Glacier fluctuations in the Italian Mont Blanc massif from the Little Ice Age until the present

Historical reconstructions for the Miage, Brenva and Pré-de-Bard Glaciers

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“The glacier was God's great plough set at work ages ago to grind, furrow, and knead over, as it were, the surface of the earth.”

Louis Agassiz (1807-1873)

The veined structure of the ice stream of the Brenva tongue with alternating bluish-green and greenish-white bands. The drawing was taken from the mule-road leading to the chapel Notre Dame de la Guérison by James David Forbes in 1842 (“Glacier of la Brenva. Shewing the structure of ice.”; signed down left “Drawn from Nature by Professor Forbes. L’Highe lith”, down right “Day. Highe. Lith. to the Queen”; lithograph, blue watercolour; 13.7 x 21.0 cm; Pl. V, p. 202-203, Forbes, 1843)

Recent view of the highly debris-covered glacier tongue (Photograph by P. Imhof, 26.06.2009).

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Abstract

To predict the future development of Alpine glaciers and to judge whether glacier variations under the current climate change lie within natural variability or not, an understanding of past glacier fluctuations is crucial. Glacier length, though an indirect and delayed signal of climate conditions, can be used to determine the glacier-climate relationship. This study presents glacier length change reconstructions for the Miage, Brenva and Pré-de-Bard Glaciers in the Italian Mont Blanc massif, from the Little Ice Age (LIA) until the present.

Instrumental measurements of glacier length fluctuations only started at the end of the 19th century. As the preceding time of the LIA is not documented by instrumental data, interdisciplinary approaches that use both historical and physical methods are needed; Pictorial glacier representations (maps, drawings, prints and photographs), written accounts as well as glacio-morphological mapping of the moraine apparatus were used to determine historical glacier stages.

The revised and refined glacier length curves go back to AD 1640 (Miage), 1767 (Brenva) and 1781 (Pré-de-Bard) and show three major glacier advances during the LIA. The Miage reached its LIA maximum expansion in 1640. The Brenva and the Pré-de-Bard reached their LIA maximum in 1818 and 1818/19, respectively, and thereby overran all moraines formed during previous advances. As documented by several pictorial sources, all three glaciers reached a third major maximum during the mid 19th century. Since then, the glaciers have retreated more or less continuously (except for some minor advances around 1890, 1920, 1940 and 1989); the Miage by about 300 m, the Brenva by 270 m and the Pré-de-Bard by almost 1.5 km until the present day.

The temperature and precipitation record from Gr. St. Bernard, dating back to 1818, was used to study the meteorological conditions leading to the glacier advances. Based on statistical correlation analysis different time lags for each study glacier could be found; The small-sized Brenva and Pré-de-Bard Glaciers react first, whereas the highly debris-covered Miage follows with a time lag of some decades.

Despite the individual behaviour of each glacier, all three curves indicate the characteristic LIA maxima. Comparing the three study glaciers with the Mer de Glace revealed a clear simultaneity of fluctuations on the north and south slope of the Mont Blanc. Considering the amplitude though, the Mer de Glace was found to be much more rapidly oscillating. The findings coincide well with the fluctuations of most Alpine glaciers, thus indicating the generalizability of the LIA event for the Alps.

Zusammenfassung

Um die künftige Entwicklung der Alpengletscher zu bestimmen und um zu beurteilen, ob Gletscherschwankungen im Rahmen des derzeitigen Klimawandels innerhalb der natürlichen Variabilität liegen oder nicht, ist ein Verständnis der Gletschergeschichte von entscheidender Bedeutung. Gletscherlänge, wenn auch ein indirektes und verzögertes Signal der klimatischen Bedingungen, kann verwendet werden um die Gletscher-Klima-Beziehung zu untersuchen. Diese Studie präsentiert Rekonstruktionen der Längenänderungen für den Miage, Brenva und Pré-de-Bard Gletscher auf der Mont Blanc Südseite von der Kleinen Eiszeit bis in die Gegenwart.

Instrumentelle Messungen der Gletscherlängenänderungen wurden erstmals Ende des 19. Jahrhunderts durchgeführt. Da die vorhergehende Zeit der Kleinen Eiszeit nicht durch instrumentelle Daten dokumentiert ist, braucht es interdisziplinäre Ansätze, die sowohl historische als auch physikalische Methoden einschliessen: Historische Bilddokumente (Karten, Zeichnungen, Drucke und Fotografien), schriftliche Berichte sowie die glazial-morphologische Kartierung der Moränen wurden angewandt, um historische Gletscherstände zu bestimmen.

Die revidierten Längenänderungskurven reichen zurück bis ins Jahr 1640 (Miage), 1767 (Brenva) und 1781 (Pré-de-Bard) und zeigen drei große Gletschervorstösse während der Kleinen Eiszeit. Der Miage erreichte seine maximale Ausdehnung im Jahre 1640. Der Brenva und der Pré-de-Bard Gletscher erreichten ihr Maximum der Kleinen Eiszeit um 1818 und 1818/1819, wobei sie die bei früheren Vorstössen gebildeten Moränen überfuhren. Wie mehrere Bildquelle belegen, erreichten alle drei Gletscher ein drittes Maximum um die Mitte des 19. Jahrhunderts. Seitdem haben sich die drei Gletscher mehr oder weniger kontinuierlich zurückgezogen (mit Ausnahme kurzzeitiger Vorstösse um 1890, 1920, 1940 und 1989); der Miage bis heute um ca. 300 m, der Brenva um 270 m und der Pré-de-Bard um 1.5 km.

Um die meteorologischen Bedingungen zu studieren welche zu den Gletscherschwankungen geführt haben, wurde die homogene Temperatur- und Niederschlagsreihe vom Gr. St. Bernard verwendet. Basierend auf einer statistischen Korrelationsanalyse konnten unterschiedliche Verzögerungen für die Gletscherreaktion (time lag) bestimmt werden; Die mittelgrossen Brenva und Pré-de-Bard Gletscher reagieren zuerst, während die Reaktion beim stark mit Schutt bedeckten Miage mit einer Verzögerung von einigen Jahrzehnten folgt.

Trotz des individuellen Verhaltens jedes einzelnen Gletschers zeigen alle drei Kurven die charakteristischen Maxima der Kleinen Eiszeit. Vergleicht man die drei Studiengletscher mit dem Mer de Glace, wird die Parallelität der Schwankungen auf der Nord- und Südseite des Mont Blanc deutlich. Das Mer de Glace fluktuiert jedoch rascher und hat eine erhöhte Amplitude der Gletscherschwankungen. Die Ergebnisse stimmen überein mit den Schwankungen der meisten Alpengletscher, woraus hervorgeht, dass die Kleine Eiszeit in den Alpen parallel verlief.

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1. Introduction

1.1 Glacier fluctuations and climate

During the 20th century the mean global Earth surface temperature has risen by 0.6°C. Depending on the CO_2 emission scenario, global warming will lead to an increase in temperature of 1.8-4.5°C by the end of the 21st century (IPCC, 2007). In the Alps the climate change has particular impacts on the cryosphere. Self-reinforcing processes, especially due to decreasing reflectivity (albedo) from darkening glacier surfaces, retreating snowlines, and enhanced dust deposition from snow-free surrounding slopes have increasingly come into play (Oerlemans *et al.*, 2009). To predict the future development of Alpine glaciers and to judge whether glacier variations under the current climate change lie within natural variability or not, an understanding of past glacier fluctuations is crucial. Vice versa, glaciers are also good climate indicators, as they are sensitive to climate variability and their mass balance and length fluctuation are mainly controlled by climate. Regional climate determines the amount and phase (rain or snow) of precipitation, as well as the solar radiation and air temperature, which are converted into the energy available for melting. Locally climatic conditions are influenced by the topography of the glacier's environment, its exposure and elevation. The local climate determines accumulation processes (e.g., snow, avalanches, rime formation, freezing of rain) and ablation processes (e.g., melting and run-off, evaporation, wind erosion, calving of icebergs), which are summed up in the net mass balance of a glacier. A glacier responds to different climate conditions in a change of size or front position, detectable as glacier advance or retreat. If the glacier is under balanced conditions (net mass balance = 0), the glacier reflects the current general climate conditions (Paterson, 1994). However, Nussbaumer *et al.* (2007) emphasize that changes in glacier form may not exclusively be controlled by mass balance changes, but also by ice dynamics (i.e., subglacial hydrological conditions, temperature conditions in and under the glacier).

Glacier length change is an indirect and delayed signal of a climate perturbation, but much easier to determine than mass balance. Extensive mass balance observations have only been carried out in the last decades, as they are labour-intensive and expensive to maintain (Steiner, 2005). Glacier length data in contrast, are much easier to obtain and can be reconstructed back to the 16th century (e.g., length record of Lower Grindelwald Glacier back to 1535; Zumbühl, 1980). Moreover, Oerlemans (2005) was able to show that data on glacier length from all over the world reflect a distinct global temperature signal (the signal indicated the start of moderate global warming in the mid 19th century, increasing in the recent decades). The study confirmed that glacier length can be used as a climate proxy independent of instrumental data and other proxies. This is of uttermost importance, as the “Little Ice Age” (LIA; see Section 1.3) is not documented by instrumental glacier length data. The importance of past glacier fluctuations, and the lack of widespread instrumental data during the LIA, call for interdisciplinary approaches that combine historical and physical methods to reconstruct the behaviour of glaciers back in time (Nussbaumer *et al.,* 2007). To obtain a complete view of the climate signal, it is necessary to include a large number of glaciers all over the world.

In the European Alps a wealth of documents exists, and glacier monitoring was introduced relatively early (WGMS, 2008). The Mont Blanc massif in the western Alps is home to several large ice streams (e.g., Mer de Glace, Glacier des Bossons, Glacier de Trient, Glacier du Miage etc.). Valley glaciers, suspended glaciers and cirque glaciers form a system of ice that covers 40% of the massif. The work presented here investigates historical fluctuations of the Miage, Brenva and Pré-de-Bard Glaciers, three different major glaciers on the Italian Mont Blanc massif chosen as representatives for the southern slope of the western Alps.

1.2 Growing interest in glacier fluctuations

First investigations of glacier fluctuations date back to the 18th century, a time when Alpine glaciers were far more extensive compared to today. Glacier observations were sporadic and limited to glacier fronts easily accessible and reaching far down into the valleys (Haeberli & Zumbühl, 2003). In earlier times glacierized regions were perceived as dangerous areas and avoided. This perception is attested with a statement by Marc-Théodore Bourrit in which he refers to the upper Val Veni: “*Cette vallée* […] *étoit cependant inconnue avant Mr. de Saussure* […]*. Aucun Observateur n’y étoit entré, les habitants même de Cormayeur n’en parlent que comme d’un endroit horrible. En 1767 Mr. de Saussure forma le projet de pénétrer dans les glaciers* [...], *ce premier voyage ayant été comme une découverte*” (Bourrit, 1776: 49). Nevertheless, where glaciers reached down to villages or frequented pathways and passes, local people certainly noted their fluctuations. These early observations, though mostly not written down, survived in legends throughout the centuries and give us clues about the past conditions. With time the abundance as well as the quality of documentary evidence (written and pictorial documents) increased. Instrumental measurements accurately determining the glacier front positions have been accomplished since the end of the 19th century (Porro, 1902; Revelli, 1911; Sacco, 1918).

The Mont Blanc, highest mountain in the Alps, has always been a centre of attraction. Its attractiveness led to several early studies, which make the region one of the best-documented areas of the Alps (Nussbaumer *et al.*, 2007). The easily accessible valley of Courmayeur itself shows an exceptional vicinity of glaciers to settlements: the best example is the Brenva Glacier that, during its maximum extension, ended only about one kilometre from the village of Entrèves. Accordingly, there exists a rich variety of documentary data on the Brenva. The Miage Glacier, descending into the easily accessible Val Veni, is the most prominent and longest ice stream of the south slope of the massif, but nevertheless not so well documented as the Brenva. Although the Pré-de-Bard Glacier situated in the remote head of Val Ferret is similarly accessible, it has been less frequented and little documentary evidence is available.

1.2.1 Previous glacier studies in the Mont Blanc massif

First attempts to describe the Mont Blanc area were made by the English travellers Windham and Pococke in 1741, followed by studies by the French Martel in 1742 (Nussbaumer *et al.*, 2007). Whereas these authors focused on the description of the French side of the massif, the Swiss Bourrit (Bourrit, 1776) also travelled and described the Aosta Valley.

A milestone was set by De Saussure, who conducted intensive research on the whole Mont Blanc area. His very important work “Voyages dans les Alpes” (1779-1796) contains first descriptions of moraine ridges, length fluctuations of the glaciers and testimonies by local people. Half a decade later, Forbes (1843) published an extensive work on the fluctuations of the most important Mont Blanc glaciers (Miage, Brenva, Mer de Glace), including several detailed sketches, drawings and a most accurate map of the Mer de Glace. Among the pioneers for general research in the area were Agassiz (in 1845) and Tyndall (in 1873), both concentrating on glaciology, and Favre (1867) who focused on the geology of the massif.

During the 19th and early 20th century several studies on the Brenva (Marengo, 1881; Silvestri, 1925; Valbusa, 1924, 1927) and the Miage Glacier (Baretti, 1880; Sacco, 1917) in particular as well as the glaciers of the Mont Blanc south massif in general have been published (Viollet-le-Duc, 1876; Virgilio, 1883; Sacco, 1918). Besides new observations and measurements, they reprocessed former studies on the area and also worked on historical documentary data. For the Pré-de-Bard Glacier, which is located in the remote head of Val Ferret, the literature available is less abundant. In the majority of the early general works, the glacier is only briefly discussed. Sacco (1918) – besides studying other glaciers of the Mont Blanc south slope – was the first to discuss the historical fluctuations of the Pré-de-Bard Glacier.

Initial measurements of the frontal positions of several Italian Mont Blanc glaciers were conducted by Porro and Druetti (Porro, 1902), and later on resumed by Revelli (1911, 1912). For the 20th century, the Bolletini del Comitato Glaciologico Italiano (CGI) are of importance. This is an annual periodical (since 1914) containing measurements on fluctuations of the glacier tongues, as well as photographs and cartographical documents. The field work for the CGI was conducted by the authors Sacco, Valbusa, Capello, Lesca, Vanni and Cerutti. Since the Pré-de-Bard was elected as a study glacier in 1960, the Bolletini CGI constitute a rich source of specific information presented in several case studies on the Pré-de-Bard.

While visiting all major Alpine glaciers, Kinzl (1932) also studied the moraine apparatus of the Miage and Brenva Glaciers. The moraines of the Pré-de-Bard Glacier are discussed in detail by Zienert (1965). In his work he re-evaluates the most important documentary material on the glacier history in the southern part of the Mont Blanc massif and in the Gran Paradiso area. A special focus on historical glacier fluctuations in the Mont Blanc area is given by Le Roy Ladurie (1971). Whereas the first edition mainly evaluates original archival sources from the north side of the massif, the second edition, translated into English and published in 1971, is complemented by several archival sources documenting glacier stages on the Italian Mont Blanc slope. Furthermore, Aeschlimann (1983) discusses the glacier history of the Italian Mont Blanc area in his dissertation. Of importance are Aeschlimann's dendrochronological datings in the Miage forefield. The Miage moraine apparatus was also extensively studied by Deline (1999). Using dendrochonology, lichenometry, fossil wood and documentary data, Deline identified and dated the moraines of the major advances in the Miage bilobal forefield.

Probably the most important studies on the reconstruction of historical fluctuations of the Brenva Glacier are those of Aliprandi & Aliprandi (1986) and Porter & Orombelli (1982a). Whereas Aliprandi & Aliprandi evaluate the abundant documentary material on the Brenva

(mainly maps and drawings), Porter & Orombelli reconstruct a glacier length change curve by additionally including field evidence (moraines, fossil soils and wood, lichenometry).
Recent studies discuss areal and altimetric variations (Smiraglia *et al.,* 2000), surface movements (Pelfini *et al.*, 2007) and debris cover (Deline, 2005). As the Mont Blanc south slope is particularly prone to rock avalanches, several recent studies investigate the interaction between rock avalanches and glaciers (Porter & Orombelli, 1980; Deline, 2001, 2009).
General works by Pfister (2005, 2007) provide information on the climatological history of the study area. Monterin (1936) revised centenary variations of the climate of the Gr. St. Bernard Pass and asked the question: “Il clima sulle Alpi ha mutato in epoca storica?” Later, Cerutti (1977, 1985) applied the climate variations studied by Monterin to the glacier fluctuations in the Val Veni and Val Ferret. The climate and climate variations of the Gr. St. Bernard, situated only 8 km southeast from the Pré-de-Bard Glacier, were also studied by Janin (1970) and by Schüepp (1991).

1.2.2 Motivation for this study

Several studies have been conducted on the historical glacier fluctuations of the eastern Alps (Nicolussi 1990, 1994) and central Alps. Especially well reconstructed are the fluctuations of the major glaciers in the Swiss central Alps; Lower and Upper Grindelwald Glacier (Zumbühl, 1980) Grosser Aletsch Glacier (Holzhauser, 1984), Gorner Glacier (Holzhauser *et al.*, 2005), Rhone Glacier, Unteraar Glacier and Rosenlaui Glacier (Zumbühl & Holzhauser, 1988). In the western Alps, several studies have been carried out on the north slope of the Mont Blanc massif (Wetter, 1987; Reynaud & Vincent, 2000). Nussbaumer *et al.* (2007) recently reconstructed glacier length changes of the Mer de Glace back to AD 1570. The fluctuations in the south-western Alps though, are less well documented. The Brenva is the only glacier on the south slope of the Mont Blanc for which a length change curve has been reconstructed in detail (Porter & Orombelli, 1982a). Although being reasonably accurate for the modern time, the fluctuations before 1818 are only vaguely outlined back to 1767. The aim of this work is thus to establish a revised and refined glacier length change curve for the Brenva Glacier, including newly available data. For the Miage Glacier, Deline (1999) reconstructed a rough length change curve for the left lobe. Based on the morphologic evidence and by using additional documentary data, this study aims to establish two length change curves; a newly established curve for the right lobe and a refined and revised curve for the left lobe. In the case of the Pré-de-Bard Glacier, the few studies available describe its historical fluctuations only fragmentarily (Sacco, 1918; Zienert, 1965; Aeschlimann, 1983; Cerutti, 1985) and the historical documents - although few in number - have never been analysed extensively. This study intends to establish a length change curve for the Pré-de-Bard Glacier by analysing the historical documentary material available and incorporating previous results. The main time of interest is the period prior to instrumental measurements (before the early 20th century) going back to about AD 1600.

Following this introductory chapter, the Mont Blanc south massif as the study site is presented in Section 2. After the geographical positioning of the three study glaciers, the geomorphology and geology of the massif are introduced. The Section is concluded by an outline of the climate in the region.

The third Section treats the data and methods used in this study. A special focus lies on the introduction of historical methods, mainly using written accounts, pictorial sources and cartographic evidence to reconstruct glacier fluctuations in the pre-instrumental era. Secondly, glacio-morphological methods used to analyse the moraine apparatus of the Miage, Brenva and Pré-de-Bard forefields are described. Finally, the climatological data and methods used to study the glacier-climate relationship are introduced.

Section 4 first introduces the findings from the analysis of cartographic documents of the Mont Blanc area. Then, the pictorial and written sources used to reconstruct the fluctuations of each individual glacier are described. The Results Section also presents the three newly established glacier length curves of the Miage, Brenva and Pré-de-Bard Glaciers.

Section 5 puts the new length curves into a greater context and compares them to length change curves of other glaciers, such as the Mer de Glace curve by Nussbaumer *et al.* (2007). The glacier fluctuations identified are linked to the prevailing meteorological conditions, as given by time series measurements of temperature and precipitation from Gr. St. Bernard Pass, dating back to 1818.

A synthesis of fluctuations of the Brenva, Miage and Pré-de-Bard Glaciers for roughly 400 years is drawn, and the most significant conclusions are finally resumed in Section 6.

1.3 Temporal setting: the "Little Ice Age"

During the Last Glacial Maximum (LGM), about 20'000 calendar years ago, large ice streams originating from tributary catchment basins of the Val d'Aosta coalesced to form a major glacier that descended near to Ivrea. Ice limits inferred from the apparent limit of glaciations on mountain spurs indicate that then, the ice over the site of Courmayeur was about 1500 m thick (Porter & Orombelli, 1982b). A pronounced warming about 11'700 calendar years ago denotes the beginning of the Postglacial or Holocene (Wanner, 2009). The Postglacial was marked by rapid deglaciation, interrupted by several oscillations of melt back and advance. For the upper Val d'Aosta, Porter & Orombelli (1982b) identified at least two advances: During the Courmayeur advance (dated after LGM but before 8'400 ^{14}C years ago), the glaciers of Val Veni and Val Ferret were confluent and reached down close to the site of Courmayeur. During the Planpincieux advance (corresponding to the Egesen advance in the Austrian Alps), the glacier system was divided into three separate ice tongues: one in the upper Val Ferret, a second tongue in the upper Val Veni ending in an ice-dammed lake and a third tongue consisting of an expanded Brenva glacier that terminated somewhere below Entrèves.

Finally, the glaciers retreated to the familiar dimensions of the modern era. A prolonged phase with increased mean temperatures, occurred during the Medieval Warm Period (MWP) around AD 800-1300 (Wanner, 2009). It is after this Medieval Climate Optimum that the glaciers started to recover and re-advance.

The term "Little Ice Age" (LIA) was first introduced by Matthes (1939) to describe an "*epoch of renewed but moderate glaciations which followed the warmest part of the Holocene*". Nowadays the term is considered to be misleading, as the climatic situation and glacier stages during this period did not correspond to ice age conditions (Wanner *et al,* 2000b). Nevertheless, the term was able to persist until the present.

The term "Little Ice Age" generally refers to the few centuries of cooling after the Medieval Warm Period (MWP) and before the beginning of the warm phase in the 20th century (Grove, 2004). The dates assigned to the LIA differ depending on the source. According to Grove (2004) the LIA was a global phenomenon that began in or around the 14th century and that was not a unique event in the Holocene. Depending on author and study, the term is used back to AD 1300 (Nussbaumer *et al.,* 2007). In the European central Alps, the LIA is often meant as the time from the Late Middle Ages (AD 1300-1500) until the beginning of the 20th century (Widmer, 2008). In this study the term "Little

Ice Age" is further narrowed and restricted to the time period from the end of the 16th to the end of the 19th century.
The climate during the LIA was marked by lower than average temperatures, which though did not sustain throughout the entire period and varied significantly from region to region (Grove, 2004). Consequences were especially severe in sensitive areas at high latitudes and altitudes, where conditions for agriculture were difficult. Poor harvests and famines became frequent (Pfister, 2007). However, these climatic conditions were "glacier-friendly". So called "Little Ice Age Type Events" (LIATES) (Wanner *et al.,* 2000b) occurred at certain times and led to glacier advances due to favourable temperature and precipitation patterns. In the 17th century Alpine glaciers expanded and their termini advanced, damaging and destroying villages that had been built during periods of more remote glacier snouts (Grove, 2004). In the western and central Alps, the glacier advances peaked around 1600, 1640, 1720, 1780, 1820 and 1850 (Zumbühl & Holzhauser, 1988). However, there seems to be a large divergence between the LIA glacier maxima of different glaciers (e.g., asynchronous LIA maxima in southern Norway and the European Alps; Nesje & Dahl, 2003).
In summary, the LIA can be described as a period of average "glacier-friendly" conditions: Mountain glaciers expanded and covered larger areas than they did during the previous centuries, or even millennia in some areas. The warming phase in the decades around 1900 finally reduced them to the dimensions they had during earlier Holocene warm periods (Grove, 2004; Pfister, 1999).

2. Study site: the Italian Mont Blanc massif

The Mont Blanc massif is situated in the western Alps and part of the Graian or Savoyard Alps. Its highest point is the Mont Blanc, which rises to an altitude of 4808 m above see level (m a.s.l.). Oriented in northeast - southwest direction, the massif marks the border between France in the northwest, Switzerland in the northeast and Italy in the southeast. The Mont Blanc south slope is limited by the Italian Val Veni and Val Ferret in the upper Aosta Valley. Figure 1 shows the geographical positioning of the Mont Blanc massif and the study glaciers. In the following Sections the glaciology, geomorphology and geology as well as the climate of the study area are introduced.

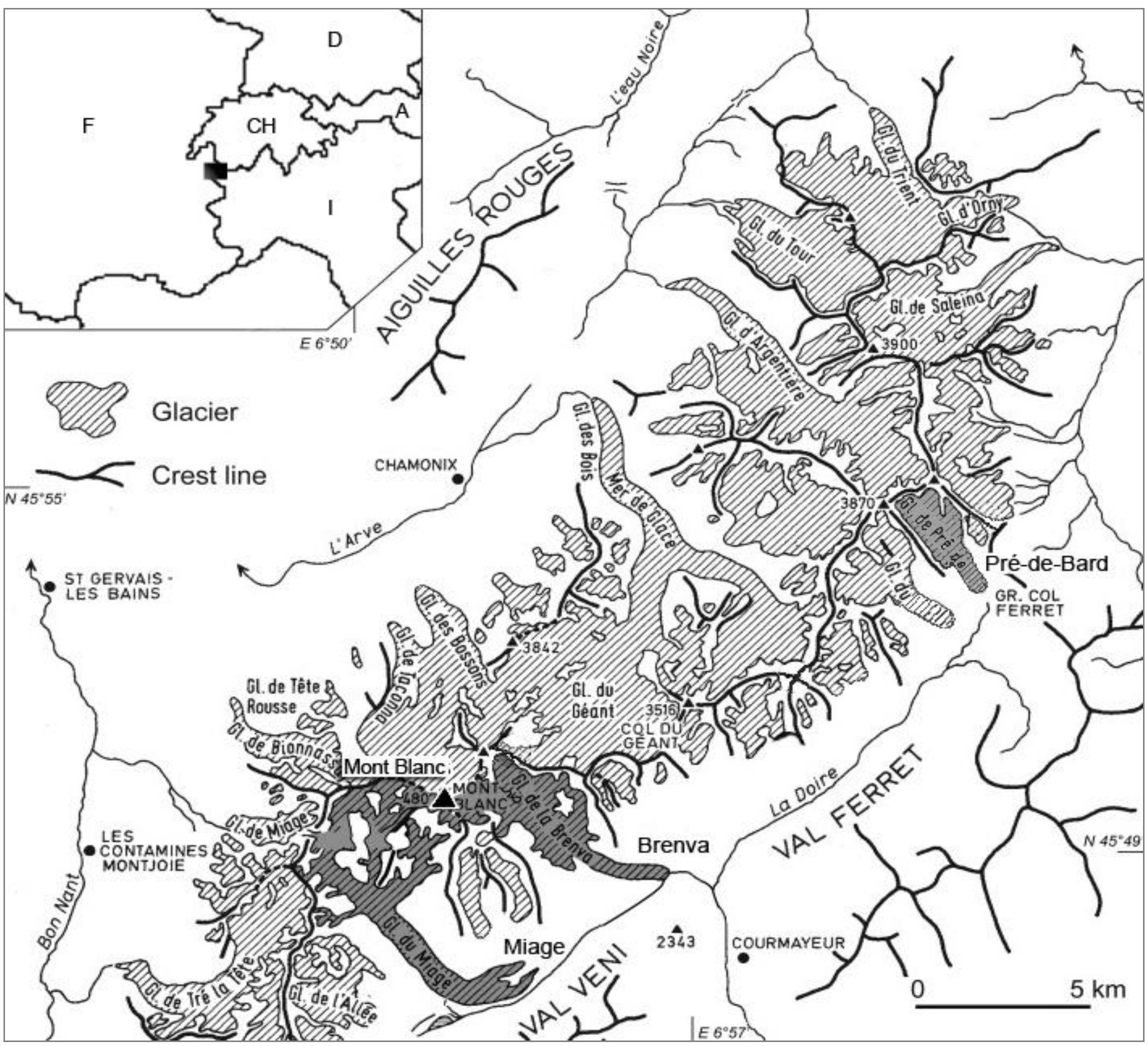


Figure 1: Geographical location of the Mont Blanc massif and the Miage, Brenva and Pré-de-Bard Glaciers (adapted from Grove, 2004)

2.1 Geographical setting of the glaciers

Climatic conditions and geographical location (latitude and longitude), are only two components affecting the fluctuations of a glacier. Another important factor is the elevation of a glacier. It determines the glacier's ambient climatic conditions, since temperature declines with an altitudinal gradient of about 0.5°C/100m. Moreover, higher elevations profit from orographically induced precipitation. On a local scale there are three main factors influencing glacier dynamics: (1) exposure, (2) surface area and (3) morphology of the bedrock (Vanni, 1954). (1) A study by Vanni (1954), conducted on the glaciers of the Mont Blanc south slope, showed that glaciers exposed towards the east, are particularly prone to melting by solar radiation, whereas those oriented towards south-east are better protected. (2) During periods of negative mass balance an extensive ice body exhibits a smaller percentage of loss compared to a smaller glacier, as the reaction time is proportional to the size of a glacier (Holzhauser *et al.*, 2005). (3) At last, the morphology of the bedrock is more complex and characteristic for each individual glacier. The inclination of the bedrock and morphological elements such as depressions, rises and steps in the bedrock particularly influence glacier dynamics. The following Sections present the influence of these deterministic factors on each study glacier.

2.1.1 Miage Glacier

The Miage is the most extensive glacier on the south slope of the Mont Blanc massif and the third largest glacier of Italy. The main topographical properties of the Miage are listed in Table 1.

Table 1: Topographical characteristics of the Miage Glacier. Data adapted from glacier cadastre 2005, Fondazione Montagna Sicura (www.fondazionemontagnasicura.org, accessed at 14.02.2010).

	2005
Location (latitude and longitude)	45°48‘ N / 6°51’ E
Exposure	SSE
Surface area	10.6 km^2
Length	10.3 km
Elevation of head	4808 m a.s.l.
Elevation of terminus (right lobe)	1720 m a.s.l.
Average height (mean)	3264 m a.s.l.
Estimated ELA (Equilibrium Line Altitude)	2450 m a.s.l.
Average slope	29 %

The compound valley glacier is fed by four steep tributaries descending from the Mont Blanc (4808 m), Dôme du Goûter (4304 m), Aiguille de Bionassay (4051 m) and Tête Carrée (3732 m). After the merge of these tributaries, the upper glacier is entrenched in a deep, straight valley. In this section situated below the equilibrium line, the glacier is alimented by avalanches frequently descending from the numerous couloirs.

When reaching the Val Veni, the glacier bends in a sharp curve to the east and is channelized by huge lateral moraines, partly extending over a width of 200 m. The enormous right lateral moraine barricades the Val Veni and, until the end of the 19th century, impounded the *Lac de Combal* (Figure 3). Nowadays, a marshy plain drained by the meltwaters from the Allée Blanche and Estellette Glaciers remains. In the glacier bent a sequence of arc-shaped moraines has been built during the Neoglacial (Deline, 1999b). This so-called morainic amphitheatre encompasses the *Lac du Miage*, a glacial lake dammed to the north by an ice wall.

At the terminus, the glacier forms three distinct lobes that enclose an area of ancient moraine deposits overgrown with conifers - the *Jardin du Miage*. The left lobe ends in a regularly shaped bulb. Presently, it exhibits the only glacier snout of the Miage and the source of the Miage meltwater stream. The middle lobe is a short ice protuberance with little fluctuation, which leads into the *Jardin du Miage*. The right lobe at last is a thin branch narrowing into a pointy tongue. Ending at 1720 m a.s.l., this is also the lowest point of the glacier. Until the early 20th century, an ice protuberance branched off the right lobe to the north. After the ice has melted away, a small, greenish lake was formed in the glacial basin; the *Lac Vert*. Figure 2 gives an overview of the Miage Glacier, its tributaries and the geographical positioning of the ice system.

In the central parts the ice flow velocity of the glacier amounts to 150 m per year. In the terminal parts the velocity is reduced to 60 m per year (Vivian, 2001). The Miage Glacier has been debris-covered during most of the Neoglacial. Momentarily, the supraglacial debris cover extends over 4 km^2 and a length of 7 km, with a mean thickness of 15 cm (Deline, 2009). As a consequence, huge lateral moraines have accumulated over the centuries. As Deline (2009) reports, over 75 % of the debris is derived from rock falls and rock avalanches. The debris cover translates signals of climatic variation in such a way that the fluctuations of the glacier are smoothed.

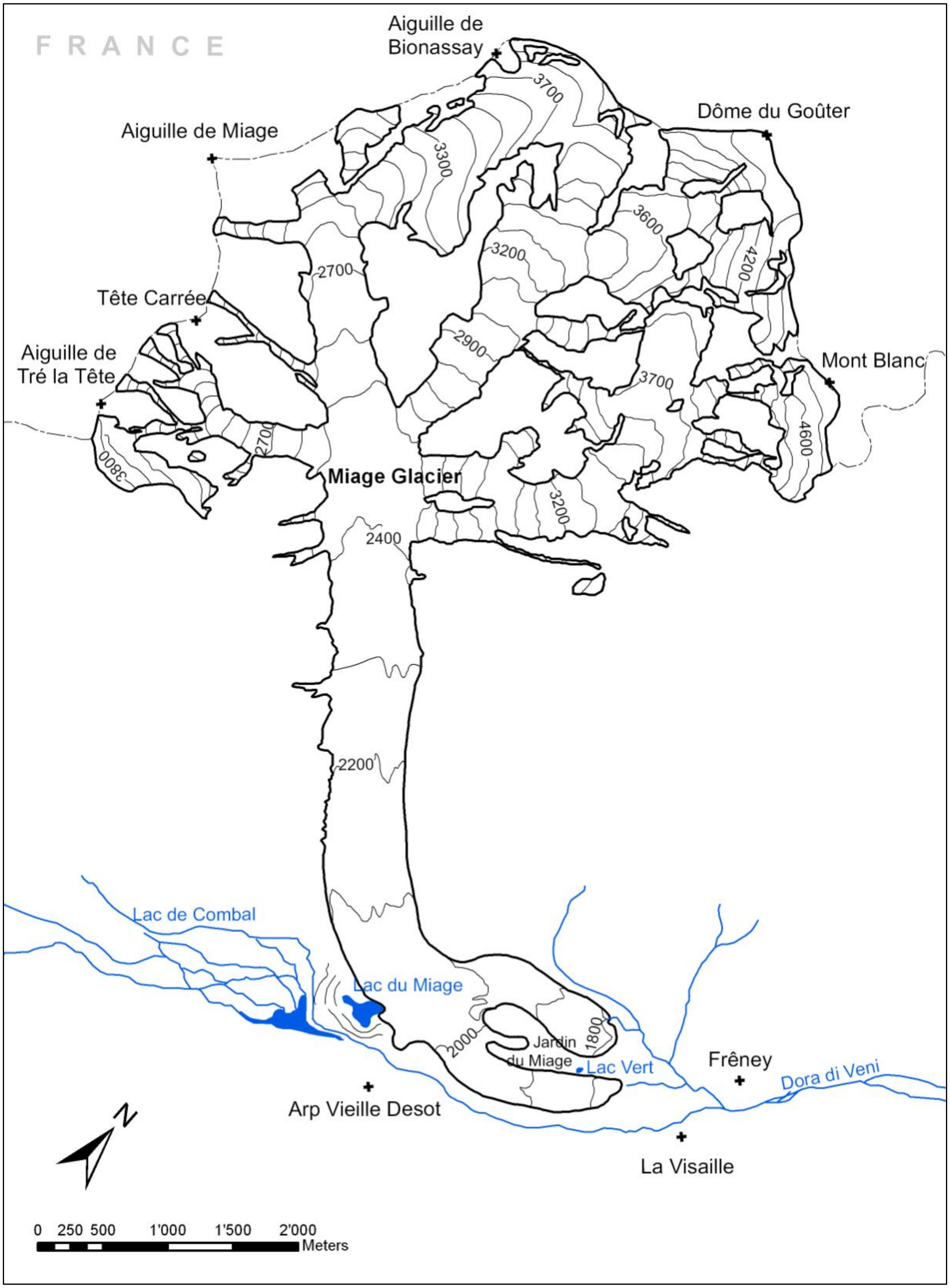


Figure 2: Map showing the outline of the Miage Glacier with its main branches and tributaries (glacier outline and elevation contour lines adapted from Swiss Map 50, V4; swisstopo, 2004), the surrounding mountain peaks and important geographical localities.

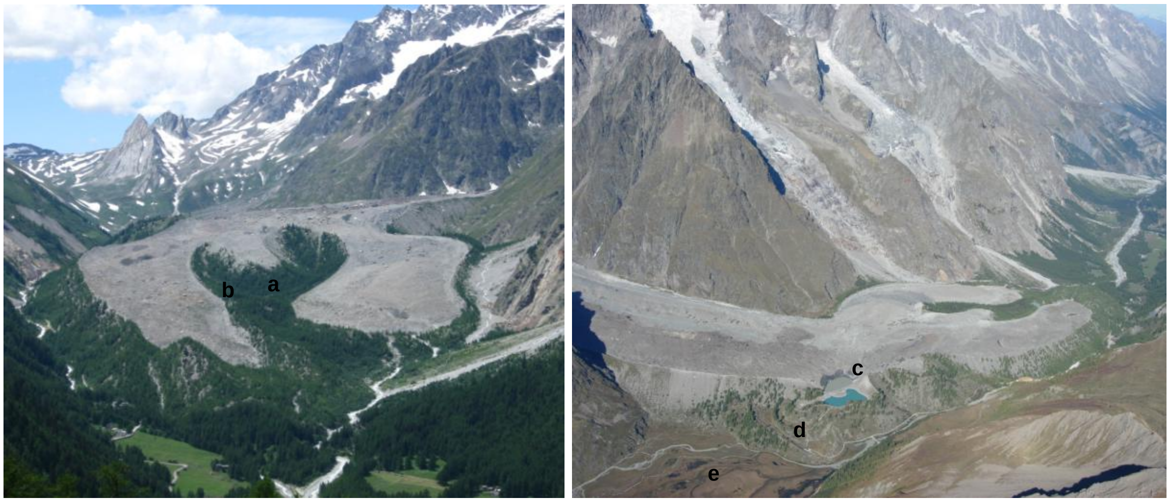


Figure 3 : Left: The Miage Glacier termini enclosing the *Jardin du Miage* (a) in a recent view as seen from Mont Chétif. The position of the Lac Vert is indicated by the letter b (Photograph by P. Imhof, 25.06.2009). Right: Aerial view of the glacier tongue descending into the Val Veni and enclosing the *Jardin du Miage* (a), and the *Lac du Miage* (c) encompassed by the Miage morainic amphitheatre (d). In the lower left corner the plain of the former *Lac de Combal* is depicted (e) (Photograph by S.U. Nussbaumer, 30.09.2009).

2.1.2 Brenva Glacier

The Brenva Glacier is, after the Miage Glacier, the second largest glacier on the south slope of the Mont Blanc. It is a simple basin or valley glacier situated between Aiguille de la Brenva (3011 m), Tour Ronde (3792 m), Mont Maudit (4465 m), Mont Blanc (4808 m), Aiguille Blanche de Peuterey (4107 m) and Aiguille Noire de Peuterey (3772 m). This disposition is favourable to the conservation of the ice, as the mountain peaks intercept the solar radiation and thus reduce the ablation. Moreover, the steep surrounding rock walls are the origin of frequent avalanches, additionally feeding the glacier basin below the equilibrium line. The Brenva Glacier consists of three branches, originating from Mont Maudit, Mont Blanc (main branche) and Tour Ronde, respectively. In its upper part, the glacier reaches a flow velocity of 180 m per year (Vivian, 2001). Figure 4 gives an overview of the glacier outline and also indicates the most important mountain peaks and geographical localities.

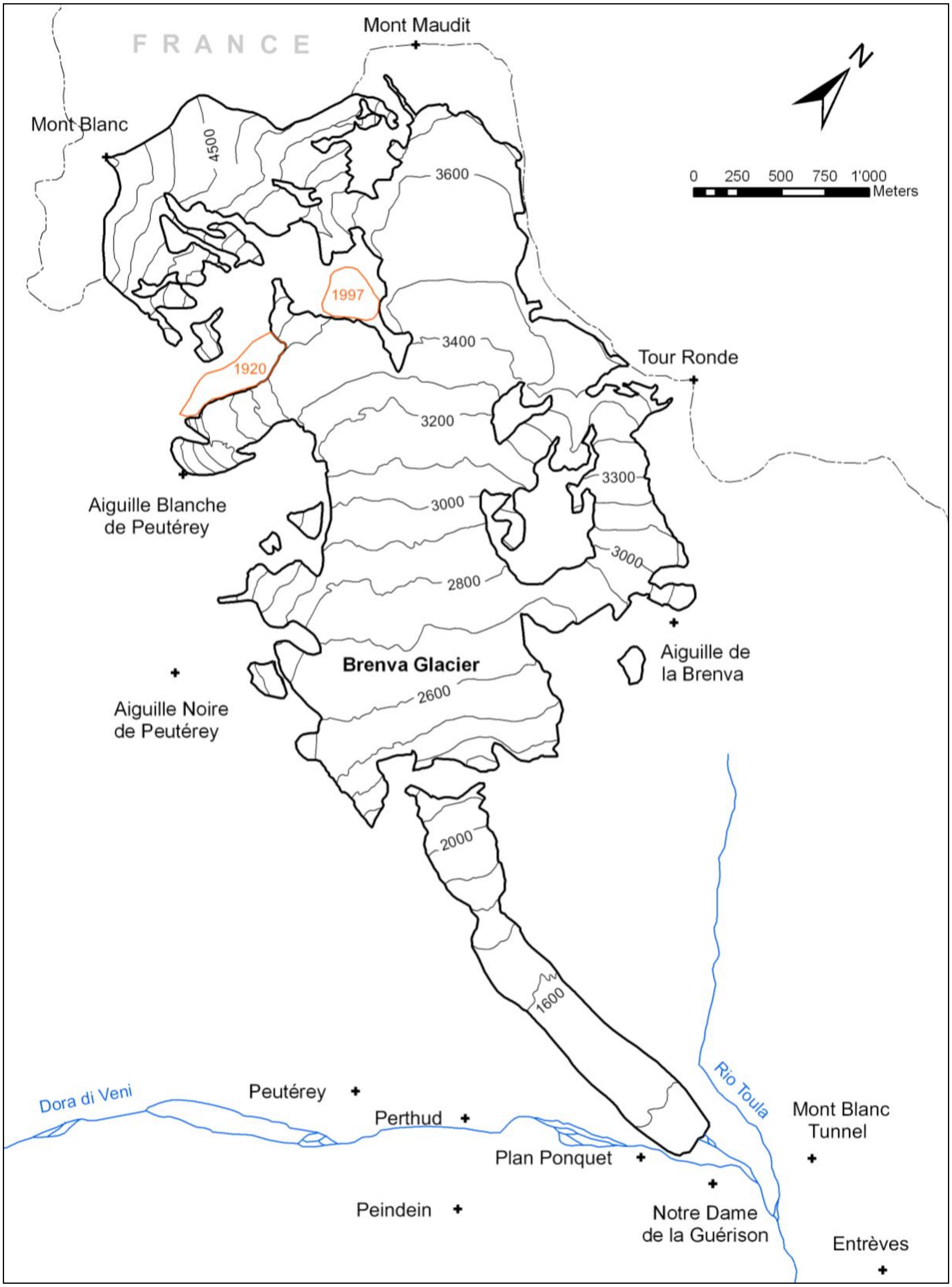


Figure 4 : Map showing the outline of the Brenva Glacier with its tributary ice streams, the surrounding mountain peaks and important geographical localities. The detachment areas of the 1920 and 1997 rock avalanches are shown in orange (detachment areas after Deline, 2001. Glacier outline and elevation contour lines adapted from Swiss Map 50, V4; swisstopo, 2004. Icefall at *Pierre à Moulin* reconstructed after photographs from 2009, glacier front position from 2009).

From the top of the Mont Blanc (4808 m), the ice descends over a vertical distance of 3388 m to reach the valley bottom at 1420 m a.s.l. (Table 2). During the LIA, the Brenva was one of the Alpine glaciers reaching the lowest elevations, and its front ended at 1370 m a.s.l., only one kilometre from the village Entrèves.

A steep rock escarpment separates the relatively steep and highly crevassed accumulation basin from the sparsely inclined valley tongue (Figure 5). Depending on the volume of the icefall, a more or less extensive rock window named *Pierre à Moulin* protrudes. The *Pierre à Moulin* (French for millstone) was given its name by the locals due to the ice blocks frequently detaching and toppling over the always bare rock window.

Reaching the valley floor, the ice is channelized within steep-walled moraines that extend obliquely across the Val Veni. Since September 2004 however, the valley tongue has been completely separated from the accumulation basin (Cerutti, 2005). The active terminus of the Brenva has settled at the top of the *Pierre à Moulin* (2300 m a.s.l.), whereas the valley tongue was left as a regenerated glacier, which is only fed by calving of the active parts.

Table 2: Topographical characteristics of the Brenva Glacier. Data adapted from glacier cadastre 2005, Fondazione Montagna Sicura (www.fondazionemontagnasicura.org, accessed at 14.02.2010).

	2005
Location (latitude and longitude)	45°50‘ N / 6°54’ E
Exposure	ESE
Surface area	6.5 km^2
Length	6.6 km
Elevation of head	4808 m a.s.l.
Elevation of regenerated terminus (valley tongue)	1420 m a.s.l.
Elevation of active terminus (above Pierre à Moulin)	2300 m a.s.l.
Average height (mean)	3114 m a.s.l.
Estimated ELA (Equilibrium Line Altitude)	2850 m a.s.l.
Average slope	40 %

Figure 5: Left: The Brenva glacier in a recent view as seen from Mont Chétif. The accumulation basin is separated from the valley tongue by the *Pierre à Moulin* (a). The lateral moraines (b) channelize the ice flow obliquely across the Val Veni (Photograph by P. Imhof, 01.07.2009). Right: The extensively debris-covered valley tongue and glacier snout (c). During more advanced positions, the Dora di Veni (d) was covered by the glacier front (Photograph by P. Imhof, 05.10.2009).

The valley tongue or the lower 2.5 km of Brenva Glacier are extensively debris-covered. Like the Miage Glacier, the Brenva has accumulated huge lateral moraines derived from frequent rock avalanches. During the last century, the Brenva Glacier experienced two major rock avalanches: The first event occurred on November 14th, 1920 (Valbusa, 1921) and the second on January 18th, 1997 (Deline, 2001), both having had severe impacts on the dynamic of the glacier (see Sections 4.4.8 and 4.4.9).

2.1.3 Pré-de-Bard Glacier

The Pré-de-Bard Glacier is located at the head of Val Ferret, near the border to the Swiss canton of Valais. It is the smallest and also most elevated glacier among the studied glaciers. The Pré-de-Bard is a valley glacier situated between Monts Grépillon (3580 m), Mont Dolent (3820 m), Aiguilles Rouges de Triolet (3870 m) and Monts Rouges de Triolet (3435 m). Until the 1930s, the Pré-de-Bard glacier was connected to the Glacier du Petit Grépillon, which is now an individual, suspended glacier beneath the Monts Grépillon. Figure 6 shows an outline of the Pré-de-Bard glacier and indicates its geographical positioning. Figure 7 shows the Pré-de-Bard glacier in summer 2009.

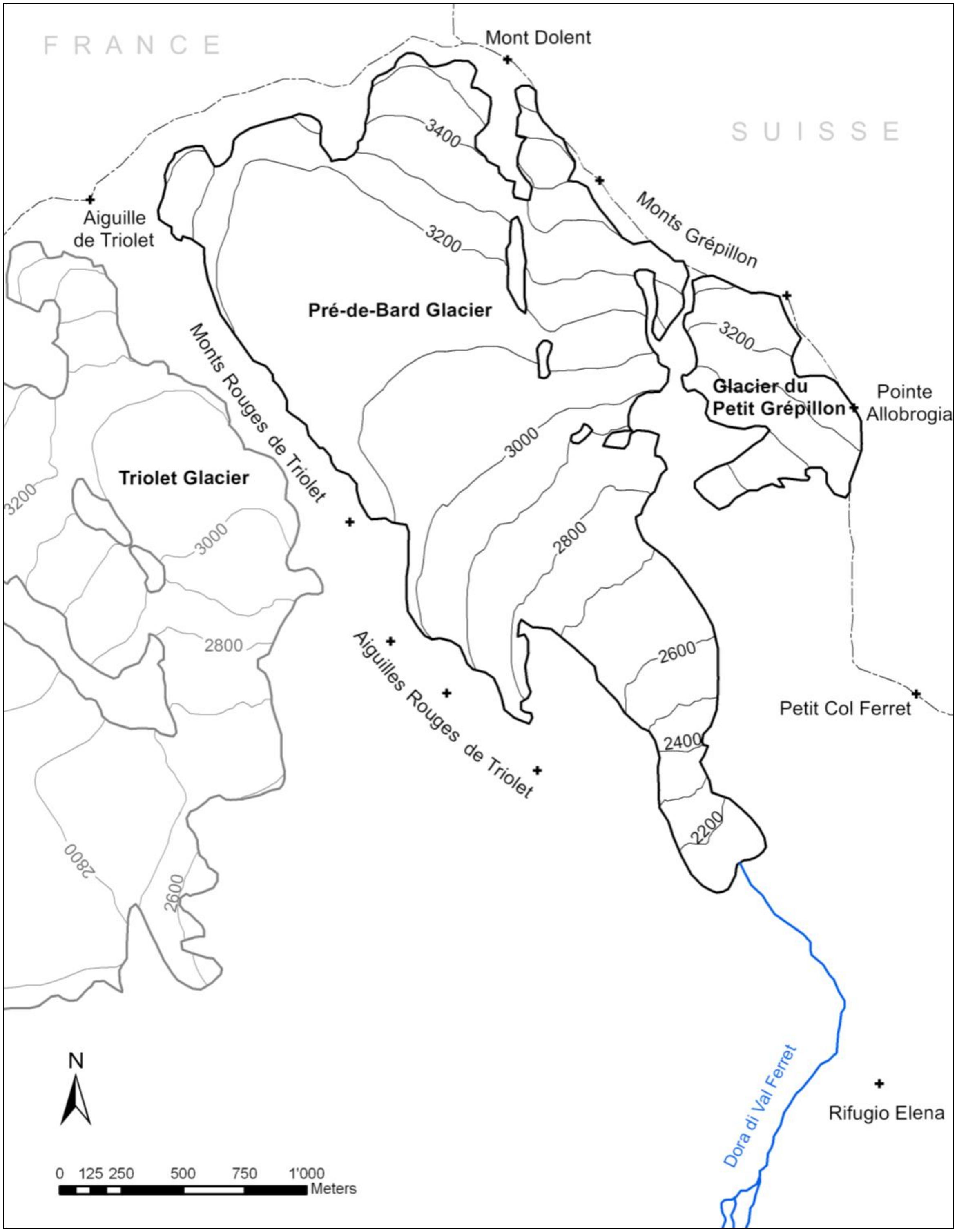


Figure 6 : Map showing the outline of the Pré-de-Bard Glacier with its tributary ice streams (glacier outline and elevation contour lines adapted from Swiss Map 50, V4; swisstopo, 2004. Glacier front position from 2009), the surrounding mountain peaks and important geographical localities.

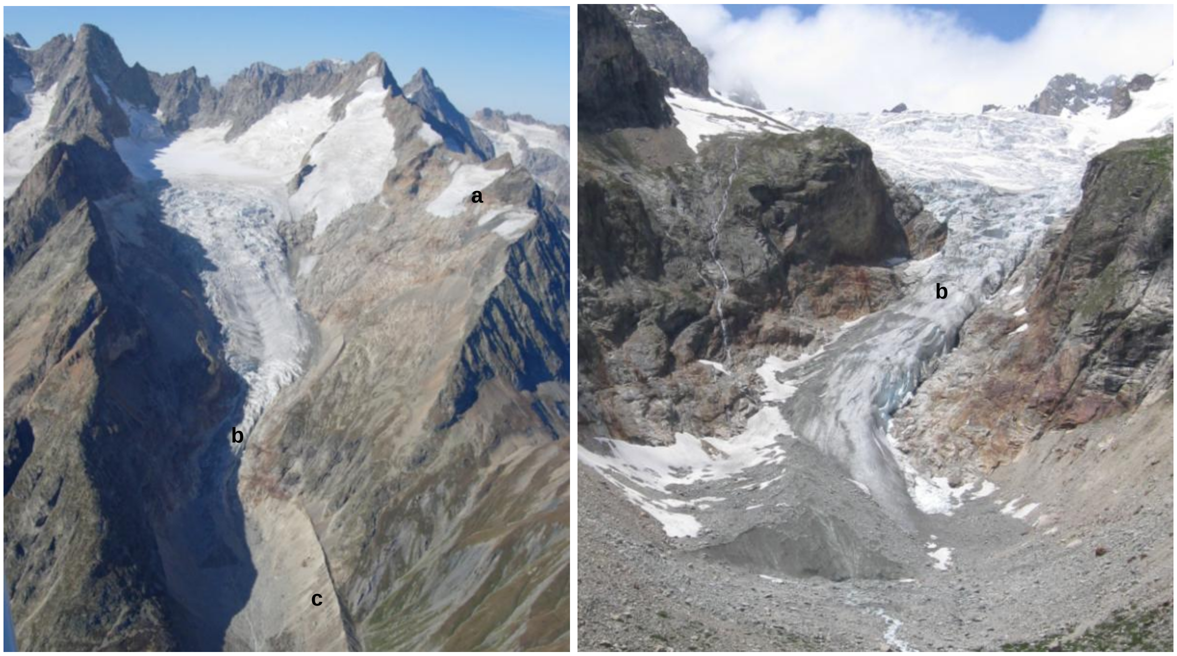


Figure 7: Left: Aerial view of the Pré-de-Bard accumulation basin. The Pré-de-Bard icefield is clearly separated from the Glacier du Petit Grépillon (a). The accumulation basin is separated from the valley tongue by a narrow, intensely crevassed ice fall (b). The lateral moraine (c) indicates the icelevel during the LIA maximum extension (Photograph by S. U. Nussbaumer, 30.09.2009). Right: Proximal view of glacier snout and ice fall (b). (Photograph by P. Imhof, 27.06.2009)

From the accumulation basin, the ice masses are constricted into a narrow rock escarpment (Figure 7). In this zone, the highly crevassed icefall reaches a flow velocity of about 100 m per year (Vivian, 2001). In the lower glacier basin the tongue is imbedded in a U-shaped valley, mantled with ancient moraine deposits. Presently (2009), the glacier tongue reaches down to 2120 m a.s.l. During the 20th century, the front ended in a regularly shaped bulb. In the recent years though, the lobe has changed to an asymmetrical shape, with the right side projecting further down the valley and containing more debris cover. This effect is due to differential ablation and alimentation. Firstly, the Aiguilles Rouges de Triolet, flanking the tongue to its right, cast their shadow until the early afternoon, and thus protect the right part of the ice from melting. In addition, the steeply inclined rockwalls of the Aiguilles Rouges de Triolet are often the origin of rock falls. These are responsible for a higher fraction of debris cover on the right side, which in turn insulates the ice buried underneath. Moreover, during winter the Monts Rouges are source of frequent avalanches that contribute to the alimentation of the right lateral glacier part.

The morphology of the lower glacier basin is a determinant factor for the glacier dynamics. The glacier bed descends in several differently inclined steps that influence the velocity of length changes. Descending in south-eastern direction from the Mont Blanc chain, the

Pré-de-Bard valley after about 5 km turns westwards, to form the Val Ferret. During the LIA, the glacier lay in the Val Ferret and nearly joined the Triolet Glacier.
Table 3 lists the most important topographical characteristics of the Pré-de-Bard Glacier.

Table 3 : Topographical characteristics of the Pré-de-Bard Glacier. Data adapted from glacier cadastre 2005, Fondazione Montagna Sicura (www.fondazionemontagnasicura.org, accessed at 14.02.2010).

	2005
Location (latitude and longitude)	45°54‘ N / 7°03’ E
Exposure	SE
Surface area (without separated Glacier du Petit Grépillon)	3.1 km^2
Surface area of Glacier du Petit Grépillon	0.3 km^2
Length	3.4 km
Elevation of head	3750 m a.s.l.
Elevation of terminus	2081 m a.s.l.
Average height (mean)	2915 m a.s.l.
Estimated ELA (Equilibrium Line Altitude)	3150 m a.s.l.
Average slope	37 %

2.2 Geomorphology and geology of the Mont Blanc massif

The Mont Blanc massif is formed by crystalline rocks (granite, gneiss and schists) of Variscan age and part of the Hercynian system (Grove, 2004). There are two main petrologic units; magmatic rock and metamorphic rock. The main part of the massif consists of magmatic granite. The Brenva and Pré-de-Bard Glacier lie on granite bedrock. In the south-western part of the massif we find metamorphic gneiss, like underneath the Miage Glacier. The summit of the Mont Blanc lies at the contact of these two units. The valley floor of Val Ferret and Val Veni and the southward following area on the other hand, consist of sedimentary rocks (schists, sandstone, limestone etc.).
The Mont Blanc massif comprises a large vertical elevation gradient with a marked relief. While the northwest side of the Mont Blanc massif has less steep slopes, the southeast flank is very steep, with abruptly descending slopes. The steep rockwalls have been affected by intense glacial erosion. Glaciers that descend on such intensively inclined slopes exhibit swift length variations and easily reach down to lower elevations (e.g., Brenva in 1818 about 1370 m a.s.l.).

Due to the steepness of the massif and the geological composition, there have been numerous big rockfall events in the past. The debuttressing of rockwalls due to glacier retreat, oversteepening of rock slopes by glacial erosion and the effects of glaciers on permafrost are additional rock-avalanche triggering factors (Deline, 2009).
On the Italian southwest side of the massif, the Dora di Veni drains the Val Veni overlooked by the Allée Blanche, Miage and Brenva Glaciers. The Val Ferret to the northeast comprises several smaller glaciers and the Pré-de-Bard, Triolet as well as the Frébouge Glaciers and is drained by the Dora di Ferret. The Dora di Veni and Dora di Ferret confluence to form the Dora Baltea that finally supplies the Po. On the other side of the watershed an extensive glacier system (Glacier de Tour, Glacier d'Argentière, Mer de Glace, Glacier des Bossons etc.) descends into the Arve valley of Chamonix.

2.3 Climate of the Mont Blanc area

The climate prevailing during the LIA in Europe has already been discussed in Section 1.3. To complement the climatological characterisation of the study area, this Section describes the current climate in the Courmayeur region.
According to the climate classification by Köppen, the climate in the region of Courmayeur can be classified by the formula *Dfc*: *D* stands for a boreal or sub-arctic climate, *f* indicates that an arid season is missing and *c* stands for short, mild summers and long, cold winters with abundance of snow (Società Meteorologica Subalpina, 2003).
The Mont Blanc chain forms the border between the north-western and the southern Alps, and thus separates two completely different climate regions. The meteorologic conditions on the Italian south slope are comparable to those in Valais in the southern Swiss Alps.
The climate is markedly determined by the surrounding mountains. The shading effect of the massif partly blocks external influences and makes the Val Veni and Val Ferret secluded, dry valleys. However, it has to be distinguished between the more humid and colder high elevations and the much drier and warmer valley bottom. When meteorological data from Courmayeur (1220 m a.s.l.) and Col du Géant (3370 m a.s.l.) are compared, the high vertical precipitation gradient becomes evident (Table 4): the Col du Géant receives more than twice the amount of precipitation of Courmayeur (ΔP=1321 mm). To explain this difference, we have to consider the predominant wind-system. The region of Courmayeur is dominated by westerly winds, originating from the

Atlantic Ocean and southerly winds advecting from the Mediterranean are less important (Cerutti, 1995a). After having traversed western France, the precipitation-rich westerly winds are forced to rain out in the higher elevations of the Mont Blanc massif. Hence, the climate is much drier on the lee side of the massif than on the northern slope (annual precipitation sum for Chamonix (1054 m a.s.l.) 1262 mm in the period 1934-1964; Nussbaumer *et al.*, 2007).

Table 4 : Comparison of precipitation, temperature and frost days in Courmayeur and on Col du Géant (The observation periods for the Col du Géant are 1928-1973 (P) / 1958-1976 (T) and for Courmayeur 1933-1983 (P) / 1961-1990 (T); Cerutti, 1995a).

	Courmayeur (1220 m a.s.l.)	**Col du Géant** (3370 m a.s.l.)
Mean annual temperature	7.9 °C	-5.7 °C
Mean annual precipitation sum	919 mm	2240 mm
Number of frost days per year	144	330
Mean temperature in January	-0.9 °C	-11.5 °C
Mean temperature in July	17.0 °C	1.6 °C

The predominant climatic factor of the inner alpine climate is the scarcity of precipitation. The resulting relative aridity favours the rapid rising of temperature in the warm season (Janin, 1970). Due to high summer temperatures the monthly temperatures vary considerably over the year (Table 5).

Table 5 : Monthly and annual mean temperature values of the Courmayeur meteorological station at 1220 m a.s.l. The data are averages for the observation period 1961-1990 (http://clisun.casaccia.enea.it; ENEA, February 2010).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean**
T [°C]	-0.9	0.4	3.0	6.8	11.3	14.7	17.0	16.0	13.4	8.5	3.2	0.7	7.9

What are now the implications of these climatic conditions for glaciations in the Val Veni and Val Ferret? In the accumulative basins, the glaciers profit from abundant precipitation received at the mountain summits. In the valley bottoms though, the glacier tongues encounter relatively arid conditions. In summer, the main season determining the temperature-glacier interaction, temperatures rapidly rise. Moreover, descending in south-eastern direction from the Mont Blanc massif, the glaciers are highly exposed to solar radiation. Thus, the climatic conditions for glaciations are not especially favourable. The high amount of glacierized area can only be explained by the fact that large areas are situated at high elevations (Corbel, 1963) and due to the steep slopes on the southern massif.

3. Data and methods

Today, several techniques are applied to determine glacier variations (Zumbühl & Holzhauser, 1988). The *geodetic method* compares topographical maps or aerial photographs from two different points in time to observe the difference in glacier thickness and determine the mass balance. The *hydrologic-meteorologic method* calculates the mass balance via indicators of melt, sublimation, precipitation and evaporation on the glacier area, as well as runoff of meltwater. For the *direct glaciological method* the difference between accumulation and ablation is inferred from direct measurements of thickness change on the glacier surface.

These glaciological methods though, are not available for the quantification of historical glacier fluctuations, because mass balance studies were only conducted since mid last century (Zumbühl & Holzhauser, 1988). Only measurements on the glacier snout, where changes are most evident, go back to the end of the 19th century, but still remain discontinuous until the first decades of the 20th century (e.g., Brenva Glacier: 1878/79 Marengo, 1897 Porro & Druetti, continuous measurements since 1910).

To verify glacier fluctuations before the 20th century other techniques have to be used. These are mainly historical, glacio-morphological and archaeological methods. The *archaeological method* is based on (1) finding human traces such as foundations and wooden beams from buildings, old alpine routes or remains of abandoned irrigation channels, and (2) connecting them with glacier history (Holzhauser *et al.*, 2005). As this method was not used in the study presented here, it will not further be explicated. The most useful *historical* and *glacio-morphological methods* are presented in the following two Sections.

In the last Section, the climatological data and methods used in this study are presented.

3.1 Historical methods

Historical length fluctuations of Miage, Brenva and Pré-de-Bard Glaciers are reconstructed using documentary evidence in the form of maps, pictorial sources such as etchings, paintings, lithographs and drawings, written accounts and photographs. The historical method can achieve a resolution of decades or, in some cases, even single years (Holzhauser *et al.*, 2005). In the following Sections, the main categories of historical documents are introduced.

3.1.1 Written accounts

Written accounts include chronicles, land ownership certificates, pasture contracts, early scientific works about glaciers, travel journals etc. The majority of written accounts date from the modern era (since the 16th century). Older accounts are often difficult to interpret and have to be confirmed and complemented by other methods (Zumbühl & Holzhauser, 1988). For the Italian side of the Mont Blanc chain, in contrast to the French side, historical documents are less abundant and go back only to the 18th century. Unfortunately the archives of Courmayeur burnt down twice and valuable records of the village were destroyed.

3.1.2 Pictorial sources

The first pictorial documents illustrating the study glaciers date back to the late 18th century (e.g., Brenva by Jalabert, 1767). The occurrence increases with the upcoming popularity of journeys to the Alps in the 19th century. Three conditions have to be fulfilled in order to reliably reconstruct former glacier extents (after Zumbühl & Holzhauser, 1988):

1. The dating of the document has to be known or reconstructed,
2. the representation of the glacier and the surrounding areas has to be realistic and topographically correct,
3. the point of view of the artist in the field has to be known.

Topographical reference points, such as rock steps or hills in the forefield facilitate the determination of the front position. If such elements are missing, the interpretation of the glacier extent becomes difficult. When evaluating the topographical composition it has to be taken into account that artists often decorated their pictures with staffage, or omitted unaesthetic elements to better pronounce the main subject. Usually the topographic accuracy increases with the quality of the picture and the skills of the artist.

Comparing a work of art with the present-day situation in the field is often helpful and allows a reasonably precise positioning of the former glacier terminus. The careful consideration of prominent mountain peaks in the background helps to estimate the accuracy and reliability of the pictorial document. Problematic is the rapid re-forestation of the Val Veni, which conceals the view at the position of the artist and makes a comparison with earlier documents sometimes rather difficult. The biography of the artist or his travel notes are additional sources of information helping to date the document and improve the reliability of the interpretation.

The geographical settings on the picture often limit the possible range where the glacier front could have been located at that time (Nussbaumer *et al.*, 2007). The Pré-de-Bard glacier for example was only visible from the Val Ferret if it bent around the Monts Rouges and protruded into the main valley. Similarly, the Brenva Glacier was only perceptible from Courmayeur when it exceeded a certain extent and flowed out of the Val Veni. At very advanced positions the Brenva reached the chapel Notre Dame de la Guérison, which the glacier damaged at its LIA maximum. In addition, depending on the glacier extent the Dora di Veni river flowed either unimpeded or subglacially. For the Miage Glacier points of reference are missing. As the glacier flows rather unimpeded down the open Val Veni, no distinctive morphological elements help in the determination of the front position.

Remarkable examples of glacier representations are given by the drawings by Jean-Antoine Linck (Brenva, 1795), Henri Hogard (Miage and Brenva, 1849) and Jules-Fréderic d'Ostervald (Pré-de-Bard, around 1820/21) (see Section 4). As already mentioned, the abundance of documents declines with the glacier's distance to inhabited areas and its accessibility. Accordingly, the Miage Glacier is less well documented than the Brenva Glacier, but still more visited and studied than the Pré-de-Bard Glacier at the head of the Val Ferret.

3.1.3 Cartographic evidence

Early cartographic documents are only schematic and rather imprecise. The repulsive and myth-enshrouded glacier areas were mostly avoided and are thus either not drawn or only sketched by vague contours (Zumbühl & Holzhauser, 1988). The first maps that allow indications on the exact glacier extent appeared only in the mid 19^{th} century (e.g., Gran Carta degli Stati Sardi in Terraferma, 1867; Dufour map, 1861; Mieulet map, 1865). To reconstruct the historical glacier stage, it is mandatory to know the exact date of the ground survey. However, the ground survey can often only be dated to a range of several years. Often old maps lack triangulation and standardized representation, which makes it difficult to compare them.

3.1.4 Photographs

Photographs are documents of inestimable value for the reconstruction of historical glacier stages. In contrast to pictorial documents, they are not a result of the subjective interpretation by the artist, but capture the reality at the corresponding point in time. First photographs of Alpine glaciers appear since the mid 19^{th} century. The first known photograph of the study glaciers is a daguerreotype by J.G. Dardel from 1849 picturing the upper Brenva Glacier (De Decker Heftler, 2002). As the glacier terminus is not visible, the photograph is not evaluable for the front position. The first photograph that shows the terminus of the Brenva is by A. Civiale and dates to 1861 (Civiale, 1882).

3.2 Glacio-morphological methods

As described in the previous Sections, historical methods are generally only applicable back to the 16^{th} century. To reconstruct glacier fluctuations in the centuries before historical documents appeared, other methods have to be employed.

Advancing glaciers often overrun vegetated and tree-covered areas, whereby they push down and bury trees. In later phases of melt back, as for example since the end of the 19^{th} century, tree stumps buried by the ice and soil horizons (ancient vegetated areas besieged by the advancing glacier) reappear. With the help of the radiocarbon method (or ^{14}C-method) such fossil wood and soils can be dated and the time of their dieback can be determined. However, the so-called radiocarbon age (indicated in years before present (yBP), where 'present' is the year 1950) is only reliable for dates older than 200 years and best applicable before the modern era (Zumbühl & Holzhauser, 1988). In addition, the lifetime of a well-preserved wood sample can be dated with dendrochronology. This method allows a precise dating (resolution of a single year) back to the Middle Ages, impossible to obtain with the radiocarbon method alone (Holzhauser *et al.*, 2005). To connect fossil evidence to a glacier stage, the basis of any glacio-morphological analysis is the detailed mapping of the glacier forefield with its moraine walls.

Within this study, the mapping of the moraines in the forefields of the Miage, Brenva and Pré-de-Bard Glaciers was realised in a glacio-morphological survey in July and October 2009. The GIS-based maps created in this way, show the forefields' morphology and help in the deduction of the historical glacier stages. The collection of fossil organic evidence was not within the scope of this study. Nevertheless, data from fossil wood and soils published in previous studies (e.g., Porter & Orombelli, 1982a; Aeschlimann, 1983; Deline, 1999a) were incorporated in the reconstruction of the historical glacier fluctuations.

3.3 Climatological data and methods

On the Gr. St. Bernard Pass, situated only 8 km southeast from Pré-de-Bard Glacier, one of the longest weather records is available (Schüepp, 1991). This meteorological data was used for studying the relationship between glacier and climate. The main aim is to extend the knowledge on the glacier-climate relationship, as illustrated by the example of the three study glaciers.

The Gr. St. Bernard Pass is a depression in the Alpine barrier and thus a channel for the exchange of air masses between north and south. Similar to the Mont Blanc, it is influenced by Atlantic winds. They are rich in humidity in every season. Together with the high elevations of the mountain ridges, this provokes abundant precipitations in the form of snow. The precipitation measurements at the station (2479 m a.s.l.) undertaken by the monks began in September 1817. It is the longest precipitation series in the higher Alps (Schüepp, 1991). The data used in this study were provided by the MeteoSchweiz, and are based on the homogenisation by Schüepp (1991). Both homogenised mean annual temperature and precipitation data are available back to 1818. In addition, the homogenised time series of mean monthly temperature reaches back to 1818. Unfortunately, the monthly precipitation series only goes back to December 1864.

For the mass balance of a glacier, changes in the meteorological conditions or anomalies are important rather than the absolute values. To determine the glacier response to temperature signals, mean ablation season temperatures were used.

The response time of the glacier tongue

The response of a glacier to changes in climatic conditions is delayed. After a certain reaction time (or time lag) ranging from a few years to several decades, glacier length changes and finally reaches a new equilibrium after a response time from several years to about 100 years (Haeberli, 1995). Basically, the reaction and response time of a glacier to a climatic forcing is proportional to its size. In fact, there are two different response times depending on whether the glacier is advancing or retreating. Glacier advances are of a more dynamic character than retreats, which are dominated by ablation and thus more dependent on climate parameters (Nussbaumer *et al.*, 2007). Furthermore, it has to be noted that dependent on the prehistory of the glacier, the snout can also react more immediate to climate, e.g. after successive cool summers (Zumbühl *et al.*, 2008).

Estimation formulae and a simple (optical) analysis of the time lag between a temperature signal and the corresponding glacier front reaction suggest values of about 15 years for the Pré-de-Bard, about 18 years for the Brenva and about 50 years for the Miage Glacier. To determine the time lag mathematically, a correlation analysis between ablation season temperature anomalies (in the period 1818-2009) and the length change was calculated for each glacier. The anomalies were defined as departures from the 1901-2000 period (see Figure 60 and Figure 61, Appendix 8.2). For the Brenva and the Pré-de-Bard Glaciers a 20-year Gaussian lowpass filter was applied. For the much more slowly fluctuating Miage Glacier however, a 30-year Gaussian lowpass filter was used. The results are discussed in Section 5.5.

4. Results

4.1 Glacier fluctuations during the early LIA

Although little information is available on glacier fluctuations in the Mont Blanc area for the Middle Ages, some notion of the state of the glaciers may be gathered from local tradition and myth. These yield indirect evidence that the first LIA advances occurred in the Late Middle Ages (Grove, 2004). Thus, before 1500 the glaciers in the Aosta Valley were less extensive than during the three centuries of the LIA that would follow. The abbot Joseph-Marie Henry reports that in the collection of notarial records of Valpelline (lower Aosta Valley) from 1490 until 1572, no toponyms that name glaciers appear, even though there are meticulous descriptions of the position of elevated alpine pastures with a rich toponymy of reference points (Cerutti, 2006). This could hint at their reduced extension. Tree ring data from the Miage suggest that summer temperatures were higher than the longtime average during the period from 1439 to 1569: According to the low density of the late wood a worsening of the climate occurred around 1570 (Aeschlimann, 1983). In general, the years around 1570 were the onset of a period of climatic deterioration which led to far-reaching glacier advances during the 1590s and early 1600s (Pfister, 2007).

For the French side of the Mont Blanc massif Le Roy Ladurie (1971) provides indirect evidence that the glaciers were advancing in the second half of the 16th century and reached two major advances during the 17th century. Also, on the Italian side the glaciers were far advanced by the beginning of the 17th century: A written account by Jacques Cochet, dated April 6, 1600 states that "*the* [Italian] *glaciers have not retreated and they are as threatening as ever*" (Grove, 2004). In accordance with the glaciers on the Mont Blanc north slope, the Miage reached its LIA maximum extension in 1640 (Aeschlimann, 1983; Deline, 1999a). This shows that the climatic conditions around AD 1600 were 'glacier-friendly' in the whole Mont Blanc area.

During the medieval optimum there had been a lot of travel between Courmayeur and Chamonix across the mountain range of the Mont Blanc. Viollet-le-Duc (1876) remarks that according to a chronicle from the 12th century, one passed by mule over the Col du Géant. In 1691 Philibert-Amédée Arnod, a judge from the Aosta Valley, wrote an "Account of the Passes and Cols of the Alps": "*l'on prenoit autres fois un passage à droitture d'Entrèves par dessus les glaciers de Mont Frety pour descendre en Chamonix en*

Faucigny” (Cerutti, 1995b). But as he himself ascended towards the “*Col Major*” in 1689, his passage was prevented “*a cause des grandes crevaces et interruptions qui se sont faits depuis bien d'années*” (although in cartographic documents the path over the Col Major persists up to 1748). Thus by the end of the 17th century the glaciers have expanded to a length that they had not reached in the centuries before.

Most glaciers on the south slope of the Mont Blanc reached their LIA maximum not until the early 19th century (e.g., Zienert, 1965; Porter & Orombelli, 1982, Aeschlimann, 1983 etc.). During this maximum the moraines of the smaller 17th and 18th century advances were overrun. Little is known on the glacier fluctuations during the 18th century. However, already before the maxima were reached around 1818/20, the glaciers had started to swell by the end of the 18th century. In 1783 Vignet des Etoles reported on the condition of the forests in Val d'Aosta: “*dans quelques localités, comme Cogne, La Sale, Courmayeur, on s'etonne de ce que les bois ne repoussent plus sur les sommités même après un siècle. On attribue cela à l'augmentation des glaciers*. “(Monterin, 1936)

The evidence used to reconstruct the glacier fluctuations of the Miage, Brenva and Pré-de-Bard during the LIA are described in the following Sections. The discussion starts with the presentation of cartographic documents illustrating the entire study area. Thereafter, the pictorial and written sources considered for each individual glacier are discussed.

4.2 Cartographic evidence

The first maps of the Mont Blanc show the massif as an aggregation of mountains. Early cartography refers to the many glaciers of the Mont Blanc massif as “*les Glacieres*” (i.e., “Carta Generale degli Stati di Sua Altezza Reale by G.T. Borgone”, 1680). A map of the canton of Valais (Switzerland) from 1768 by Gabriel Walser contains the notes “*SAVOYEN abscheuliche Eisberge Gletscher Glaciers Montes Glaciales genannt*” (Aliprandi & Aliprandi, 2007). It is only by the end of the 18th century that glaciers appear as individual objects and are named individually.

4.2.1 Early cartography in the 18th and first half of the 19th century

The first specific map that comprises the Mont Blanc glaciers as a whole and names individual glaciers on the Italian slope was drawn by Marc Auguste Pictet .The “Carte de la partie des Alpes qui avoisine le Mont Blanc” was published in 1786 in De Saussure’s famous “Voyages dans les Alpes” (Figure 8). The coarse illustration depicts the Miage and Brenva, but no glacier in the Val Ferret. The Brenva Glacier bends around the Aiguille de la Brenva and reaches the valley floor, but the river Dora is flowing unimpeded. The *Ruize de Miage* (patois for glacier) descends into the Val Veni, whereas its characteristic curvature and the three-lobed tongue are missing.

Figure 8 : Cut-out of the “Carte de la partie des Alpes qui avoisine le Mont Blanc” at a scale of 1:140’000 by Marc-Auguste Pictet, published in De Saussure (1786) (Universitätsbibliothek Bern, Zentralbibliothek, Sammlung Ryhiner, Ryh 2805:50).

A decade later (1797-1799) Jean-Baptiste Raymond made surveys of the Mont Blanc for his map that for editorial reasons would not be published until 1815. As the caption precises, the objective of the map was to “*servir de complément aux voyages de De Saussure dans les Alpes et pour l’utilité des voyageurs qui vont visiter les Glaciers de*

Chamonix". Thus, it is the first map compiled for tourists. On the map, the Miage Glacier descends well into the Val Veni, and comes to a stop at the level of the Frêney stream. The Brenva seems restricted to higher altitude. Even so, the thinned section of the valley tongue quasi joins the axis of the descending Toula stream. The Pré-de-Bard Glacier bends into the Val Ferret but is clearly separated from the Triolet Glacier.

The ground surveys for the Atlas Suisse, the first Atlas of Switzerland, were conducted from 1796 until 1802. The 13th sheet, representing the Mont Blanc and western canton of Valais, was published in 1800. Unfortunately, in contrast to the other parts of Switzerland, the topography and toponymy in the 13th sheet is of low quality (Zumbühl, 1998). In the Val Veni only the Miage and the Brenva are represented (and named), and both glaciers are restricted to the remote parts of their lateral valleys. In the Val Ferret, simply a thin blue line along the mountain crest marks the presence of ice at the site of the Pré-de-Bard Glacier.

From 1813 we have a sketch map by Keller (in Vallot, 1922), with dotted outlines of most Mont Blanc glaciers. The Brenva is shown not reaching the Dora di Veni.

One of the first documents with good accuracy is the important "Carta topografica degli Stati di Terraferma di S.M. il Re di Sardegna", sheet H8 Mont Blanc, surveyed by Lieutnant Felice Muletti in 1823. However, the manuscript map, at a scale of 1:50'000 and composed of 113 sheets, was never published (Aliprandi & Aliprandi, 2007). It shows the glaciers shortly after their maximum expansion around 1818-1820. On the map, the single tongue of the Miage reaches the Frêney stream. The Brenva ends in a long, thin tongue that almost exits the Val Veni to reach the village Entrèves. Due to this big extent, the Dora di Veni is forced to flow subglacially. The shape of the Pré-de-Bard Glacier is drawn rather coarse, with the tongue descending into the Val Ferret but being clearly distant to the Triolet Glacier.

Raoul-Rochette's volume "Voyage pittoresque dans la vallée de Chamouni et autour du Mont-Blanc" (1826) includes a map that was designed by Duvotenay after a survey by M. Lapie. The shape of the Miage resembles a drop, which indicates the spread of the glacier in the Val Veni. Again, the Brenva is drawn as restricted to higher elevations and not reaching the valley floor – in contrast to a drawing by Coignet published in the same volume (see Section 4.4.5, Figure 25). The Pré-de-Bard Glacier even lacks a denomination, but is depicted as descending the upper Val Ferret.

Referring to Raymond's map, François Jules Pictet drew a topographical map that was published in 1829. Again, this map is very schematic: both Brenva and Pré-de-Bard

Glacier are reduced to their uppermost parts, none of them drawn with a curvature. The Miage seemingly merges with the Breuillat Glacier, and does not reach the Frêney stream anymore.

A map representing the Mont Blanc plateau was published in 1840 by canon Rendu in his “Théorie des Glaciers de la Savoie” (1874). As stated in the title, the map is drawn after De Saussure and represents only three glaciers in the Val Veni (Glacier du Mt. Suc (Allée Blanche Glacier), Miage and Brenva), but no glaciers in the Val Ferret. According to Rendu’s theory, as also indicated on the map, the glaciers descend as cascades of ice originating from a vast central reservoir the “*Grand Glacier Reservoir Du Mont Blanc*”.

The “Carta degli Stati di Sua Maestà Sarda” at a scale of 1:250’000 was first published in 1840. The field surveys were carried out under direction of V. Brambilla. While the French slope of the Mont Blanc massif contains accurate depictions of the glaciers and a rich toponymy, the glaciers on the Italian side are less evident and anonymous. In the upper Val Ferret for example, the three glaciers Frébouge, Triolet and Pré-de-Bard seem to be confluent.

4.2.2 Abundance of cartographical documents since the mid 19th century

From the mid 19th century onwards, a wealth in cartographic documents arises. In 1854 Alexander Keith Johnston published his map of the glacier systems of the Mont Blanc after the surveys and sketches of J.D. Forbes. Thus, the document refers to the glacier stages at the time of Forbes travels through the Alps in 1842. The front of the Miage is illustrated as being bilobal, whereas the rounded terminus of the Pré-de-Bard does not exit the lateral valley. The Brenva reaches into the valley floor and trespasses the Dora. There exist individual sketches of the Miage and the Brenva Glacier by Forbes, published in his famous “Travels through the Alps” in 1843 (see Sections 4.3 and 4.4).

From 1856 we have the “Travellers map of Mont Blanc” by the Johnston brothers William and Alexander Keith, which was published by King (1858). There are little differences considering the glacier stages when comparing the 1854 Johnston map to this one from 1856. The Miage’s terminus is drawn undivided, but this is probably due to the small scale of the map.

The second maximum of the 19th century is well recorded in the “Gran Carta degli Stati Sardi in Terraferma” (Figure 9). The map at a scale of 1:50’000 is based on ground surveys from 1856 and was published in 1867. The glaciers are furnished with contour lines. It is the first map to show the three lobed glacier front of the Miage. Its right tongue ends at a distance of about 500 m from the confluence of the meltwater with the Dora. The pointy front of the Brenva runs past the Notre Dame de la Guérison, and forces the Dora di Veni to flow subglacially. In the upper Val Ferret, the Triolet and Pré-de-Bard Glaciers nearly merge. Because the glacier occupies the valley, the path to the huts of Pré-de-Bard passes directly by the Combette Valley. It was only after around 1875 that the glacier had retreated far enough that the path could lead through the main valley floor (Sacco, 1918).

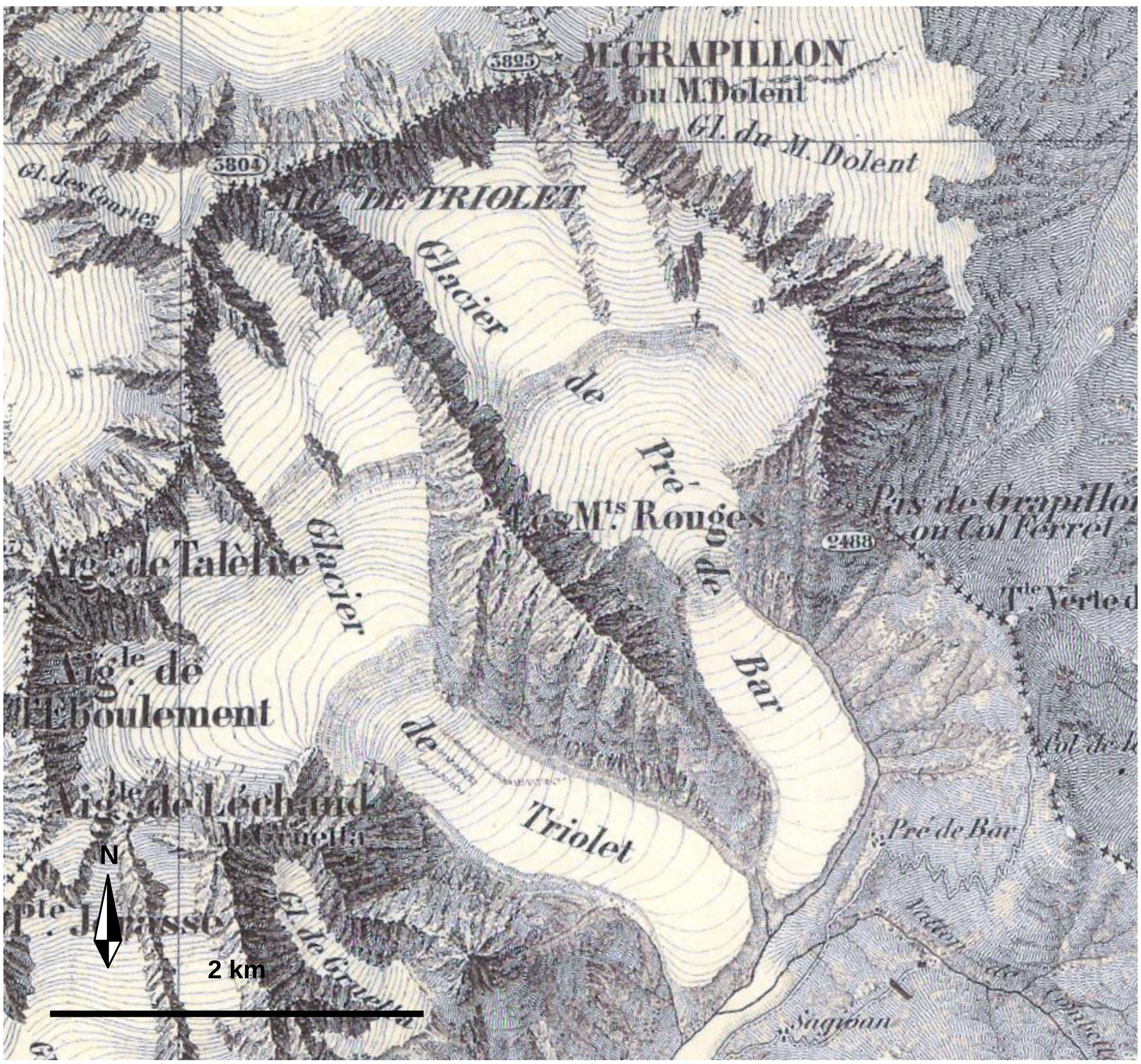


Figure 9: The Pré-de-Bard and Triolet Glaciers in a cut-out of the “Gran Carta degli Stati Sardi in Terraferma” surveyed in 1856 and published in 1867 at a scale of 1:50’000. The Pré-de-Bard descends well into the Val Ferret and ends in a pointy tongue (Zentralbibliothek Zürich, Kartensammlung).

The first official map of Switzerland was surveyed between 1832 and 1864 under the supervision of General Guillaume-Henri Dufour (1787-1875) and is therefore also named Dufour map. Published in 1861, the sheet XXII includes the Mont Blanc massif with the three study glaciers. The map at a scale of 1:100’000 depicts the bilobal front of the Miage Glacier ending up at the level of the descending Frêney Glacier. Similar to the “Gran Carta degli Stati Sardi in Terraferma” (survey 1856), the Brenva has a pointy tongue that slightly overpasses the chapel. However, the tongue has receded over the five years, because the Dora di Veni is now flowing unimpeded. The pointy tongue of the Pré-de-Bard bends well into the Val Ferret, and ends up very near to the Triolet Glacier.

One year later, the Swiss geologist Alphonse Favre published an accurate geologic map of the Mont Blanc region. For the topography, including the glacier stages, he relied on the Dufour map that had been published a year earlier in 1861. Thus, Favre’s geologic map contains no new information on the glacier extents.

Published in 1864, the map by Pitschner gives a nice overview on the glaciers of the Mont Blanc chain. But as stated in the title, the basis for this document was the map of the Mer de Glace by Forbes. For the remaining parts of the massif he probably relied on other preceding maps. Thus, the glacier stages on the map correspond to earlier years. This supposition is consistent with the representation of the Brenva, which blocks the Dora. According to other documents (i.e., Dufour map) the river was unimpeded in the 1860s.

In the years 1863-1864/65 the French and British cartographers Jean-Joseph Mieulet (1830-1897) and Anthony Adams-Reilly (1836-1885) accomplished the investigations for their maps, both published in 1865. According to Aliprandi & Aliprandi (2000) Mieulet surveyed the Italian side in 1864. The Mieulet map, at a scale of 1:40’000 contains figurative contour lines that give an impression of heights (Figure 10). On this map, the Miage appears in a stage very similar to today. The rounded tongue of the Brenva has retreated to a position some 250 m behind Notre Dame de la Guérison, leaving the Dora to run freely. A similar retreat can be noted for the Pré-de-Bard that comes to a stop in the curvature where the lateral valley enters the upper Val Ferret. In comparison to the Mieulet map, the map by Adams-Reilly is much more figurative and topographically less accurate. Especially when considering the lower part of the Miage Glacier, the difference between the two maps is apparent.

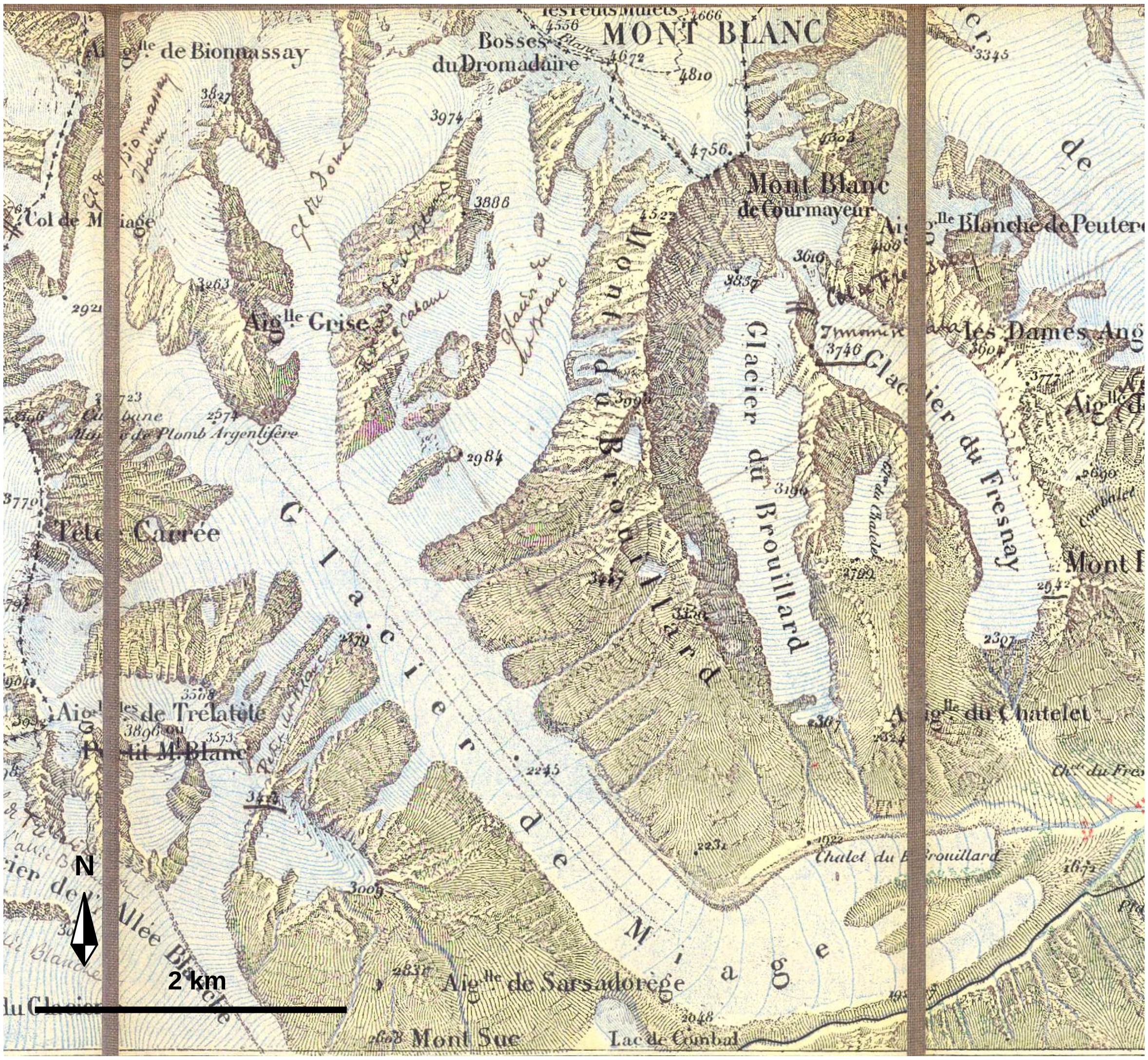


Figure 10 : The Miage glacier in a cut-out of the Mieulet map at a scale of 1:40'000 (Zentralbibliothek Zürich, Kartensammlung). The Italian part of the map is based on surveys from 1864. A decade after its maximum at around 1850 the glacier is still in a very advanced position.

From the same time we have a map by the English Alpinist Edward Whymper that was published in 1871. As indicated on the covering page of the document, it is based on the Mieulet, Dufour and Adams-Reilly maps and contains no reform of the topography.

The French map “Carte de France de l’Etat-Major” was presumably published in 1875 (Aliprandi & Aliprandi, 2007). This map also contains contour lines, which admittedly are fictive in the Italian part. The map sheet Tignes-Petit St. Bernard depicts the Val Veni. However, the map relies on previous cartographic documents, most probably on the Mieulet map.

Another important cartographical document is the map by the famous French architect Eugène-Emmanuel Viollet-le-Duc (1814-1879). His investigations in the Mont Blanc massif lasted from 1868 until 1875. Viollet-le-Duc travelled the Val Veni for a first time in September 1868 and returned for a longer stay in July 1870, when he included the Val Ferret. The aim declared by E. Viollet-le-Duc was to present "*une image aussi exacte que possible du massif come pourraient le donner une série de photographies* […]" (in Frey, 1988). However, the map was often criticized for its lack of precision concerning the toponymy, its design being too fantastic and certain topographical errors (Aliprandi & Aliprandi, 2000). The map at a scale of 1:40'000 is part of his monograph "Le massif du Mont Blanc" published in 1876. Besides his own surveys and sketches, Viollet-le-Duc additionally referred to the Mieulet map. The Pré-de-Bard Glacier, for example, is most probably adopted from this map. Nevertheless, the map accurately shows the tongue of the Brenva and the forefield with the two lateral moraines (Figure 11). The asymmetric terminus is at a distance of about 600 m from the chapel. Astonishingly, the *Pierre à Moulin* does not figure on the map, whereas it is indicated in the sketch which Viollet-le-Duc took from the Brenva (see Figure 35, Section 4.4.7). For the Miage the representation of the forefield's morphology is of similar detail. The right lobe has retreated about 400 m from a distinct frontal moraine, whereas a series of moraines is documented in front of the left lobe. The glacier, especially the right lobe, seems far retreated.

It is in 1882 that the Istituto Geografico Militare (IGM), the official Italian map authority, published the first map of the united Italian state (after the annexation of Savoy by France in 1860, the Aosta Valley is allocated to the Kingdom of Italy). The "Carta d'Italia" at a scale of 1:100'000 is a real progress in that the orography, although not the glaciers, is represented with contour lines. Due to the extensive debris cover, the outline of the Miage Glacier is difficult to perceive. Nevertheless, the frontal position can be estimated as being about 250 m further advanced than today. The Brenva in contrast is more clearly drawn; the asymmetric tongue lies between the two lateral moraines and ends up at a distance of about 630 m from the chapel Notre Dame de la Guérison. For the terminus of the Pré-de-Bard an elevation of 2007 m a.s.l. is registered.

In 1896 the Swiss Albert Barbey, Xaver Imfeld and Louis Kurz published an aesthetic map of the entire Mont Blanc range. The map at a scale of 1:50'000 is based on the official Swiss, French and Italian maps (Nussbaumer *et al.*, 2007). It therefore refers to the 1882 IGM map for the Italian side and contains no new evidence for the glacier stages. Only the second edition released in 1906 contains contour lines.

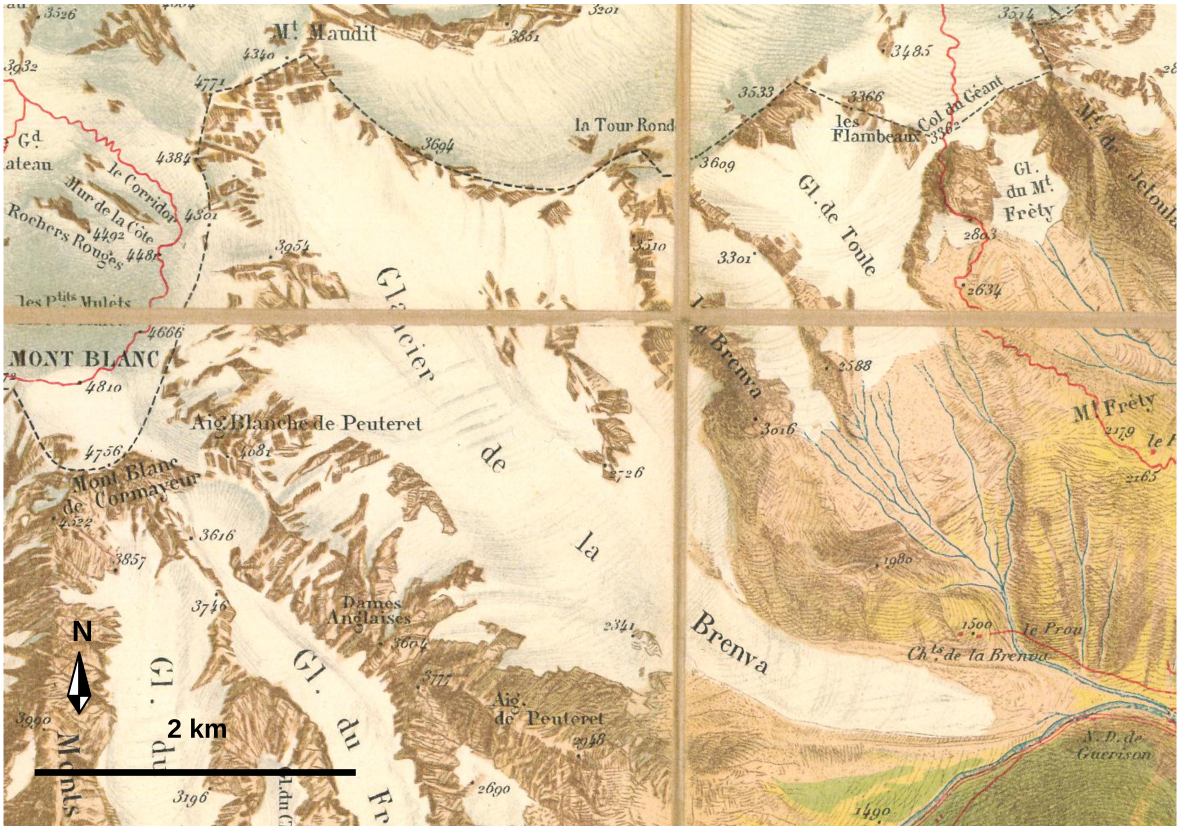


Figure 11 : Cut-out of the Viollet-le-Duc map at a scale of 1:40'000, showing the Brenva Glacier with its foreland in 1870 (Frey, 1988) (Geographisches Institut der Universität Bern, Kartensammlung, KF 231 B2).

A reprint of the Dufour map from 1908 shows the Pré-de-Bard Glacier far receded into its lateral valley. In the forefield moraine deposits from a recent advance, probably the 1890 maximum, are recognizable. While the Brenva has been adopted from the first edition, the Miage Glacier is not part of the cartographic area at all.

A series of maps by the Istituto Geografico Militare Italiano (1929, 1947, 1968, etc.) reproduced the frontal positions of the Mont Blanc glaciers during the 20th century.

To conclude, it can be said that cartographical documents depicting the Mont Blanc massif before the 19th century are rare. Those maps existing are rather coarse, rudimentary and either in the form of sketches or only at scales of low resolution. Several maps have been drawn to serve as tourist guides, or as a supplement of books. It is only from the 1850s onwards that a considerable number of quality maps (i.e., "Gran Carta degli Stati Sardi in Terraferma", Dufour, Mieulet, Viollet-le-Duc maps) appear. In the majority of cases old maps lack triangulation and standardized representation, and are therefore mostly not comparable with each other. A major constraint is the often unknown exact date of the ground survey, which is fundamental for the historical reconstruction of the glacier stages.

4.3 Length fluctuations of the Miage Glacier

The Miage Glacier is characterized by its weak fluctuations. Since the end of the LIA, it has retreated by less than 300 m. This inertia is attributed to three factors: The size of the Miage, which explains a long response time and the small amplitude of the fluctuations. Secondly, due to the debris cover the response to climatic variation is delayed, subdued and the glacier responses by thickening or thinning rather than an advance or retreat (Thomson *et al.*, 2000). Thirdly, a reasonable fraction of the Miage's accumulation basin is situated above 3000 m a.s.l., which makes the glacier less sensitive to unfavourable climatic phases. The following Sections describe the glacier fluctuations of the Miage from the LIA until the present.

4.3.1 Miage Glacier foreland and LIA moraines

The tongue of the Miage Glacier is embedded in enormous lateral moraines, barring the Val Veni over a length of 3 km. Near the *Lac du Miage*, the right-lateral moraine reaches a height of 150 m and extends over a width of 300 m. The lateral moraines consist of a succession of sedimentary accretions of multiple advances before the LIA, and the LIA advances only added a minor sediment layer (Deline, 1999a).

A speciality of the Miage moraine apparatus is the morainic amphitheatre located in the outer bent of the glacier. This sequence of arc-shaped moraines has been built during the Neoglacial (Deline, 1999b). Depending on author and study, the moraines are classified into three to nine main arcs.

Besides studying the morainic amphitheatre, Deline (1999a, 1999b; Deline & Orombelli, 2005) extensively examined and mapped the moraine apparatus of the foreland. Deline attributed the different moraine walls to the main glacier advances by geometrical, dendrochronological and lichenometrical evaluation. The following map showing the Miage foreland (Figure 12) is based on Deline (1999a) and completed by field surveys by the author. The glacier foreland of the Miage consists of a hundred complexly arranged moraine walls built during the LIA by the two tongues. Numerous moraines are covered with well developed soil and vegetated by scrubs and metre-high larch trees. The rapid re-forestation of the forefield makes the distinction of the moraine apparatus quite difficult.

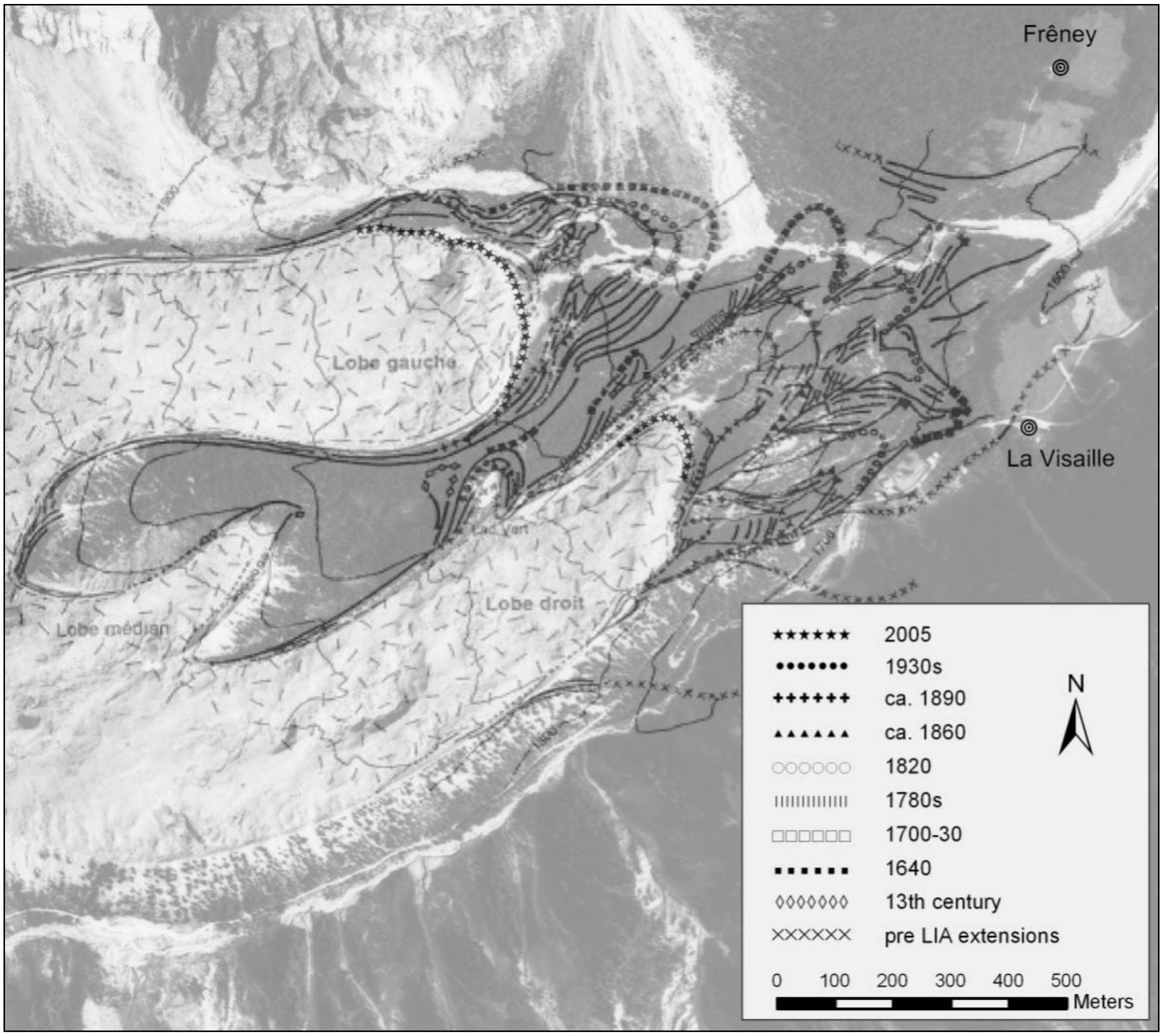


Figure 12: Miage forefield with moraines and front positions during the LIA and the present. Note that certain terminal moraines are missing; the arcs are completed by the line types corresponding to the year of the advance (adapted from Deline, 1999a. Aerial photograph from 22.08.2004, © IGM, Italy).

Since 1860 the Miage left lobe has retreated by 245 m, and the right lobe by about 270 m. In the forefield of the right glacier tongue we find several fronto-lateral moraine crests: The innermost sequence of moraine walls, about 30 m in front of the actual terminus, is attributed to the advance of the mid 1930s. This advance was reported in the measurements of the CGI by Capello. Deline (1999a) found a lichenometrical age of 50 yr and a minimal *Larix* age of AD 1853-1913. However, the larch tree has probably started to grow already on the detritic glacier surface, before the moraine was installed. Thus, the dating to the mid 1930s advance seems reasonable.

Advancing another 170 m, the front position of the 1890 maximum is reached. For these moraines the dating by lichenometry (36 mm; ~ 95 yr) is in accordance with the minimal *Larix* age of AD 1890-1895 (Deline, 1999a). The moraines following next further down the

valley are attributed to the 1860 advance. The attribution was made only by geometrical reasoning, and they were not absolutely dated by lichenometry or dendrochronology. However, historical evidence suggests, that the moraines were formed after 1856 (see Section 4.3.3). The maximum around 1820 is attested by moraines at the *Lac Vert*, as well as different moraines in the forefield of the left and right lobe. This major maximum partly buried moraines from former advances (e.g., 1700-30 and 1780s moraines). The exact dating of these moraines is difficult, as the dendrochronology risks to be perturbed by anthropogenic logging and the ^{14}C dating for this modern period only yields a large time range. A historic source though, dates the maximum to 1820 (see Section 4.3.3).
Deline (1999a) dated two advances during the 18th century with dendrochronolgical analyses on the left lateral moraine of the right lobe. On its external flank he found a minimal *Larix* age of AD 1725, indicating an advance between 1700 and 1730. This lateral moraine was partly superimposed by another advance half a decade later, during which a new sediment layer was added to the crest. Locally, Deline found trees that grew on ground stabilized around AD 1779-1788. However, evidence for the 1780 advance is rare, as the moraines were mostly destroyed and superimposed in the later 1820 maximum.

The LIA maximum in 1640

The Miage Glacier most probably attained its LIA maximum extension in 1640. Evidence for this maximum was reported by Aeschlimann (1983) in the *Jardin du Miage*. He dated a fossil tree trunk that had grown on an ancient moraine; the tree counted 305 tree rings, the last of which had been built in 1639. The scenario suggests that in 1640 the glacier swells to such an extent that the left lobe barricades the *Jardin du Miage*. The glacial stream of the middle lobe is impounded and the larch forest submerged in sand and glacial clay. Around the same time the Miage also overflows the right lateral moraine, which is recorded in the soil profile of the morainic amphitheatre (Aeschlimann, 1983). Another proof for the LIA maximum to occur in 1640, delivers the dating of the frontal moraine of the left lobe. On the left lateral crest, Deline (1999a) found a *Larix* counting 281 tree rings. Accordingly the moraine has to be in place since at least AD 1640 and was not reached again. On the same moraine Deline dated a lichen of 100 mm in diametre, which proved a moraine age of about 350 years.

The oldest moraines found in the Miage Glacier foreland are two arcs at the *Lac Vert*. Based on the dendrochronological evidence Aeschlimann (1983) concluded that the moraine has to be in place since the 13th or early 14th century.

The history of the Miage Glacier is tightly linked to the *Lac de Combal*, which was formed when the Miage blocked the Dora di Veni. Outbursts from *Lac de Combal* are recorded from 1594, 1595, 1629/1630, 1640, 1646 and between 1678 and 1680 (Grove, 2004). The 1594 and 1595 lake outbursts correspond to the glacier advances at the beginning of the LIA. The triple sequence of flood disasters in 1629-30, 1640 and 1646 demonstrate the rapid advance of the Miage Glacier to its LIA maximum position in 1640. Similarly, the lake outbursts between 1678 and 1680 suggest another glacier maximum by the end of the 17th century.

4.3.2 Scientific interest in the 18th century

During the 18th century the frontal parts of the Miage fluctuated in a range of about 300 m. Based on the moraine sequence, Deline (1999a) dated a maximum around 1730 and a slightly smaller advance around 1780.

About the glacier fluctuations in the early 18th century little is known. Only lateral moraines, dated by Deline (1999b), testify an advance between 1700 and 1730.

The famous Swiss scientist Horace-Bénedict De Saussure (1740-1799) visited the Miage Glacier several times. In 1781 – around the time when the Miage attained a new maximum – he was accompanied by Francesco Bartolozzi, an Italian drawer and engraver who drew the Miage as seen from near Arp Vieille on the opposite valley slope (Figure 13, top). There is doubt concerning the painter of the drawing; De Saussure stated "*M. Bartolozzi en avoit fait un grand tableau […]. C'est sur cette copie réduite que cette planche a été gravée*" (p. 325, Tome 2, De Saussure, 1786). In the lower corner of the engraving, however, "Bourit del." is indicated as author. From this viewpoint the spectactor beholds a panorama extending from the Col de la Seigne to the Col Ferret. In the centre of the engraving the Miage is descending from the Mont Blanc. Compared to a recent photograph (Figure 13, bottom), it appears more voluminous and fills out its lateral valley more extensively. Halfway down the moraine, a bulge represents the morainic amphitheatre comprising the *Lac du Miage*. In the distance, the lateral moraine of the Brenva can be recognized (compare Section 4.3.4).

Figure 13 : “Le Mont-Blanc vu en face du Coté de l’Allée-Blanche“ in 1781 by M.T. Bourrit or F. Bartolozzi (signed down right “Bourit del.“; down left “Adam Töpffer Sculp.“; engraving; 9.5 x 30.3 cm; Pl. V, p. 325, Tome 2, De Saussure, 1786) and in October 5th, 2009 (photograph by P. Imhof)

From 1799 we have an engraving from a drawing by Jean Bourcet (Figure 14). The rudimentary panorama of the western Mont Blanc massif most schematically shows the glaciers of the Val Veni – although the title states "plan…avec l'étendue et la direction des glaciers". The Allée-Blanche Glacier is incorrectly named "Glacier du Talèfre", which in reality is located on the north side of the massif. The glacier tongue of the Miage extends far into the Val Veni, but its division into different lobes is omitted. Four arcs in front of the terminus indicate former extensions, probably corresponding to the 1780, 1730 and 1640 advances and an additional advance by the end of the 17th century.

To summarize, the Miage Glacier attained two maxima during the 18th century. The first maximum occurred between 1700 and 1730, followed by a probably slightly smaller one during the 1780s (attested in the engraving by Bourrit / Bartolozzi, 1781). As shown in the panorama by Bourcet, the Miage has withdrawn again by the end of the 18th century.

4.3.3 Maximum advances in 1820 and around 1860

After having retreated before 1800, the Miage started to recover and advance again in the 19th century. According to De Charpentier (1841) the Miage was in a progressive phase until 1820 and the lobes started to shorten again afterwards. During this second largest advance of the LIA the left lobe was 60 m, the right lobe 120 m shorter than in 1640. Still, in the "Carta topografica degli Stati di Terraferma" based on surveys from 1823 the Miage looks considerably extended (see Section 4.2.1)

In 1826 Jules-Fréderic d'Ostervald (1773-1850) published several plates illustrating different locations of Val Veni and Val Ferret, supplemented with an explicative text by Désiré Raoul-Rochette. Besides a panorama from "Col de la Seigne" drawn by Maximilien de Meuron, the volume contains a view of the "Lac Combal et glacier de Miage" (Figure 15) by Jules-Louis-Philippe Coignet (1798-1860). Raoul-Rochette writes: "*Le glacier de Miage est un des plus imposants par sa masse et par son aspect, qu'offre le groupe gigantesque du Mont-Blanc [...].C'est un épouvantable amas de quartiers de glace et de roche, mêlés et confondus ensemble ; c'est une véritable image du chaos*". The illustration of Coignet though, is less chaotic; the moraine seems to float on the *Lac Combal*.

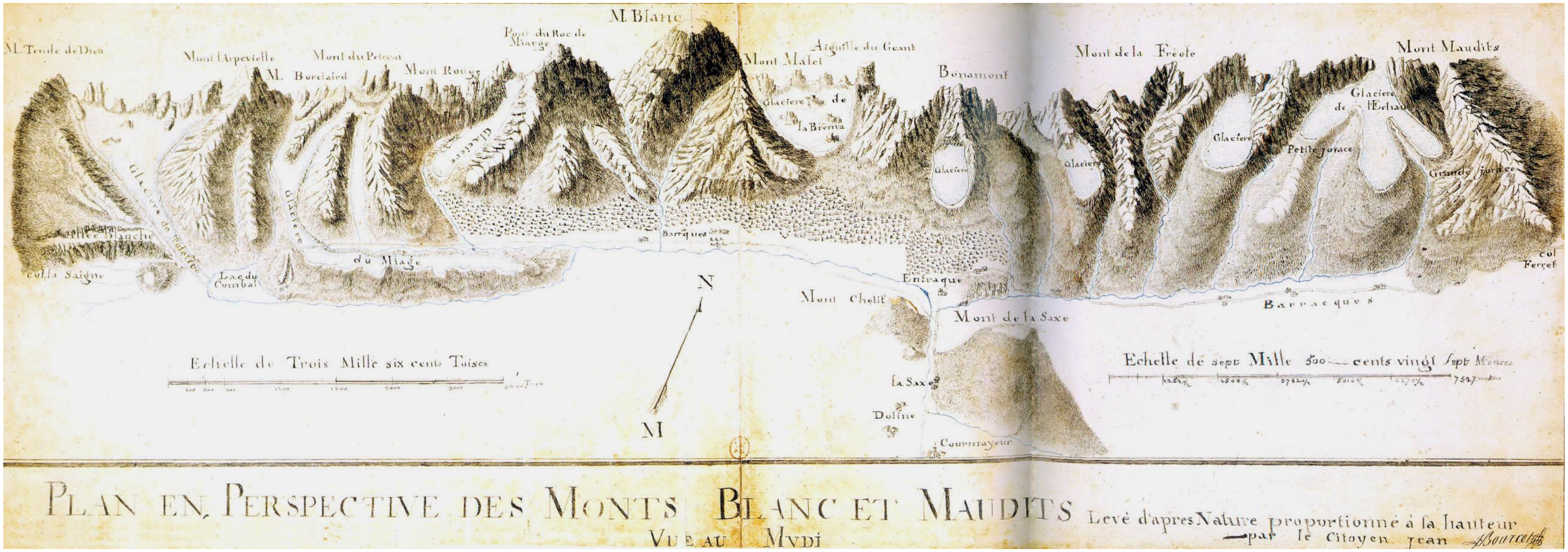


Figure 14 : Panorama of the Mont Blanc chain in 1799 ("Plan en perspective des Monts Blanc et Maudits, avec l'étendue et la direction des glaciers. Vue au Midi. Levé et dessiné par le citoyen Bourcet adjoint à la démarcation des limites, l'an 7 de la République";manuscript map; 21.0 x 71.0 cm; Paris; printed in Aliprandi & Aliprandi, 2007, p. 134)

Figure 15 : Right lateral moraine and morainic amphitheatre of Miage Glacier around 1821-22 ("Lac Combal et glacier de Miage"; signed down left "Coignet pinxt."; marked down right "Salathé sculpt."; aquatint; 14.5 x 21.0 cm; Raoul-Rochette, 1826)

In 1842 the Scot James David Forbes (1809-1868) travelled through the Alps of Savoy and visited the Val Veni where he examined the Miage and Brenva Glaciers. In his famous work published in 1843 Forbes describes: "*The moraine of the Glacier de Miage is, perhaps, the most extraordinary in the whole Alps*." (p. 191) and "*it occupies* [the valley] *for several miles in length, nearly a mile in breadth, and several hundred feet in depth.*" (p. 193).

Figure 16 : The Miage Glacier occupying the Val Veni as seen from near Peutérey in July 1842 by Forbes ("The Glacier de Miage and its Moraine"; engraving; 5.0 x 7.0 cm; p. 192, Forbes, 1843)

In an engraving Forbes illustrated “The Glacier de Miage and its Moraine” (Figure 16). The glacier looks considerably swollen and reaches down into the plain where it ends near the hamlet of Frêney. As it seems, the left lobe is longer than the right lobe, which bends towards north. Is this only an artefact attributable to the perspective? In the eye sketch Forbes did not repeat these relations of the terminus, which he drew as divided into two branches (Figure 17). In addition, according to the moraine apparatus, such a composition is not possible and the right lobe has always been the longer one. Forbes ascended the glacier and descended through the *Jardin du Miage*, but unfortunately he made no statement on the termini of the two lobes.

Figure 17 : Cartographic sketch of the lower Miage Glacier from July 1842 by Forbes (“Eye Sketch of the Glacier de Miage“; lithograph; 8.6 x 12.2 cm; Topographical Sketch N° I, p. 192-193, Forbes, 1843)

In 1854 Henri-Joseph Hogard (1776-1837) and Daniel Dollfus-Ausset (1797-1870) published their volume “Principaux Glaciers de la Suisse”. It contains a series of beautiful drawings, among them a view of the Miage (Figure 18). On this drawing it is difficult to distinguish the glacier fronts amidst the huge moraine ridges. They end at the level where the Frêney glacier descends into the Val Veni. The moraines themselves are sparsely vegetated. As is indicated in the text, the wood has been cut, possibly by the locals who used the logs as firewood. Several indications let Hogard to deduce that the glacier has once been more extensive: “*Sa hauteur* [moraine latérale droite] *un peu au-dessus de la glace, les Mélèzes qui la recouvrent, et dont quelques-une, déjà très vieux, se sont élevés* *près de troncs d'arbres plus anciens, l'envahissement de ses pentes par des plantes et des mousses, l'absence de récents déjections, tout concourt à prouver que le glacier est en retraite de ce côté et qu'il était plus puissant autrefois*". Comparing the two lobes, Hogard explains that the right lobe is protected by the north-facing mountains and the moraine, whereas the left lobe, exposed to the Sun, exhibits stronger ablation and is thus more sagged. Compared to Forbes' engraving the tongues have flattened and appear less bloated. However, as Hogard reports "*de nouvelles déjections indiquent des progrès récents et démontrent que le glacier est de nouveau en voie de progression*".

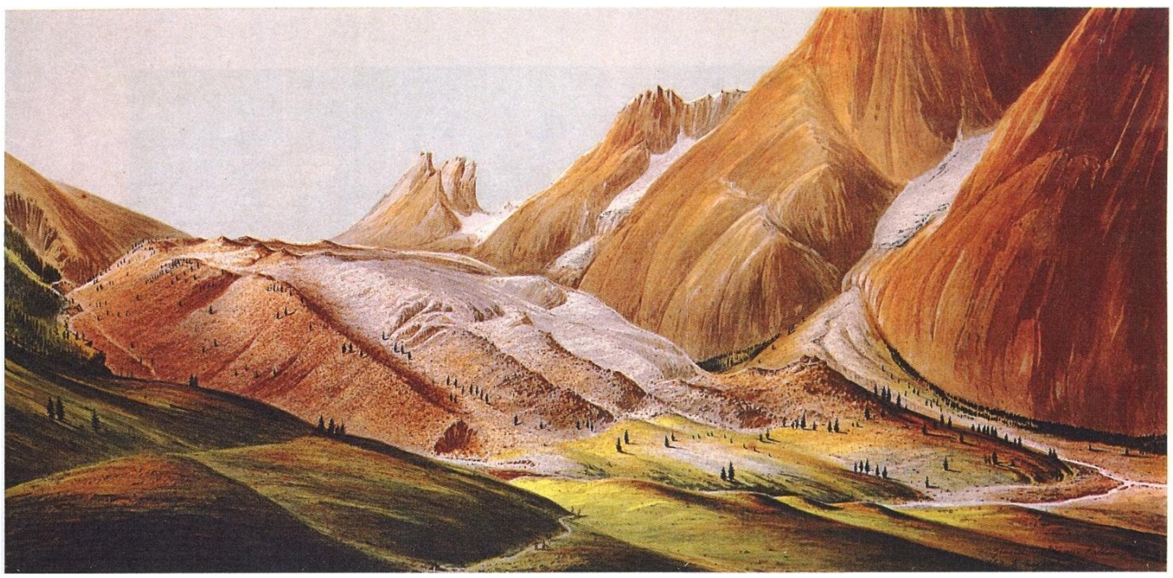


Figure 18 : Glacier snout of the Miage as seen from near Dzérottaz around 1849 by Hogard ("Glacier de Miage (allée blanche au pied du Mont Blanc)"; chromolithograph; 27.0 x 50.0 cm; graved by E. Simon, Strasbourg; Plate X, Hogard, 1854; reproduced in Vivian, 2001, p. 241)

In August 13th, 1855, S. W. King visited the Miage Glacier and described it as being covered by debris. From the path, which runs on the right external moraine, King was not able to see the glacier itself, but some blocs of ice that protruded from the moraine (King, 1858). This indicates the considerable volumetric extent of the Miage at that time. Nowadays, the glacier surface has sagged between the lateral moraines and is only visible from their crests. The advanced position of the glacier in 1856 is documented in the "Gran Carta degli Stati Sardi in Terraferma" (see Section 4.2.2.).

As proved by the moraine sequence and geometry, the Miage reached a new maximum around 1860, where he deposited moraines only 100 m (left terminus) and 288 m (right terminus) shorter than during the LIA maximum in 1640 (Deline, 1999a). During this time, Édouard Aubert (1820-1877) ascended the Allée-Blanche (Val Veni). In his volume "La vallée d'Aoste", published in 1860, he included several illustrations. One drawing shows the "Chalets de Vény" and in the background the "*gigantesque glacier du Miage*" arising as a huge ice stream. Continuing towards the *Lac Combal,* Aubert passed the right lateral moraine, which he described as bald and rocky (Aubert, 1860: 53). Thus 40 years after the 1820 maximum the moraine was still barren of vegetation.

Summarizing, the Miage attained its second and third biggest maximum during the LIA in 1820 and around 1860, respectively. The quality and number of documentation started to increase around the mid 19th century. Between 1842 and 1855 the Miage was visited and vigorously described by Forbes, Hogard and King.

4.3.4 Continuous retreat and a minor advance by the end of the 19th century

According to Viollet-le-Duc (1876) the Miage, as several other glaciers in the Mont Blanc massif, was notably retreating between 1868 and 1875. In the Viollet-le-Duc map, the glacier, especially the right lobe, seems much retreated (see Section 4.2.2)

In 1880 Baretti published a comprehensive monograph on the Miage Glacier. The work is accompanied by a map of the lower glacier that is based on measurements by Bruno and Marengo in 1879 (see Appendix 8.1, Figure 52). The well drawn map shows the three distinct terminal lobes as well as the morainic amphitheatre and prefrontal complex. The wide left terminus ends significantly higher than the pointy right terminus, which is embedded in a valley of longitudinal moraines. Measured from the point of separation of the distinct ice flows, Baretti (1880) gave a length of 1400 m for the left and 1500 m for the right lobe, respectively. Baretti reported that the terminus lay at 300-400 m from the line it had reached during its maximal extent. At the time of Baretti's study, the large lateral moraines were tree-covered to such an extent that he attributed to them an age of at least 300 years. In the right forefield Baretti found a "relative recent frontal moraine" in a distance of 200 m from the glacier terminus, as well as a completely forested ancient ridge some 50 m lower. These numbers are not consistent with the moraine crests drawn in the map. According to the map, the right front is 350 m behind the 1640 moraine, and 200 m behind the 1820 moraine (in accordance with the "relative recent frontal moraine" mentioned by Baretti). However, this is not consistent with the map by Viollet-le-Duc (the Val Veny was surveyed in 1870; Frey, 1988), where the right front is already in a distance of about 400 m and still retreating afterwards. Compared to Baretti's elaborated topographic survey the Viollet-le-Duc map is admittedly more schematic. In addition, the larger scale of the Baretti map (1:10'000 vs. 1:40'000) acknowledge it to be more reliable.

The negative phase led to a minimum which is difficult to date, but probably occurred in the early 1880s.

According to Sacco (1918) and Mayr (1969), the Miage Glacier was again advancing around 1890. This statement is supported by a moraine ridge, which Deline (1999a), using dendrochonological and lichenometrical methods, attributed to a maximum in 1890.

In 1897 Francesco Porro and Alessandro Druetti conducted a comprehensive survey of several glaciers of Val Veni and Val Ferret (Porro, 1902). On September 30 they installed a set of reference points in the Miage forefield. Compared to the descriptions of Baretti, Porro and Druetti reported a retreat of a minimum of 50 m for the right lobe and about 25 m for the left lobe over the 18 years (Porro, 1902). Though, Porro admitted that both fronts were extensively debris-covered and the position of the termini difficult to estimate.

A decade later, in September 1910, Revelli (1911) resumed the measurements made by Porro and Druetti in 1897 for seven glaciers (Estellette, Allée Blanche, Miage, Brenva, Entrèves, Toula and Pré-de-Bard Glaciers). For the Miage Glacier though, Revelli was not able to find the signals installed by Porro and Druetti. Accordingly he was not able to measure the frontal variations, but he nevertheless estimated a retreat of some decametres. Revelli measured the elevations of the fronts (middle lobe 1730 m and left lobe 1740 m a.s.l.) and installed new reference points. Thus, in 1911 he was able to quantify the retreat of the left terminus with 8 m. For the right lobe he gave an elevation of 1795 m a.s.l. (Revelli, 1912). This elevation would result in a notably retreated tongue, lying 750 m behind the 1640 moraine. Also the other elevations that Revelli indicated do not fit his descriptions according to which the glacier has retreated since 1897. Thus, considering the inevitable error range in altimetric measurements, a conversion into a horizontal distance between the terminus and the moraine is not very reliable.

The first stereoscopic relief was recorded in 1913 by Porro (1914). Using stereoscopic photographs, he produced a map at a scale of 1:5'000 with contour line intervals of 5 m. Although there seems to be an error in the altimetry, the work nevertheless, accurately delineates the glaciological relief and topography. After several sources with indirect indications (Porro, 1902; Revelli, 1911, 1912; Sacco 1918), this stereoscopic relief is a first benchmark to determine the position of the termini in the first decade of the 20th century.

Reconstructing the length fluctuations of the Miage between 1870 and 1910 turns out to be very difficult; the indications by Baretti (1880), Porro (1902) and Revelli (1911) are (1) given relative to each other and (2) inconsistent with the moraine apparatus. Referring to Baretti, Porro reports a retreat between 1879 and 1897. According to Revelli the fronts are again some decametres shorter in 1910. However, this long series of retreats does not fit the more advanced position testified by the stereoscopic relief from 1913. It is hardly possible that the Miage did not experience the advance in the 1880s signalled by all other glaciers of the Mont Blanc massif. Moreover, the lichenometry and dendrochronology prove a maximum with the formation of a moraine ridge around 1890 (Deline, 1999a). Which of the three sources (Baretti, Porro or Revelli) is incorrect is difficult to evaluate. The problem is that both Porro and Revelli do not give absolute measures, but only refer to the previous study. Momentarily excluding these two uncertain sources, the length fluctuations at the turn of the century can be summarized as follows: After a long phase of retreat initiated after 1860, both lobes attained a minimum in the early 1880s. Then, the glacier resumed its forward motion, which culminated in the formation of terminal moraines around 1890 (dated by lichenometry and dendrochronology; Deline, 1999b). Afterwards the phase was again reversed and by 1910 both lobes were in a phase of prolonged withdrawal.

4.3.5 Measurements by the CGI and long, moderate phase of retreat during the mid 20th century

In 1916/1917 Federico Sacco studied the Miage Glacier and published the results in two studies in 1917 and 1918. As a complement to the study of 1917 a map at a scale of 1:10’000 is included (see Appendix 8.1, Figure 53). The document reveals the moraine apparatus as well as the frontal positions during August 1916. On the map, the right front is separated into one main lobe and the remains of two lateral ramifications. Sacco found it difficult to define the position of this branch, but according to the map the front ends at a distance of 600 m to the Miage torrent and about 220 m behind a lake formed where the ice had ended in 1879. To quantify the variation since 1879, he estimated a retreat of 300-400 m (Sacco, 1918). This seems to be a rather big retreat and has to be relativised when considering Sacco’s apprehension of the Marengo map; He interpreted the right lobe to be 600 to 900 m behind the 1820 moraine, an improbable value when evaluating the topography of the map. Considering the left lobe, Sacco noticed that compared to 1879 it had retreated by about 70 m on its right side, but only little on its left side. In the prefrontal area he identified a series of chaotic moraine ridges. Although the fronts had retreated in the past years, Sacco concluded his observations mentioning an increase in volume and apparent signs of an expansion during the years of 1917 and 1918.

Carlo Capello measured the frontal variations between 1929 and 1961 (Bolletini CGI); measures are given annually for the left lobe, more sporadic for the right lobe. According to the measurements published in 1948 in the Bolletino del CGI, the glacier has retreated during the period of 1935 to 1944, a phase that would be prolonged until 1967. When comparing photographs from 1930 and 1971, an inconsistency becomes apparent (Figure 19). At first glance a more voluminous glacier with bloated termini can be observed in 1930 (Figure 19, left). The terminus lies in a distance of about 60 m from a recent moraine wall. Judged by the vegetation in the central part of the vacated area, the moraine probably belongs to the 1890 advance.

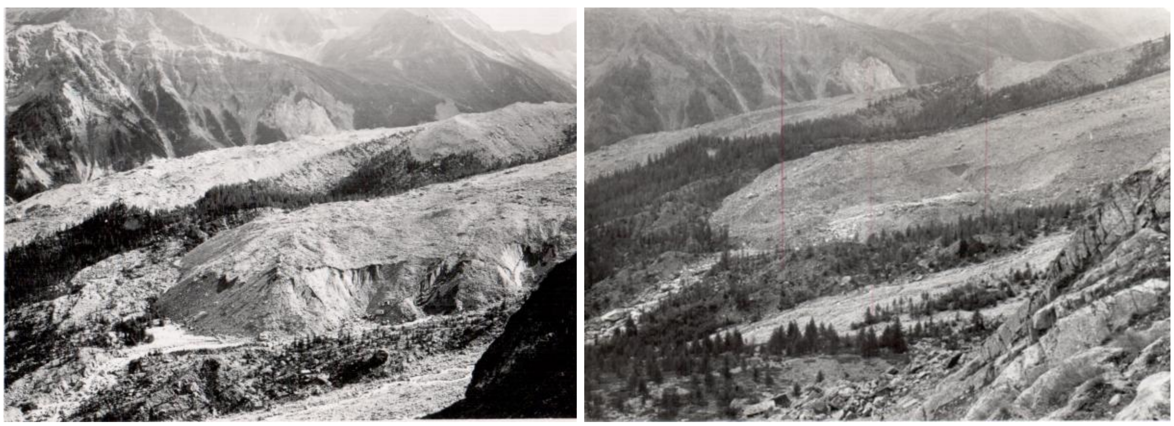


Figure 19 : The left lobe of the Miage Glacier in 1930 and in 1971 (left: C.F. Capello; 7.0 x 13.0 cm; inv. 213.01; CGI, Torino / right: C. Lesca; 7.0 x 13.0 cm; inv. 213.56; CGI, Torino)

In the photograph from 1971 (Figure 19, right) the forefield of the left tongue is covered with debris up to a line which has been free of ice in 1930. Thus, after 1930 an advance set in, bringing the front to about 30 m from the recent moraine. Then, the left lobe started to retreat again and reached its shortened position in 1971. This sequence is consistent with the measurements when inversing the arithmetic sign of Capello's measure from 1935 (advance of 39 m instead of retreat).

4.3.6 Extensive debris cover and relative stationarity by the end of the 20th century

After 1969 the measurements of the frontal variations got rare again. First, the glacier front was intensively covered with debris and its position difficult to identify. Second, the fronts remained more or less stationary and were thus of little interest. Most studies in the recent decades concentrated on altimetric variations (Smiraglia *et al.*, 2000), surface movements (Pelfini *et al.*, 2007) and debris cover (Deline, 2005). Nevertheless, some of them contain indirect information on length changes and are discussed below.

Smiraglia *et al.* (2000) suggested that there was no significant change to the terminus position between 1975 and 1991. Though, they attributed the detected change in surface area of -0.3 % to changes at the termini of the two main lobes and the calving ice wall at *Lac du Miage*. Most frontal retreat was associated with the main outwash portal of the left lobe, whereas the terminus of the right lobe had slightly narrowed. When comparing aerial photographs, Giardino *et al.* (2001) identified a growth phase, where the fronts changed from concave in 1975 to convex shape in 1988. By studying growth disturbances of supraglacial trees, Pelfini *et al.* (2007) revealed a kinematical wave that crossed the glacier in the 1980s. The results of these different studies coincide with the observations of the CGI, who reported that the glacier was advancing between 1983 and 1987. Thus, by the end of the 1980s a kinematical wave reached the fronts, which in consequence started to swell and advance.

In the last two decades the Miage persisted in a stage of apparent immobility. Minor reductions in volume in the years before 1995 were reported by Landry (1996). The right lobe though, continued its slight advance up to 2001. In 2005 the lobes were in a distance of 345 m (left front) and 550 m (right front) from the 1640 moraines.

Presently (fieldwork; July 2009) the Miage presents itself as follows: both lobes are extensively debris-covered. In addition, the right lobe is sparsely vegetated with larches. Whereas the left lobe exhibits a glacier cavern and is the source of the Miage river, no superficial melt water stream exits the right lobe.

4.3.7 Two length change curves for the Miage Glacier

As described in the previous Sections, documentary as well as geomorphological data have been applied to reconstruct two curves depicting terminal fluctuations of both terminal lobes of the Miage Glacier (Figure 20). Fluctuations before the 19th century were adopted from Deline (1999a) and complemented by own results. The period of continuous measurements is short (1930-1970), and less frequent for the right lobe (blue curve).

Every inflexion point of the curve corresponds to a piece of evidence (e.g., moraine, painting, written account, instrumental measurement etc.) and reflects a mean value with the most likely position of the glacier front. The characteristics of the main historical documents used to reconstruct the length change curve are listed in Table 6 (see Appendix 8.1). Each determination of the front position has a certain error, which is indicated on the graph. This error depends on the quality of the data source, but also on the interpretation of the data, which was reduced to a minimum by selecting reliable sources. The uncertainty of the reconstructed glacier length curve is increasing going back in time. Though, even where the error is high, the curve is able to reflect the general position of the glacier front. Probable advances during the 17th century are deduced from indirect evidence (e.g. outbursts of Lac de Combal) and indicated by an arrow.

Indirect evidence suggests that the first LIA advances occurred in the Late Middle Ages. By the end of the 16th century the glaciers on the Mont Blanc massif concomitantly started to swell and adopt the general big extension that they would maintain over the whole LIA. According to dendrochronological evidence the Miage attained its LIA maximum in 1640. The moraines accumulated during this maximum reached down to 1620 m a.s.l. (they serve as reference points to quantify the subsequent fluctuations). The Miage reached its second maximum in 1820, at a time when the other glaciers of the Val Veni and Val Ferret reached their LIA maximum. Subsequently, minor advances occurred around 1860, 1890 and in the mid 1930s. The amplitude of the LIA fluctuations is small; whereas the right lobe has retreated about 600 m since the LIA maximum, the left lobe has shortened by less than 400 m.

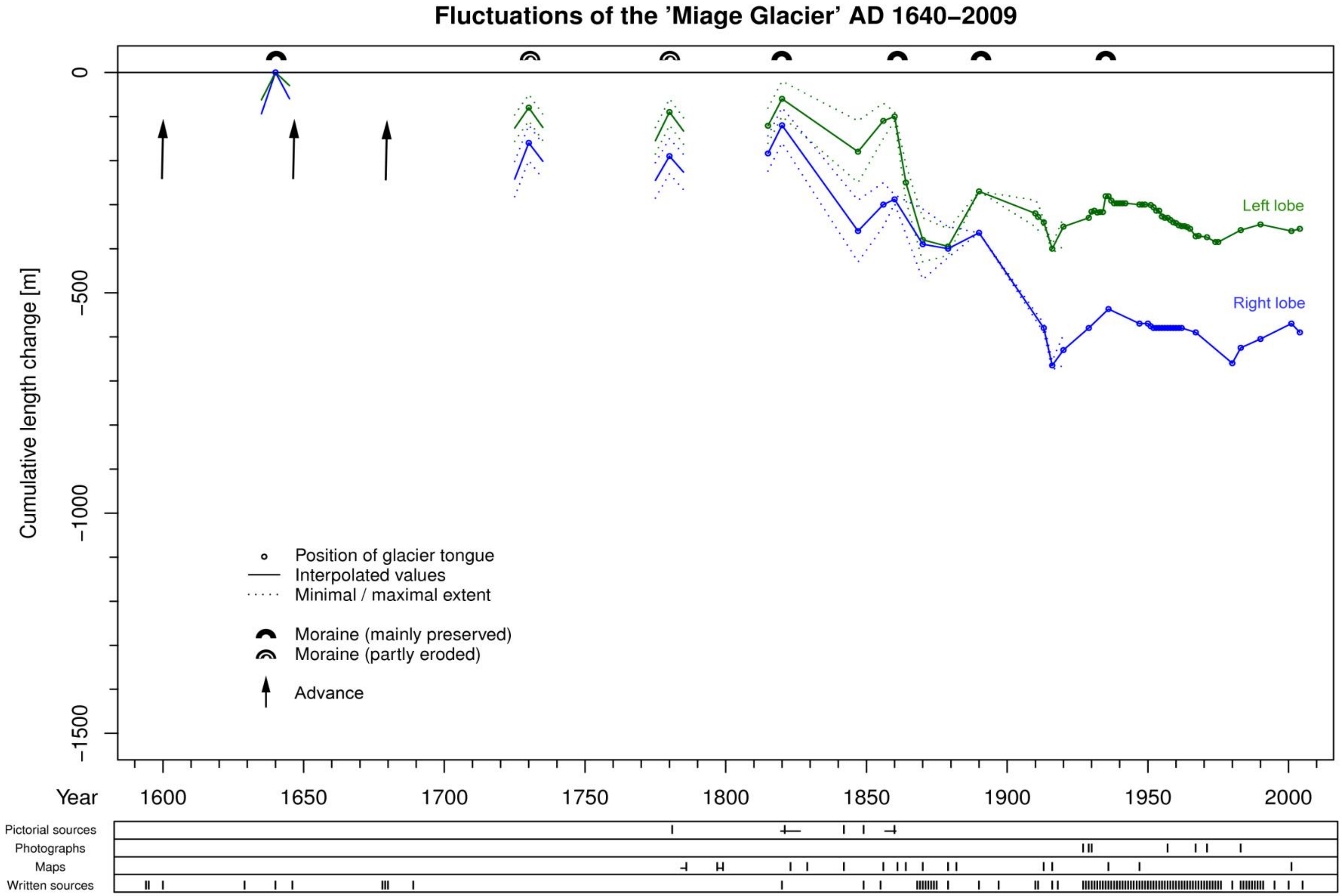


Figure 20 : Cumulative length fluctuations of the Miage Glacier from 1640 until 2009. Front positions of both lobes are given relative to their corresponding LIA maximum position in 1640 (=0). The error range (min, max) is shown by the dotted line. Probable advances before the 18th century are indicated by an arrow. Each inflexion point corresponds to a reliable source, listed in the box below the x-axis. Uncertainties concerning the dating of a document are indicated by a small horizontal line. The dating of the moraines is based on Deline (1999b) and Aeschlimann (1983).

4.4 Length fluctuations of the Brenva Glacier

The Brenva Glacier is among the best known glaciers in the Italian Alps. As the glacier reaches low elevations and ends near the village Entrèves, it has always been a central landmark in the inhabitants' environment. Accordingly, its terminal fluctuations have been observed and documented for several centuries. The abundance of documentary material allows a detailed reconstruction of glacier fluctuations, even though the moraine system has only been partly preserved.

4.4.1 Brenva Glacier foreland and LIA moraines

The forefield of the Brenva Glacier has a rather simple composition with few terminal moraines. Terminal moraines built prior to the 19th century were overrun by the LIA maximum expansion in 1818. New moraines formed in subsequent smaller advances (e.g., in 1850 and the 1890s) were superimposed during the rock-avalanche triggered glacier advance between 1920 and 1940 (cf. Section 4.4.9). As Mayr (1969) reports they have been re-exposed in the 1960s without any significant changes. Unfortunately, extensive parts of the historical moraine apparatus have been destroyed in the late 1960s for gravel exploitation. Today, only erratic boulders from the LIA maximum advance in 1818 and lateral moraines from the anomalous 1940 advance remain. In addition, the frontal area contains several small, weakly developed moraines of recent formation. Figure 21 shows the frontal area and the different moraines of the Brenva Glacier. For illustration, the moraines are also shown in an aerial photograph in Figure 55 (see Appendix 8.1).

The valley tongue of the Brenva Glacier is embedded in enormous lateral moraines, crossing the lower Val Veni over a length of 1.5 km. Near Perthud, the right-lateral moraine reaches a height of 200 m, and extends over a width of 600 m (measured horizontally from the moraine crest to the foot of the slope). The right-lateral moraine of the Brenva was built not only by glacial processes, but also by a high frequency of successive rock avalanches during the Holocene (Deline, 2001). On the proximal slope of the upper right-lateral moraine, Porter & Orombelli (1982a) found a fossil tree stump dated to a calendar age of AD 760-980. This points to an advance of the glacier between the 8th and 10th century. As the dated sample lay only 8 m below the crest of the 150 m high moraine, the results suggest that the moraine consists of a succession of sedimentary accretions of multiple advances extending well back beyond AD 1000. Another wood sample with an age of 285

± 60 yr BP indicates a possible advance between AD 1520 and AD 1670 (Porter & Orombelli, 1982a). After all, the lateral moraines were superimposed during the LIA maximum in 1818, but also during the 1850 and 1940 advances. In the forefield of the Brenva Glacier no moraines built prior to 1818 can be found. But as the Miage Glacier was advancing around 1600, 1640 and 1678-80, it is probable that also the other Italian Mont Blanc glaciers and thus the Brenva knew these advances.

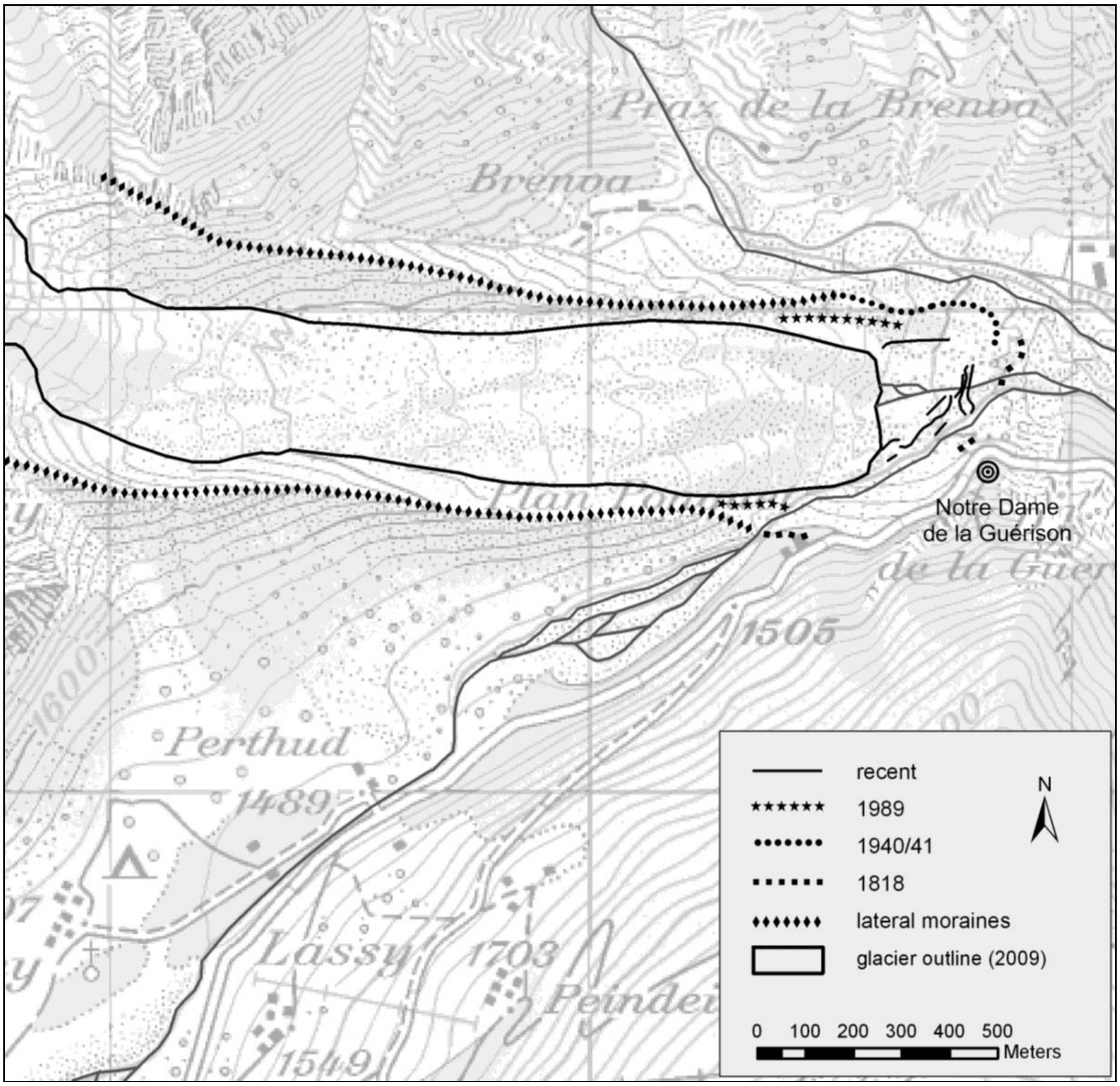


Figure 21 : Map of the Brenva frontal area with lateral and frontal moraines (after Valbusa, 1927; Capello, 1941; Porter & Orombelli, 1982a; Cerutti, 1985. Map: Swiss Map 50, V4; swisstopo, 2004).

4.4.2 The Brenva Glacier and the destruction of St. Jean de Pertuis in the late Middle Ages

It is told that in former times a village named St. Jean de Pertuis lay near the site of modern Purtud, on a plain where today the right lateral moraine of Brenva Glacier is extending (Virgilio, 1883). The legend says that local people instead of honoring St. Margaret's Day on July 15th were cutting their hay. The following day the glacier came down, overwhelmed the village and buried everyone. Alternative accounts mention the existence of the village of St. Jean de Pertuis in front of the chapel of Notre Dame de la Guérison (Dollfus-Ausset, 1867). According to Dollfus-Ausset the village was destroyed by a landslide or rockfall and was subsequently overridden by the Brenva – an interpretation that is consistent with the history of Brenva Glacier and the rockfall activity in the area. As to the dating of this event, evidence is missing; Sacco (1918) suggested that the village was destroyed in the 16th century. Le Roy Ladurie (1971) proposed that the destruction must have occurred in the 12th or 13th century, because although St. Jean de Pertuis is said to be the oldest parish in the region, its name does not appear on any parish list of the Aosta Valley in the late Middle Ages.

4.4.3 A threatening glacier in the 17th century

By the end of the 16th century the glaciers on the Mont Blanc massif concomitantly started to swell and adopt the general big extension that they would maintain over the whole LIA (see Section 4.1). On April 6th, 1600 Jacques Cochet of Les Bois (hamlet near Mer de Glace) visited the notary Blanc in Aosta to inquire if it was true that the parish of Courmayeur had requested the Pope to pray that the glaciers might withdraw. And he wanted to known whether the Italian glaciers, and particularly the Brenva, had recently retreated to the great relief of the people living nearby. Notary Blanc replied that the people of Courmayeur had not appealed to Rome and the glaciers had not retreated but were as threatening as ever (Le Roy Ladurie, 1971). This text is of uttermost importance, as it shows that on both the French and the Italian sides of Mont Blanc the glaciers had extended so far by the beginning of 17th century that the people were in panic.

An interesting note is the report from Giulio Rogiero, conserved in the state archives of Turin. Rogiero visited the village Courmayeur on May 8th, 1631 and reported that he was not able to arrive into *Lasblangia* (Allée Blanche) because of the enormous quantity of snow present there (Aliprandi & Aliprandi, 1986).

In 1691 Philibert-Amédée Arnod, member of the Conseille des Commis, highest organ of the government of the Duke of Aosta, was appointed by the King of Savoy to write a report about the strategic access to the Val Aosta territory. In the manuscript that would not be published until 1968, Arnod described the Val Veni and its glaciers. Regarding the Brenva he reported that the glacier closed the great plain named "*Veyni*" and "*Fresnoz*" and that the valley ended with a very narrow passage at "*La croix du Berrier"* (where in the 18th century the chapel of Notre Dame de la Guérison would be built) (Le Roy Ladurie, 1971). Thus, when Arnod descended the Val Veni in 1691, he could already see from the distance the white ice masses of the Brenva Glacier which were far advanced across Val Veni and nearly closed the entry of the valley.

To summarize, the 17th century was documented by individual accounts hinting to the advances of the Brenva Glacier. The Brenva reached far across the Val Veni and the people living in the nearby villages were frightened by the enormous ice masses blocking the valley. In accordance with the Miage Glacier, the Brenva most probably reached maximal extensions around 1600, 1640 and 1678-80 (see Section 4.3).

4.4.4 First artistic works on the Brenva and beginning advance by the end of the 18th century

For the glacier fluctuations during the 18th century little evidence is available, as the corresponding moraines were eroded by the 1818 advance. As the Miage Glacier built terminal moraines around 1730, it is probable that also the Brenva knew this maximum. The second maximum of the 18th century at the Brenva is relatively well documented.

A first historical document is given with the drawing by François Jalabert from 1767 (Figure 22), published as an engraving in De Saussure (1786). On the engraving, the moraine is covered with larches, an indication that it has not been overrun by the glacier for several decades. In the lower right corner huts of the farmers, who cultivated the fields near the glacier, are depicted. De Saussure found the chapel of "*Notre Dame de Bon Secours*" destroyed and attributed it to the superstition of the locals. According to Aliprandi & Aliprandi (1986), the chapel was destroyed by the pastor of Courmayeur himself, after having had a contestation with the constructor of the chapel concerning the appropriation of the oblations. As De Saussure (1786) remarks, the Dora di Veni emerges from the glacier in the lower middle part of the drawing. However, Deline (2005) argued that the drawing exhibits a rock avalanche. Indications are the rocks on the lower tongue and the glacier overflowing the lateral moraine. Considering this possibility, the ice masses on the other side of the Dora are part of the rock avalanche that has been undercut by the river. Also, Forbes disbelieved that the Dora passed under the glacier: "*It seems almost certain that at that time the Doire did not pass under the glacier at all, but in front of it*" (p. 204). Thus the extent of the Brenva in 1767 has to be considered similar to its 1923 position (also shortly after a rock avalanche).

Figure 22 : The Brenva Glacier as seen from Notre Dame de la Guérison in 1767 by Jalabert ("Vue du Glacier de la Brenva" Jalabert del., marked down right "Töpfer Sculpsit"; engraving; 21.5 x 33.7 cm; Pl. III, p. 286, Tome 2, De Saussure, 1786)

On August 18th, 1776 Marc-Théodore Bourrit (1739-1819) from Geneva visited the Brenva glacier and noted: "*Le lit de ce glacier est d'une lieue* [about 4 km] *de large, de sorte que le torrent, qui descend de l'Allée Blanche, se perd sous les glaces, d'où il sort ensuite par une arche de glace d'une beauté extraordinaire*" (Bourrit, 1776: 54). Thus, in 1776 the Brenva probably reached the rock buttress of Mont Chétif, so that the Dora di Veni was forced to flow subglacially.

14 years after its first visit, De Saussure returned to the Val Veni in 1781, this time accompanied by M. Bartolozzi, who took a drawing of "Le Mont-Blanc vu en face du coté

de l'Allée-Blanche". Besides the Miage on the centre of the image (Figure 13), the Brenva can be recognized in the distance. Apparently the voluminous glacier rose above the moraine crest and spilled across the upper part to reach the valley floor, similarly to the drawing by Jalabert. The engraving shows the Brenva around the time of the maximum.

Five years later, the glacier has apparently retreated. The map by M.A. Pictet published in 1786 (Section 4.2.1) depicts the Dora di Veni detached from the glacier, flowing freely.

A drawing by Jean-Antoine Linck (1766-1843) from 1795 shows the Brenva in a clear distance from the path to the Val Veni. High up on the rock, the old chapel that would be destroyed in the 1818 advance is depicted. The glacier itself is highly crevassed and swelled over the whole extent. In addition, the *Pierre à Moulin* is very small and nearly swallowed by the ice masses. It can be suggested that the glacier was much more voluminous compared to 1767 and today. The terminus of the apparently advancing glacier seems to be at a similar position as in 2000.

Figure 23: The Brenva as seen on the way to Notre Dame de la Guérison in 1795 by Jean-Antoine Linck („Le glacier de la Brenva et l'arête de Peuterey"; signed down right; pencil, white chalk on beige paper; 41.0 x 56.0 cm; Annecy, Collection Paul Payot; printed in Conseil Géneral de la Haute-Savoie, 1990, p. 45)

According to the map by Raymond, the Dora was detached from the ice around 1797 (Section 4.2.1). The distance to the river was also indicated by Bourcet in 1799. In the crude panorama of the Mont Blanc chain (see Section 4.3.2, Figure 14) the Brenva Glacier is reduced to its upper part, including the *Pierre à Moulin*, but lacking its valley tongue.
Summarizing, it can be said that the Brenva after a probable maximum around 1730, reached another maximum around 1780, where the swollen, highly crevassed glacier superimposed the river Dora di Veni. In the final decade though, the Brenva retreated again and detached from the river.

4.4.5 The well-documented LIA maximum in 1818

Contradictory statements exist as to the position of the front of the Brenva Glacier for the years before the LIA maximum. A contemporary account is given by D'Aubuisson (1811): "*Il y a quelques années qu'il s'avançait vers le hameau* [d'Entrèves] *et menaçait de le détruire; mais il a pris une marche retrograde, et il en est aujourd'hui à mille mètres environ*" (p. 255) and he adds that the front stands at 1440 m a.s.l. However, as Favre (1867) reports, in 1852 the canon Carrol from Aosta gave for this time a distance of 2000 m from Entrèves and only in 1818 a distance of 1000 m from the village. The 1818 frontal moraines lie at a distance of 1 km from Entrèves, which partly proves Carrol's statement right. However, it is unlikely that the glacier advanced 1000 m in six years. According to the frontal elevation of 1440 m a.s.l. indicated by d'Aubuisson, the front was about 360 m behind the 1818 maximum extent. Apparently, in 1810 the Brenva was in a withdrawn position and only afterwards started its advance for the LIA maximum.
In October 7th, 1817 the Brenva was visited by H.A. Fortescue who took a drawing on the path to the chapel. The ice masses are clean and highly crevassed. The icefall at *Pierre à Moulin* shows only one rock exposure.
In 1818 the Brenva Glacier attained its LIA maximal expansion, which is documented by several sources (e.g., Venetz, 1833; Forbes, 1843; Virgilio, 1883). An important witness statement was delivered by the abbot Menabrea, pastor of Courmayeur: „*Le glacier de la Brenva ayant augmenté considérablement de volume depuis le commencement du siècle vient s'adosser contre la montagne sur laquelle était bâtie la chapelle; il travailla cette montagne avec une force si incroyable, qu'il souleva d'enormes masses de rocher de cette montagne surtout vers le sommet, où la chapelle était assise. Celle-ci ayant les fondements ébranlés, ses murs laissèrent voir des crevasses de toutes parts. C'est*

pourquoi on jugea prudent de n'y plus laisser entrer personne et le 2 juillet 1819 le curé Atalle […]*, accompagné du peuple réuni en procession monta à la dite chapelle et fit emporter tout ce qu'il y avait encore.*" (Virgilio, 1883: 67). As Forbes (1843) specified, the potent ice masses overtopped the rock with a height of 300 feet (about 91 m) and damaged the chapel standing on it.

Ignaz Venetz (1788-1859) travelled to the Val Veni and Val Ferret in August 1820. Venetz (1833) reports that the Brenva (as also the Lex Blanche, Frébouge and Pré-de-Bard Glaciers) was no more advancing, but has retreated about 15 m since the maximum. He observed larches with 220 tree rings that the advancing ice had overrun in 1818.

Hans Conrad Escher von der Linth (1767-1823) visited the Brenva shortly after its LIA maximum in 1820. „Der gewaltige Brenvagletscher", as Escher von der Linth refers to the glacier in its travel notes, is illustrated as a wave of clean and crevassed ice of a thickness outreaching today's by many metres (Figure 24). The drawing was taken at Plan Ponquet, showing the right side of the valley tongue with the lateral moraine, which apparently was barren of vegetation.

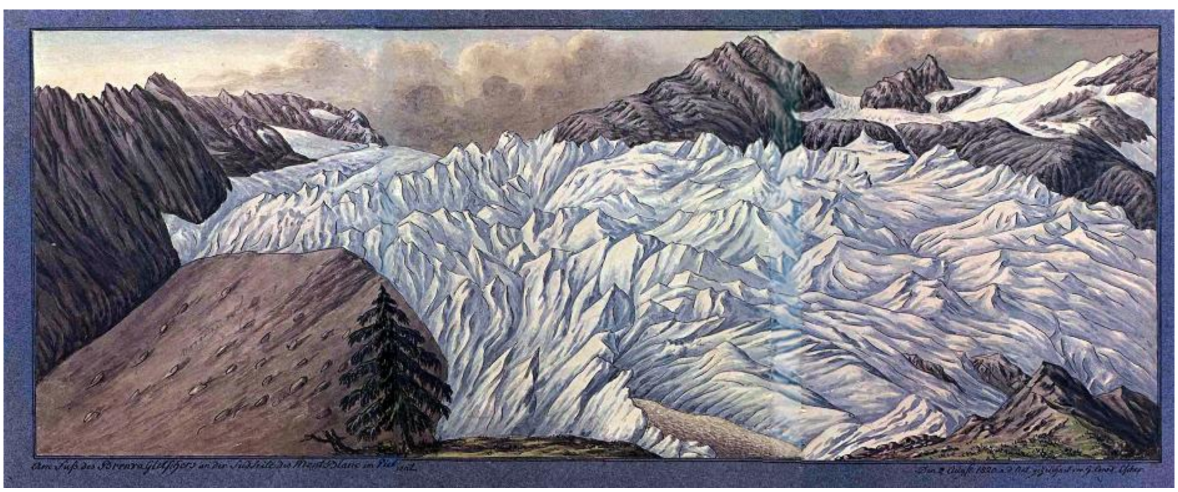


Figure 24: "Der gewaltige Brenvagletscher" as seen from Plan Ponquet in 1820 by H.C. Escher von der Linth ("Am Fuss des Brenva Gletschers an der Südseite des Mont Blanc im Piemont"; marked down right „Den 2. Augst 1820. n.d. Nat. gezeichnet von H. Conrd. Escher."; pencil, pen, watercolour; 20.7 x 51.6 cm; printed in Solar & Hösli, 1974, No. 144)

From around 1821-22 we have a drawing by Jules-Louis-Philippe Coignet (1798-1860), where the glacier is seen from a view point near La Saxe in the valley of Courmayeur (Figure 25). The glacier reaches far into the plains of Entrèves. The accompanying text published in Raoul-Rochette (1826), states that since the last advance some years ago, the glacier has retreated to the flank of the opposing mountain, leaving an amassment of stones in the formerly occupied gorge.

A contemporaneous view as seen from Courmayeur was published in the travel journal of William Rose in 1827. The ice masses flowing out of the Val Veni indicate that at this time the glacier terminus was clearly visible from Courmayeur. The accompanying text states: "*The river Doria runs under it* [Brenva Glacier]*, foaming and roaring, and forms an arch of ice very much resembling that at the source of the Arveiron*" (Rose, 1827: 102).

A first distant view of the Brenva from the east is given with the aquatint by Alphonse Dousseau drawn on August 6th, 1839. The drawing depicts the whole Val Veni as seen from the Monte della Saxe. It illustrates the glacier flowing down from the Mont Blanc and reaching the valley floor. The terminus is considerably distant from the foot of the Mont Chétif, and has retreated more than 200 m since 1818.

Figure 25 : The Brenva as seen from La Saxe around 1821-22 by J.L.P Coignet ("Le Mont Blanc vu de la vallée de Courmayeur"; signed down left "Coignet pinxt."; marked down right "Salathé sculpt."; aquatint; 14.5 x 21.0 cm; Raoul-Rochette, 1826)

Summarizing, after considerable advances since the turn of the century, the Brenva Glacier attained its LIA maximal extension in 1818. The glacier front rose to the level of the chapel Notre Dame de la Guérison and damaged it. Whereas the documentary evidence before this maximum is scarce and contradictory, the maximum itself is exceptionally well documented by pictorial documents and written accounts.

4.4.6 The second maximum of the 19th century in 1850

After the LIA maximal extension in 1818, the Brenva entered in a short phase of retreat that lasted until the early 1840s. Then the direction of movement was inversed again. The Brenva prepared itself for a new advance that would bring the front to only a few metres from the 1818 maximum.

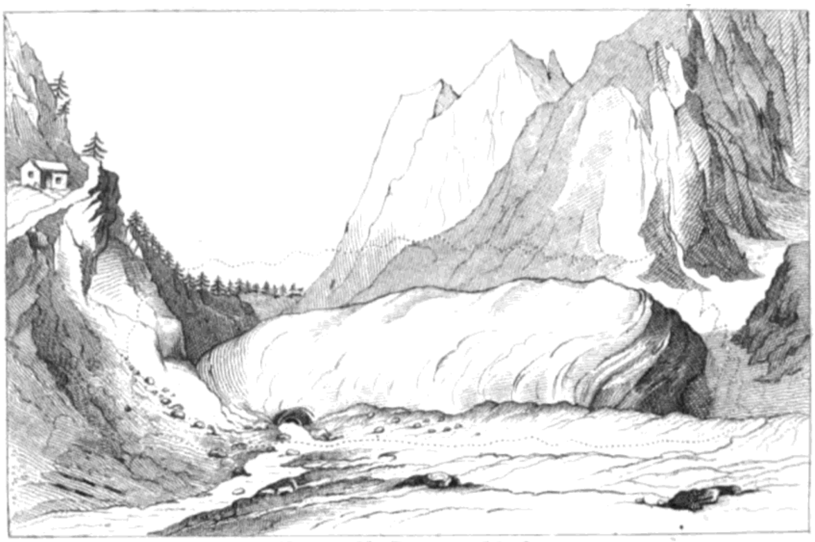
In 1842 J. D. Forbes (1843) reported that the Brenva had undergone remarkable changes in dimension since 1818. He found the ice of the glacier abutting against the foot of Mont Chétif, as can be observed in his drawing from near Entrèves (Figure 26). Though, the glacier no longer threatens the chapel Notre Dame de la Guérison. The rounded tongue spans the Dora, which exits an arch that appears rather small below the immense ice masses.

Figure 26 : In 1842 the glacier tongue touches the rock buttress of Notre Dame de la Guérison ("The glacier of la Brenva in the Allée Blanche, from Entrèves." signed down left "Drawn from Nature by Professor Forbes. T. Pichon lith", down right "Day. Highe. Lith. to the Queen"; lithograph; 13.7 x 21.0 cm; Pl. IV, p. 200-201, Forbes, 1843)

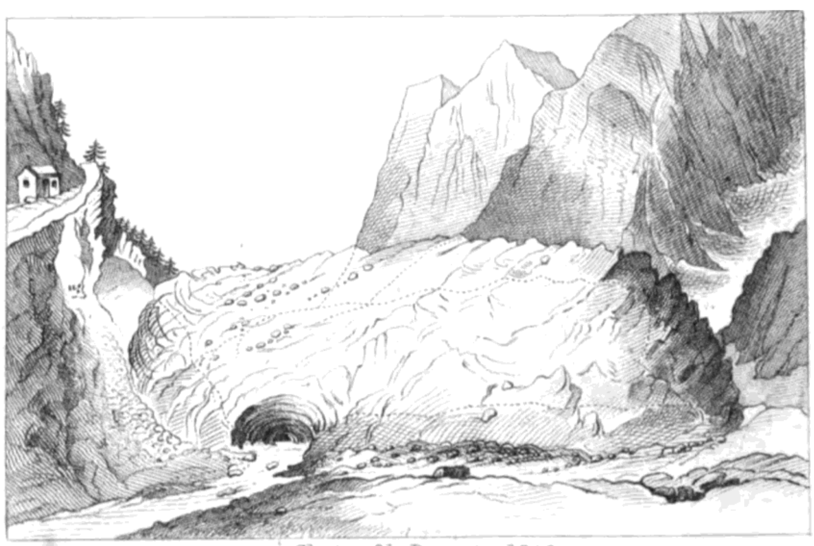
In a second lithograph, Forbes illustrated the glacier's right lateral valley tongue showing its veined structure with alternating "bluish-green and greenish-white bands" (Figure 27). The ice protrudes from the right lateral moraine. The proportions of the glacier become evident when looking at the path and the people ascending it (in the lower left corner). In a topographic sketch (see Appendix 8.1, Figure 56) Forbes documented the position of the valley tongue during his first visit. He included the outline of the area that the glacier occupied during its LIA maximum in 1818.

Figure 27 : The ice stream of the Brenva tongue illustrated by Forbes in 1842 ("Glacier of la Brenva. Shewing the structure of ice."; signed down left "Drawn from Nature by Professor Forbes. L'Highe lith", down right "Day. Highe. Lith. to the Queen"; lithograph, blue watercolour; 13.7 x 21.0 cm; Pl. V, p. 202-203, Forbes, 1843)

Four years later Forbes returned to the Brenva. As depicted in the lithographs by F. Schenk (after drawings by Forbes), the voluminous front is exceedingly crevassed. The glacier has undergone a significant increase in length and height since 1842 (Figure 28). Forbes, Carrel and Guicharda quantified the advance with 60 m, with the terminus standing now at 91 m from the 1818 moraine. Forbes designated as the cause of the advance the great snow falls during the winters of 1843/44 and 1844/45 and the cold wet summers following them.



Glacier of la Brenva in 1842



Fr. Schenk 4 St Andrew Sq Edinburgh. Glacier of la Brenva in 1846

Figure 28 : Comparison of the terminus in 1842 and August 6th, 1846 as seen from Entrèves by Forbes (”Glacier of la Brenva in 1842”, ”Glacier of la Brenva in 1846.”; marked down left “Fr. Schenk 4th St.Andrew Sqr. Edinburgh”; lithograph; both 8.4 x 12.8 cm; Fig. 1 & Fig. 2, Pl. VII, p. 177, Forbes, 1859)

A coloured lithograph by Henri-Joseph Hogard (1776-1837) from August 27th, 1849 depicts the Brenva from the south, with a frontal view of the *Pierre à Moulin* (Figure 29). The coherent icefall is interspersed by two distinct rock exposures in the middle part, from which two medial moraines depart. The right lateral moraine is displayed as a whole, showing only sparse vegetation cover. The surface of the valley tongue lies slightly below the level of the moraine crests, whereas the terminus apparently reaches the south slope of Val Veni. In his later work Hogard (1858) published a sketch (see Appendix 8.1, Figure 57) most probably taken during the same visit in August 1849. It is a detailed view of the right lateral moraine, which is partly covered by larch trees that the voluminous ice masses are overturning.

Figure 29 : The Brenva Glacier as seen from Peindein in August 8th, 1849 by Hogard ("Glacier de la Brenva"; coloured lithograph; 35.5 x 66.0 cm; graved by J. Bürck at E. Simon, Strasbourg; Hogard, 1854; printed in Noussan & Priuli, 1985, No. 268, p. 193)

From 1849 we have the first photograph of the Brenva: A daguerreotype by Jean-Gustave Dardel (1824-1899) that exposes the upper part of the *Pierre à Moulin (*Figure 30). Dardel was in the service of Daniel Dollfus-Ausset (1797-1870), who worked with different photographers on the typology of Swiss glaciers.

Figure 30 : The *Pierre à Moulin* in the first photograph of the Brenva from August 1849 by J.-G. Dardel ("Mont Blanc, 4811 m"; inversed daguerreotype; 8.0 x 10.6 cm; printed in De Decker Heftler, 2002, p. 18)

In 1850, the Brenva attained a maximum for the second time in the 19th century (e.g., Virgilio, 1883). As the following documents demonstrate, this advance brought the glacier terminus to a point only 40 m distant from its 1818 position.

The eremite of Notre Dame de la Guérison documented that in 1850 the glacier surface rose up to a few metres below the level of the chapel (Virgilio, 1883). After 1818, the Brenva apparently reached the chapel for a second time, this time though only threatening to destroy it.

A drawing by Andrea Gastaldi (1826-1889) depicts the Brenva during this big extent in 1850 as seen from Peutérey (Figure 31). Compared with the lithograph by Hogard, the ice surface has risen above the crest of the right lateral moraine, which is still sparsely wooded.

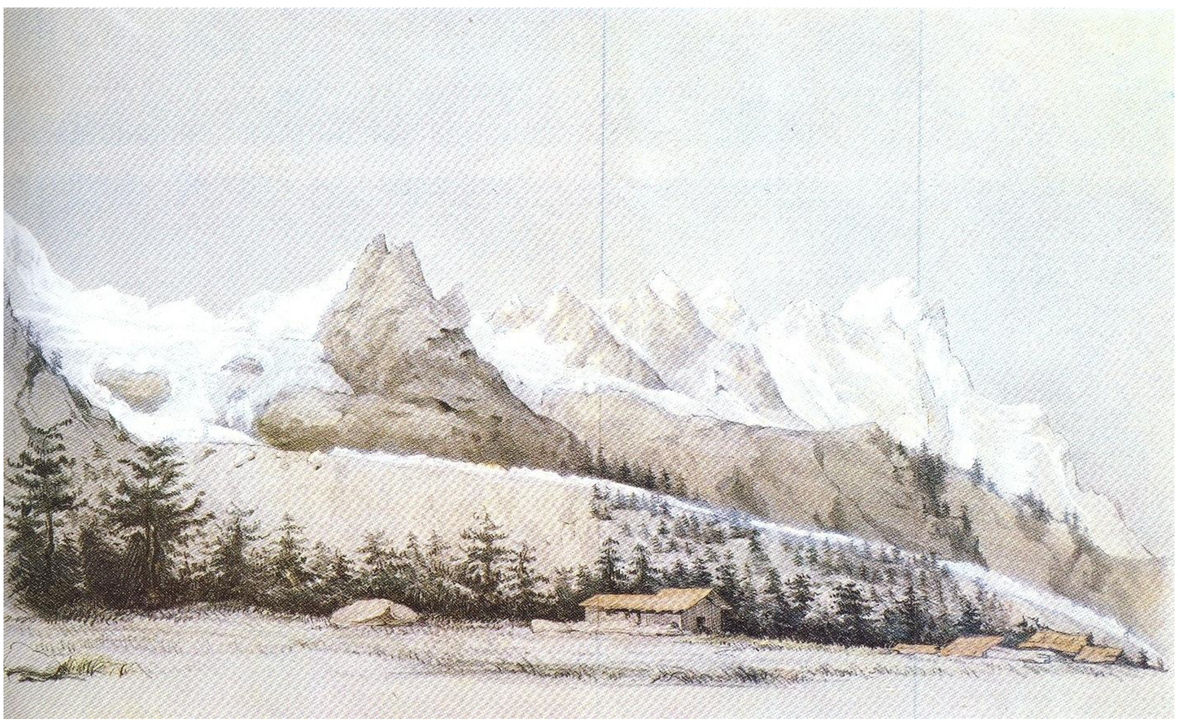


Figure 31 : The Brenva Glacier as seen from Peutérey in 1850 ("Estremità della morena laterale destra della Brenva vista dalla sega meccanica.", signed down left "A. Gastaldi dis.", marked down right "Lit. F.lli Doyen & C."; lithograph; 19.2 x 31.5 cm; B. Gastaldi, 1853; printed in Noussan & Priuli, 1985, No. 269, p. 193)

Probably from the same year we have a drawing by Gabriel Loppé taken from the path leading to the chapel Notre Dame de la Guérison (reproduced in Peyrot, 1983, p. 105). Although the *Pierre à Moulin* is not very accurately drawn one can register the big extent of the valley tongue, occupying the valley floor. Compared to the drawing by Linck from 1795, taken from approximately the same position, the glacier reaches further down the valley.

A third drawing from 1850 by Téophile Ladner shows the Brenva from a point of view near Entrèves (Figure 32, left). In the front of the picture a bridge crosses the Dora di Val Ferret and in the distance the village of Entrèves can be seen. The glacier extends well into the valley floor and comes to a halt near the farmlands, where the Dora di Veni exits the voluminous tongue through an arch. The *Pierre à Moulin* escarpment is well covered with ice. Considering this illustration, the terminus probably lay only some 40 m behind the 1818 moraine. The accuracy of the drawing becomes evident when comparing it with a photograph from 1929. Compared to 1929, the *Pierre à Moulin* is more extensively covered with ice and the swollen glacier tongue projects about 150 m further down the valley in 1850.

Figure 32 : The Brenva descending from the Mont Blanc as illustrated by Ladner in 1850 ("Mont-Blanc (Hauteur 4,810. m)"; lithograph (?); 11.5 x 8.6 cm; Ladner, 1851) and in a photograph by M. Bossolasco in June 5th, 1929 (10.0 x 7.0 cm; inv. 219.182; CGI, Torino)

A beautiful wood engraving from August 1855 by Samuel William King (1821-1868) shows the ice cavern of the Dora that emerges from the Brenva Glacier (Figure 33). In front of the ice cavern two persons are depicted on a "*pile of rude blocks which had been left by the receding glacier*" and that the glacier had touched in 1854. Considering the amount and size of the blocks, they are supposed to belong to the moraine of the 1850 maximum. King's guide, Otto Laurent from Courmayeur reported that in 1849 the glacier nearly gained the expansion of 1818, reaching up to the path beneath the chapel. In 1855 the glacier had retreated by 45 m from the pile of blocks and ended significantly below the path (King, 1858).

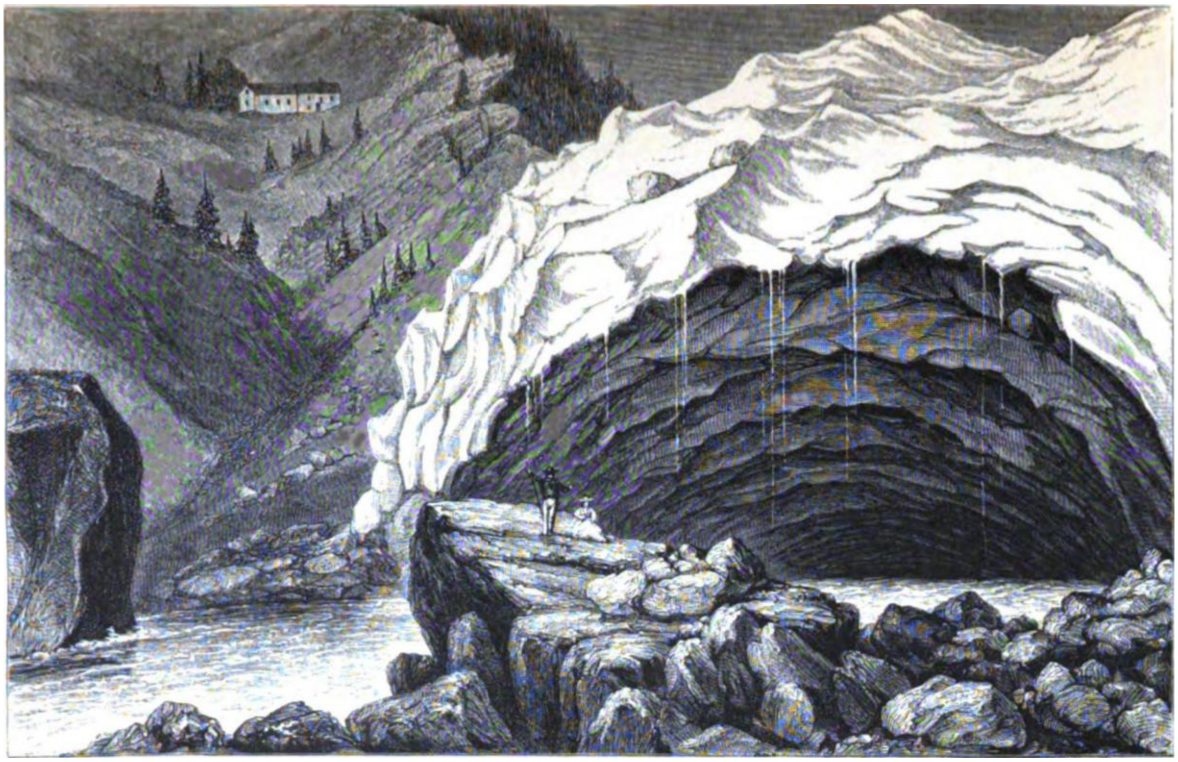


Figure 33: The Ice cavern of the Doire in August 1855 ("The Glacier of la Brenva – Val d'Entrèves", "Notre Dame de Bons Secours", "Ice Cavern of the Doire"; signed down left "S.W. King, Deli."; wood engraving; 9.3 x 14.8 cm; p. 51, King, 1858)

In 1860 Aubert wrote about the Brenva: "*dans une gorge assez étroite, […] s'entassent les pics de glace du glacier de la Brenva*." (Aubert, 1860). Thus in 1860 the glacier still reached close to the Notre Dame de Guérison escarpment.

The second known photograph of the Brenva Glacier was taken by A. Civiale in 1861 and published in 1882. It is a cut-out of a panorama *pris du Carmel* (which is the Mont Cormet), showing the Mont Blanc and the Brenva Glacier (Figure 34). This is the first known photograph that shows the glacier tongue and therefore the first document that testifies the exact front position. The front position suggests a retreat of about 140 m since the second maximum in 1850. As documented by the Dufour map (see Section 4.2.2) the Brenva has released the Dora that now flows uncovered.

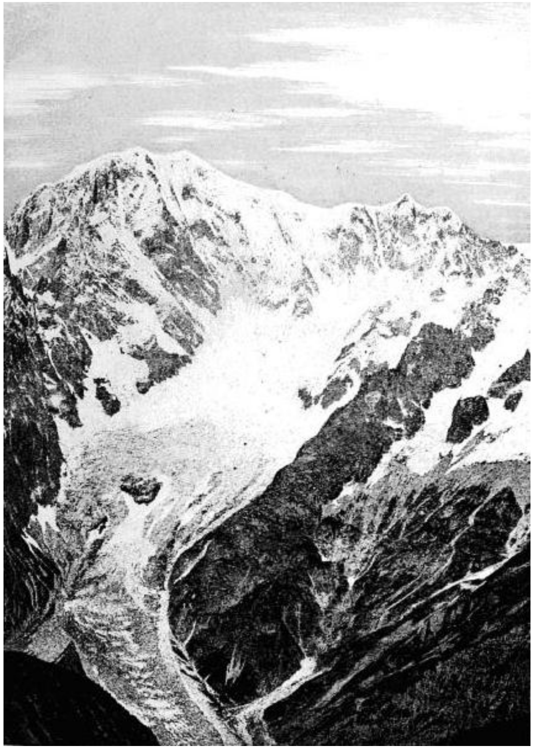


Figure 34 : Panorama of the Mont Blanc and Brenva Glacier in 1861 (“Le Mont Blanc – 4810 m. Pris du Carmel”; signed down left “Civiale, phot“; marked down right “Ch. Chardon Imp.”; lithograph; 14.0 x 10.0 cm; p. 218, Civiale, 1882)

To conclude, it can be stated that the Brenva reached a second major maximum in 1850. This time the glacier lay only 40 m behind the moraine formed during the 1818 maximum. The mid 19th century and the maximum are particularly well documented by the observations of Forbes (1943) and King (1858) and by several pictorial documents (e.g., Hogard, 1849; Gastaldi and Ladner, 1850). At the same time the first photographs of the Brenva Glacier were taken.

4.4.7 Marked retreat by the end of the 19th century

After the two maxima in 1818 and 1850, the Brenva entered the end of the “glacier-friendly” LIA period. A long phase of rapid withdrawal set in that would bring the glacier to a pronounced minimum before the end of the 19th century.

After extensive travels in the western Alps, E. Viollet-le-Duc (1814-1879) travelled the Val Veni and Val Ferret in the summer of 1870. On July 28th, 1870, he stayed in Entrèves where he studied the Brenva Glacier (Frey, 1988). His sketch depicts the *Pierre à Moulin* and the shortened valley tongue (Figure 35, left). The quality of this sketch is evident when comparing it with the photograph by Vittorio Besso (1828-1895) from 1878 (Figure 35, right). The glacier reaches only half way down the channel formed by the lateral moraines, whereas the *Pierre à Moulin* is clearly visible, interrupting the icefall as two large stone windows. The detachment of the ice from the right lateral moraine is also visible in a lithograph by Doyen (around 1870), showing the Notre Dame de Guérison with the Brenva Glacier in the background. These documents demonstrate the pronounced minimum by the end of the 19th century. As Viollet-le-Duc (1876) reported, the Brenva had been retreating without interruption from 1868 to 1875.

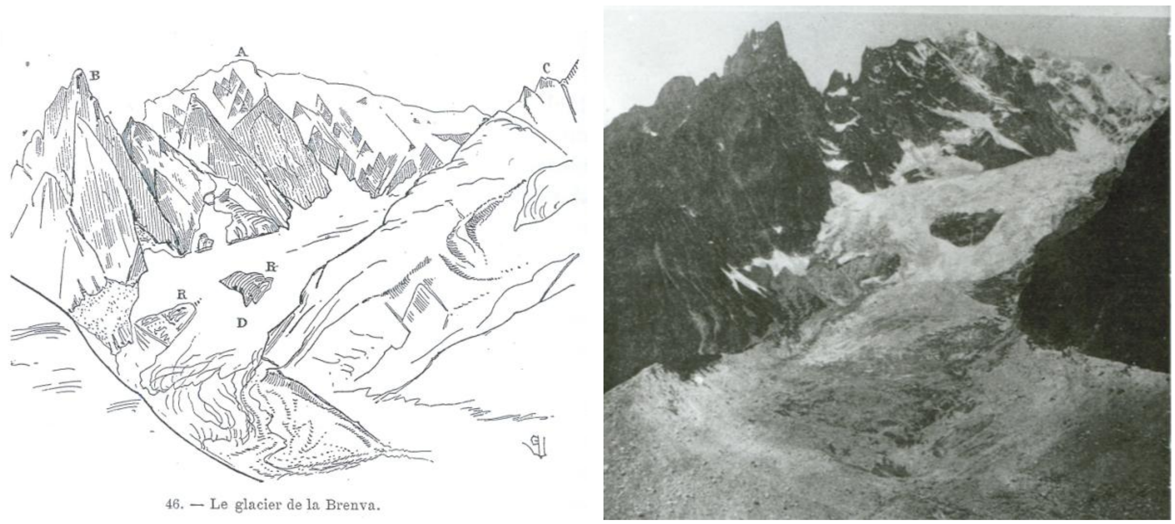


Figure 35 : The Brenva in a sketch from 1870 ("Le glacier de la Brenva"; sketch by E. Viollet-le-Duc; 7.0 x 10.0 cm; Fig. 46, p. 90, Viollet-le-Duc, 1876) and in a photograph from 1878 (photograph by Vittorio Besso; 7.3 x 8.7 cm; Fig. 12, Tav. II, Sacco, 1918)

An important document for this minimum is the text and accompanying map by Marengo (1881), which is based on surveys from 1879 (see Appendix 8.1, Figure 54). He reported that in a long retraction phase since the maximum of the mid 19th century, the front had retreated by about 1000 m by 1878. As he studies the Brenva Glacier a year later in 1879, the front had pushed forward by 30 m. The sketch illustrates a substantially retreated glacier tongue of asymmetric shape. For the elevation of the terminus, Marengo inscribed 1435 m a.s.l. However, this would result in a much longer glacier tongue (about +600 m), which is not consistent with the minimum position of the front at that time. In addition, this elevation does not fit the topography depicted in the sketch.

After a long phase of negative mass balance that leaded to a retreat of about 1000 m, the Brenva reached a minimum in 1878. After 1878 the direction of movement was inversed. Virgilio (1883) quantified the advance in the three years from 1878 to 1881 with a "*cinquantina di metri*". Ruffier (in Porro, 1903) confirmed that while the glacier was in strong retreat in 1872, a couple of years before 1891 it experienced a pronounced phase of advance. According to Ruffier, the Brenva reached an intermittent maximum in 1891, which, however, was considerably smaller than the two precedent maxima (Porro, 1903).

4.4.8 Rock avalanches and anomalous advance after 1920

On August 24th, 1897, Porro and Druetti came to investigate the Brenva (Porro, 1902). They documented the frontal position with several photographs. The photograph by Druetti shows the glacier snout flattened and sagged between the huge lateral moraines (Figure 36). Porro and Druetti installed three reference points in the forefield, among them a granitic boulder (1424 m a.s.l.) close to Chalet Proment. This boulder subsequently served as a reference point for future scientists, who named it “Masso Porro”. Both Masso Porro and the Chalet would later be overrun by the glacier; their positions are marked on the sketch by Valbusa (Figure 37).

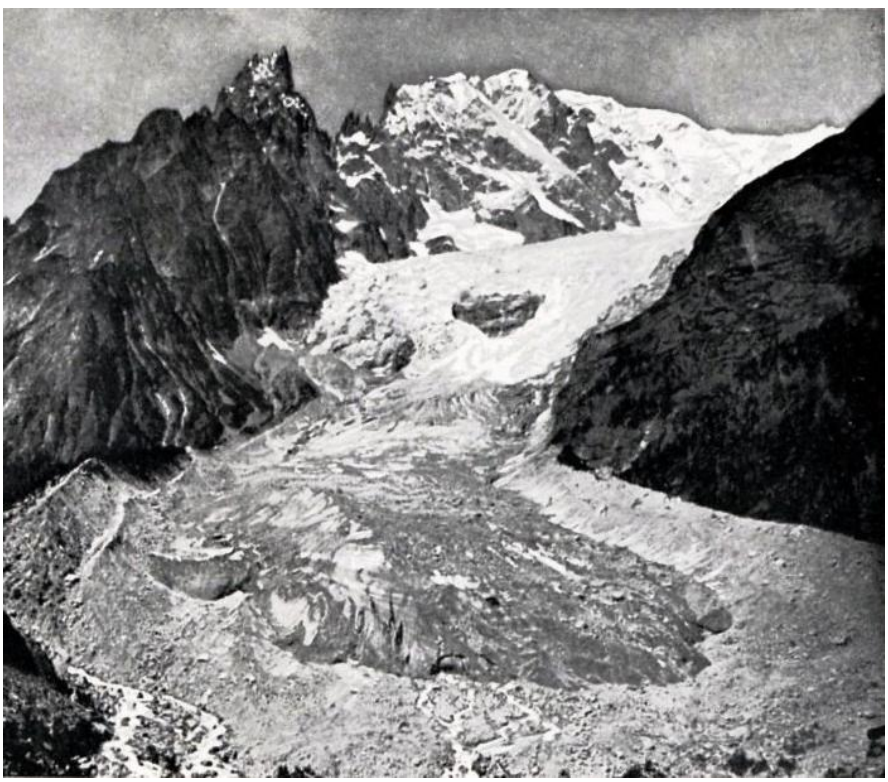


Figure 36: The glacier tongue of the Brenva photographed by Alessandro Druetti in August 24th, 1897 (13.0 x 18.0 cm; Fig. C, p. 151, Porro, 1903)

In September 1910 Paolo Revelli (1911) resumed the measurements of Porro and Druetti. With regard to the Masso Porro the front had retreated by about 86 m (distance in 1910, 285 m; in 1897, 199 m). The following year, in August 1911 the central part of the front had shortened by another 7 m (Revelli, 1912).

Federico Sacco (1918) studied the Brenva for a first time in September 1907 and found a series of moraine crests on the inside of the lateral moraines - three on the right, six on left side - proof for the ongoing retreat in the previous years. As he returned a decade later in August 1916 and in 1917 the direction of motion had changed (Sacco, 1918). The front now appeared turgid and more voluminous. In 1915 the reference point named *St. Jean de Pertud* lay 60-70 m in front of the terminus. A year later the distance was reduced to 37 m and in April 1917 finally, the boulder was incorporated by the glacier. The same year Sacco (1918) measured a distance of 300 m to the Masso Porro, a length which was reduced to about 270 m in 1918.

Thus, by 1920 the Brenva had been in a phase of positive mass balance for seven years (Valbusa, 1921). What happened in late November 1920 would have impacts on the Brenva for the following twenty years. On November 14th, 1920 a huge amount of rock detached from the east side of the Mont Blanc and plunged down to the valley floor as a mixture of rock and ice. Five days later, on the afternoon of November 19th four more consecutive rockfalls occurred. In total, about 4-5 Mio m^3 of rock and ice were accumulated on the valley tongue (Valbusa, 1921). In the following years the deposits preserved the valley tongue by protecting it from melting. Furthermore, the weight imposed by the deposits resulted in a thinning of the tongue and forward motion of the front (Valbusa, 1921). However, considering the impact of the insulation effect on the advance, one should hold in mind that the glacier had already been densely debris covered before the rock avalanche event (Heybrock, 1940). Silvestri (1925) did not believe that the rock avalanche was able to trigger such a marked forward motion of the glacier, but at the most to reduce the ablation. In 1925 he attributed the advance of the Brenva to the extensive precipitations between 1836 and 1841. At this time Silvestri could not have known that the advance would last for more than twenty years, leading the glacier to a maximum in 1940/41.

In late October 1923, a lake was impounded on the Purtud plain by rocks toppling from the right lateral front that formed a dam on the Dora. In the same year the glacier reached the Belvedere escarpment. The margins given by the lateral moraines were too tight, so that the glacier erased the upper 10 m of their crests (Valbusa, 1924). After having reached the rock of Belvedere, the movement of the glacier was redirected to the left, increasing the pressure on the left lateral moraine. A sketch of the glacier's frontal positions from 1919 to 1927 (Figure 37) summarizes Valbusa's studies of the Brenva.

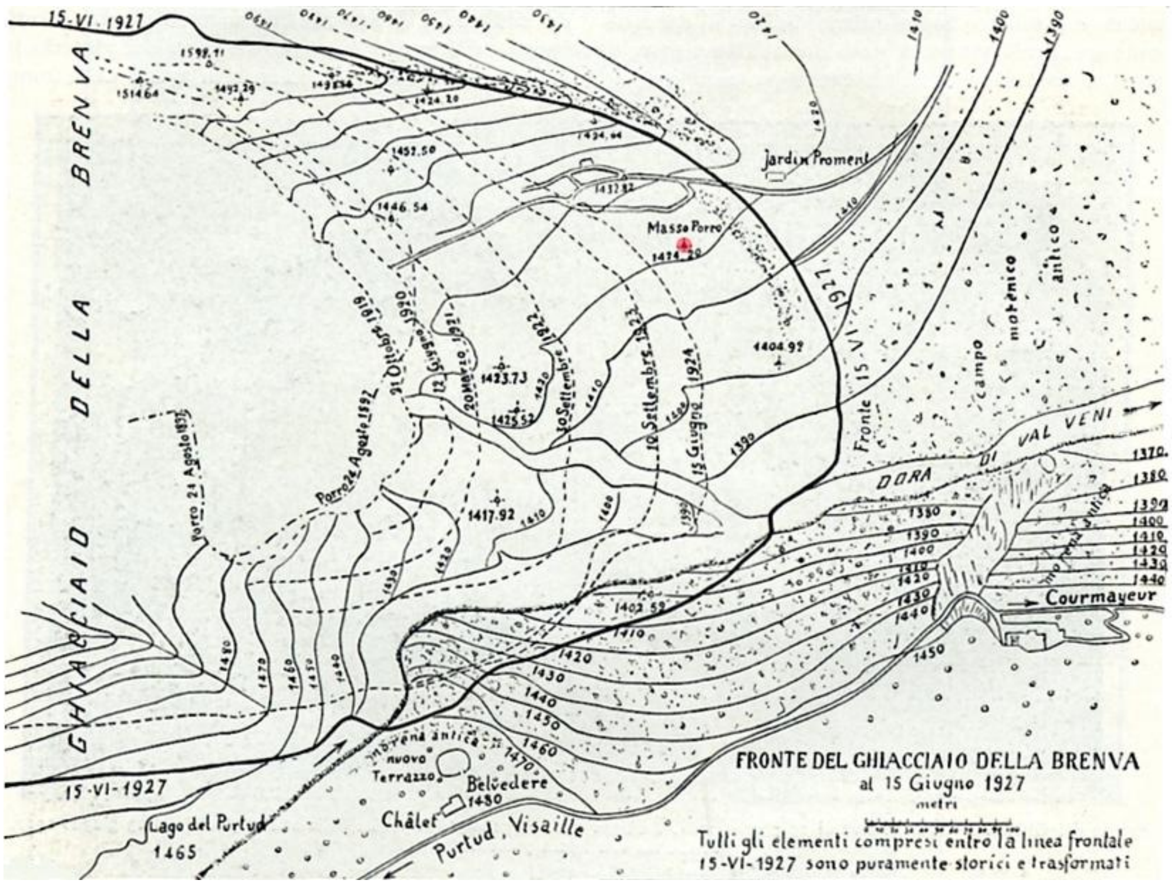


Figure 37: Frontal movements of the Brenva Glacier during the period of 1919 to 1927 (Valbusa, 1927).

In 1925 Silvestri published his findings on the frontal variations of the Brenva during the last century. As a reference point he used the Masso Porro located in the left lateral forefield, which, as Silvestri (1925) stated, lay 550 m behind the 1818 moraine. When comparing the sketches by Valbusa (1927; Figure 37) and Capello (1941), it becomes clear that the Masso Porro (altitude 1424 m) was situated only about 350 m from the 1818 moraine.

The Masso Porro, for several years a reference point for measurements, was overrun by the ice masses in 1925. Some years later Capello established new reference points. Besides the Masso Valbusa on the left lateral maximum moraine, he added a second measurement point; the down-valley situated Masso Capello, which had the advantage to be in the axial alignment of the flow direction. Frontal variations from 1920 to 1940 were measured by Capello (1941). The 1921-1924 phase of rapid advance was followed by a continued but more moderate advance until around 1929. According to Kinzl (1932) the Brenva gained 400 m in length between 1920 and 1930. In 1931 the glacier reached the Notre Dame de la Guérison escarpment and in consequence was redirected to the northeast. Figure 38 shows the Brenva around 1932 in a photograph by Jules Brocherel (1871-1954). On the photograph, the valley tongue is still extensively coated with debris from the rock avalanche. Around 1935 the forward motion was slowed down again to about 10 m per year. The long advance phase ended in 1940/41, bringing the Brenva to a distance of only 50 m from the LIA maximum moraine.

Figure 38 : The Brenva Glacier in a photograph by Brocherel around 1932 (17.8 x 12.9 cm; fonds Brocherel-Broggi, RAVA, Aosta)

4.4.9 The beginning of continuous glacier retreat, another rock avalanche and the separation of the valley tongue

Having had disposed of the rock avalanche deposits from 1920 the Brenva returned to "normal" glacier behaviour after 1941. Together with the other Mont Blanc glaciers that had been retreating since 1920, the Brenva entered a long phase of withdrawal lasting until the mid 1960s. A new strong phase of advance that started in 1965 was able to return the terminus to a position similar to the 1850 maximum in 1989. During these 24 years the Brenva, according to the measurements by the CGI, gained nearly 400 m in length. Afterwards the direction of motion was again inversed and the glacier started to withdraw.

77 years after the catastrophic rock avalanche in 1920, a second natural disaster occurred on January 18th, 1997. About 2 Mio m^3 of rock that detached from *Sperone della Brenva*, rapidly descended the glacier and mounted on the opposite valley slope where the pressure wave erased a wood of conifers and killed two people. As in 1920, the debris accumulated, temporarily dammed the Dora di Veni (Cerutti, 2006). This time though, the glacier was in a phase of retreat that had started after 1989. Instead of accelerating an existing advance, the debris cover slowed down the melt back of the glacier.

Nevertheless, a serious change set in on the upper parts of the glacier. At the steep walls of the *Pierre à Moulin* the large seracs had begun their depletion towards the end of the 1980s, but from 1997 onwards the phenomenon was accelerated. In September 2004, the thin band of ice uniting the upper basin with the valley tongue finally disappeared completely (Cerutti, 2005). The active front settled at the threshold of the *Pierre à Moulin* at 2350 m a.s.l., with what the Brenva became a cirque glacier.

Presently (during fieldwork in June, July and October 2009) the Brenva valley tongue presents itself covered with an extensive amount of debris that alters the fusion process of the ice. Despite the apparent inactivity of the valley tongue, ogives in the upper part reveal the dynamic of the glacier. After the almost total extinction in 2006, the conoid regenerated by the calving ice wall starts to swell again and a modest volumetric and in the last two years also linear increase can be registered (Cerutti, 6.7.2009; personal communication). In the forefield a series of faintly developed recent moraines are assembled. In 2009 the terminus lies in a distance of about 310 m from the historic 1818 moraine.

4.4.10 Revised length change curve for the Brenva Glacier

As described in previous Sections, various data on the position of the front have been used to construct a curve displaying terminal fluctuations of the Brenva (Figure 39). The uncertainty before the measuring period (before 1914) is high, and increases going back in time. As already explained for the Miage glacier length curve, every inflexion point of the curve corresponds to a piece of evidence and reflects a mean value with the most likely position of the glacier front. The characteristics of the main historical documents used to reconstruct the length change curve are listed in Table 7 (see Appendix 8.1). Probable advances before the late 18th century are deduced from indirect evidence (see Sections 4.1 and 4.4.3) and indicated by an arrow.

By the end of the 16th century the glaciers on the Mont Blanc massif concomitantly started to swell and adopt the general big extension that they would maintain over the whole LIA. In accordance with the Miage Glacier, the Brenva probably reached maximal extensions around 1600, 1640, 1680 and 1730. Since the mid 18th century the Brenva was in a phase of advance, interrupted by short phases of retreat. The glacier reached its culmination point during the LIA in 1818. The frontal moraine accumulated during this maximum subsequently served as reference point for the length fluctuations. A second maximum was reached in 1850. After the termination of the LIA, a long period of continuous retreat followed, bringing the glacier to a halt over 1 km upstream of the 1818 moraine in the year 1878. The Brenva had restarted to advance, when in November 1920 a major rockfall event accelerated the forward motion and continued the advance until a new maximum was reached in 1940/41. At this time the front overrode most of the 19th century moraines and lay only about 50 m behind the 1818 moraine. The last culmination occurred in 1989. Afterwards, a steady phase of retreat was initiated, which was slowed down by the impacts of a second rockfall event in January 1997. Nevertheless, the depletion of the lower glacier parts eventually resulted in the separation of the valley tongue from the active glacier in September 2004.

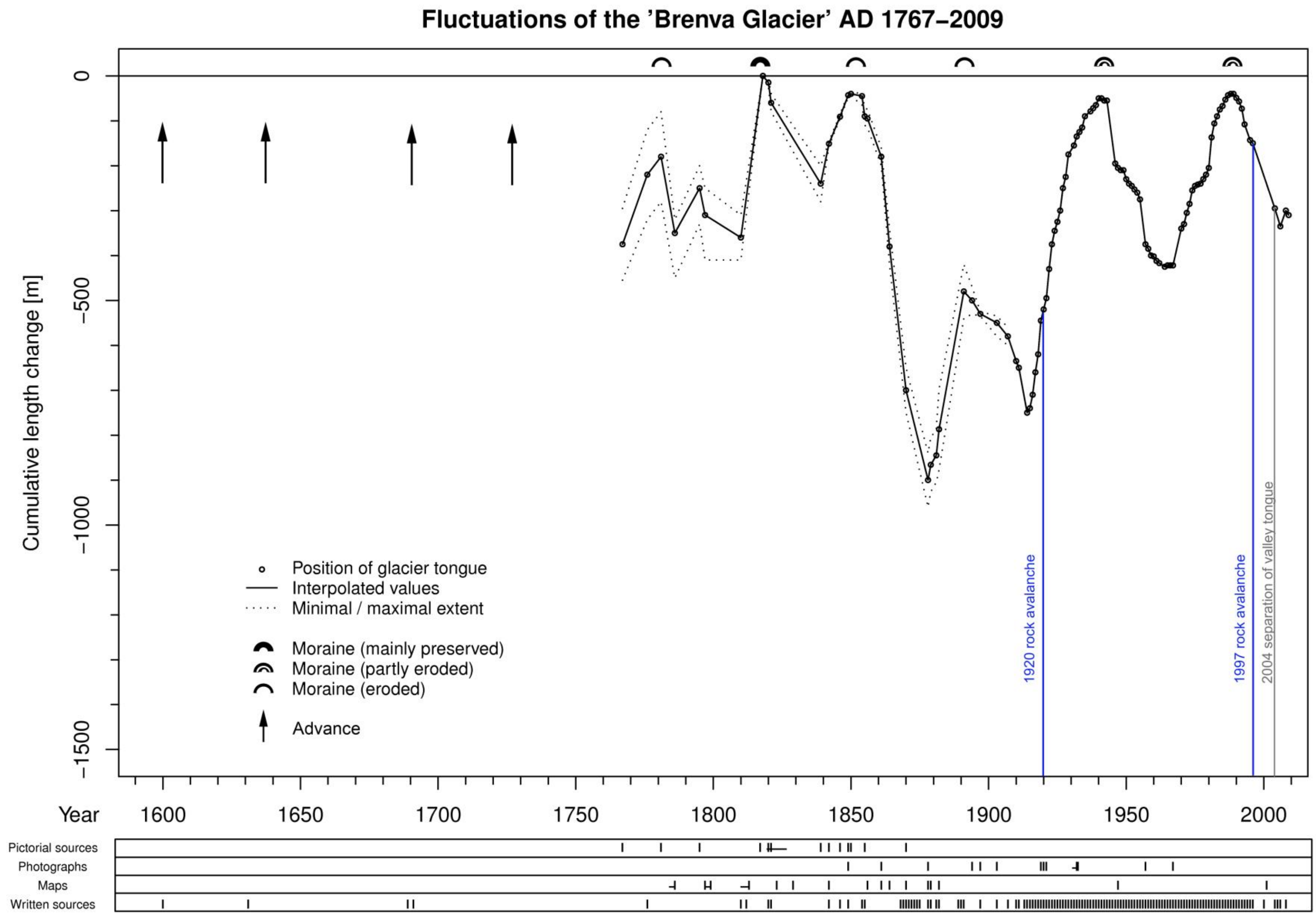


Figure 39 : Cumulative length fluctuations of the Brenva Glacier from 1767 until 2009. Front positions are given relative to the LIA maximum in 1818 (=0). Error range (min, max) is shown by the dotted line. Probable advances before the 19th century are indicated by an arrow; the advance around 1730 is deduced from the Miage maximum. Each inflexion point corresponds to a reliable source, listed in the box below the x-axis. Uncertainties concerning the dating of a document are indicated by a small horizontal line.

4.5 Length fluctuations of the Pré-de-Bard Glacier

For the history of the Pré-de-Bard Glacier very little evidence is available before the maximum around 1818. Even in the 19th century, only four pictorial documents illustrate this glacier. Considering the high altitude and remote location in the head of Val Ferret such scant evidence is not surprising. Compared to the Brenva, the Pré-de-Bard was not as accessible and also not a central landmark in the inhabitant's surroundings. However, a rich apparatus of distinct moraines helps in the interpretation of the historical terminal positions. They testify fluctuations of high amplitude; since the maximum around 1818 the glacier has retreated over 1500 m (Brenva about 300 m, Miage about 560 m).

4.5.1 Pré-de-Bard Glacier foreland, LIA moraines and the dating of the LIA maximum

A first glance on the Pré-de-Bard foreland (Figure 42) reveals several distinct moraine crests dispersed over a length of 1.5 km. For illustration, the moraines are also shown in an aerial photograph (see Figure 58, Appendix 8.1). Due to the high elevation of the foreland most moraines are barren of trees and more evolved vegetation, which makes the morphology easy to recognize and interpret (Figure 41).

The moraines in the lower part of the forefield are mostly of asymmetrical form. To the left side of the river the terrain ascends rapidly and soon converts into a steep rock wall. Accordingly the boulders are linearly spread rather than being amassed in a completely developed moraine wall. On the hydrographical right in contrast, the moraine crests are distinctly formed.

The moraine sequence starts with a uniformly built terminal arch (A), loosely covered with young larch trees. According to lichenometrical measurements and historical sources (see Section 4.5.2), this most prominent moraine ridge is attributed to the 1818/19 advance (Venetz, 1833; Zienert, 1965; Aeschlimann, 1983). To the left, a sequence of *lateral moraines* (B) has been left by the glacier in front of the 1818/19 ridge. In the forefield of the Pré-de-Bard no *frontal moraines* older than the early 19th century exist. Is this a proof that prior to the late 18th century, the Pré-de-Bard Glacier was conjugated with the Triolet Glacier? According to Zienert (1965) the sequence of the lateral moraines (B) were formed during the 17th-18th century (Figure 40). Based on lichenometry, Aeschlimann (1983) argues that there is a considerable age difference between the moraines B and A.

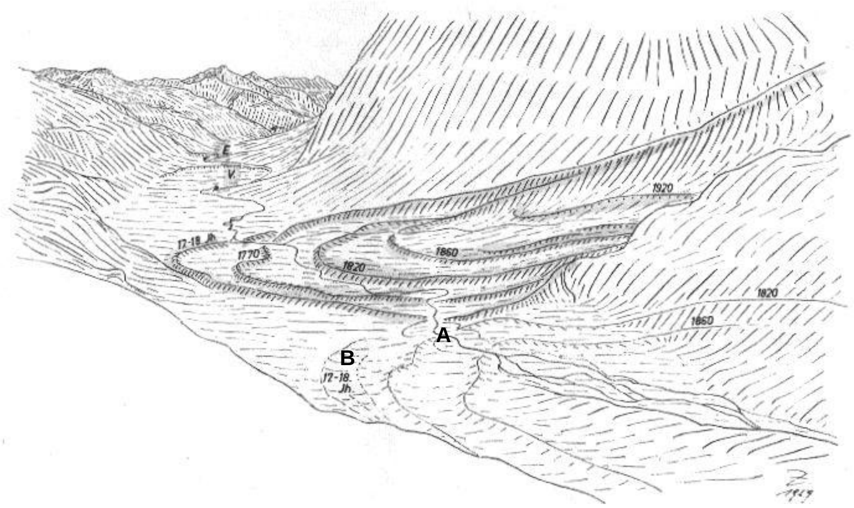


Figure 40: Val Ferret with historical moraines of Pré-de-Bard (lower right corner) and Triolet Glacier (middle) (Zienert, 1965)

One possible scenario explaining the absence of the frontal parts of these outermost moraines is that the Pré-de-Bard joined the Triolet Glacier during the early LIA. This would imply that the 1818/19 advance does not correspond to the LIA maximum (Sacco, 1918). Another possibility comes up in relation with a catastrophic event in 1717; in this year a rock avalanche originating from the upper Triolet basin ran down the Val Ferret and dammed the Dora di Ferret with granite debris (Deline, 2009). The lake formed could have immersed and destroyed the frontal parts of the oldest moraines (Zienert, 1965). Also thinkable is that during the 17th and 18th century the glacier only laterally overtopped the 1818/19 extent and the frontal moraines were superimposed later during the 1818/19 advance. Whether or not the 1818/19 extent corresponds to the LIA maximum cannot be proven conclusively.

Only about 70 m behind the most prominent moraine, the pronounced moraine ridge attributed to the 1850 advance follows. Receding another 140 m a terminal arc with a smaller radius is embedded in the valley. The moraine sequence dates the formation of this ridge to sometime between 1850 and 1890 (next moraine ridge following backwards). The pointy shape of the moraine fits the depiction of the Pré-de-Bard glacier in the Dufour map published in 1861 (see Section 4.2.2). Thus, the arc can be attributed to a prolonged phase of stationarity or to a small advance around 1860.

The upper part of the forefield is marked by a sequence of symmetrically formed terminal moraines. In this part, the glacier stages are especially easy to recognize due to the different stages of development of vegetation in the sectors between two moraine ridges (generally the vegetation is more developed on the hydrographical left, as the right side is shaded longer by the Aiguilles Rouges de Triolet). The dating of the moraines is achieved by photographs dating from the early 20th century and measurements by the CGI (see Section 4.5.2). Various reference points installed in this part of the forefield document the measuring activities of the CGI members.

Between the moraines of the 1890 and 1920/22 advance, a triple sequence of short frontal moraines has been formed by the glacier in the 1890s. Whereas downstream of the 1890 moraine grass-covered humus has developed, the area upstream of the 1920/22 moraine is only discontinuously vegetated. According to the CGI measurements, the Pré-de-Bard reached two new maxima in 1942 and 1989. The moraine wall corresponding to the 1942 maximum lies about 200 m behind the 1920/22 moraine. Remarkably, this wall encloses an area of more developed vegetation compared to the area downstream, probably because the inclination of this section permits better interception from the sunlight. Besides the moraine wall, the extent of the ice in 1989 is clearly distinguishable as an area covered by greyish boulders lacking any vegetation.

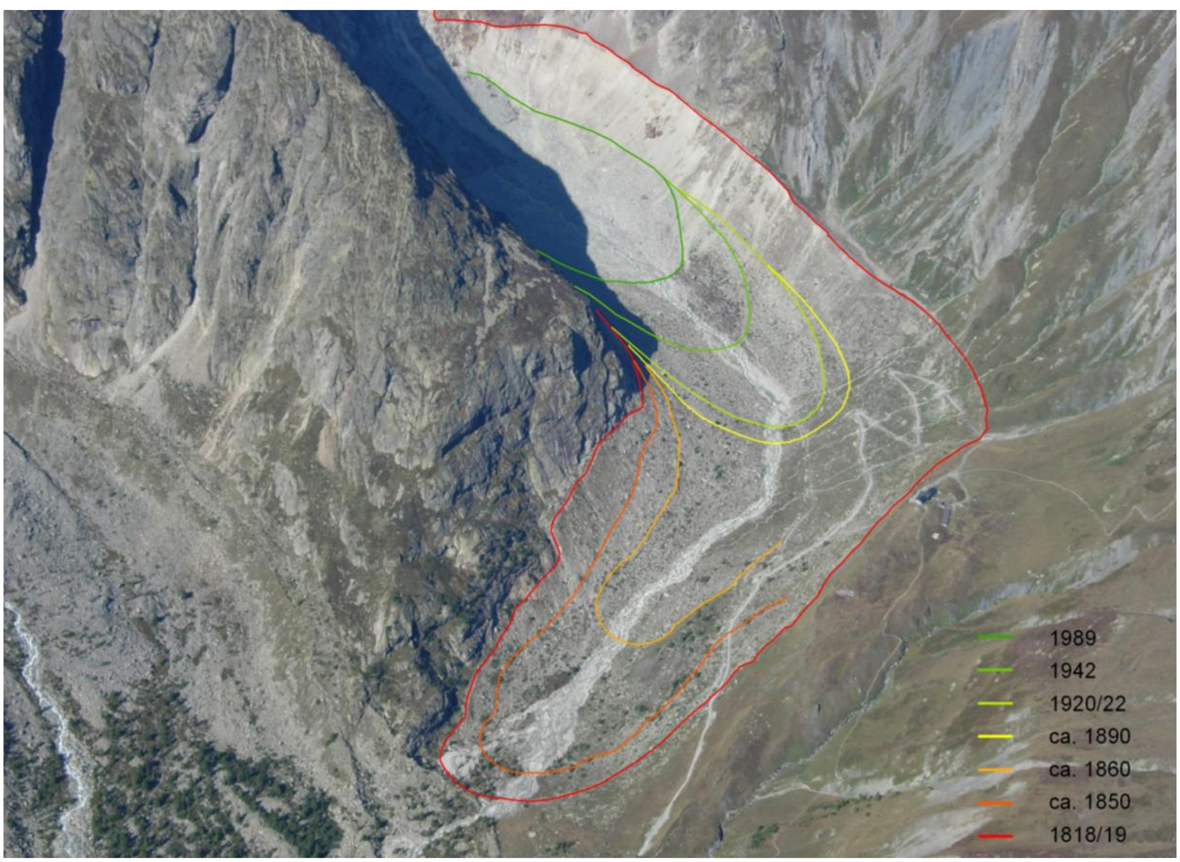


Figure 41 : Aerial view of the Pré-de-Bard frontal area with approximate glacier outline in 1818/19, ca. 1850, ca. 1860, ca. 1890, 1920/22, 1942 and 1989 (Photograph by S.U. Nussbaumer, 30.09.2009)

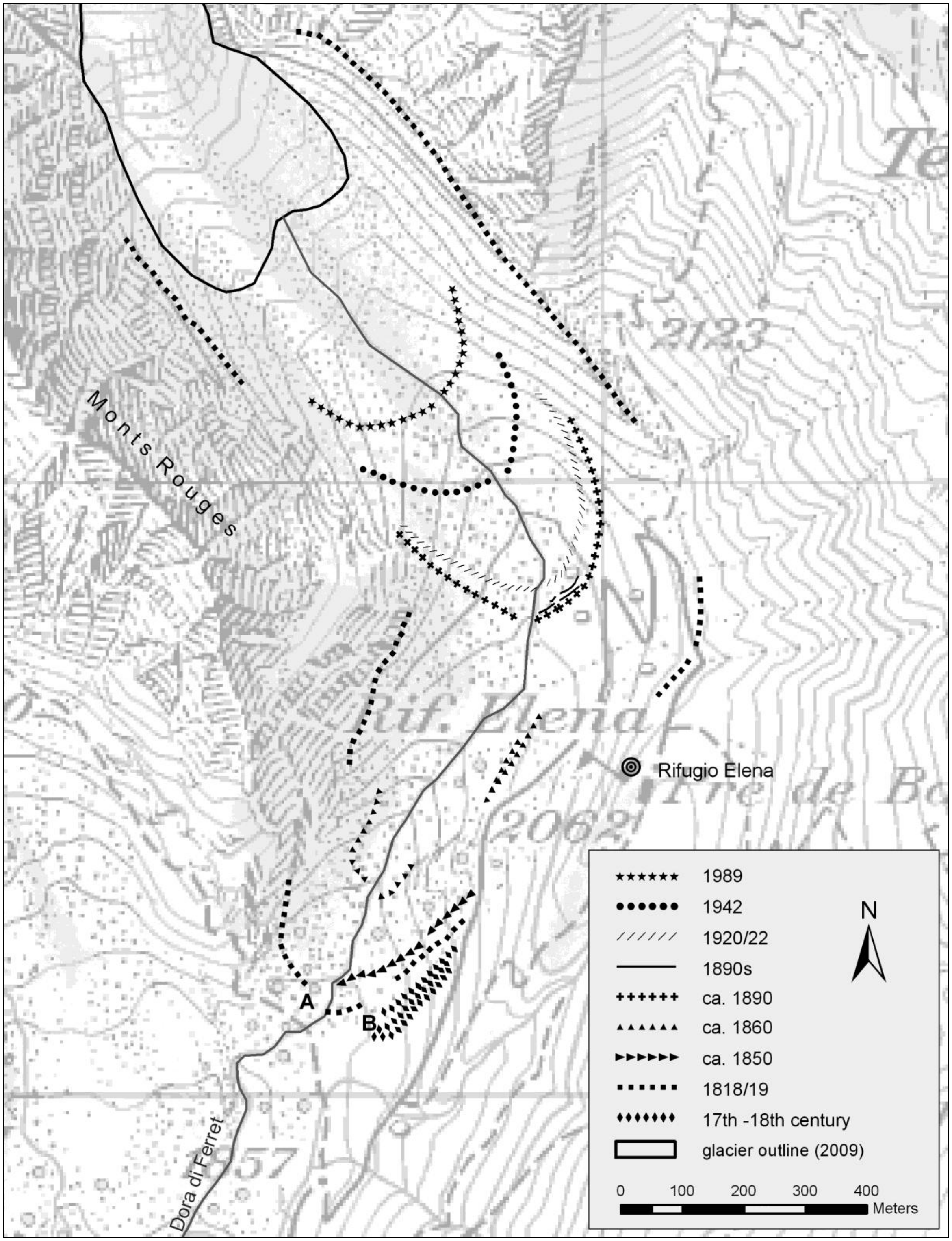


Figure 42: Map of the Pré-de-Bard frontal area with the moraine arc from the 1818 advance (A), the lateral moraine sequence formed during the 17th and 18th century (B) and the other LIA moraines (after Capello, 1940; Zienert, 1965; Cerutti, 1975; Aeschlimann, 1983. Map: Swiss Map 50, V4; swisstopo, 2004).

4.5.2 The Pré-de-Bard Glacier in the Val Ferret until the end of the LIA

During the entire LIA the Pré-de-Bard Glacier bent around the Monts Rouges and descended the upper Val Ferret. As described in the previous Section, it is not sure whether the Pré-de-Bard Glacier joined the Triolet Glacier during the earlier LIA. After all, the Pré-de-Bard Glacier was separated from the Triolet when De Saussure (1786) visited them in 1781. The title of the paragraph on the Pré-de-Bard is labelled "*Glacier qui a diminué*", the paragraph on the Triolet Glacier in contrast, is named "*autre glacier qui a augmenté*" (De Saussure, 1786: Vol. 2, p. 292). De Saussure observed granitic blocs deposited during a former advance on a hill between the huts of Pré-de-Bard and the "*Mont Dolent*" glacier. The glacier is separated from this hill by a profound valley and lies 61 m lower than the huts. This description suggests that the front was about 100 m shorter than in the impending 1818/19 advance.

When Venetz (1833) visited the upper Val Ferret in August 1820, the Triolet and Pré-de-Bard glacier lay in a distance of about 24 m. Venetz reports that the Pré-de-Bard (which he names Glacier du Triolet) has started to retreat, whereas the Triolet (which he names Glacier d'Ameron) is still advancing. Thus in 1820 the Pré-de-Bard has started to retreat, but is still very near to the Triolet Glacier. Accordingly the maximum is likely to have occurred one or two years earlier, in 1818 or 1819.

As mentioned above, the Pré-de-Bard flowed out into the Val Ferret during most of the 19th century. This advanced state is recorded by several pictorial documents. For the Pré-de-Bard we have two drawings by Jules-Fréderic d'Ostervald (1773-1850), published in Raoul-Rochette (1826). The first drawing mainly depicts the Triolet Glacier (Figure 43). On the lower left corner, the terminus of the Pré-de-Bard Glacier is exposed as well. The Pré-de-Bard ends only in a short distance to the Triolet: "… *les deux* [Pré-de-Bard and Triolet Glacier] *presque confondus en une seule masse…*" (Raoul-Rochette, 1826). The tongue seems flattened and thinned, indicating the start of withdrawal.

Figure 43 : The Pré-de-Bard nearly touches the Triolet Glacier (“Glacier du Triolet”; signed down left “J.F.d’Ostervald delt.”, marked down right “Salathé sculpt.”; aquatint; 14.5 x 21.0 cm; Raoul-Rochette, 1826)

A second drawing illustrates the middle part of the “Mont-Dolent” Glacier as seen from the Alp of Pré-de-Bard (Figure 44, top). The ice masses fill the whole homonymous valley. Compared to a modern photograph, the glacier seems to end at the level of the 1818/19 lateral moraines. No signs of a recent retreat, such as lateral moraines, are visible in the drawing. Figure 43 and Figure 44 show the Pré-de-Bard in a healthy state, comparable to the maximum extent. Regarding the terminus, however, there are signs of a beginning meltback. Thus, the drawings were probably sketched two or three years after the 1818/19 maximum, around 1821-1822.

In the following two decades the Pré-de-Bard was continuously retracting. The map by F.J. Pictet (see Section 4.2.1) published in 1829 depicts the glacier substantially shortened. When Forbes visited the Val Ferret in summer 1842 he reported: “*Beyond the glacier just named* [Triolet] *is the Mont Ru, which separates it from the Glacier of Mondolent, the highest in the valley. This one appears to have greatly retreated of late years.*” (Forbes, 1843: 246).

Figure 44 : The Pré-de-Bard as seen from the Alp of Pré-de-Bard by d'Ostervald around 1821-22 ("Glacier du Mont-Dolent"; signed down left "J.F.d'Ostervald delt.", marked down right "Salathé sculpt."; aquatint; 14.5 x 21.0 cm; Raoul-Rochette, 1826) and in July 2009 (photograph by P. Imhof)

From the mid 19th century we have another set of illustrations, again showing the Triolet and Pré-de-Bard from similar points of view as the d'Ostervald drawings. The Swiss geologist Alphonse Favre sketched the glaciers during his stay in the upper Aosta Valley in 1851 (?) (Favre, 1867). In his view of the lower Triolet Glacier, the Monts Rouges de Triolet stand as an island in the sea of ice formed by the Triolet and the Pré-de-Bard. From this perspective, the two glaciers seem to be confluent. However, in Favre's work the paragraph on the Triolet reads: "*Ce glacier est séparé de celui du Mont-Dolent par le Mont-Rouge…*" (Favre, 1867: 579). Appearing from behind the Monts Rouges, the Pré-de-Bard gives the impression of a healthy and voluminous valley glacier. Another sketch by Favre figures the upper basin of the Pré-de-Bard Glacier as seen from Pré-de-Bard Alp (see Appendix 8.1, Figure 59). Compared to the d'Ostervald drawing from around 1821-22, the glacier has lost in volume. Nevertheless, the gorge separating the upper from the lower basin looks considerably filled out with ice.

In 1917 Sacco would be told by the herdsmen of Pré-de-Bard that the former owner remembered well the first half of the 19th century, when they could chill the meat on the glacier that had only lain some metres from the huts (Sacco, 1918). This required a glacier extent during which the front was only about 80 m from the 1818/19 maximum – which is also the distance where the moraine attributed to around 1850 was built. According to the lifetime of this former owner (1828-1914), his description most probably refers to around 1840-1850. Thus, around 1850 the Pré-de-Bard had regenerated in volume and length and readvanced to a position very similar to the 1818/19 maximum.

S.W. King (1858) travelled "The Italian Valley of the Pennine Alps" between 1855 and 1856 and described the Pré-de-Bard as descending for a long distance into the Val Ferret. The moraine sequence and the Dufour map from 1861 suggest that the glacier again reached an intermittent maximum around 1860, where it deposited a frontal moraine about 200 m behind the 1818/19 moraine (see previous Section).

As Viollet-le-Duc reports (1876), several glaciers of the Mont Blanc had been retreating without interruption during the period of 1868 to 1875, among them the Pré-de-Bard. The withdrawal phase continued until about 1878-1880 (Sacco, 1918); by then the terminus had retracted another 800 m behind the moraine deposited around 1860. In 1878 Baretti (1880) stated that the "Mont Dolent" Glacier was one of the glaciers in the Val Ferret that was to some extent entering into the main valley.

To summarize, the maximum extent of the Pré-de-Bard Glacier during the LIA cannot be determined conclusively. However, the Pré-de-Bard Glacier attained a maximum around

1818/19 and ended next to the Triolet Glacier until the mid 19th century. After around 1850 and an intermittent stationarity around 1860, the glacier entered an extensive phase of retreat and reached the very head of the Val Ferret around 1880.

4.5.3 Minor advances and the first photographs of the Pré-de-Bard Glacier at the turn of the century

After the long phase of retreat until around 1880, the glacier started to recover. According to the IGM map published in 1882 (see Section 4.2.2) the front ended at 2007 m a.s.l. and had readvanced by about 60 m. The moraine sequence and the first known photograph of the Pré-de-Bard Glacier indicate that a new maximum was attained around 1890: The first known photograph was taken in 1893 by a mountain guide from the Aosta Valley, from a view point on the way to Col Ferret (Figure 45). The tongue looks considerably swollen, but on the right lateral side a small moraine crest indicates the recent retraction. Thus, the maximum is likely to have occurred some years earlier, around 1890.

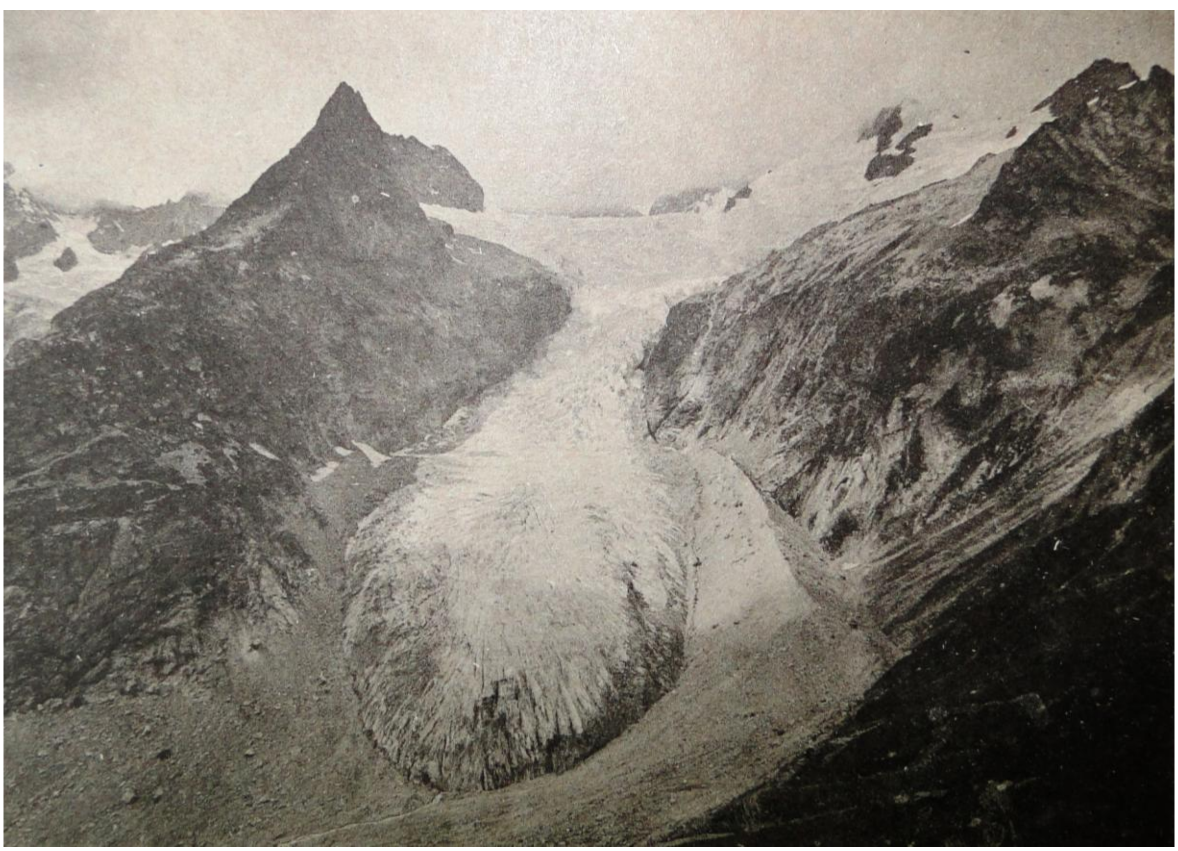


Figure 45 : The first known photograph of the Pré-de-Bard Glacier taken in 1893 by a mountain guide from Aosta Valley (photograph; 11.0 x 14.8 cm; private collection, A. Roveyaz, Courmayeur)

During their survey of the Pré-de-Bard in August 1897, Porro and Druetti took several photographs. These still present the glacier as in a healthy state, although with a slightly flattened tongue (Figure 46). The narrow band of freshly accumulated debris that marks the extension of the ice around 1890 has widened since 1893.

Figure 46: The Pré-de-Bard in a photograph by A. Druetti in August 1897 (photograph; 18.0 x 13.0 cm; inv. 235.57; CGI, Torino)

Where Porro registered an elevation of the front of 1982 m a.s.l. in 1897, Revelli (1911) measured 2015 m a.s.l. in 1910. From the inclination of the moraine apparatus he deduced a retraction of 65-70 m since 1897. A year later, in August 1911 the front had shortened by another 5 m (Revelli, 1912).

During the period of Sacco’s observations (1915-1918), the glacier resumed the forward motion. The herdsman at Pré-de-Bard Alexis Proment believed to have recognized an advanced of half a metre per day in July and August 1917. An assertion that Sacco (1918) evaluated as being “a bit exaggerated”. Nevertheless, the advance culminated in 1920/22 with the deposition of a moraine wall less than 50 m behind the 1890 moraine. Already in 1924, a photograph shows the glacier with a flattened tongue, lying about 14 m behind the 1920/22 moraine.

4.5.4 Continuous measurements and a long period of retreat (1922-63) followed by a pronounced phase of advance (1963-89)

After the maximum around 1920/22, the Pré-de-Bard entered for 40 years a phase of negative mass balance, which would only be interrupted by a short but marked advance between 1941 and 1942. During this period the negative glacier fluctuations were measured annually by Carlo Capello from the CGI. It is in 1960 that Augusta Vittoria Cerutti took over the observations for the CGI and chose the Pré-de-Bard as the main study glacier. Firstly, because unlike the Brenva and Miage it is free of debris cover. Secondly, on account of its regularly shaped valley tongue that descends down into the valley and therefore is easily accessible (in contrast to suspended glaciers as Triolet, Frébouge, Toula etc.). The following twenty years Cerutti monitored a continuously advancing glacier regaining previously vacated areas, and had therefore to install new reference points twice (in 1970/73 and 1985/87). According to the measurements by the CGI, the Pré-de-Bard achieved a new maximum in 1989, where it accumulated a moraine nearly 1.2 km upstream of the 1818 extent. Since 1996 the retreating glacier is observed by Alberto Fusinaz.

The general trend of withdrawal over the 20th century is summarized in Figure 47. In 1929 the front ended shortly before the lateral valley enters the Val Ferret. 49 years later the ice had retreated over the steeper slope and lay on a sparsely inclined plane. In 2009 the tongue scarcely enters the lower valley level, whereas the icefall has been thinning considerably.

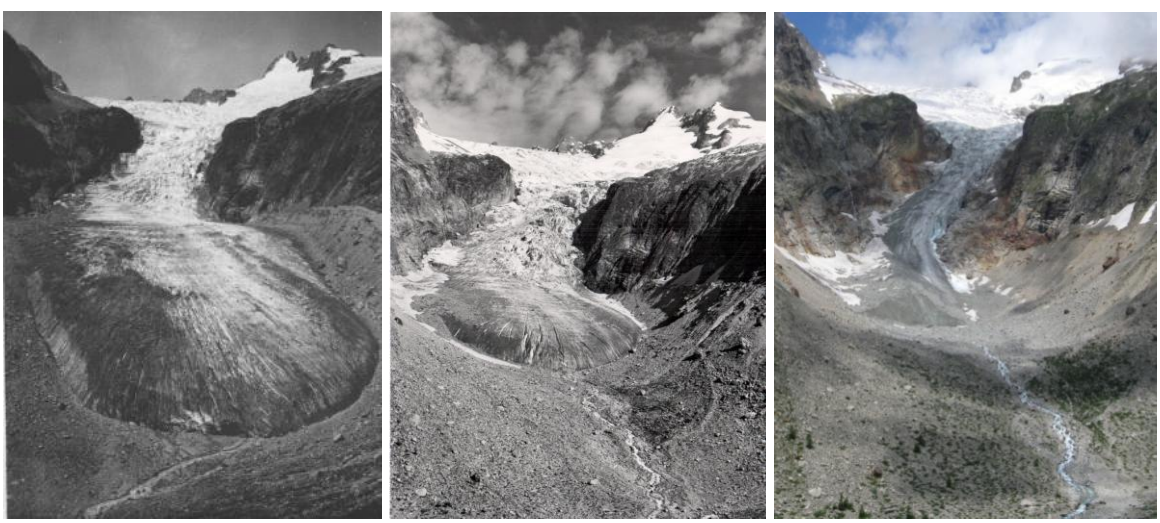


Figure 47 : The continuous retreat of the Pré-de-Bard illustrated by photographs from 1929, 1978 and 2009 (left: M. Bossolasco, 1929; inv. 235.98; CGI, Torino / middle: A.V. Cerutti, August 1978; inv. 235.91; CGI, Torino / right: P. Imhof, June 27th, 2009)

Presently (during fieldwork in June, July and October 2009) the Pré-de-Bard presents itselfs with a cone-shaped tongue extensively covered with debris. The glacier ends in a distance of 1566 m from the 1818 moraine. According to A. Roveyaz (26.06.2009; personal communication) the front has retreated by 14 m in its central part since 2008. Assuming an ongoing retreat of the glacier, the Pré-de-Bard will in a few years suffer the same fate as the Triolet and Brenva Glaciers, which lost their valley tongue and became cirque glaciers in 1934 and 2004, respectively.

4.5.5 New length change curve for the Pré-de-Bard Glacier

Similar to the length change curves of the Miage and Brenva, Figure 48 shows the length changes of the Pré-de-Bard Glacier. The characteristics of the main historical documents used to reconstruct the length change curve are listed in Table 8 (see Appendix 8.1). Probable advances before the late 18th century are deduced from indirect evidence (see Sections 4.1) and from the Miage maxima, and are indicated by an arrow.

By the end of the 16th century the glaciers on the Mont Blanc massif concomitantly started to swell and adopt the general big extension that they would maintain over the whole LIA. In accordance with the Miage Glacier, the Pré-de-Bard probably reached maximal extensions around 1600, 1640, 1680 and 1730. The Pré-de-Bard reached its culmination during the LIA most probably around 1818/19. The frontal moraines accumulated during this maximum subsequently served as a reference point for the length fluctuations. A second, similarly extensive culmination was reached around 1850, followed by another smaller maximum around 1860. After the termination of the LIA, a long period of rapid retreat followed, bringing the glacier to a stop about one kilometre upstream of the 1818 moraine around 1878-1880. Two similar maxima occurred around 1890 and 1920/22, when the Pré-de-Bard stopped twice in the bent where the lateral valley enters the Val Ferret. The following, forty years long continuous period of withdrawal shortened the valley tongue by about 600 m. The last culmination occurred in 1989. At the present time the depletion of the valley tongue and the icefall is going on.

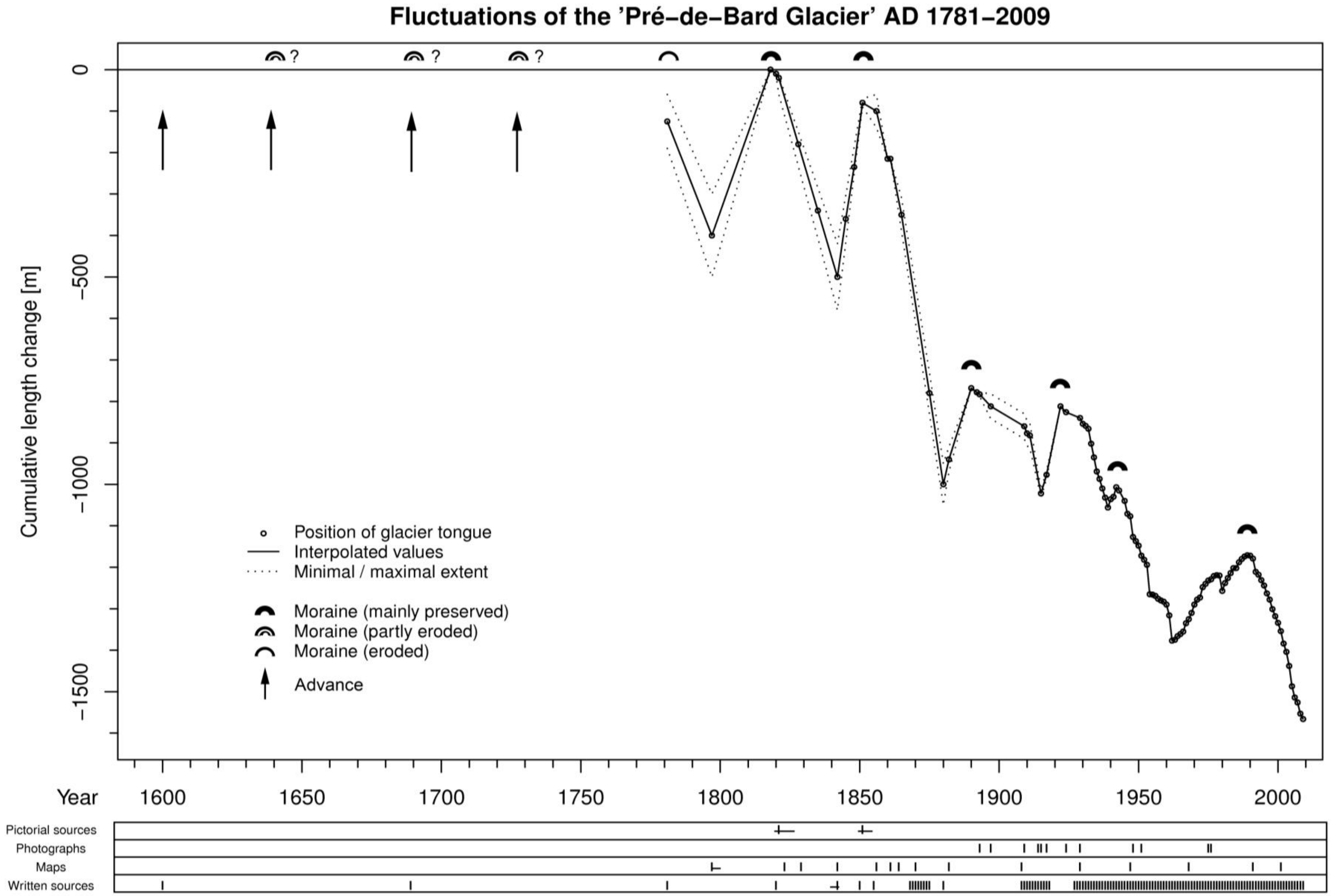


Figure 48 : Cumulative length fluctuations of the Pré-de-Bard Glacier from 1781 until 2009. Front positions are given relative to the LIA maximum in 1818/19 (=0). Error range (min, max) is shown by the dotted line. Probable advances before the 19th century are indicated by an arrow; the advances around 1640 and 1730 are deduced from the Miage maxima. The attribution of the 17th-18th century moraine sequence (in the external left forefield) to the corresponding advances is uncertain. Each inflexion point corresponds to a reliable source, listed in the box below the x-axis. Uncertainties concerning the dating of a document are indicated by a small horizontal line.

5. Discussion

5.1 The new Miage, Brenva and Pré-de-Bard glacier length change curves

The aim of this study was to establish a revised and refined length change curve for the Brenva Glacier and to reconstruct new length change curves for the Miage and Pré-de-Bard Glaciers by analysing the historical documentary material available and incorporating previous results. The main time of interest was the period prior to instrumental measurements (before the early 20th century) back to about 1600.

The new and revised glacier length curves date back to AD 1640 for the Miage, 1767 for the Brenva and 1781 for the Pré-de-Bard (Figure 49). Until 1920 the Miage, Brenva and Pré-de-Bard Glaciers showed analogous oscillations in the same direction. The oscillations are well synchronized, although the culmination points have a time lag of a few years. The small differences in the chronology can be attributed to differences in time delay and reaction time. The Brenva is the first of the three glaciers to change the direction of motion, 1-2 years before the Pré-de-Bard and 2-10 years before the Miage. The fluctuations before the late 18th century cannot be compared, as there is not enough evidence available for the detailed reconstruction of the length change of the Brenva and Pré-de-Bard Glaciers.

During the LIA, the three glaciers showed three major advances. The Miage reached its LIA maximum expansion in 1640. During its second maximum in 1820 it was lying roughly 60 m (left lobe) and 120 m (right lobe) behind the 1640 moraines. The Brenva and the Pré-de-Bard reached their LIA maximum in 1818 and 1818/19, respectively and thereby overran all moraines formed during previous advances. All three glaciers reached a third major maximum during the mid 19th century. The Brenva culminated in 1850, the Pré-de-Bard around 1850 and the Miage attained a new maximum around 1860. During this advance the glaciers lay about 40 / 160 m (Miage left / right lobe), 40 m (Brenva) and 80 m (Pré-de-Bard) behind their well-formed 1818-1820 moraines. A new progressive phase of the Italian Mont Blanc glaciers started around 1912-1916 and lasted until 1920-1922. Whereas the Pré-de-Bard Glacier started its regressive phase in 1922, the Miage's retreat was delayed until 1936, and the Brenva continued the rock-avalanche triggered advance until 1940/41.

Comparing the amplitudes of the fluctuations, it is evident that the smoothed fluctuations of the Miage have the lowest amplitude. The Pré-de-Bard has the highest amplitude of oscillations. The Brenva finally, fluctuates synchronously but with slightly smaller amplitude than the Pré-de-Bard. In the 20th century though, the Brenva's 'normal' glacier dynamic was interrupted by the two rock avalanche events in 1920 and 1997. Since the mid 19th century maximum until today the Miage has retreated by about 300 m, the Brenva by 270 m and the Pré-de-Bard by nearly 1500 m.

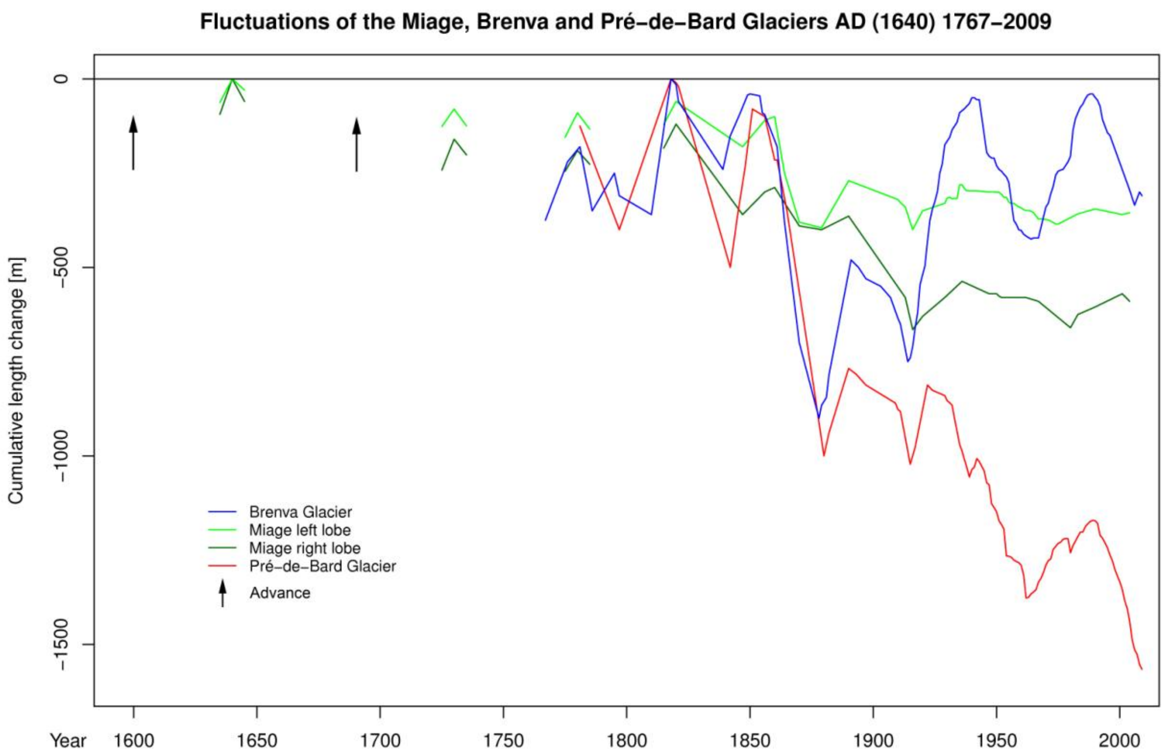


Figure 49: Cumulative length variations of the Miage, Brenva and Pré-de-Bard Glaciers AD (1640) 1767-2009 relative to their LIA maximum extent (1640 for the Miage, 1818 for the Brenva and 1818/1819 for the Pré-de-Bard).

5.2 Comparing the study glaciers with other Alpine glaciers

The Ruitor Glacier is another glacier in the upper Aosta Valley, situated only 15 km southeast from the Brenva, above the village La Thuile. Its advances in the late 16th and early 17th century are well recorded due to the flood disasters they provoked. A first flood disaster occurred in 1594, and they continued to recur annually until 1598, perhaps even 1606 (Pfister, 2007). After 1606 the flood disasters held off for nearly two decades. The 'year without a summer' 1628 probably caused the glacier to advance again and the floods resumed for some years after 1628 (Pfister, 2007). The period of flood disasters, between 1594 and 1598/1606 at the Ruitor Glacier, corresponds well with the advance phase at the

Miage Glacier at the turn of the 16th to the 17th century. The second flood disaster period, which started in 1628, corresponds to the glacier advance which led the Miage to a maximum around 1640. Outbursts from the *Lac de Combal*, which was dammed by the Miage Glacier, are recorded from 1594, 1595, 1629/1630, 1640, 1646 and between 1678 and 1680 (Grove, 2004). This shows the simultaneity of glacier fluctuations in the upper Aosta Valley.

Similar glacier fluctuations can also be found in the nearby Gran Paradiso area. Based on moraine mappings, Zienert (1965) showed that the Gran Paradiso glaciers reached their maximum positions around 1600, 1680, 1770, 1820, 1860 and 1920.

Cerutti (1985) compared glacier fluctuations in the Mont Blanc and Monte Rosa area between 1815 and 1985. According to Cerutti (1985), the Brenva and Pré-de-Bard Glaciers showed phase inversions about 10 years before the glaciers of the Monte Rosa started to react (start of advance: Brenva 1965, Pré-de-Bard 1963, Grande di Verra 1973, Piccolo di Verra 1972, Lys 1972). Whereas the Mont Blanc glaciers reached their maxima around 1818 and 1850, the Monte Rosa glaciers only culminate around 1821 and again around 1860. Cerutti (1985) further reported that the delays of the Monte Rosa glaciers correspond to a delay in the establishment of the climatic conditions, which in turn differ according to the geographical positions of the two massifs. The Miage Glacier attained its 19th century maxima, similar to the Monte Rosa glaciers, in 1820 and around 1860. This underlines the exceptional status of the Miage among the Mont Blanc glaciers, which is due to its dense debris cover.

A comparison of Glacier des Bossons, Mer de Glace, Glacier d’Argentière and Glacier du Trient on the Mont Blanc north side since 1875 is given by Reynaud & Vincent (2000). All four glaciers fluctuated nearly synchronous and showed advances around 1890, 1920 and 1970. Whereas the 1890 and the 1920 advance can also be identified at the Miage, Brenva and Pré-de-Bard Glaciers, the 1970 advance of the north slope occurred on the Mont Blanc south slope only in 1989 (for the detailed comparison of the study glaciers with the Mer de Glace see Section 5.3).

Many glaciers in the central Alps reached their 19th century maximum in the 1850s. For example the Aletsch Glacier; after maxima in the 1370s and 1670s, it reached a third maximum in 1859/60 (Holzhauser *et al.,* 2005). The Lower Grindelwald Glacier had its second biggest maximum, after the LIA maximum around 1600/1641, in 1855/56 (Zumbühl, 1980). The Gorner Glacier even reached its LIA maximum in 1859 (Holzhauser *et al*., 2005). The Rosenlaui Glacier though, had its 19th century maximal extent in 1826 similarly to the glaciers in the Mont Blanc region (Zumbühl *et al.*, 2008).

5.3 Comparing the study glaciers with the Mer de Glace

On the Mont Blanc north slope we find several large ice streams. The Mer de Glace is a compound valley glacier, 12 km long and covering a surface area of 31.9 km^2 (Nussbaumer *et al.*, 2007). It is among the best-documented Alpine glaciers with a wealth of different historical sources documenting its behaviour (Zumbühl *et al.,* 2008). Nussbaumer *et al.* (2007) recently reconstructed a new length change curve for the Mer de Glace starting in 1570 and thus being a very long glacier curve. The documentary data available on the Mer de Glace is far more abundant than for the glaciers in this study. The Brenva is the only glacier on the Mont Blanc south slope, which is similarly well documented. Nevertheless, the quality of the documents for the Mer de Glace is distinctly better. Most artists that portrayed the Italian Mont Blanc glaciers also worked on the Mer de Glace (e.g., François Jalabert, Jean-Antoine Linck, James David Forbes, Hans Conrad Escher von der Linth, Eugène-Emmanuel Viollet-le-Duc etc.).

Comparing the Miage, Brenva and Pré-de-Bard Glaciers with the Mer de Glace reveals a clear simultaneity of glacier fluctuations on the south and north slope of the Mont Blanc. For the Miage and Mer de Glace, the LIA maximum occurred in the first half of the 17th century, in 1640 and 1644, respectively. The Brenva and Pré-de-Bard though, only reached their LIA maximum in 1818/1819. The same progressive phase led the Miage and Mer de Glace to new maxima in 1820, and 1821, respectively. When the LIA started in the 15th century, large glaciers that already had a certain ice volume were able to react fastest. This would explain why the bigger Mont Blanc glaciers (e.g., Miage, Mer de Glace) reached their maximum already in the 17th century, whereas most middle-sized glaciers reached their LIA maximum only in the advance around 1818-1820 (Zienert, 1965).

Similar to the Brenva and Pré-de-Bard Glaciers, the Mer de Glace reached its secondary maximum of the 19th century in 1852. For the time period covered by instrumental glacier front data, the Mer de Glace again shows a delay of 2-8 years compared to the Pré-de-Bard.

Compared to the glaciers in this study, the Mer de Glace generally shows higher amplitude of length changes, with stronger advances and retreats. Especially since the end of the

LIA, the Mer de Glace has dramatically retreated. A dramatic retreat could also be observed at the Pré-de-Bard Glacier. Compared to their 19th century maximum (Pré-de-Bard, 1818/19; Mer de Glace, 1821), the Pré-de-Bard has lost 30.4 % and the Mer de Glace 16.2 % of length until 2005 (Nussbaumer *et al.*, 2007). The Brenva on the other hand has only lost 4.6 % of length, which is mainly due to the two rock avalanche events in 1920 and 1997. The inert Miage Glacier has only shortened by 3.3 % (left lobe), and 5.4 % (right lobe), respectively.

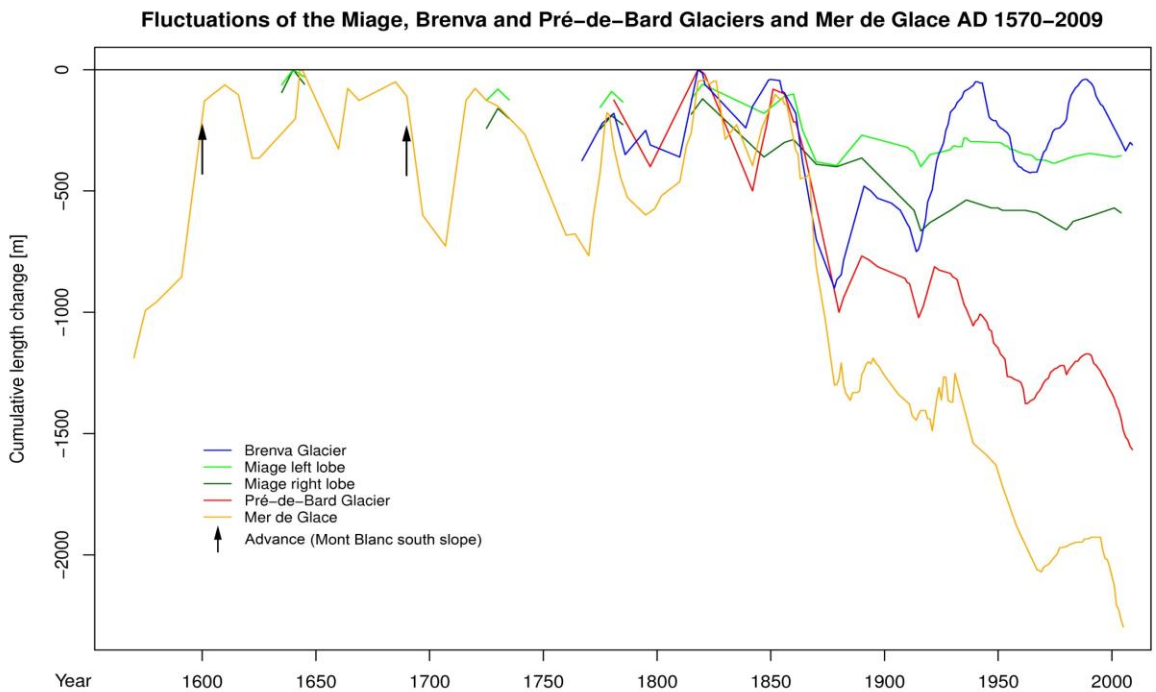


Figure 50: Cumulative length variations of the Miage, Brenva and Pré-de-Bard Glaciers AD (1640) 1767-2009 and the Mer de Glace AD 1570-2005 (orange line; Nussbaumer *et al.*, 2007) relative to their LIA maximum extent (1640 for Miage, 1644 for Mer de Glace, 1818 for Brenva and 1818/19 for Pré-de-Bard).

To summarize, the temporal beginning of phase changes at the Mer de Glace is most similar to the Miage Glacier. Both react with a time delay of some years when compared to the Brenva and Pré-de-Bard Glaciers. This simultaneity can be attributed to their similar size. However, the fluctuations of the Miage are significantly smoother compared to the Mer de Glace. The debris-covered Miage has an amplitude of only about 600 m. In this aspect, the Mer de Glace compares better with the Pré-de-Bard Glacier.

5.4 Glacier changes at the Miage, Brenva and Pré-de-Bard

For the Miage the left frontal lobe is more responsive than the right frontal lobe, which is more stagnant. Apparently the relationship had been inverse during the LIA. In this period the right lobe underwent bigger fluctuations, as can be reconstituted when considering the distances between the LIA moraines. The relative stability could be associated with changing hydrological conditions within the lobes (Deline, 18.11.2009; personal communication). The fluctuations of the Brenva Glacier are spasmodic with rather high amplitudes due to the relationship between the geometries of the accumulation and the ablation basin; the vast caldron like accumulation basin is funneled through the steep *Pierre à Moulin* into the narrow valley tongue (Heybrock, 1940). The same behaviour can be observed at the Pré-de-Bard, which has similar proportions of accumulation and ablation basin. However, its glacier basin is less inclined than that of the Brenva.

The length fluctuations correlate well with variations in volume. As D'Agata and Zanutta (2007) showed, the Brenva increased in thickness during the period of 1959-1983 (average +23m), followed by a period of thinning in 1983-1997 (average -11m). These variations correspond to the phase of advance from 1959 to 1989 and the subsequent retreat. However the signal is delayed. The thinning of the ice started in the period of 1983-1991, whereas the retraction of the terminus only began in 1990. The rock avalanche in 1997 initiated a new period of vertical growth, while for the moment, the length reduction was decelerated. For the Miage the length fluctuations correspond to the volumetric changes as well. Thomson *et al.* (2000) identified four periods of volume change between 1913 and 1999: A net increase in volume during the period of 1913-1957 (Δ elevation +5.98m) was followed by an inverse phase between 1957 and 1967 (Δ elevation -3.83m) and again two positive phases during the periods of 1967-1975 and 1975-1999 (Δ elevation +2m and +1m respectively). The spatiotemporal pattern is consistent with the length changes, if it is assumed that the major thickening during the 1913-1957 interval occurred prior to the high stand in 1935/36. The advance beginning around 1975 corresponds to the arrival of a zone of increased mass flux at the terminus (Thomson *et al.*, 2000). Comparing the volume changes of the Brenva and Miage, it becomes evident that the two glaciers do not respond synchronously. The difference can be attributed to the insulation and size effects already mentioned when comparing the differential length changes of the two glaciers.

5.5 Climate at the Gr. St. Bernard and glacier response

Comparing mean annual temperature and precipitation series of the Gr. St. Bernard with glacier length change at the Pré-de-Bard reveals striking parallels (Figure 51). Considering the temperature and precipitation series, the lowpass filtered curve shows significantly positive linear trends for both parameters (linear trends: +0.0062°C/yr for temperature and 3.25 mm/yr for precipitation; calculated by Wanner *et al.* (2000a) for the period 1818-1996). Apart from the last 40 years, the two parameters are more or less anticorrelated. Intervals characterized by low mean annual temperature tend to coincide with intervals of high precipitation. Episodes of glacier advance at the Pré-de-Bard follow upon such intervals with a time lag of about 13 years (see Section reaction time and time lag). Conversely, periods of rising temperature and decreasing precipitation are followed by terminal recession.

Wanner *et al.* (2000a) classified the temperature and precipitation record of the Gr. St. Bernard into four distinct periods. The first period, or LIATE 1, ranges from 1818 until 1890 and includes the two 19th century maxima. It is characterized by progressively lower temperatures and a wet peak around the 1840s, which brought enormous amounts of winter precipitation with snow and avalanches (Schüepp, 1991). The phase following next, with three temperature and two precipitation peaks, forms the transition from the LIA to the 20th century warm phase. It was followed by a period of several snowy winters and moderate temperatures between 1950 and 1974. The last phase is characterized by a strong temperature rise and a precipitation peak around 2000.

Reaction time and time lag

Based on a correlation analysis, the time lag for a change in temperature was found to be about 13 years for the Pré-de-Bard Glacier. The Brenva Glacier, which descends rapidly over steep slopes, has an even shorter time lag of about 9 years. Clearly, the more than 10 km long Miage Glacier has the longest reaction time with about 49 years (both lobes). Such a long time lag can be explained by the extensive surface debris cover of the Miage, which translates climatic signals in a smoothed way. In addition, the time lag at the Miage is a function of its relatively small surface slope of only 29 % (compared to 40 % and 37 % for the Brenva and Pré-de-Bard Glaciers, respectively). Small and medium-sized glaciers

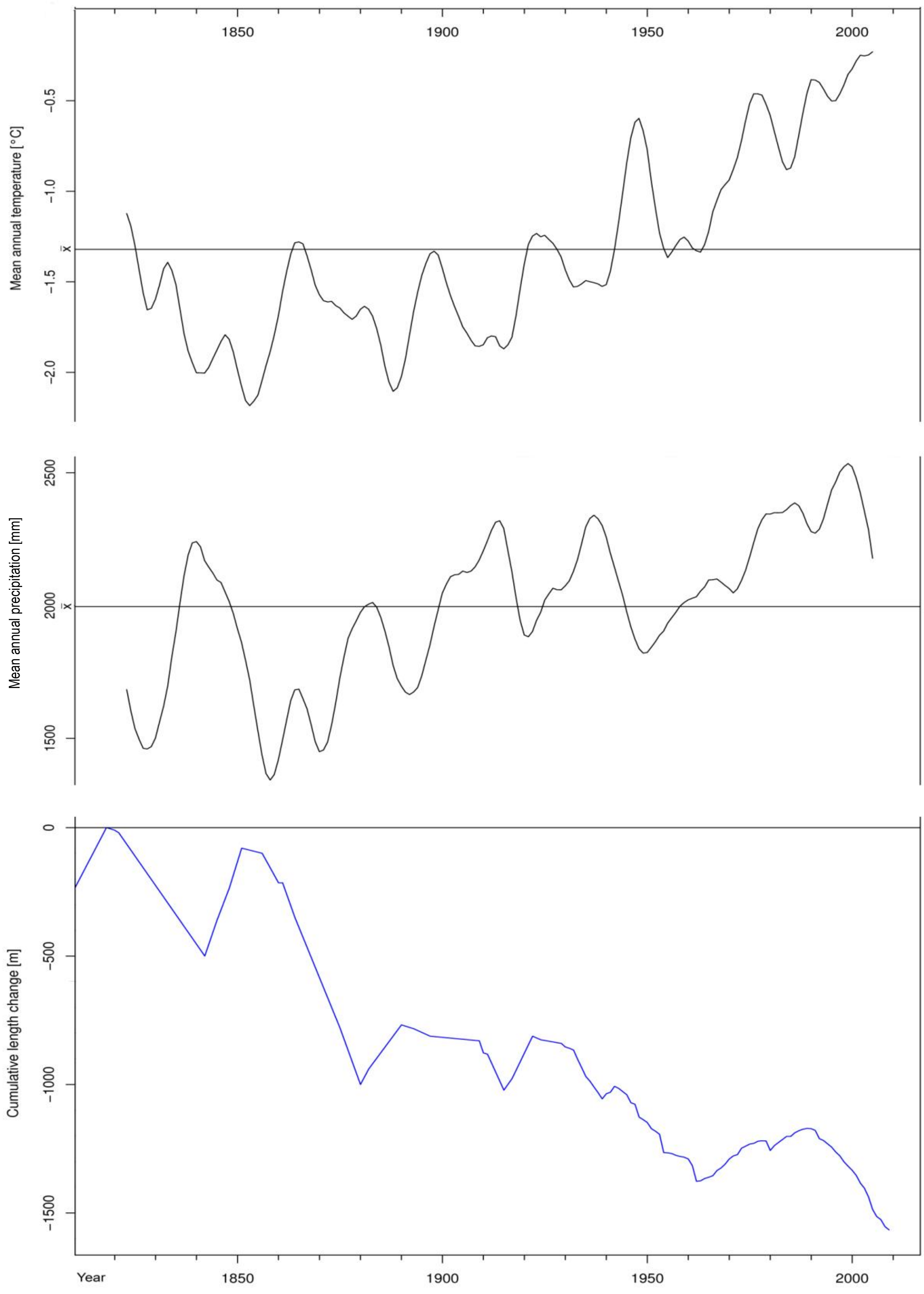


Figure 51 : Comparison of mean annual temperature and precipitation series of the Gr. St. Bernard (10-year running means, 1818-2009, data from MeteoSchweiz) with length changes of the Pré-de-Bard Glacier from 1818 until 2009.

as the Brenva and Pré-de-Bard may show changes within a few years and are sensitive to decadal variations in climate. Larger glaciers (e.g., Aletsch Glacier) though, need much more time to react and indicate long-term climatic fluctuations. The present-day position of the glacier front is therefore a reflection of the climatic conditions of past decades (Holzhauser *et al.*, 2005).

Comparison with other studies

Although the temperature-precipitation record at Gr. St. Bernard covers less than two centuries, it has to be assumed that earlier periods of glacier expansion were also related to phases when winter accumulation was above average and temperature, especially during the ablation season, was below the long-term mean. Based on documentary proxy data, tree-ring data and historical documents Wanner *et al.* (2000a) reconstructed temperature and precipitation for winter and summer in the northern Swiss Alps back to 1550. The first period they identified corresponds to the end of the second advances of the glaciers in the LIA (LIATE 2, 1550-1645). This period was characterized by low temperatures in both seasons and wet summers. In the same period, in 1587 and 1628, two 'years without a summer' occurred (Pfister, 2007; see 'year without a summer 1816' below). The summer snowfalls in the higher elevations led to a high albedo and therefore positive mass balances of the glaciers. The following period was the so-called 'Maunder Minimum' with low solar activity (1645-1715). Even though the climate was very cold the glaciers stayed relatively retreated, because the winters were too dry. A transitional phase with warm and wet summers, as well as cool and dry winters, led to the fourth period with the two last glacier advances of the LIA in the early and mid 19th century. Finally, we arrive at the time of the instrumental temperature and precipitation record at the Gr. St. Bernard. As described above, this period (according to Wanner *et al.*, 2000a, LIATE 1, ca. 1815-1890) was characterized by progressively lower temperatures and a wet peak around the 1840s which brought enormous amounts of winter precipitation. For the Mont Blanc south slope this was also reported by King (1858), who mentioned unusual snowfalls in the winters 1843/44 and 1844/45.

The 1818/20 glacier maximum advance can be linked to the 'year without a summer' 1816: After the eruption of the volcano Tambora (Indonesia) in April 1815, the climate on the northern hemisphere deteriorated for several years. Intensive rain falls and low temperatures led to severe crop failures and famines in south-western Europe. In

Switzerland it snowed down to 800 m a.s.l. every month in 1816 (Pfister, 1999), evidently with positive consequences on the glacier mass balances.

An example of a glacier response to such climatic conditions is given with the Lower Grindelwald Glacier; according to Zumbühl *et al.* (2008) the 1820 glacier advance was driven by low summer temperatures and high autumn precipitation. The 1860-1880 retreat period was mainly forced by high temperatures.

Cerutti (1971) reports that retreat phases at the Italian Mont Blanc glaciers are most often preceded by an elevation in the mean annual temperature. Periods of advancing glacier fronts however, coincide with a previous increase in precipitation. Nussbaumer (2007) showed that glacier fluctuations at the Mer de Glace are driven slightly stronger by temperature (over 52% of importance) than by precipitation. In addition, precipitation is more important during winter and spring, whereas temperature is the deterministic factor during summer and autumn.

Climate change in the European Alps during the 20th century has been characterized by temperature increase, little trend in precipitation data, and a general decrease of sunshine duration through to the mid 1980s (Haeberli & Beniston, 1998). Temperature increase has been most intense in the 1940s, followed by the 1980s. Accordingly, these changes caused pronounced effects on Alpine glaciers; since the middle of the 19th century they have lost about 30 to 40 % in glacierized surface area and around 50 % in ice volume (Haeberli & Beniston, 1998). The temperature increase and thus the glacier behaviour in the mid 20th century seem to be strongly correlated to solar radiation. Huss *et al.* (2009) showed that the extraordinary melt rates at three Swiss Alpine glaciers (Aletsch, Clariden and Silvretta Glaciers) in the 1940s can be attributed to enhanced solar radiation in summertime, which was 8% above the long-term mean. From 1941 to 1947 the Brenva lost 2.2 % of length, which corresponds to a meltback of about 26 m/yr. The Pré-de-Bard even lost 3.0 % of length (-20 m/yr) in the period 1942-1948. Moreover, Holzhauser *et al.* (2005) report that solar activity was a major forcing factor of climatic oscillations in west-central Europe during the late Holocene.

6. Conclusion

Historical methods allowed the reconstruction of three new glacier length curves for the Miage, Brenva and Pré-de-Bard Glaciers dating back to 1640, 1767 and 1781, respectively. The new curves show several glacier advance and retreat phases during the LIA. For the Miage the LIA maximum occurred in the first half of the 17th century (1640). The Brenva and Pré-de-Bard though, only reach their LIA maximum in 1818. The same progressive phase led the Miage to a new maximum in 1820. A third major maximum was reached by all three glaciers during the mid 19th century. Whereas the Brenva and the Pré-de-Bard culminated around 1850, the Miage only attained a new maximum around 1860.

The Miage Glacier is the most stable among the three glaciers investigated, only fluctuating to a minor extent. Due to its size and the regulative effect of the debris cover, this large valley glacier has a long reaction time. The Pré-de-Bard Glacier in contrast, is almost free of debris cover and much smaller. These characteristics explain the short reaction time and the resultant rapid fluctuations of the Pré-de-Bard. Finally, the behaviour of the Brenva Glacier has been governed by sporadic rock avalanches. The 1920 rock avalanche triggered an acceleration of the glacier's forward movement, resulting in a pronounced advance.

Glacier variations are sensitive indicators to climate variability. The analysis of the temperature and precipitation record from Gr. St. Bernard showed that periods of glacier expansion are related to previous phases of low temperature (especially during the ablation season) and high amounts of precipitation (especially during the accumulation season).

Despite the individual behaviour of each glacier, all three curves indicate the characteristic LIA maxima. These findings coincide well with the fluctuations of most Alpine glaciers thus indicating the generalizability of the LIA event for the Alps. Comparing the new glacier length curves with the curve of the Mer de Glace showed a clear simultaneity of fluctuations on the north and south slope of the Mont Blanc. Whereas the time lag of phase inversion is most similar between the Miage and Mer de Glace, the amplitude of the Mer de Glace fluctuations is best comparable to that of the Pré-de-Bard.

The Mont Blanc area is among the probably best-documented regions in the world regarding historical glacier data. However, the findings of this study are based on few data dating back far in time, therefore making interpretations of early fluctuations very difficult. Unless new historical materials become available, the uncertainty of these times will remain high. To further validate and deepen the knowledge on glacier fluctuations during the LIA in the Alps, it would be interesting to include additional glaciers, and to compare these findings to glacier fluctuations around the world.

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8. Appendix

8.1 Appendix 1: Additional pictorial documents

Figure 52 : Map of the lower Miage Glacier surveyed in 1879 by Marengo and Bruno (“Carta del Ghiacciaio del Miage. Parte inferiore”; signed down left “G.C. Marengo dis.”; Scale 1:10’000; Tavola I., Baretti, 1880)

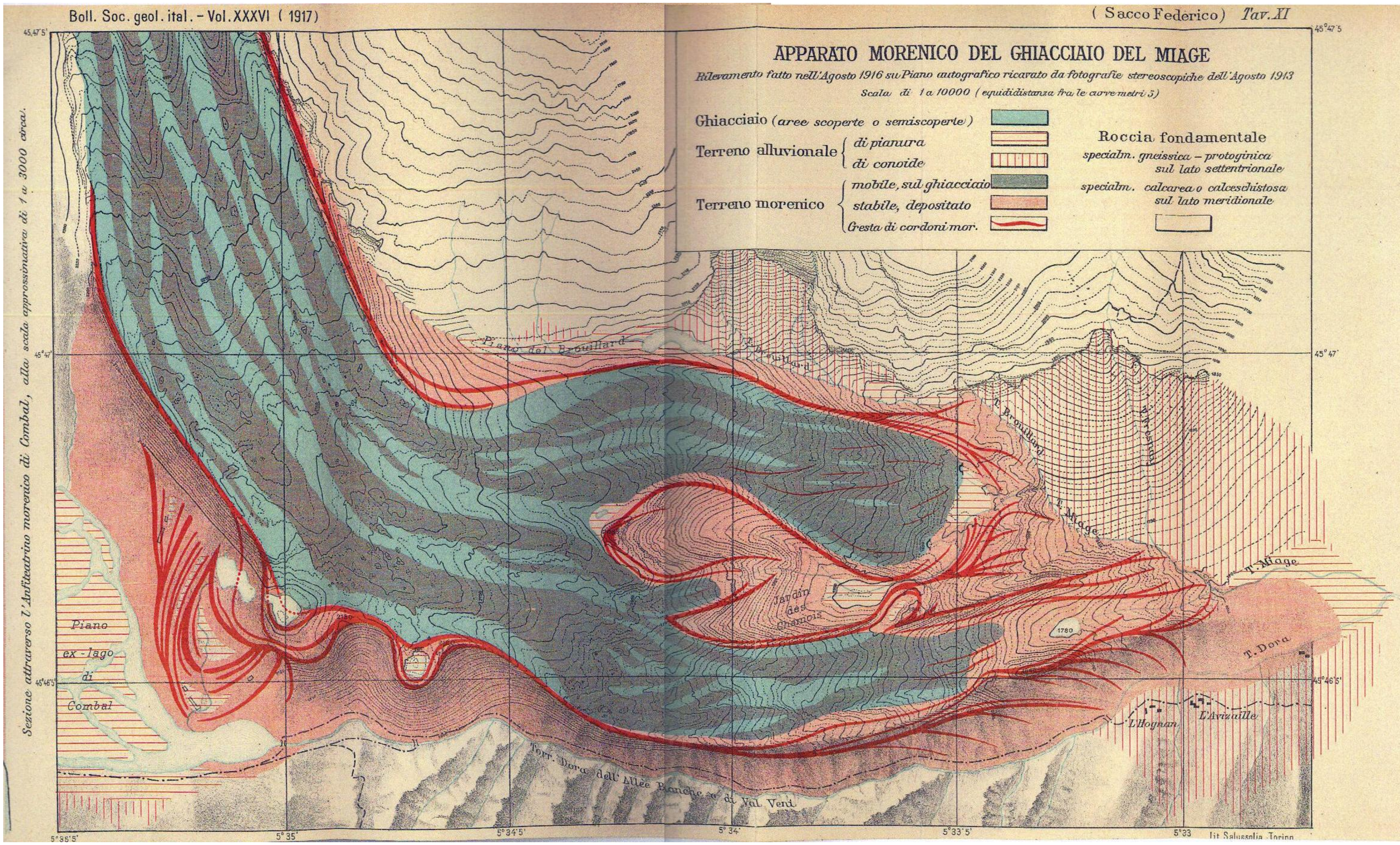


Figure 53 : Map of the lower Miage Glacier surveyed in August 1916 by Sacco (“Apparato morenico del Ghiacciaio del Miage”; Scale 1:10'000; Tavola XI., Sacco, 1917)

Table 6 : Characteristics of the main historical documents used to reconstruct the glacier length change curve of the Miage Glacier (non-exhaustive list).

Date	Document type	Title	Author [engraving by]	Literature / source
1594-1595, 1629-30, 1640, 1646, 1678-80	written source	Outburst of lake Combal		Grove (2004)
April 6th, 1600	written source		J. Cochet	Le Roy Ladurie (1971)
May 8th, 1631	written source		G. Rogiero	Aliprandi & Aliprandi (1986)
1689	written source		P.A. Arnod	Cerutti (1985b)
1781	engraving	"Le Mont-Blanc vu en face du Coté de l'Allée-Blanche"	M.T. Bourrit / F. Bartolozzi [A. Töpffer]	De Saussure (1786)
1786	map	"Carte de la partie des Alpes qui avoisine le Mont Blanc"	M.A. Pictet	De Saussure (1786)
1797-1799	map	"Carte physique et minéralogique du Mont Blanc et des montagnes…"	J.B. Raymond	Kartensammlung, ZB Zürich
1799	map (manuscript)	"Plan en perspective des Monts Blanc et Maudits…"	J. Bourcet	Aliprandi & Aliprandi (2007)
1820	written		J. De Charpentier	De Charpentier (1841)
1821/22 (?)	aquatint	"Lac Combal et glacier de Miage"	J.L.P. Coignet [F. Salathé]	Raoul-Rochette (1826)
1823	map (manuscript)	"Carta topografica degli Stati di Terraferma di S.M. il Re di Sardegna"	F. Muletti	Kartensammlung, ZB Zürich
1829	map	"Carte topographique du Mont Blanc et des vallées qui l'environnent…"	F.J. Pictet	Kartensammlung, ZB Zürich
1842	engraving	"The Glacier de Miage and its Moraine"	J.D. Forbes	Forbes (1843)
1842	topograph. sketch	"Eye sketch of the Glacier de Miage"	J.D. Forbes	Forbes (1843)
1849	chromolithograph	"Glacier de Miage (allée blanche au pied du Mont Blanc)"	H.J. Hogard	Hogard (1854)
1849	written source		H.J. Hogard	Hogard (1854)
August 13th, 1855	written source		S.W. King	King (1858)
1856	map	"Gran Carta degli Stati Sardi in Terraferma"		Kartensammlung, ZB Zürich
around 1860	drawing	"Chalets de Vény"	E. Aubert	Aubert (1860)
1861	map	"Dufour Karte"	G.H. Dufour	Kartensammlung, Universität Bern
1864	map	"Massif du Mont Blanc"	J.J. Mieulet	Kartensammlung, ZB Zürich
1863-1864	map	"The chain of Mont Blanc from an actual survey in 1863-4"	A. Adams-Reilly	Kartensammlung, ZB Zürich
1868-1875	written source		E. Viollet-le-Duc	Viollet-le-Duc (1876)
1870	map	"Le massif du Mont Blanc"	E. Viollet-le-Duc	Kartensammlung, Universität Bern
1879	map	"Carta del Ghiacciaio del Miage. Parte inferiore"	G.G. Marengo	Baretti (1880)
1879	written source		M. Baretti	Baretti (1880)
1882	map	"Carta d'Italia"	Istituto Geografico Militare	Aliprandi & Aliprandi (2007)
1890	written source		F. Sacco	Sacco (1917)
1897	written source		F. Porro	Porro (1902)
1910-1911	written source		P. Revelli	Revelli (1911,1912)
1913	stereoscopic relief		F. Porro	Porro (1914)
1916	map	"Apparato morenico del Ghiacciaio del Miage"	F. Sacco	Sacco (1917)
1916-1918	written source		F. Sacco	Sacco (1918)
1930	photograph	Miage left tongue	C.F. Capello	Bolletino CGI (1931)
1971	photograph	Miage left tongue	C. Lesca	Bolletino CGI (1972)

Figure 54: The valley tongue of the Brenva in the map by Marengo from 1879 ("Parte inferiore del ghiacciaio della Brenva. Scala di 1:20'000"; lithograph; signed down left "G.G. Marengo, Geometra, dis. e ril."; marked down right "Torino, Lit. Flli Doyen"; Tavola I, Marengo, 1881)

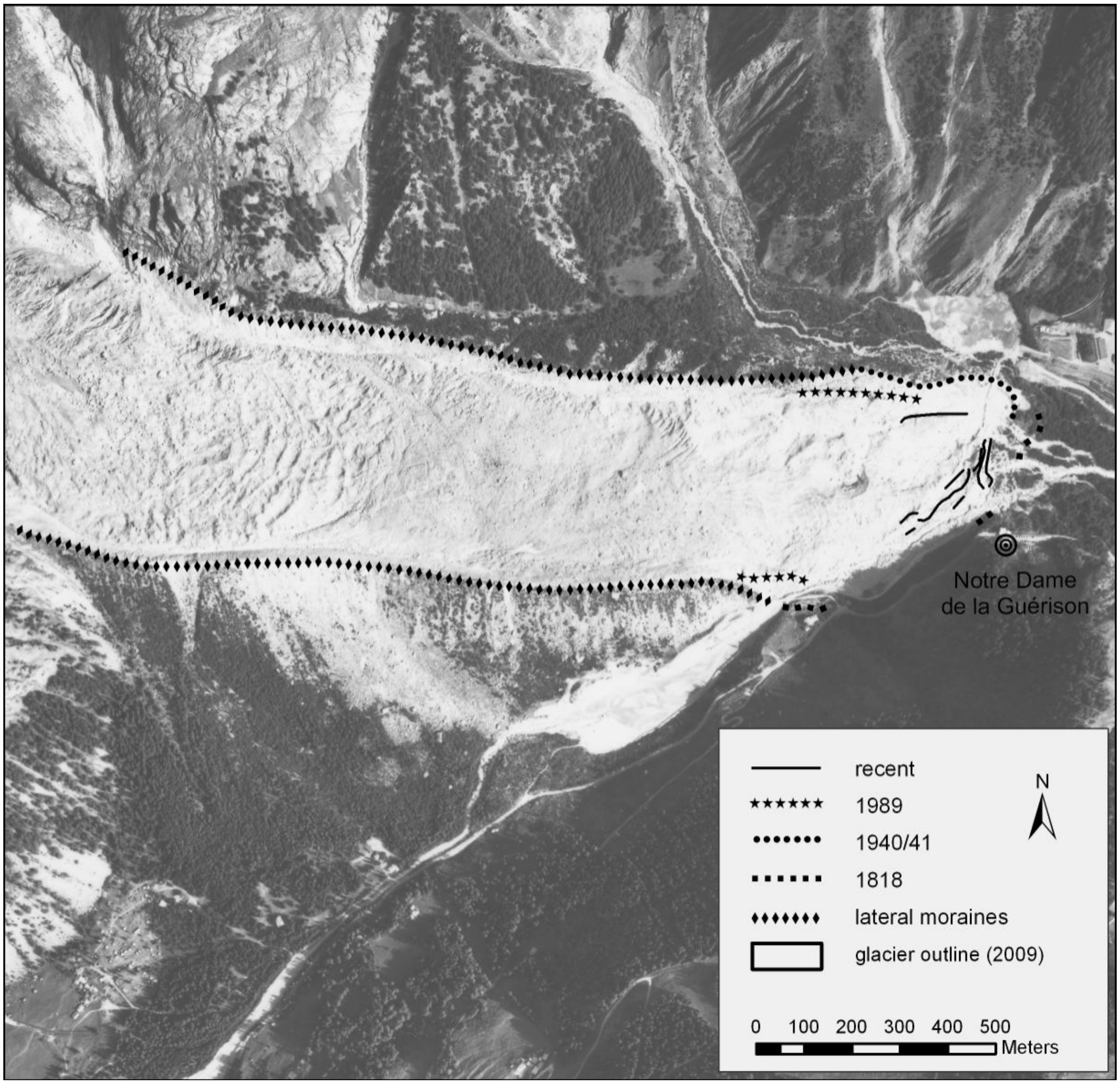


Figure 55 : The Brenva frontal area with lateral and frontal moraines in an aerial photograph (dating of moraines after Valbusa, 1927; Capello, 1941; Porter & Orombelli, 1982a; Cerutti, 1985. Aerial photograph from 22.08.2004, © IGM, Italy).

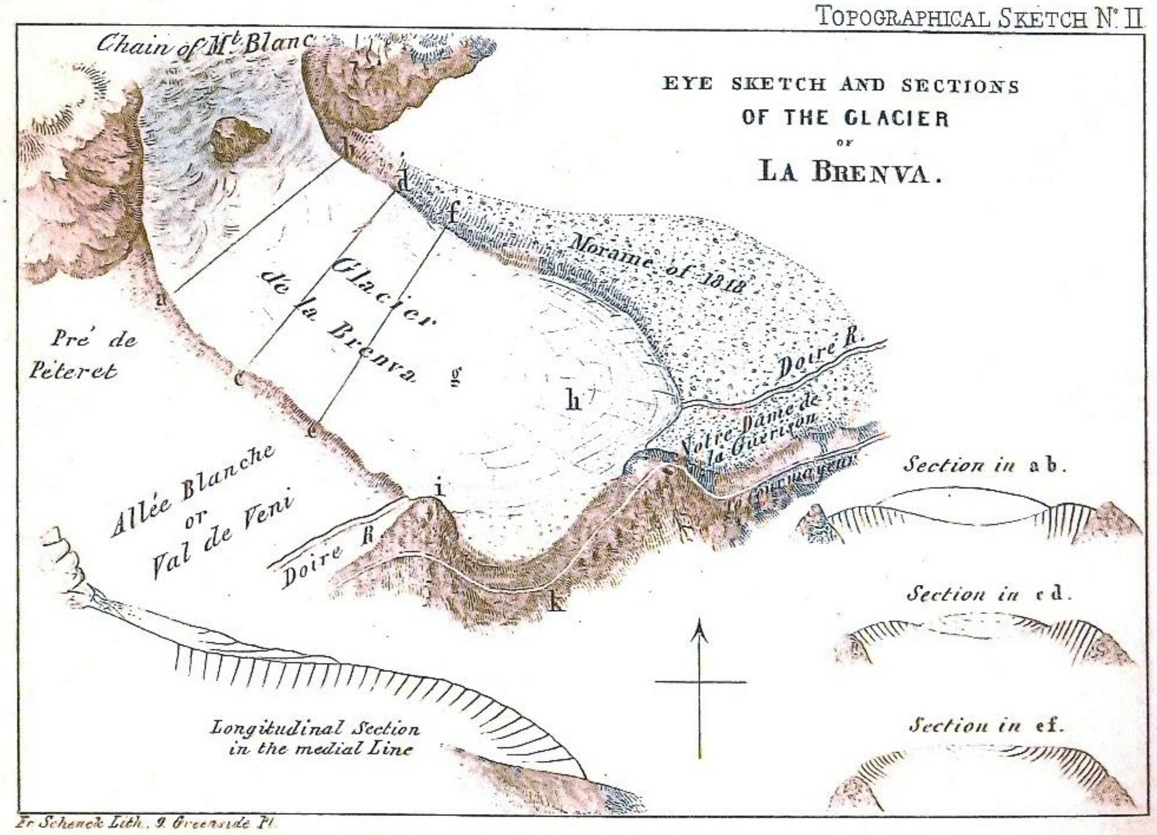


Figure 56: Cartographic sketch of the lower Brenva Glacier from July 1842 by Forbes ("Eye Sketch and sections of the Glacier of la Brenva"; lithograph; 8.6 x 12.2 cm; Topographical Sketch N° II, p. 192-193, Forbes, 1843)

F. 1.

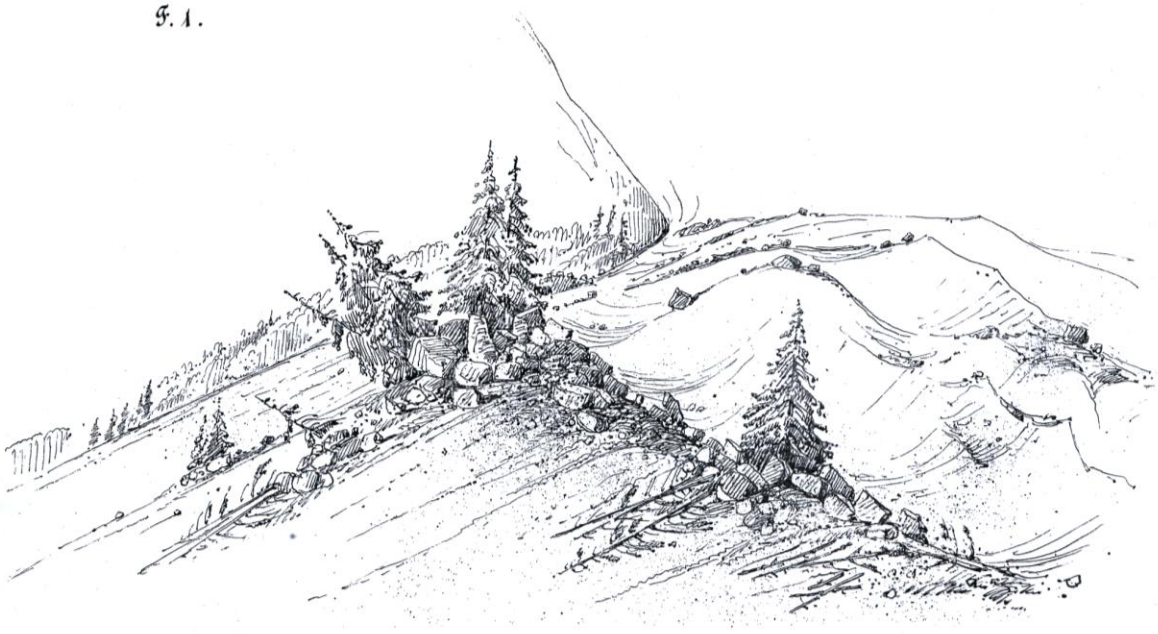


Figure 57: The enormous ice masses of the Brenva Glacier are overturning fir trees on the right lateral moraine ("Glacier de la Brenva (Mont-blanc)"; sketch by H. Hogard; lithograph by Didlon, Épinal; 8.0 x 15.0 cm; F.1, Pl. 21, Hogard, 1858)

Table 7 : Characteristics of the main historical documents used to reconstruct the glacier length change curve of the Brenva Glacier (non-exhaustive list).

Date	Document type	Title	Author [engraving by]	Literature / source
April 6th, 1600	written source		J. Cochet	Le Roy Ladurie (1971)
May 8th, 1631	written source		G. Rogiero	Aliprandi & Aliprandi (1986)
1689	written source		P.A. Arnod	Cerutti (1985b)
1691	written source		P.A. Arnod	Le Roy Ladurie (1971)
1767	engraving	"Vue du Glacier de la Brenva"	F. Jalabert [A. Töpffer]	De Saussure (1786)
1776	written source		M.T. Bourrit	Bourrit (1776)
1781	engraving	"Le Mont-Blanc vu en face du Coté de l'Allée-Blanche"	M.T. Bourrit / F. Bartolozzi [A. Töpffer]	De Saussure (1786)
1786	map	"Carte de la partie des Alpes qui avoisine le Mont Blanc"	M.A. Pictet	De Saussure (1786)
1795	drawing	"Le glacier de la Brenva et l'arête de Peuterey"	J.A. Linck	Conseil Géneral Haute-Savoie (1990)
1797-1799	map	"Carte physique et minéralogique du Mont Blanc et des montagnes…"	J.B. Raymond	Kartensammlung, ZB Zürich
1799	map (manuscript)	"Plan en perspective des Monts Blanc et Maudits…"	J. Bourcet	Aliprandi & Aliprandi (2007)
1810	written source		M. D'Aubuisson	D'Aubuisson (1811)
1812	written source		Canon Carrol	Favre (1867)
1813	map		Keller	Vallot (1922)
October 7th, 1817	drawing		H.A. Fortescue	Porter & Orombelli (1982a)
1818	written source		Abbot Menabrea	Virgilio (1883)
August, 1820	written source		I. Venetz	Venetz (1833)
August 2nd, 1820	watercolour	"Am Fuss des Brenva Gletschers an der Südseite des Mont Blanc im Piemont"	H.C. Escher von der Linth	Solar & Hösli (1974)
1821	written source		W. Rose	Rose (1827)
1821/22 (?)	aquatint	"Le Mont Blanc vu de la vallée de Courmayeur"	J.L.P. Coignet [F. Salathé]	Raoul-Rochette (1826)
1823	map (manuscript)	"Carta topografica degli Stati di Terraferma di S.M. il Re di Sardegna"	F. Muletti	Kartensammlung, ZB Zürich
1829	map	"Carte topographique du Mont Blanc et des vallées qui l'environnent…"	F.J. Pictet	Kartensammlung, ZB Zürich
August 6th, 1839	drawing	"Le Mont Blanc et l'Allée blanche"	A. Dousseau	Porter & Orombelli (1982a)
1842	lithograph	"The glacier of la Brenva in the Allée-Blanche, from Entrèves"	J.D. Forbes [Highe]	Forbes (1843)
1842	lithograph	"Glacier of la Brenva. Shewing the structure of ice"	J.D. Forbes [Highe]	Forbes (1843)
1842	written source		J.D. Forbes	Favre (1867)
1842	topograph. sketch	"Eye sketch and sections of the Glacier of la Brenva"	J.D. Forbes	Forbes (1843)
1846	lithograph	"Glacier of la Brenva in 1842 / 1846"	J.D. Forbes [Fr. Schenk]	Forbes (1859)
1846	written source		J.D. Forbes	Forbes (1859)
August, 1849	lithograph	"Glacier de la Brenva"	H.J. Hogard [J. Bürck]	Noussan & Priuli (1985)
August, 1849	daguerreotype	"Mont Blanc, 4811 m"	J.G. Dardel	De Decker Heftler (2002)
1850	lithograph	"Estremità della morena laterale destra della Brenva vista dalla sega meccanica"	A. Gastaldi	Noussan & Priuli (1985)
1850	lithograph (?)	"Mont Blanc (Hauteur 4,810 m)"	T. Ladner	Ladner (1851)

1849, 1854, 1855	written source		S.W. King	King (1858)
August, 1855	wood engraving	"The Glacier of la Brenva - Val d'Entrèves"	S.W. King	King (1858)
1856	map	"Gran Carta degli Stati Sardi in Terraferma"		Kartensammlung, ZB Zürich
1861	photograph	"Le Mont Blanc - 4810 m. Pris du Carmel"	A. Civiale	Civiale (1882)
1861	map	"Dufour Karte"	G.H. Dufour	Kartensammlung, Universität Bern
1864	map	"Massif du Mont Blanc"	J.J. Mieulet	Kartensammlung, ZB Zürich
1863-1864	map	"The chain of Mont Blanc from an actual survey in 1863-4"	A. Adams-Reilly	Kartensammlung, ZB Zürich
1868-1875	written source		E. Viollet-le-Duc	Viollet-le-Duc (1876)
July 28th, 1870	sketch	"Le glacier de la Brenva"	E. Viollet-le-Duc	Viollet-le-Duc (1876)
1870	map	"Le massif du Mont Blanc"	E. Viollet-le-Duc	Kartensammlung, Universität Bern
1878	photograph		V. Besso	Sacco (1918)
1878	written source		G.G. Marengo	Marengo (1879)
1878-1879	map	“Parte inferiore del ghiacciaio della Brenva”	G.G. Marengo	Marengo (1879)
1879	written source		G.G. Marengo	Marengo (1879)
1881	written source		F. Virgilio	Virgilio (1883)
1882	written source		U. Valbusa	Valbusa (1924)
1882	map	"Carta d'Italia"	Istituto Geografico Militare	Aliprandi & Aliprandi (2007)
1889-1891	written source		C. Ruffier	Porro (1903)
July, 1894	photograph		P. Bargagli	Sacco (1918)
August 24th, 1897	photograph		A. Druetti	Porro (1903)
1897	written source		F. Porro	Porro (1902)
1903	photograph		F. Porro	Porro (1903)
1903	written source		F. Sacco	Sacco (1918)
1907	written source		F. Sacco	Sacco (1918)
1910-1911	written source		P. Revelli	Revelli (1911,1912)

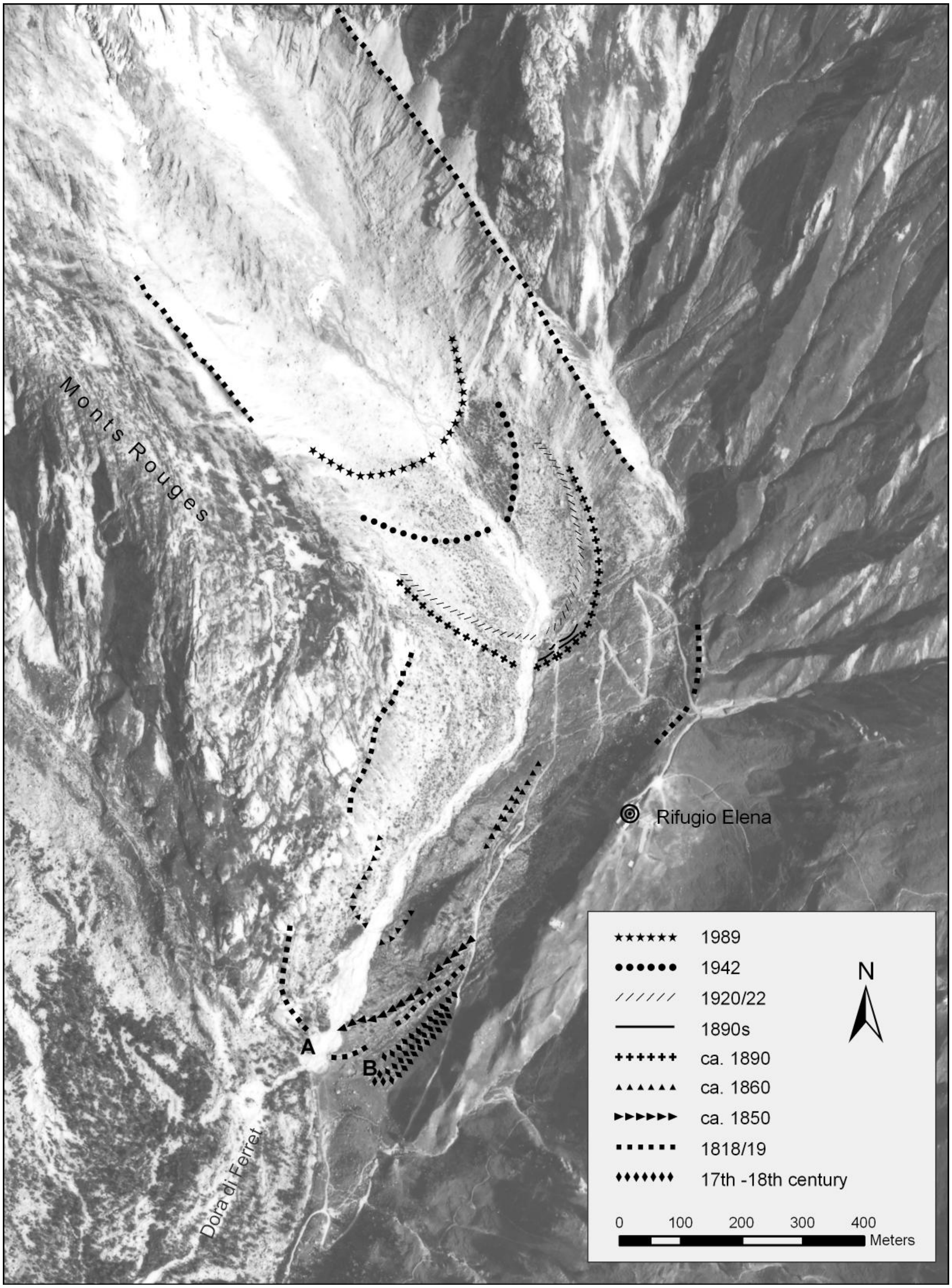


Figure 58: The Pré-de-Bard frontal area with lateral and frontal moraines in an aerial photograph (dating of the moraines after Capello, 1940; Zienert, 1965; Cerutti, 1975; Aeschlimann, 1983. Aerial photograph from 22.08.2004, © IGM, Italy).

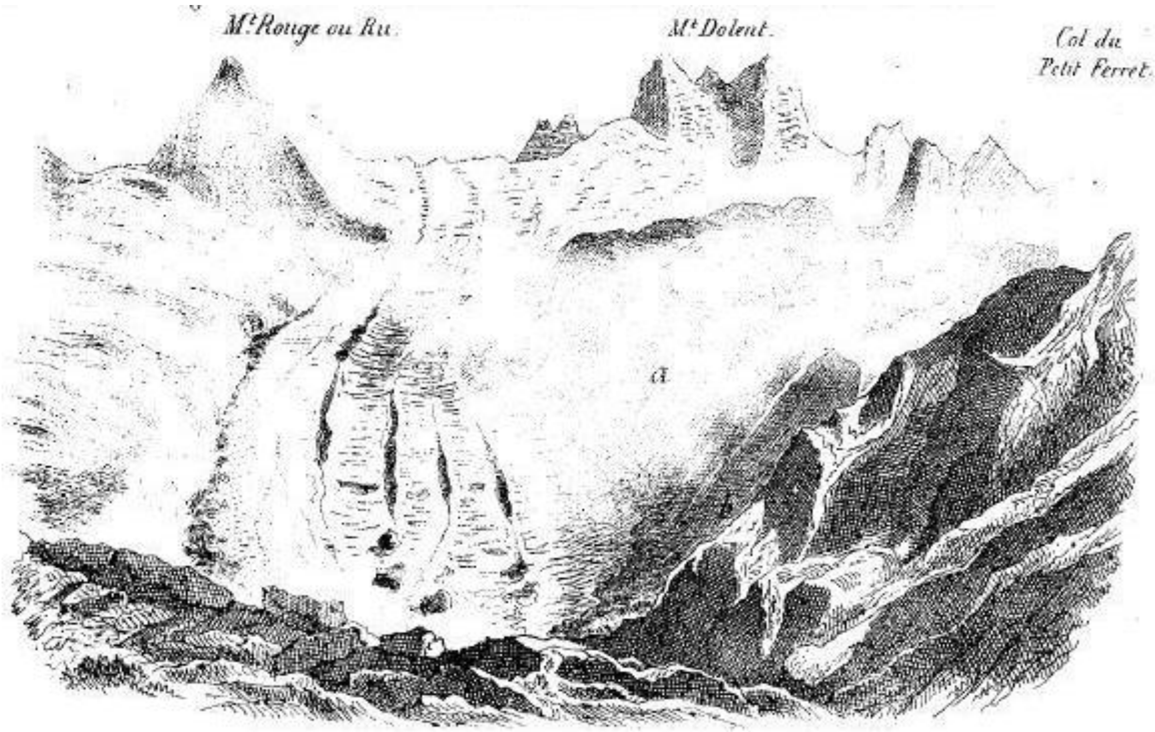
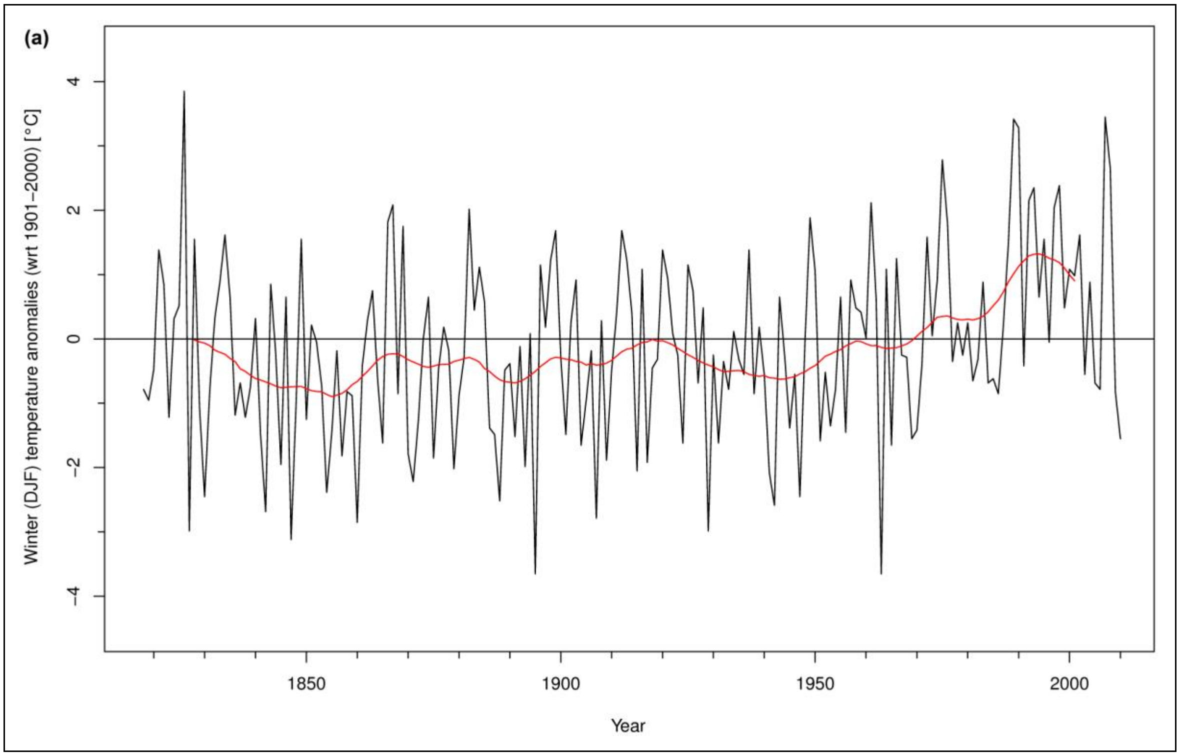


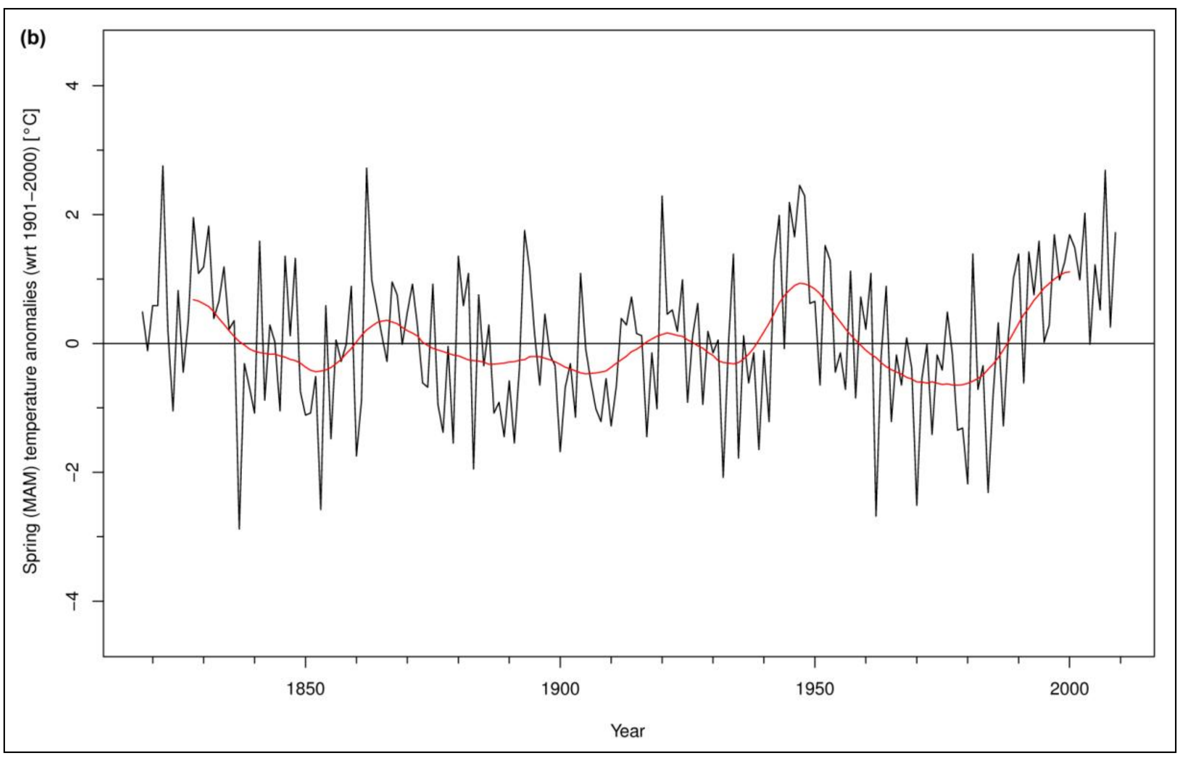
Figure 59: The Pré-de-Bard as seen from near the actual Rifugio Elena (“Glacier du Mont Dolent vu de Pré de Bar”; sketch by A. Favre; lithograph; 9.6 x 15.0 cm; Fig.1, Pl. XXI, Atlas, Favre, 1867)

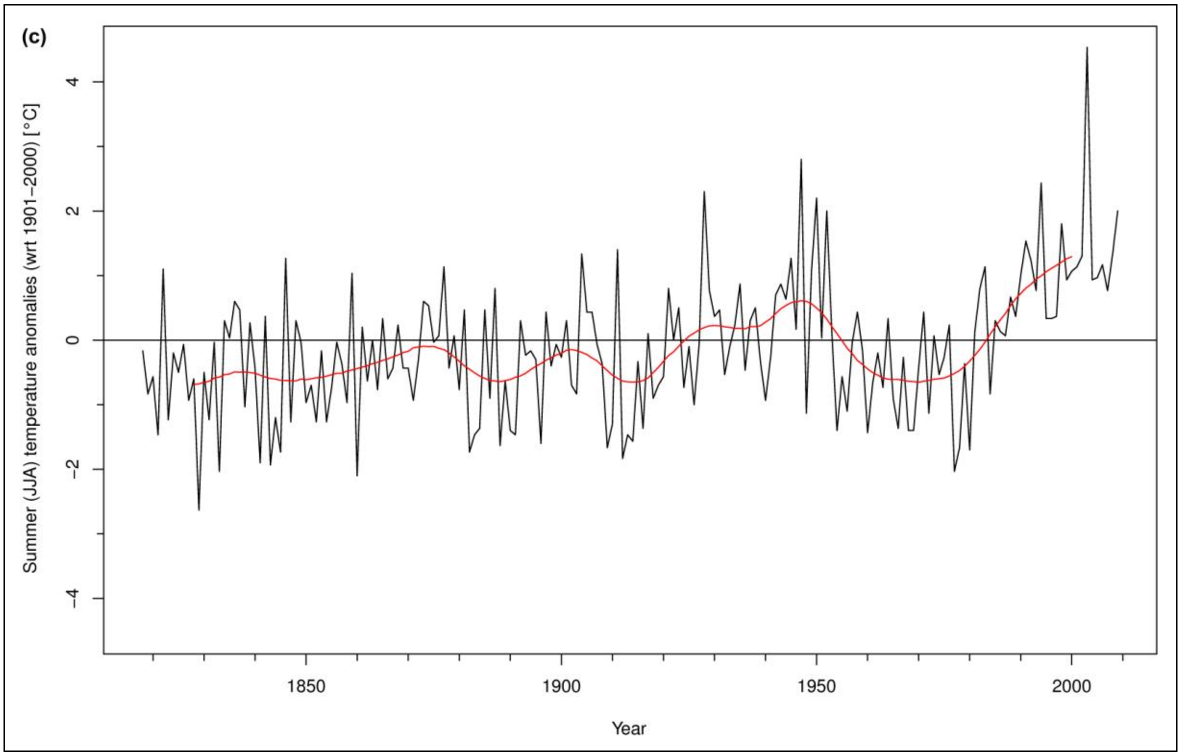
Table 8: Characteristics of the main historical documents used to reconstruct the glacier length change curve of the Pré-de-Bard Glacier (non-exhaustive list).

Date	Document type	Title	Author [engraving by]	Literature / source
April 6th, 1600	written source		J. Cochet	Le Roy Ladurie (1971)
1689	written source		P.A. Arnod	Cerutti (1985b)
1781	written source		H.B. De Saussure	De Saussure (1786)
1797-1799	map	"Carte physique et minéralogique du Mont Blanc et des montagnes…"	J.B. Raymond	Kartensammlung, ZB Zürich
1820	written source		I. Venetz	Venetz (1833)
1821/22 (?)	aquatint	"Glacier du Triolet"	J.F. d'Ostervald [F. Salathé]	Raoul-Rochette (1826)
1821/22 (?)	aquatint	"Glacier du Mont-Dolent"	J.F. d'Ostervald [F. Salathé]	Raoul-Rochette (1826)
1823	map (manuscript)	"Carta topografica degli Stati di Terraferma di S.M. il Re di Sardegna"	F. Muletti	Kartensammlung, ZB Zürich
1829	map	"Carte topographique du Mont Blanc et des vallées qui l'environnent…"	F.J. Pictet	Kartensammlung, ZB Zürich
1842	map	"Map of the glacier systems of the Mont Blanc"	A.K. Johnston	Forbes (1855)
1842	written source		J.D. Forbes	Forbes (1843)
1850	written source		Herdsman at Pré-de-Bard Alp	Sacco (1918)
1851 (?)	sketch	"Glacier du Mont Dolent vu de Pré de Bar"	A. Favre	Favre (1867)
1856	map	"Gran Carta degli Stati Sardi in Terraferma"		Kartensammlung, ZB Zürich
1855	written source		S.W. King	King (1858)
1861	map	"Dufour Karte"	G.H. Dufour	Kartensammlung, Universität Bern
1864	map	"Massif du Mont Blanc"	J.J. Mieulet	Kartensammlung, ZB Zürich
1863-1864	map	"The chain of Mont Blanc from an actual survey in 1863-4"	A. Adams-Reilly	Kartensammlung, ZB Zürich
1868-1875	written source		E. Viollet-le-Duc	Viollet-le-Duc (1876)
1870	map	"Le massif du Mont Blanc"	E. Viollet-le-Duc	Kartensammlung, Universität Bern
1875	written source		F. Sacco	Sacco (1918)
1880	written source		F. Sacco	Sacco (1918)
1882	map	"Carta d'Italia"	Istituto Geografico Militare	Aliprandi & Aliprandi (2007)
1893	photograph		Mountain guide	Private Collection A. Roveyaz, Courmayeur
August, 1897	photograph		A. Druetti	Porro (1903)
1908	map	"Carte topographique de la Suisse"	A. Barbey, X. Imfeld, L. Kurz	Kartensammlung, Universität Bern
1909	photograph		J. Brocherel	RAVA, Aosta
1910-1911	written source		P. Revelli	Revelli (1911,1912)
1908-1918	written source		F. Sacco	Sacco (1918)
1914	photograph		J. Brocherel	CGI, Torino
1915	photograph		J. Brocherel	CGI, Torino
1917	photograph		Alaria	CGI, Torino

8.2 Appendix 2: Climate input data


(a)
Winter (DJF) temperature anomalies (wrt 1901–2000) [°C]
4
2
0
−2
−4
1850
1900
1950
2000
Year


(b)
Spring (MAM) temperature anomalies (wrt 1901–2000) [°C]
4
2
0
−2
−4
1850
1900
1950
2000
Year



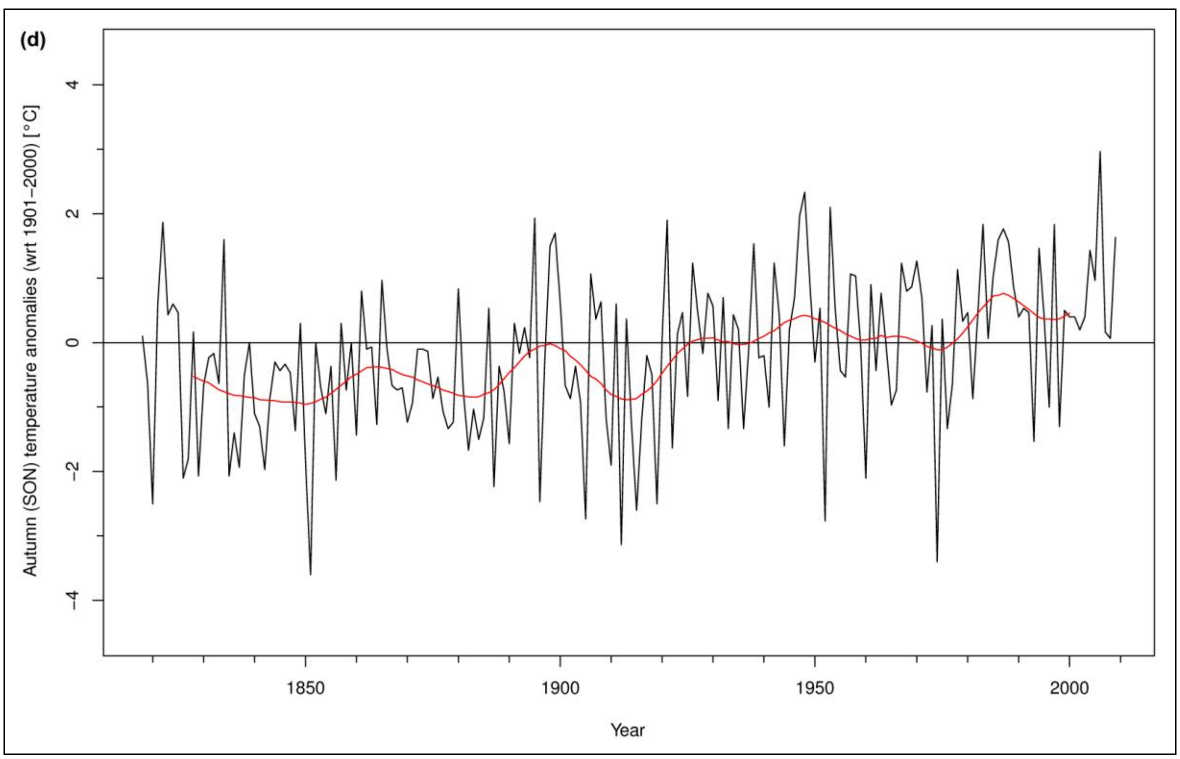
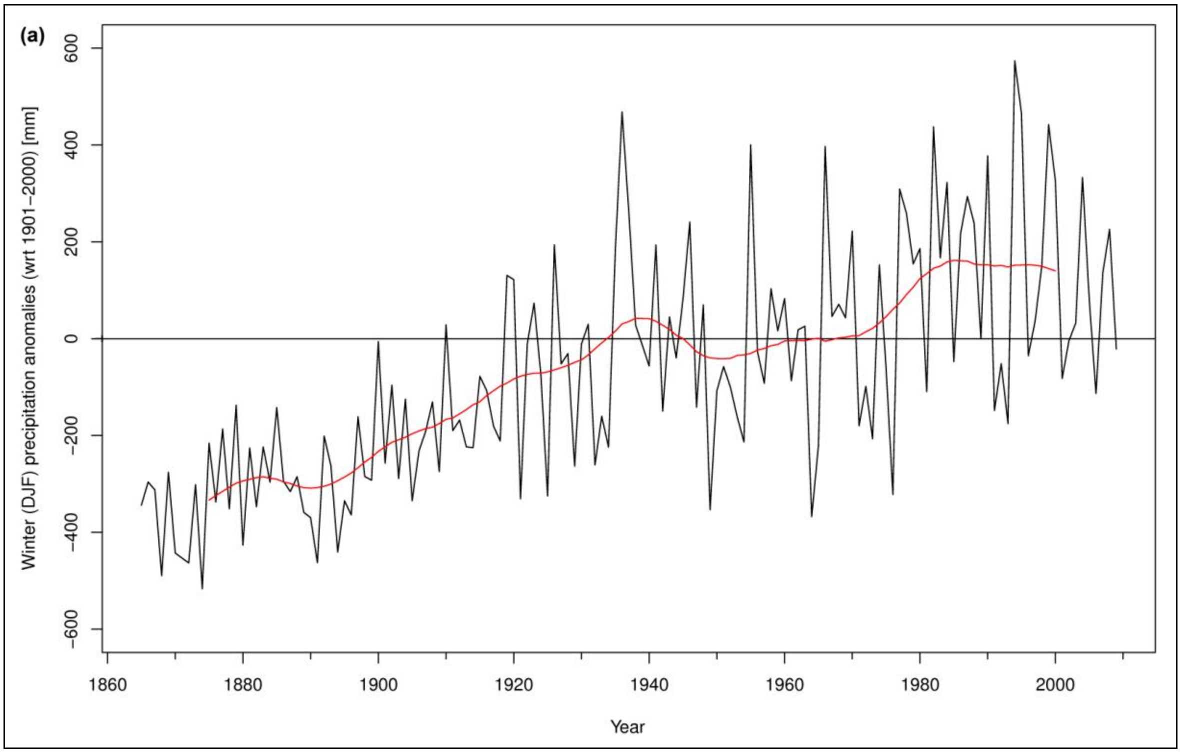
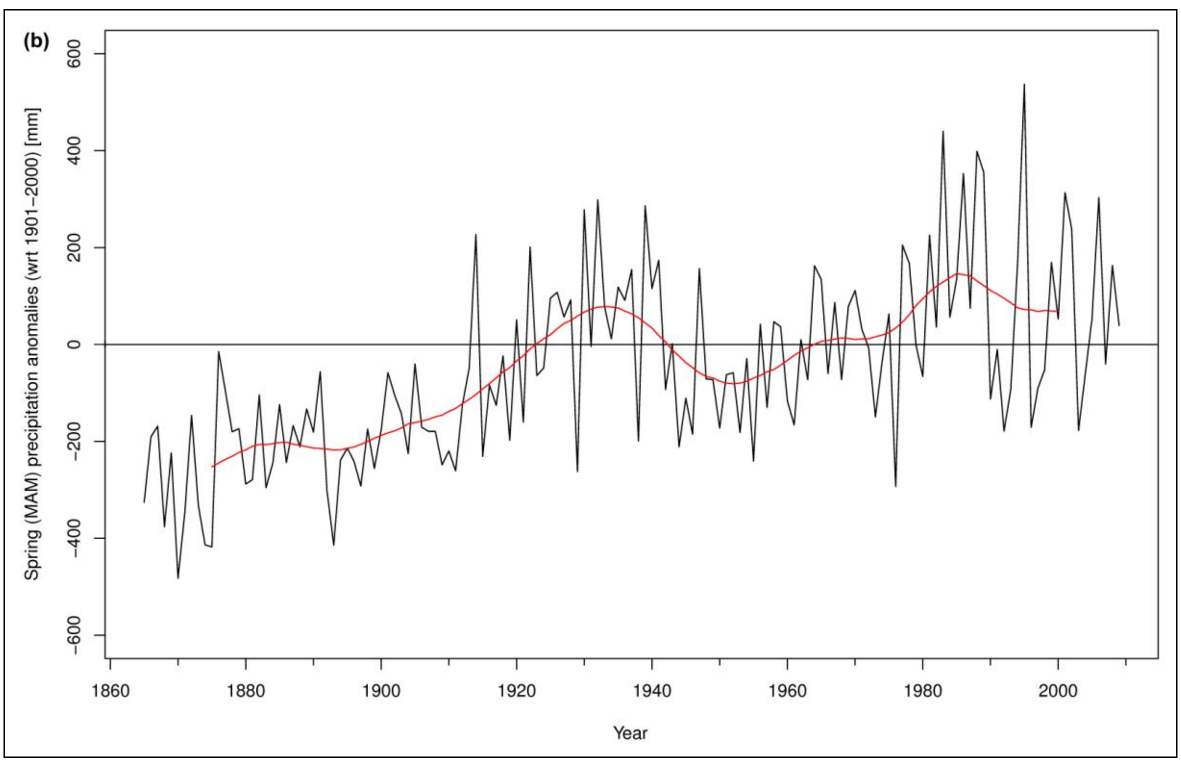
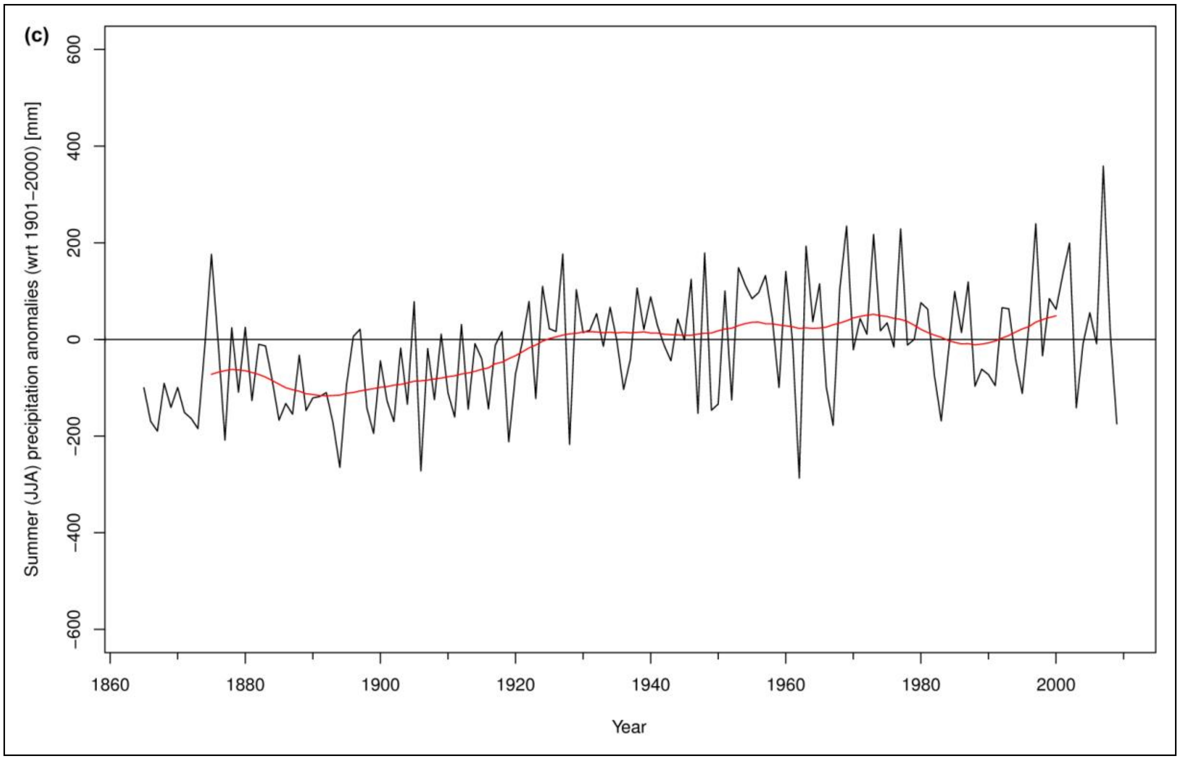


Figure 60: Mean seasonal temperature anomalies (reference period 1901-2000) from 1818 to 2009 (input data from MeteoSchweiz, 2010): (a) Winter (DJF) temperature anomalies, (b) Spring (MAM) temperature anomalies, (c) Summer (JJA) temperature anomalies and (d) Autumn (SON) temperature anomalies. The red line is the 20-year Gaussian lowpass filtered time series of the corresponding seasonal temperature.


(a)
Winter (DJF) precipitation anomalies (wrt 1901–2000) [mm]
600
400
200
0
−200
−400
−600
1860
1880
1900
1920
1940
1960
1980
2000
Year


(b)
Spring (MAM) precipitation anomalies (wrt 1901–2000) [mm]
600
400
200
0
−200
−400
−600
1860
1880
1900
1920
1940
1960
1980
2000
Year



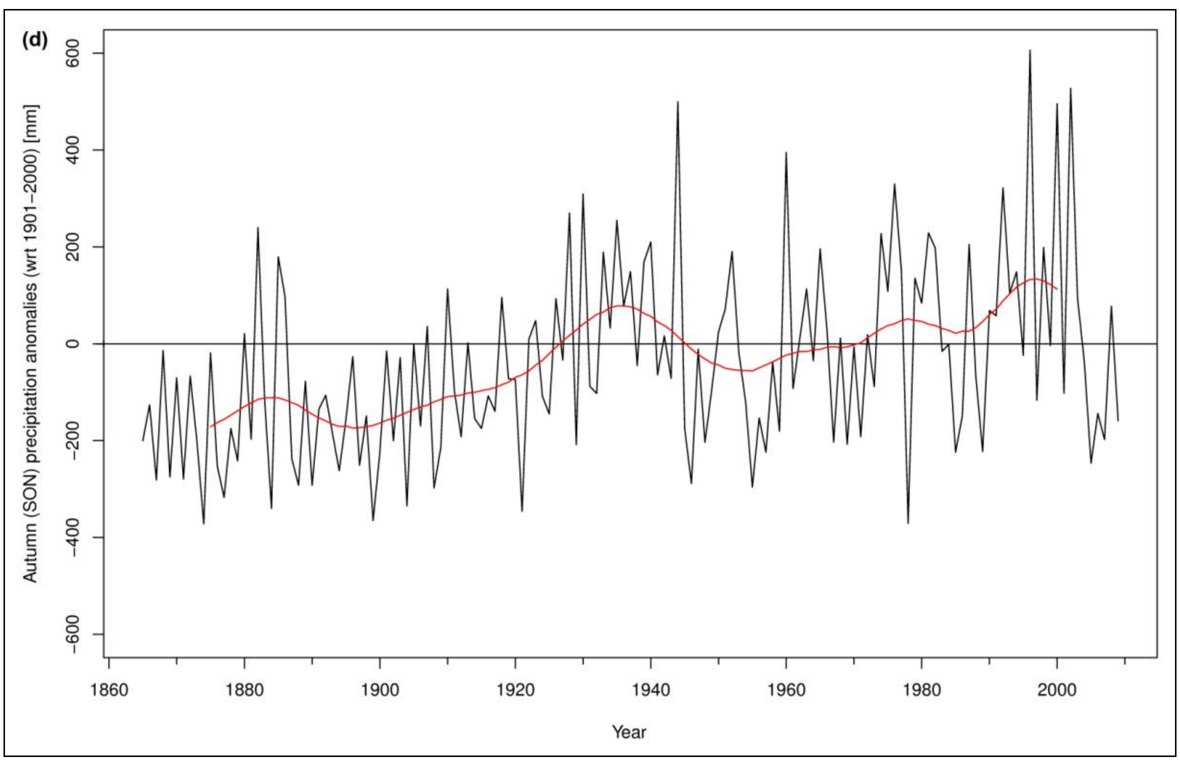


Figure 61: Mean seasonal precipitation anomalies (reference period 1901-2000) from 1865 to 2009 (input data from MeteoSchweiz, 2010): (a) Winter (DJF) precipitation anomalies, (b) Spring (MAM) precipitation anomalies, (c) Summer (JJA) precipitation anomalies and (d) Autumn (SON) precipitation anomalies. The red line is the 20-year Gaussian lowpass filtered time series of the corresponding seasonal precipitation.

Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Imhof Patrizia

Matriculation number: 05-206-461

Programme: Master in Climate Sciences

Thesis title: Glacier fluctuations in the Italian Mont Blanc massif from the Little Ice Age until the present. Historical reconstructions for the Miage, Brenva and Pré-de-Bard Glaciers

Thesis supervisor: Prof. Dr. Heinz J. Zumbühl

Institute of Geography and Oeschger Centre for Climate Change Research

Prof. Dr. Heinz Wanner

Institute of Geography and Oeschger Centre for Climate Change Research

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise.

Bern, May 2010

Patrizia Imhof