshs-03315933

HAL Id: halshs-03315933

<https://shs.hal.science/halshs-03315933v1>

Submitted on 6 Aug 2021

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This paper has been published in the Journal of Mountain Science, cite as :

Salim, E., Mabboux, L., Ravel, L. *et al.* A history of tourism at the Mer de Glace: Adaptations of glacier tourism to glacier fluctuations since 1741. *J. Mt. Sci.* **18**, 1977–1994 (2021).

<https://doi.org/10.1007/s11629-021-6723-5>

A history of tourism at Mer de Glace: Adaptation of glacier tourism to glacier fluctuations since 1741

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Funding

This study was funded by the Labex ITEM - ANR: 10-LABX-0050 and the ALCOTRA n342 AdaPT Mont Blanc project funded by the Interreg V-A Italy-France 2014-2020 program.

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Abstract: Climate change induces profound changes in mountain territories that affect the activities pursued there. Tourism is one activity that is strongly impacted by these changes. Most research on tourism in mountain regions has focused on winter sports tourism, but glacier tourism, a summer activity, is also severely affected by climate change-induced phenomena, including glacier retreat and other geomorphological processes. Given that Alpine glacier tourism has been pursued since the 18th century and glaciers have been changing throughout this period, this article aims to examine the adaptations implemented by glacier tourism operators since the activity's beginnings. Through analysis of historical documents, glaciological surveys and semi-structured interviews, this paper reveals how tourism activities around the Mer de Glace (the largest French glacier) have been impacted by glacier fluctuations since the first visit to the area in 1741. The study reveals that these developments have mainly been driven by glacier retreat and associated paraglacial dynamics. More recently, the shortening of the period of snow cover on the glacier has also impacted tourism activities. Most of the adaptation strategies implemented by tourism operators during the period in question are found to be reactive, consisting in the installation of safety equipment, the renovation of access points or the building of new structures to allow tourist activities to continue despite the consequences of glacier retreat. Other strategies, such as the adoption of new activities by workers previously specialised in another, are identified that could be considered transformative strategies, although these were only adopted by workers when their activity was no longer feasible. The analysis of materials from 1741 to the present also reveals that the recent impacts of climate change on glacier tourism are much more significant and diverse than those produced by past fluctuations. Therefore, it is important that stakeholders take suitable measures to ensure the sustainable future of the Mer de Glace and other glacier tourism destinations.

Keywords: climate change; glacier tourism; adaptation; sustainability; Mer de Glace; historical geography.

1. Introduction

Today, climate change is driving significant changes in mountain territories. An evident example of these changes is the phenomenon of glacier shrinkage, which has been occurring in mountain regions for decades (Haeberli et al., 2019). Recent estimates suggest that the volume of ice found in central Europe as of 2017 could be reduced by 60 to 99% before 2100, with these figures corresponding respectively to the representative concentration pathway scenarios 4.5 and 8.5 established by the Intergovernmental Panel on Climate Change (IPCC; Bosson et al., 2019). Glacier retreat already induces processes related to paraglacial dynamics (i.e., geomorphological dynamics which are not directly ice-related but driven by deglaciation; Ballantyne, 2002), which can manifest in rapid landslides (as in the case of the Aletsch Glacier; Kos et al., 2016) or moraine destabilisation (McColl, 2012). Moreover, increasing temperatures cause the degradation of mountain permafrost (Etzelmüller et al., 2020), which leads to a greater incidence of massive rockfalls (Ravanel et al., 2017). Recent research also suggests that cold-based hanging glaciers can be destabilised by warming (Gilbert et al., 2015) and that the surface areas of ice aprons have been significantly reduced since the 1990s (Guillet & Ravanel, 2020).

As the impact of climate change generates challenges for humanity in general (Mora et al., 2018), the effects on mountain territories described above produce important changes in mountain societies in particular. For example, glacial debuttressing and permafrost warming lead to infrastructure destabilisation in the Alps (Duvillard et al., 2018, 2019). Glacier retreat directly impacts water supply and tourism activities (Akhtar et al., 2008; Wang & Zhou, 2019). While glaciers become more difficult to access, alpinism routes become increasingly dangerous (Purdie et al., 2015; Mourey & Ravanel, 2017; Mourey et al., 2019). Meanwhile, decreased snow reliability has raised concerns for the future of the ski industry (Steiger et al., 2019), and summer heatwaves may negatively impact tourist choices in certain destinations (Scott et al., 2007). In these ways, tourism and recreational activities taking place in mountain territories are significantly impacted by the effects of climate change. These developments have a direct impact on stakeholders in the tourism industry, including mountain guides (Salim et al., 2019; Mourey et al., 2020), summer ski operators (Demiroglu et al., 2018) and winter ski operators (Moen & Fredman, 2007).

The consequences of climate change in mountain territories require planning and adaptation (Kaján & Saarinen, 2013). In this respect, the 2014 IPCC report (IPCC, 2014) defines adaptation to climate change as a global priority. To address this need, a great deal of adaptation-based research has been conducted during the last decade to provide insight into the ways socio-ecological systems adapt to the effects of climate change (e.g., Adger et al., 2017; Hashemi et al., 2017).

Various studies have been conducted on ski tourism concerning its vulnerability to climate change and the adaptation strategies implemented within the industry (e.g., Moen & Fredman, 2007; Joly & Ungureanu, 2018; Steiger et al., 2019; Steiger & Scott, 2020). Glacier tourism, on the other hand – an important activity for mountain territories during summer seasons – has not yet been sufficiently investigated. The first review of the literature in this area, published in 2015 (Welling et al., 2015), synthesised the findings yielded until then in the field of glacier tourism research. The study identified a lack of knowledge concerning the impact of climate change on the behaviour of operators in the glacier tourism industry. More recently, Wang and Zhou (2019) published a review that was intended to fill this gap which focused on the impacts of climate change on glacier tourism. Their results indicated that aesthetic, cultural and experiential dimensions of glacier tourism activities have all been altered by climate change. Welling et al.'s (2019) recent call for further research on adaptation strategies in the glacier tourism industry led Salim et al. (2021a) to conduct a third literature review focusing on adaptation strategies developed in the context of glacier tourism. Although 27 different adaptation strategies could be identified, the survey revealed that the majority of these are coping or incremental strategies that do not ensure the sustainability of glacier tourism. In addition to adaptation strategies, a case study by Paunović & Jovanović (2017) has investigated the importance of climate change mitigation, a factor that is particularly critical for tourism operators seeking to ensure the sustainability of their activities. Given the historical development of glacier tourism in the Alpine arc, adaptation and mitigation strategies are particularly important for tourism stakeholders in this region (Salim et al., 2021b).

Previous studies of adaptation strategies in glacier tourism have focused only on those strategies that are currently or have recently been implemented (e.g., Furunes & Mykletun, 2012; Stewart et al., 2016; Welling & Abegg, 2019). However, certain glacier tourism destinations have existed for more than two and a half centuries, remaining resistant to glacial fluctuations during the Little Ice Age (LIA) and later on (Paul & Bolch, 2019). Understanding how glacier tourism stakeholders adapted to past changes can help current stakeholders determine how best to react to changes in the present. Accordingly, this paper focuses on how tourism activities taking place around the Mer de Glace, the largest glacier of the French Alps, have been impacted by glacier fluctuations since 1741, when tourist activity there began, and how stakeholders have adapted. This glacier is of particular research interest given its long history of tourist development since 1741 and the detailed

insights it can provide into glacial fluctuations. The paper thus poses the following research questions:

- Have tourism activities around the Mer de Glace been affected by glacier fluctuations since 1741, and, if so, how?
- What types of adaptation strategies have been implemented to cope with the impact of glacier fluctuations on tourism activities?

2. Study area

The Mer de Glace is the third largest glacier in the Alps (after the Aletsch and Gorner Glaciers in Switzerland), with a length of 11 km, a surface area of approximately 30 km² and several tributaries, namely the Géant, Tacul, Leschaux and Périades Glaciers (Figure 1). Contemporary tourism around this glacier is oriented around three major sites: 1) the Aiguille du Midi, one of the most popular tourism attraction in the Auvergne-Rhône-Alpes region, with a cable car that provides access up to 3,842 m a.s.l.; 2) the Montenvers, where a cog railway transports visitors up to a viewpoint on the glacier tongue at 1,913 m a.s.l.; and 3) the Pointe Helbronner (3,462 m a.s.l.), which is accessible from Courmayeur (Italy) by cable car. Another tourism site, Le Chapeau, was an important tourist attraction around the Mer de Glace for centuries, but it is now much less visited than the three sites mentioned above due to the retreat of the glacier. The Mer de Glace also serves as the gateway to seven high mountain huts (Mourey & Ravel, 2017; Figure 1). The Mer de Glace was also one of the first glaciers in the Alps to have been developed for tourism, beginning with the visit of the English aristocrats W. Windham and R. Pococke in 1741 (Joutard, 1986). For instance, the Mont Blanc massif, which includes the Mer de Glace, is considered the birthplace of alpinism, mainly due to the history of its practice in the region and the famous summits that have long been destinations of mountaineers. In 2019, alpinism was inscribed by UNESCO on the Representative List of the Intangible Cultural Heritage of Humanity.

In 2019, tourism in the Chamonix valley was nearly evenly divided in terms of overnight stays between summer (51%) and winter (49%), with a total of 7,770,200 overnight stays throughout the year (Data from Chamonix Tourist Office). The Mer de Glace today can be characterised as supporting three kinds of tourism activities: i) the contemplation and visiting of tourism sites; ii) alpinism focusing on the summits around the glacier; and iii) skiing the Vallée Blanche downhill, one of the most famous off-piste ski routes in France (with about 50,000 practitioners in 2018; data provided by the Compagnie du Mont Blanc).

The Mer de Glace is currently a retreating glacier. Its thickness has decreased by 32% since the start of the 20th century, while its length has been reduced by 1.5 km since 1860 (Vincent et al., 2019). At the Montenvers site, ice thickness decreased by 140 m between 1986 and 2020 (own measurement). Past fluctuations of the Mer de Glace have also been studied and allow one to understand to a good extent how its front has evolved since the end of the 16th century (Nussbaumer et al., 2007).

3. Materials and Method

To answer the research questions posed above, three different types of data are considered: glaciological surveys; historical literature, images and maps; and semi-structured interviews.

3.1. Glacier fluctuations data

Concerning the fluctuations of the Mer de Glace over time, the paper uses data from multiple sources. Several of these, including historical images, maps and texts, have been used previously by Nussbaumer et al. (2007) to reconstruct the development of the position of the Mer de Glace's front between 1570 and 2003. These sources are supplemented with measurement data for the front of the glacier published by GLACIOCLIM, a programme which provides access to measurements of several glaciers around the world that, at the time of publication of this article, is still ongoing (Vincent et al., 2007). Combining the data yielded a dataset reflecting the fluctuation of the front of the Mer de Glace between 1570 and 2019 (Figure 2).

To complete the dataset, altimetric profiles of the Mer de Glace were added. Provided by GLACIOCLIM, it includes one measurement per year systematically conducted over five cross-profiles, allowing a reconstruction of the positions of the ice surface since 1880 (Figure 2). The data

collected from the above sources allows historical data of ice surface positions to be cross-referenced with measurements of the glacier's fluctuations.

3.2. Historical documents and grey literature

Various types of historical documents have been mobilised for this study, including tourism guides, historical books, letters, maps and pictures. A total of 90 documents were collected from different sources, such as the Amis du Vieux Chamonix, a historical association of Chamonix; the Alpine Museum (Chamonix); the French National Library (Paris); the Viatimages research portal (<https://www2.unil.ch/viatimages/>); and the private collections of inhabitants of Chamonix (the complete list of the 90 documents can be found in Appendix 1). The main objective in consulting these sources was to identify the main tourist itineraries and attractions on and around the Mer de Glace, assess their importance and understand how they have changed and developed over time.

The different types of documents have been managed in several different ways. Tourism guides and letter correspondences, some from as early as 1742, have been added to a database in which the various tourist attractions and itineraries found in each guide or letter could be listed. Historical literature including tourism guide, letters and book, have been processed using MaxQDA. Scanned versions of the documents were introduced to the software, and parts of the documents were categorised according to their themes and the information they could provide (e.g., information on the use of a route, a geomorphological aspect of the glacier or a tourism adaptation being developed). Content of the documents were analysed manually with the help of these codes. No automatic analysis was performed for any of the above documents. Other documents, such as activity reports, were used to confirm specific details (e.g., regarding administrative decisions). In addition, a collection of 1,573 historic pictures, paintings, engravings and maps were used at times to confirm certain developments or to represent changes. To better and more completely identify recent changes, aerial photographs taken since 1939 found on the website of the French National Geographic Institute (Géoportail IGN) were also used.

3.3. Semi-structured interviews

Fourteen semi-structured interviews were conducted to gain more information about fluctuations of the Mer de Glace and tourism in the region, focusing in particular on recent changes in tourist activities in the region. More specifically, the interviews allowed information to be gathered concerning such topics as recent changes in tourist infrastructure at places such as Montanvers and Aiguille du Midi or the creation of the first ice cave of the Bossons glacier. Several types of participants were interviewed: managers of infrastructure at sites such as the Aiguille du Midi and Montanvers, high mountain guides, representatives of the Amis du Vieux Chamonix historical society, members of the Chamonix high mountain security forces, employees of La Chamoniarde, a mountaineering information center, and enthusiasts of Chamonix valley history.

The interview guide was divided into segments focusing on the presentation of the interviewee, their experience in the Chamonix valley and the evolution of tourism activities around the Mer de Glace. However, because each interview was conducted to answer specific questions relevant to a given interviewee, the interview guide varied between participants. For example, mountain guides were asked specifically about the development of their work as guides, while security workers were asked about the evolution of accidentology in the context of mountain activities. Of the 14 interviews conducted, seven were recorded with the authorisation of the participant and then transcribed. As the participants of the other interviews preferred not to be recorded, no recordings were made of the other seven interviews. In these cases, notes were taken during each interview. The mean duration of the interviews was approximately one hour. Similar to the historical documents, the interview transcripts and notes were analysed using MaxQDA. A direct content analysis was carried out to review the main themes (e.g., impacts of climate change and adaptations to tourism).

4. Results

Chamonix has been a destination for glacier tourism since the first touristic visit of Windham and Pococke in 1741. From this date on, various tourist attractions and itineraries began to be mentioned in correspondence and tourism guides (Figure 3). Montanvers and the Arveyron ice arch were the first attractions to be referenced in 1742. The crossing between Chamonix and Courmayeur and Le Jardin de Talèfre both appeared in the literature beginning in 1790. Later, in 1850, references to the

Montenvers-Chapeau itinerary and the hike to Le Chapeau began to appear. The Vallée Blanche off-piste ski route was first described in 1903, but references to it in the literature disappear until 1955, when the opening of the Aiguille du Midi cable car helped it to become famous. It was found that four tourism attractions and itineraries have been directly impacted by glacier fluctuations: the Montenvers-Chapeau itinerary, the Vallée Blanche, the Arveyron ice arch and, following the end of the LIA (circa 1854) the itinerary to Le Jardin (Nussbaumer & Zumbühl, 2012). However, as the latter has already been studied by Mourey and Ravel (2017), the following discussion focuses on the first three of these.

4.1 The Arveyron ice arch

This attraction consisted of a natural ice arch at the front of the Mer de Glace (called the “glacier des Bois”; Figure 4). The ice arch was considered an easy-to-reach attraction requiring less physical effort to reach than Montenvers (a five to six hour walk between 1741 and 1820 compared to the one hour walk to reach the Arveyron ice arch). The ice arch was one of the major attractions of the Chamonix valley, described in every tourism guide from 1742 until around 1872.

Although the Arveyron ice arch was consistently featured in tourism guides, mention was often made of its changing character. For example, Manget’s guide, published in 1844 (Manget, 1844), states that the ice arch varied in size from year to year and sometimes did not even form. According to multiple guidebooks, the ice arch did not form during or around the period of 1842-43, which corresponds with a period of retreat of the Mer de Glace front (Nussbaumer et al., 2007). According to the guidebooks, the ice arch continued to be visited throughout the first half of the 19th century but disappeared in the 1870s. The last mention of the ice arch is made in the Weissen guidebook published in 1889 (Weissen, 1889), which notes that the visit to the Arveyron cave was a famous attraction that had by then disappeared.

Throughout the period when the Arveyron ice arch was visited, it was a source of employment for the inhabitants of the valley. It was advisable for visitors to employ the services of a guide to get there (for 3 francs) or even hire a mule to carry them there (also for 3 francs). For many visitors, the opportunity to fire pistols at the ice arch seems to have been as much of a motivation for the visit as viewing the arch itself, since warnings about this practice are found in many tourism guides. Beginning in the 1850s, which mark the end of the LIA, the front of the Mer de Glace was retreating (Nussbaumer et al., 2007). It was also at approximately this time that an artificial ice cave was built next to the natural arch. The Raverat guide, published in 1872 (Raverat, 1872), describes this cave as a gallery 1 m wide and 2 m high that was illuminated with candles. Called “the crystal cave”, it could be entered by visitors for half a franc. In Payot’s guide, published in 1869 (Payot, 1869), it is said that the artificial cave was up to 100 m long, but its length could be reduced by three quarters during the summer, a fact which highlights the rapid retreat of the glacier front then underway. The builders of the cave also set up a snack bar where they sold refreshments to the visitors. The data available do not indicate whether or not this ice cave was excavated in response to the uncertainty of the formation of the natural arch due to the retreat of the glacier. In any case, it was shortly before the disappearance of the Arveyron ice arch, in 1865, that the first ice cave was dug out in the nearby Bossons glacier. After the disappearance of the Arveyron ice arch and the nearby ice cave, the source of the Arveyron which emerged after the retreat of the front of the glacier, continued to be mentioned in texts such as Driou’s guide, published in 1880 (Driou, 1880), where it is noted that a visit to this site is of interest to see the stream itself that flows from the glacier. However, this new attraction is mentioned less often than the ice arch was and does not appear in every guidebook.

4.2 The Montenvers-Chapeau itinerary

The Montenvers-Chapeau itinerary allowed one to cross the Mer de Glace from Montenvers to Le Chapeau (Figure 5). The route was considered one of the major attractions of the Chamonix valley from the 1850s until passage across it was banned in 1963. During the first part of this period, leading tourists along this route was the main activity for the mountain guides of the valley. It is estimated that 320 to 340 of the valley’s mountain guides and mule drivers worked each year between 1886 and 1890, a period when about 24,000 tourists were visiting Chamonix per year (Debarbieux, 1988). It should be noted that 1860 was the year of the annexation of Savoy (formerly part of the Kingdom of Piedmont-Sardinia) by France, while in 1866 a road was opened that reduced the time required to access Chamonix. According to various tourism guides from the end of the 19th century, many tourism facilities had been established by this time to guarantee the safety of hikers on the route. The passage over the glacier was sandblasted by a municipal employee to prevent tourists from slipping, and signposts were placed advising tourists to exercise caution. Socks were sold at

Montenvers for tourists to place over their shoes, also to avoid slipping. Other tourist activities available on the Montenvers-Chapeau itinerary included setting fire to a cannon to hear it echo through the valley or having one's photo taken to be brought back a souvenir, both of which required tourists to pay. As mentioned above, the itinerary allowed the employment of many guides, who would lead tourists to Montenvers and, from there, help them complete the crossing. Meanwhile young *rentourneurs* were responsible for driving the mules back down to Chamonix once the crossing was completed before driving other mules to Le Chapeau. Following the opening of the Montenvers rack and pinion railway in 1909, the number of visitors on the route increased considerably (from 8,166 in 1908 to 23,740 in 1909, 76,620 in 1930 and 200,000 in 1950, according to Bidaut & Gendrault, 1997).

The number of tourists who took part in this itinerary was strongly affected by glacier fluctuations. Numerous texts, such as the narrative of Saussure from 1760, confirm that the route to cross the glacier did not exist until the 1840s. Around the time of Saussure's narrative, the glacier was described as very crevassed and difficult to cross. It is only during the 1850s, when the glacier started to retreat (Figure 2), that the itinerary was developed and began to be frequented by tourists. However, following its development, three sections of the itinerary would be affected by glacier changes: the descent to the Mer de Glace from Montenvers, the crossing of the Nant Blanc stream and the passage of the "Mauvais Pas" (i.e., "bad step").

Despite the impact on the above sections of the itinerary, the access to the Mer de Glace and the right lateral moraine ascent changed only slightly between 1850 and 1940, and the representation of the route in maps remained the same. However, the authors of tourism guides printed between the 1850s and the 1940s note the need to cross the moraines on the left and right margins of the glacier. A slight decrease in the thickness of the glacier at Montenvers between 1880 and 1930 (Figure 2) and an increase in the height of the moraines may explain the progressive increase in the time required for this itinerary according to guidebooks, from 4h30 in 1868 to 5h in 1892 and 6h in 1925.

In comparison with the passage through the moraines, glacier changes made the crossing of the Nant Blanc stream more challenging. The passage was made possible through the use of wooden footbridges that were installed annually. However, at the beginning of the 1900s, crossing the stream was sometimes difficult, possibly due to the effects of the melting of the Nant Blanc glacier, which was situated upstream. During this period, there was a strong retreat of the glacier front; according to the maps published between 1876 and 1925, the altitude of the front of the Nant Blanc glacier rose by 50 m between 1876 and 1925. Although the available documents do not confirm this, it is probable that the melting of the Nant Blanc glacier was the cause of the increasing difficulties in crossing the stream at that time. In 1928, the Chamonix town council voted to construct a tunnel in the rock wall, which was finally drilled in 1932, to guarantee convenient crossing.

The Mauvais Pas was another difficult passage affected by glacier change. Just before reaching Le Chapeau, this section of the itinerary required one to cross a very steep rocky passageway where a handrail and steps had been carved into the rock in 1855. However, between 1850 and 1950, the front of the glacier retreated by 1.56 km and its thickness at the Mottet profile (cf.: Figure 2) decreased by 60 m between 1880 and 1950 (Data from Glacioclim). This retreat created new difficulties for visitors prone to vertigo. Moreover, an analysis of aerial photographs taken between 1939 and 1960 indicates that the retreat of the glacier eventually caused destabilisations in the right lateral moraine and thus the destruction of the path. Glacier retreat and paraglacial processes led the local authorities to close the path and the itinerary in 1963.

4.3 Vallée Blanche ski route

The Vallée Blanche, as mentioned above, is an off-piste ski downhill situated on the Géant, Tacul and Mer de Glace glaciers that departs from the Pointe Helbronner or the Aiguille du Midi. The first descent was carried out in 1903, but the itinerary became famous after 1955, when the Aiguille du Midi cable car opened (see Figures 1 and 3). According to one ex-manager of infrastructure at the Aiguille du Midi and a representative of the local historical society who were asked about this topic, the route was highly frequented from the 1970s to the 1990s, having approximately 60,000 skiers per year. Since the 2000s, the number of skiers has decreased to around 50,000 per year. While approximately 80% of skiers depart from the Aiguille du Midi, the remaining 20% descend from the Pointe Helbronner.

While the route of the Vallée Blanche has been altered as a direct result of glacier retreat, unlike the tourist attractions mentioned above, it has also been affected by other factors such as snow cover. One development related to snow cover concerns the period of the year during which the route could be skied. According to those interviewed, this lasted six months in 1960 but has been significantly reduced since the 2000s due to the initial snow cover, and thus the beginning of the season, arriving later and the snow melting earlier in the spring. Multiple interviewees suggested that the decrease in snow cover thickness was also related to an increase in wind during snowfalls.

However, no scientific study has been conducted yet that could confirm this hypothesis. The interviewees also stated that regular episodes of strong winds limited the thickness of the snow cover, making it more difficult to ski in lower parts of the route as well as at higher altitudes, such as the point of access to the Requin hut (Figure 6). At the same time, these periods of strong wind would have increased cold snow transport at higher altitudes and contributed to the formation of snow bridges (Ravanel et al., 2017), thus improving skiing at some of the higher parts of the route.

Glacier retreat has also had a significant impact on the popularity of this route. Perhaps the most significant change provoked by glacier retreat concerns the lower part of the route. Between 1952 and 1967, the front of the glacier retreated 350 m (Nussbaumer et al., 2007) and the thickness of the glacier at Les Mottets was reduced by 55 m (Data from Glaciolim). This made it increasingly difficult for skiers to reach the historic exit of the route through Le Chapeau. In 1968, this exit was abandoned in favour of another at Les Mottets. However, the retreat of the glacier continued and eventually made it necessary for skiers to climb 30 m up the moraine in 1990 and 130 m up the moraine in 2010 (Figure 2) to reach Les Mottets. This gradually led many skiers to favour the descent to Chamonix by the Montenvers train, which opened in winter 1993 (Figure 7). Today, however, the continued decrease in the thickness of the glacier make the return to Chamonix via the Montenvers train increasingly difficult. After a slight increase in the volume of the glacier between 1972 and 1986 (a period when it became 20 m thicker), it started to retreat again, and in 1988 a new cable car and the first stairway leading up to the glacier were installed. In 2020, to take the gondola lift back from the glacier tongue to the Montenvers railway station, it was necessary to climb about 130 m up via footbridges with more than 500 steps, which each year, on average, had to be extended by 15 steps.

The development of debris cover on the glacier has also influenced the Vallée Blanche and its tourist operations. Between 1988 and 2008, the area of debris cover on the lower part of the Mer de Glace increased continually from 0.47 to 1.37 km² (Martin, 2011). This increase, which was linked to a lack of snow on the lower part of the glacier, made it necessary for skiers to remove their skis at an increasingly greater distance from the beginning of the ascent to Montenvers and therefore increased the time needed to complete the route. The top of the route, situated higher than 3,000 m a.s.l., has been less impacted than the lower part in this respect. However, the interviewees suggested that the snow-covered ridge which allows access to the Géant glacier from the Aiguille du Midi has become steeper and more frequently icy because of the lack of snow. Meanwhile, the Refuge du Requin, situated at a medium altitude (2516 m a.s.l.), has also been affected by the glaciers' receding. The fluctuations of the Envers du Plan Glacier, which dominates the access point to the Refuge du Requin, has been problematic, as between 1970 and 1980, the glacier's increase in height caused an increase in the risk of falling seracs (Mourey & Ravanel, 2017). More recently, according to the interviewees, the retreat of the Envers du Plan glacier has positioned its front at an angle that leads to regular serac avalanches and thus increases the danger of skiing on the Vallée de Blanche route.

4.4 Summary of the impacts of glacier fluctuations on tourism around the Mer de Glace since 1741

Glacier changes and paraglacial processes have impacted tourism activities around the Mer de Glace over the last two centuries, and more recently, the thickness and duration of snow cover has been a restrictive factor. From the collected data, nine processes impacting tourism could be identified. Three are related to snow cover, two to glacier retreat itself and four to associated paraglacial dynamics (Table 1). These processes have had various consequences for tourism activities, all but one of them negative, including a reduction of the period of the activity, greater difficulty in accessing the glacier, increase in the level of danger of routes and itineraries, the loss of an attraction itself and (the only positive development) improved conditions in part of the route for an activity.

The responses of tourism operators to these developments have involved three main types of strategies: installing equipment to overcome a specific problem; changing a route or itinerary when traversing a part of it becomes too problematic; and substituting the site of an activity for another when it is no longer possible to continue it at a given place (e.g., visiting ice caves). In some cases, environmental processes led to consequences that were not addressed by tourism stakeholders. For example, the expansion of the area of debris cover at the bottom of the Vallée Blanche has increased the amount of time needed for skiers to complete the route, and tourism operators have yet to develop a response. However, interviewees indicated that a new cable car project is currently underway that will address these and other issues. This new cable car, located at a higher altitude on the glacier than the current one, would limit the time required for the route by enabling skiers to get back up to Montenvers more quickly. In addition to the three strategies mentioned above, installation of new infrastructure should be recognised as a fourth type of adaptation that tourist stakeholders are currently considering.

5 Discussion

Tourism activities around the Mer de Glace have naturally evolved in relation to political, economic and cultural developments (e.g., with the opening of a road allowing easier access to Chamonix in 1866; with the establishment of the Chamonix Guide Company, which has organised tourism in the glacial basin since 1823; and with the development of the Vallée Blanche itinerary following the opening of the cable cars of the Pointe Helbronner and the Aiguille du Midi in 1946 and 1955, respectively). However, analysis of various types of documents and historical data reveal that glacier fluctuations also played an important role in the development of tourism in the region. It is now appropriate to discuss in greater detail the impacts glacier fluctuations have had on tourism at the Mer de Glace in light of the present work and other studies' findings, as well as the adaptations tourist operators have made in response to them over the last two centuries.

5.1 Most significant impacts of glacier fluctuations on current tourist activities at the Mer de Glace

In their study of the impact of climate change on alpinism routes in the Mont Blanc massif, Mourey et al. (2019) have identified 25 geomorphic changes. Moreover, the majority of these changes, most of which were consequences of climate change, have occurred relatively recently, as they affected the development of routes between 1973 and 2018. In the present study, nine different geomorphological processes have been identified, five of which concern only the Vallée Blanche and began to occur during or after the 1990s. Additionally, it is worth noting that no problems linked to permafrost warming appear in the activities or itineraries studied in this paper, which, given that changes to the region since 1741 were studied extensively, supports the notion that this is a recent process related to climate change. Ultimately, the changes observed in glaciers around the Mer de Glace in this study (glacier retreat, debris cover and moraine destabilisations) are typical of the developments identified in other studies of glaciers in areas such as New Zealand (Purdie et al., 2015) and Iceland (Welling & Abegg, 2019).

Mourey and Ravanel (2017) have studied the evolution of access routes to the huts of the Mer de Glace basin since 1900 and have demonstrated that most of the geomorphological processes that have affected routes during that period began to occur during or after the 1990s. Other studies have also demonstrated that mountain processes such as permafrost warming are currently intensifying in the region (Bodin et al., 2015) and causing issues for infrastructures (Duvillard et al., 2019). In the present study also, the impact of glacier retreat on tourism infrastructures appears to have been much more significant in the last 20 years than during the 19th and the first half of the 20th century. It is important to note, however, that although they may have been less dramatic, ice fluctuations have had an evident impact on tourism around the Mer de Glace since its beginning. Interestingly, the decrease in thickness of the glacier in and around the 1840s (Figure 2) would have facilitated access to it. Difficulties for tourist operations then arose primarily as a result of the retreat of the front (the disappearance of the Arveyron ice arch, difficulties accessing and progressing through itineraries) and the loss of ice thickness (the appearance of hazards, difficulties accessing and progressing through itineraries), as well as the appearance and destabilisation of moraines. More recent impacts on tourist operations stem from the same processes (particularly glacier retreat and moraine destabilisation) along with the expansion of debris cover. However, these seem to have produced more diverse consequences than previous changes, such as impacts on the aesthetic value of the landscape (Wang & Zhou, 2019), risks linked to proglacial lake formations (Cathala et al., 2021; Magnin et al., 2020) and changes in visitors' behaviour (Salim & Ravanel, 2020).

Ultimately, there are limits to the precision of the above analysis of changes due mainly to the sources used in the present study. Historical documents do not permit specific developments to be identified with as much precision as interviews. However, the latter method was only appropriate for gaining information concerning recent developments. Nevertheless, the historical material used for the study was sufficient to determine those developments that were significant enough to impact tourist operations and the adaptation strategies adopted by tourist stakeholders.

5.2 Adaptation strategies in response to glacier fluctuations

It is possible to identify several adaptation strategies that have been implemented by tourist stakeholders in the Mer de Glace area at one of two different levels: the local and the global. Local-level strategies are those that directly respond to the effects of geomorphological processes on tourist attractions and itineraries (Table 1). They include the installation of equipment to improve safety or

facilitate progress along a route, the creation of new itineraries or routes to replace old ones and the construction of new infrastructure in other locations. Global-level strategies are harder to interpret and not easily found in the historical sources analysed in the present study. However, some global adaptation strategies can be identified from the historical data. For instance, the “cave guides” who used to lead visitors to the Arveyron cave changed their activities after this cave disappeared. According to historical sources, the following years were characterised by an increase in the number of souvenir sellers along the main routes through the valley, and it is suggested that many of these were cave guides who had converted their operations. Another example of a global-level strategy is the change of activity made by Chamonix’s mountain guides in and around the 1950s. Helping tourists access the Montenvers and crossing the Mer de Glace to Le Chapeau was the main activity of these guides during the first half of the 20th century. However, from the 1950s onwards, as the crossing became more difficult, the guides gradually turned to assisting tourists in alpinism as their main activity (Joutard, 1986).

These adaptations can be understood as responses to glacial fluctuations as well as other processes. Although the conditions for crossing the Mer de Glace deteriorated during the 1950s, alpinism also became an increasingly popular activity during this time (Debarbieux, 1988). The mountain guides’ gradual adoption of alpinism during this period may therefore be seen as a decision made to take advantage of the developing popularity of a new activity and leave one that was becoming increasingly difficult. Similarly, it has recently been observed (cf.: Salim et al., 2019) that high mountain guides are abandoning practices considered more dangerous due to climate warming (e.g., snow courses and rock courses in locations subject to permafrost warming), in favour of other increasingly popular activities (e.g., sport climbing, mountain biking and company retreats).

Applying the framework of Fedele et al. (2019), one can observe that local adaptation strategies are mainly coping strategies (i.e., strategies used to resist the impacts of climate change and maintain business as usual) and consist of maintaining an activity that faces increasing difficulties. On the other hand, adaptations made at the global level seem to be transformative, since they lead actors to profoundly modify their activities. Unlike the adaptation strategies identified in a previous study that were developed in the context of glacier tourism (Salim et al., 2021a), the transformative strategies observed in the present study have been carried out by self-employed individuals rather than employees of major companies with high financial and skills capabilities. However, for the two cases observed (those of high mountain guides and cave guides), this strategy was a “compulsory” adaptation provoked by the disappearance of a specific tourist attraction or itinerary.

Previous studies of glacier tourism have highlighted numerous examples of coping and incremental strategies (i.e., strategies where one makes minor adjustments to a system; Fedele et al., 2019) that allow tourist stakeholders to maintain their activities by resisting in some manner the effects of climate change (Stewart et al., 2016; Welling & Abegg, 2019). However, such measures do not prepare tourism activities for future changes and can even increase these activities’ vulnerability to changes (Espiner et al., 2017). To ensure the future resilience of tourism based around the Mer de Glace and, by extension, other European glaciers whose future evolution is being modelled with increasing precision (Bosson et al., 2019; Peyaud et al., 2020; Zekollari et al., 2019), tourism stakeholders should analyse probable future developments that will affect their activities and plan appropriate adaptation strategies as a group. As Welling et al. (2019) have demonstrated, anticipatory scenario planning, that allow stakeholders to reflect on future development scenarios, is a process of interest for stakeholders seeking to achieve sustainability. In the case of tourism around the Mer de Glace, the combination of private interests (e.g., entrepreneurs and service companies with large, privately owned infrastructure) and public issues (e.g., conservation policy) makes destination governance the most promising means of carrying out such planning. Previous studies have shown that citizen participation can be an effective lever to promote sustainability (Thees et al., 2020). However, as glacier tourism is closely tied to the evolution of the environment, the community of academic researchers should also be included in destination governance procedures for the Mer de Glace to ensure that decision-making is supported by up-to-date scientific knowledge. Adopting such a transdisciplinary approach (Otero et al., 2020) could contribute significantly to ensuring the sustainability of tourist operations around the Mer de Glace.

6 Conclusions

Given the current relevance of adaptations in the study of socio-ecological systems and the significant need for adaptation in the specific context of glacier tourism, the present study has examined how tourism activities in the Mer de Glace basin have adapted to glacier fluctuations since 1741. Based on data from historical sources, glaciological surveys, grey literature and semi-structured interviews, the study has shown how tourism activities around the Mer de Glace have undergone changes related to

glacier fluctuations since the arrival of the first visitors in the region. Three major attractions corresponding to the three main tourist activities in the area have been identified and analysed, namely the Arveyron cave, the Montenvers-Chapeau crossing and the Vallée Blanche ski downhill. The processes that impacted these attractions the most were found to be mainly related to decreases in the length and thickness of the glacier. Paraglacial processes such as the appearance and destabilisation of moraines and the increased flow of streams due to the glacier's accelerated melting were also found to have impacted tourist activities. More recently, an increase in the area of debris cover has led to new difficulties in hiking on the glacier, and several snow-related issues have affected the Vallée Blanche ski route.

Tourism stakeholders have adapted to the impacts of glacier fluctuations on their activities in several ways. Most of the adaptations that could be identified using the above data sources were coping strategies and consisted in installing new equipment to facilitate access or security. Transformative adaptations could also be observed in developments such as high mountain guides' progressive adoption of new activities in response to glacier changes in the 1950s. Although these adaptations can be viewed as changes of activity that tourism operators made when an attraction or itinerary no longer permitted its previous use, they can also be understood not merely as planned adaptations but as choices made to grasp opportunities provided by the specific evolution of the Chamonix valley. In light of past developments, it seems important today, at a time when future glacier retreat can be accurately modelled and predicted, to use available scientific data to begin planning the future development of Alpine glacier tourism. In this context, participatory planning, which brings all actors with a minor or major stake in the destination together in the planning process, stands out as a promising methodology that would allow all relevant parties to take responsibility for glacier tourism's future. Previous research on glacier tourism (e.g., Welling et al., 2019) has shown that participatory planning is a valuable tool to improve anticipatory adaptations to future changes. In the case of the Mer de Glace, the goal of ensuring a sustainable future could be achieved by bringing together public (e.g., the tourism office, mountain rescue team and city council) and private actors (e.g., infrastructure managers, mountain guides and hospitality manager), as well as researchers who can provide up-to-date knowledge about environmental changes.

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Figures

Figure 1. The Mer de Glace basin (glacier area in 2004) and the main tourism places, cable cars, mountain huts and summits.

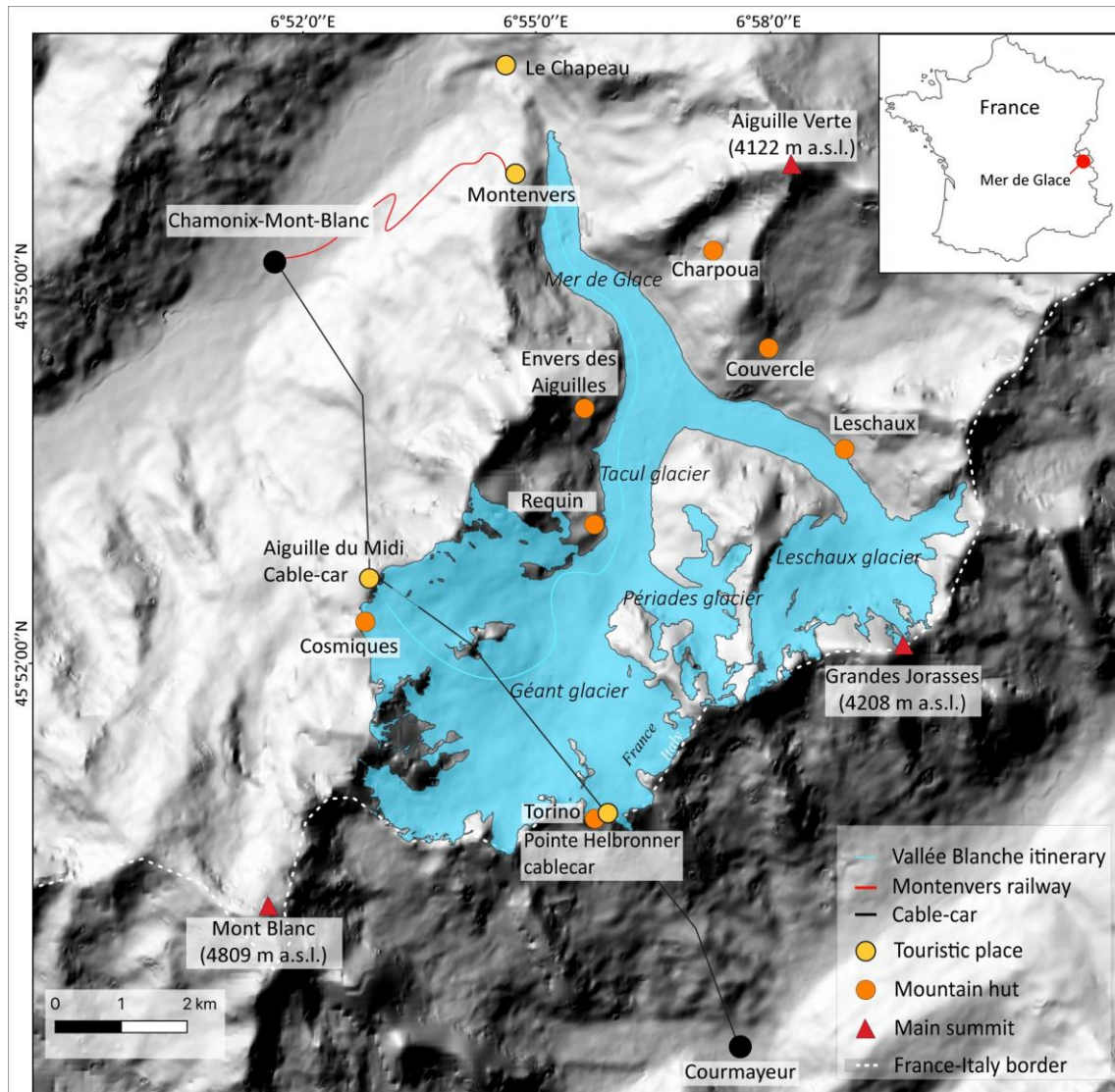


Figure 2. a. Cumulative evolution of the front of the glacier since 1560, data from Nussbaumer et al. (2007) until 2002 and from Glacioclim after; b. Evolution of the elevation of the Mer de Glace surface (data: Glacioclim). The map shows the location of the different profiles.

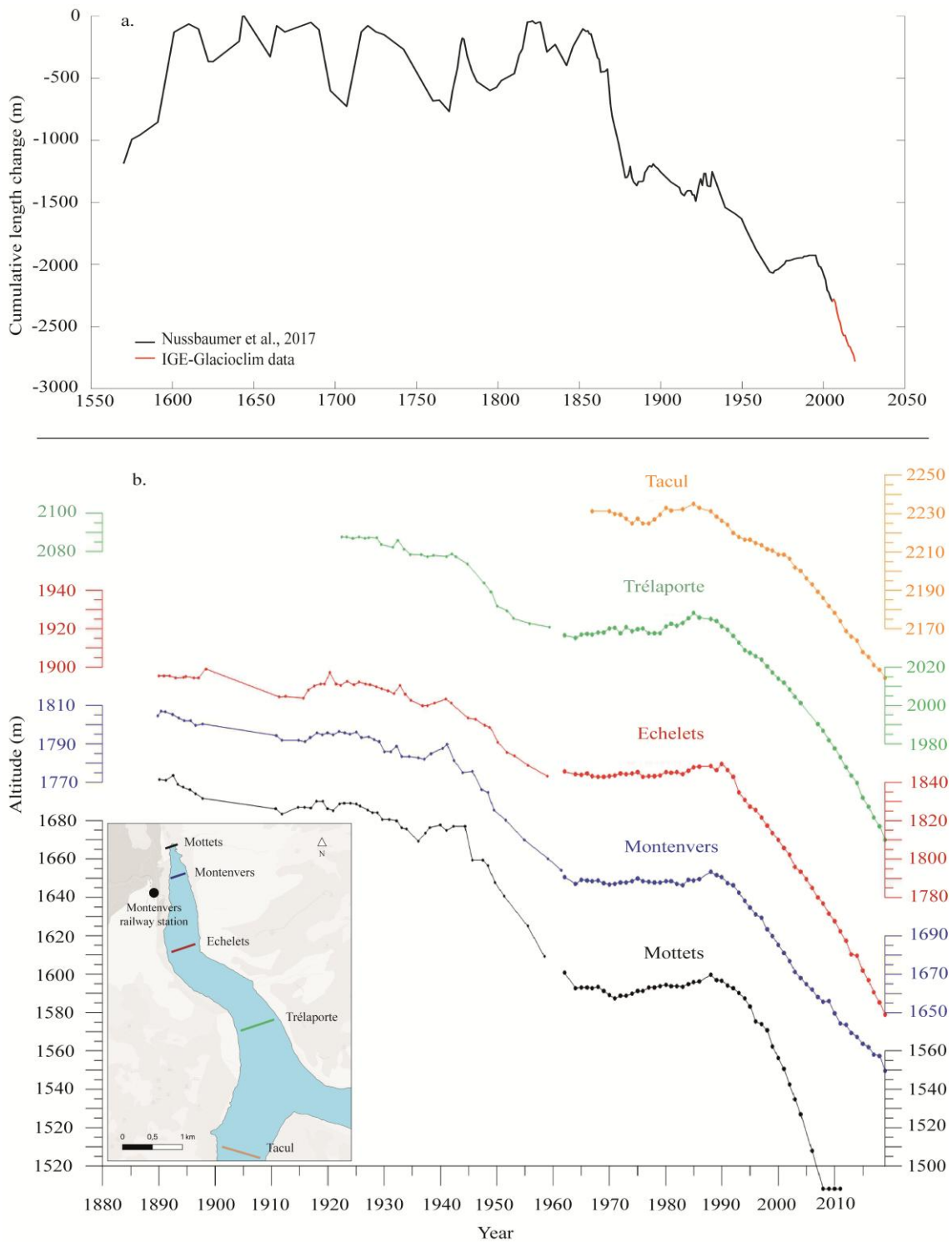


Figure 3. Attractions and itineraries around the glacier, identified through the tourism guidebooks.

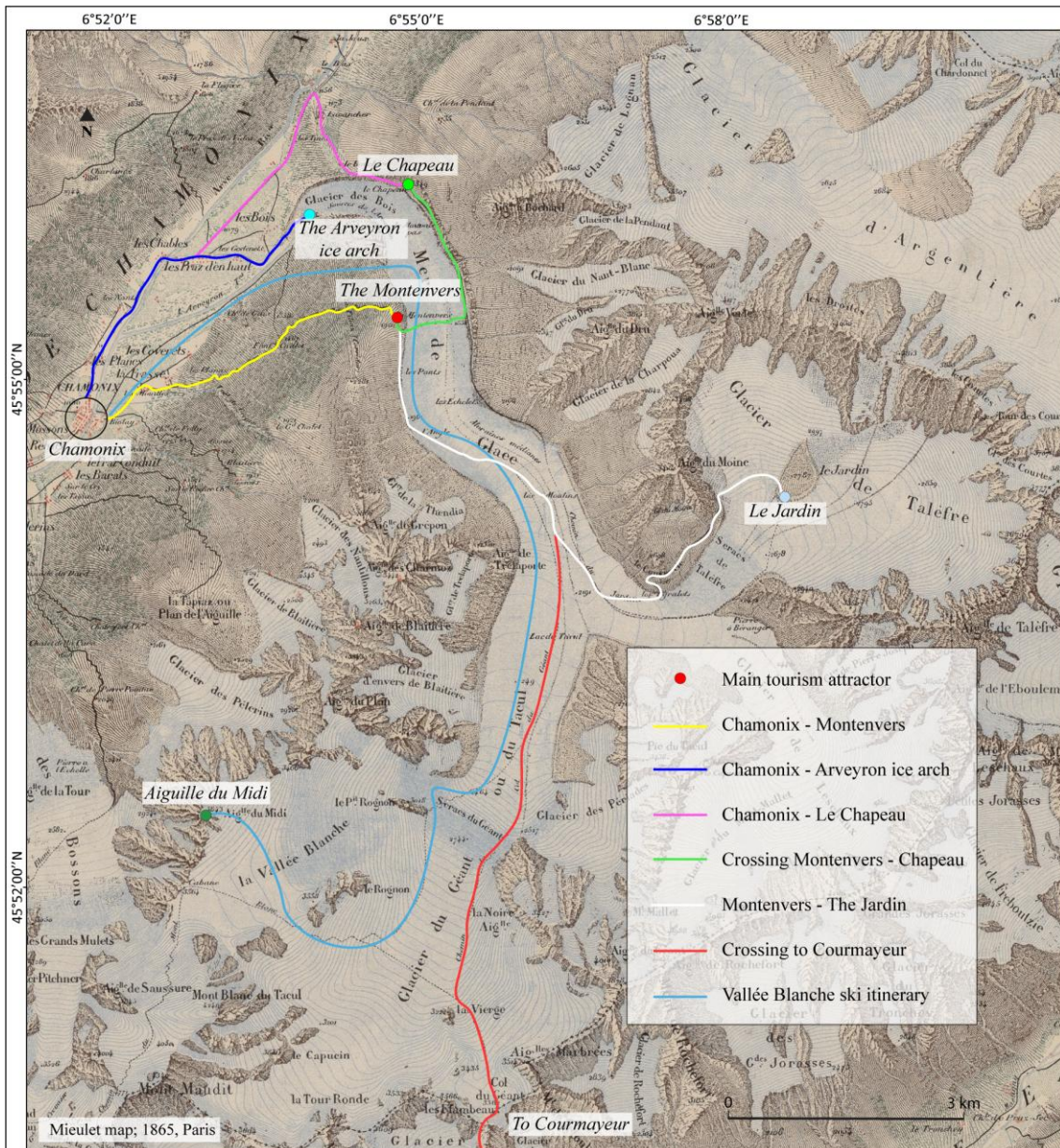


Figure 4. The Arveyron cave; a. 1780, C. Hackert; b. 1787, P. J. de Louthembourg; c. 1775, M. T. Bourrit; d. 1868, A. Braun.

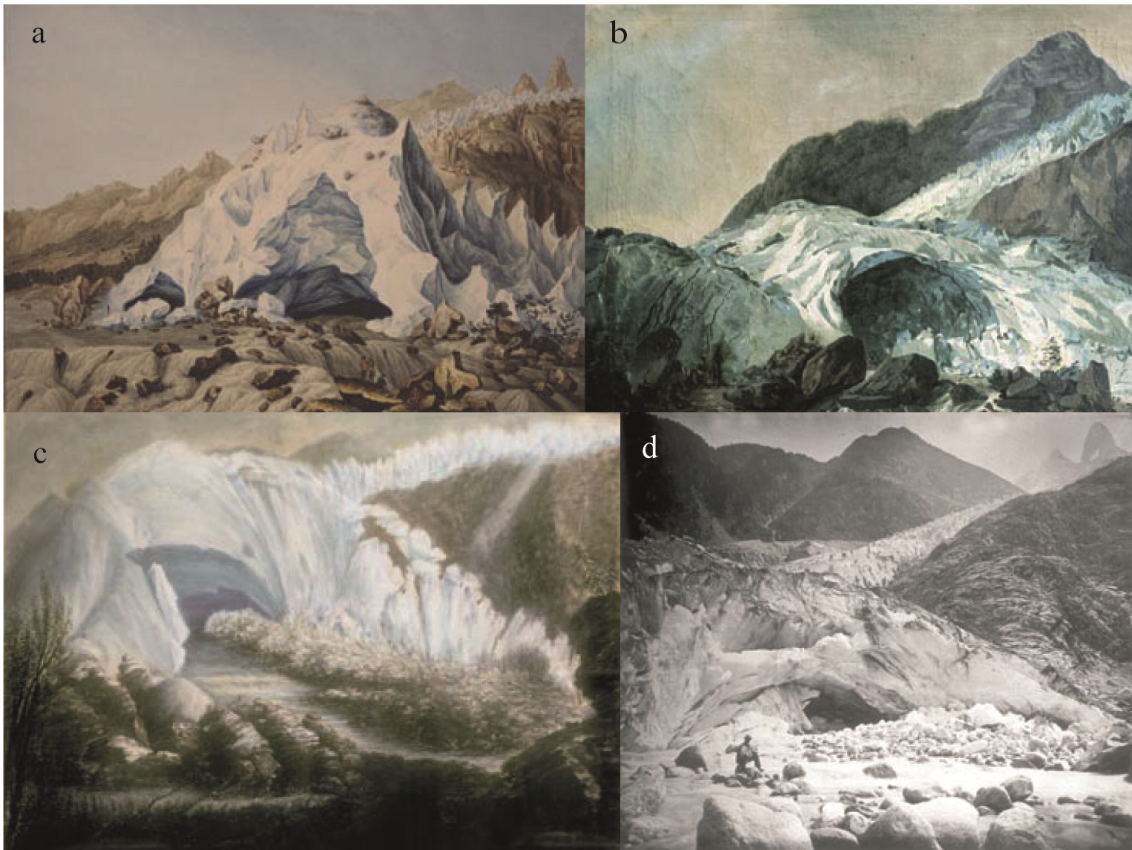


Figure 5. The Montenvers-Chapeau itinerary (map: Etat Major, 1866, 1:40,000, IGN).

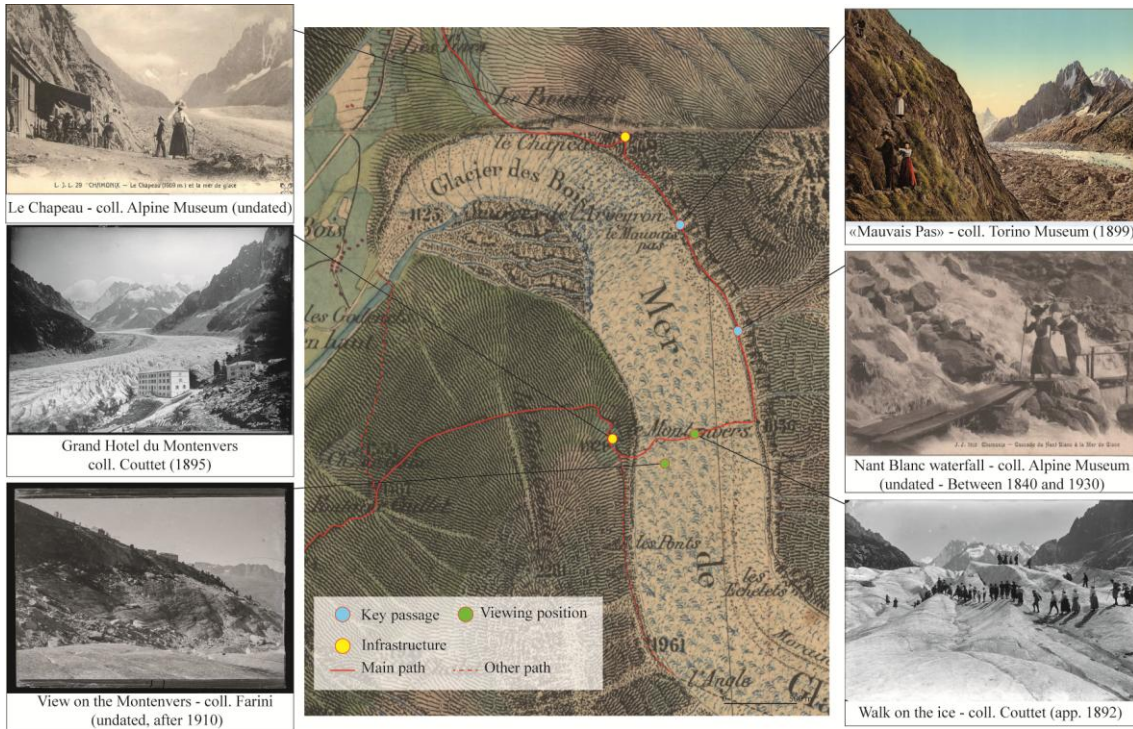
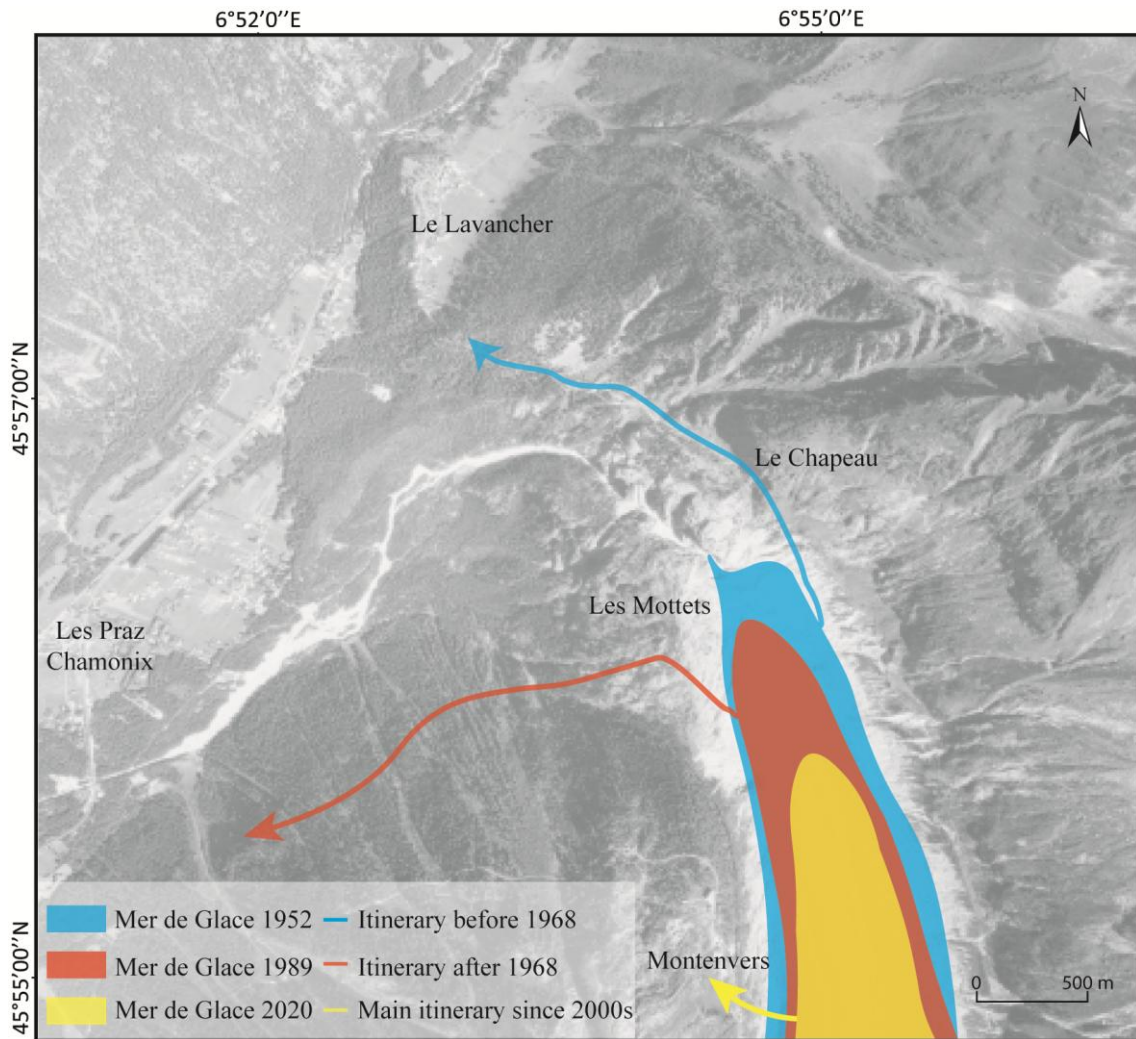


Figure 6. a. Access to the Requin hut, Alta-Via, 2017; b. The lower part of the Mer de Glace, debris-covered, taken from the Montanvers railway station, L. Ravanel, April 2019.



Figure 7. Evolution of the Vallée Blanche exit itinerary according to the fluctuations of the Mer de Glace (aerial photo IGN, 1967).



Tables

Table 1. Synthesis of the different processes impacting glacier tourism, its consequences, and the responses of tourism operators.

Main processus	Specific process affecting itineraries	Consequence on itineraries	Period	Responses from tourism operators	Itineraries concerned	
Changes of the snow cover	Late snow falls and early melting	Reduction of the practice period	1990s	-	●	
	Insufficient snow cover	Snow bridges less stable	1990s	Installation of wooden bridges	●	
		Difficulty to hike on the glacier		-	●	
	Snow ridges becoming narrower and icy	Access more difficult	1990s	Installation of safety equipment	●	
Glacier retreat	Thickness reduction	Access more difficult	1960s - 1920s	Change of the itinerary Installation of safety equipment	● ●	
		Longer progression time	1960s - 1920s		● ●	
		Increased dangerousness	1950s		●	
		Easier access	1850s		●	
	Length reduction	Access more difficult	1960s - 1920s	Change of the itinerary Installation of safety equipment	● ●	
		Longer time needed	1960s - 1920s		● ●	
		Serac avalanche	1990s	-	●	
		Loss of attractors	1870s	Creation of artificial attractors	●	
	Paraglacial processes	Increased melting speed	Increased flow of torrents	1920s	Equipment installation	●
		Development of debris covers	Difficulty to progress on the glacier	1990s	<i>New infrastructure in project</i>	●
			Longer progression time	1990s	Change of the itinerary	●
		Increasing height of the moraines	Longer progression time	1990s - 1920s	Change of the itinerary	● ●
Access more difficult			1990s - 1920s	● ●		
Moraine destabilisation		Longer progression time	1920s	Change of the itinerary	●	
Access more difficult	1920s	●				

Vallée Blanche	●
Montenvers-Chapeau	●
Arveyron cave	●