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FIFTY YEARS OF GLACIAL VARIATIONS AND CLIMATE EVOLUTION ON THE MONT BLANC MASSIF

ABSTRACT: CERUTTI A.V., *Fifty Years of Glacial Variations and Climate Evolution on the Mont Blanc Massif*. (IT ISSN 0391-9838, 2013).

On the Italian side of Mont Blanc in 1975 still four valley glaciers (Miage, Lex Blanche, Brenva and Prè-de-Bard glaciers) flowed downvalley reaching the bottom of Veny and Ferret valleys. Nowadays, Miage only can still be considered a valley glacier, while Lex Blanche and Brenva became cirque glaciers. Prè-de-Bard glacier shows a narrow tongue. The morphological variations of the glaciers of the southern side of Mont Blanc are not limited to the detachment of the valley tongue from the upper part, but also concern the separation of different ice flows in the high-altitude basins. Glaciers morphology is altered, thus resulting in the formation of new small glaciers totally independent from the original basins of which they were part of in the past.

Starting from these considerations, morphological transformations of the Lex Blanche, Miage, Brenva and Frebouzie glaciers are discussed in this paper. An analysis of the climatic evolution is also carried out, on the basis of data collected by the Gran S. Bernardo weather station. The temperature increase, that intensified after 1986, also caused a rise of about 250 m in the climatic limit of snowline, thus causing the loss, for the Mont Blanc glaciers, of about 50% of their accumulation area, as shown by the aerophotogrammetry of 1975.

KEY WORDS: Mont Blanc massif, Glacier fluctuations, Glacier dynamics, Snow line, Climatic phases.

RIASSUNTO: CERUTTI A.V. *Cinquanta anni di variazioni glaciali sul massiccio del Monte Bianco ed evoluzione del clima*. (IT ISSN 0391-9838, 2013).

Nel 1975 il versante italiano del Monte Bianco contava ancora quattro ghiacciai vallivi che portavano le loro fronti sui fondovalle delle valli Veny e Ferret. Ora soltanto il Miage ha mantenuto le caratteristiche di ghiacciaio vallivo. Lex Blanche e Brenva si sono trasformati in ghiacciai di circo. Prè-de-Bard, al posto della grandiosa cascata di seracchi di alcuni anni fa, presenta ora un misero cordone di ghiaccio che si interrompe lungo la parete rocciosa ed è destinato a sparire in breve tempo.

Le variazioni morfologiche degli apparati glaciali del versante meridionale del Monte Bianco non si limitano al troncamento della lingua valliva ma riguardano anche lo smembramento delle correnti glaciali negli alti bacini. Viene così alterata la morfologia degli apparati e dal loro smembramento traggono origine nuovi piccoli ghiacciai totalmente indipendenti dai bacini di cui in passato facevano parte.

Partendo da queste considerazioni, vengono esaminate le trasformazioni morfologiche dei ghiacciai di Lex Blanche, Miage, Brenva, Frebouzie, Triolet e Prè-de-Bard.

In base ai dati dell'osservatorio meteorologico del Gran S. Bernardo si passa poi ad indagare l'evoluzione del clima. L'incremento della temperatura, intensificatosi dopo il 1986, ha causato un innalzamento di circa 250 m del limite climatico delle nevi persistenti con la perdita, per i ghiacciai del Monte Bianco, di circa il 50% dell'area di alimentazione rilevata nel 1975.

TERMINI CHIAVE: Massiccio del Monte Bianco, Fluttuazioni glaciali, Dinamica glaciale, Limite nevi persistenti, Fasi climatiche.

RÉSUMÉ: CERUTTI A.V., *Cinquante ans de variations glaciaires sur le massif du Mont Blanc et évolution du climat*. (IT ISSN 0391-9838, 2013).

En 1975 le versant italien du Mont Blanc comprenait encore quatre glaciers de vallée dont les fronts rejoignaient le fond du Val Vény et du Val Ferret. Or, seul le Miage a conservé les caractéristiques de glacier de vallée; Lex Blanche et Brenva se sont transformés en glaciers de cirque et la langue de vallée du Prè-de-Bard s'est rétrécie en devenant un mince cordon de séracs qui s'arrête le long de la paroi de rocher soutenant le cirque.

Les modifications morphologiques des glaciers du versant méridional du Mont Blanc ne se bornent pas à la cassure de la langue de vallée mais elles concernent aussi la séparation des courents glaciaires dans les hauts bassins. Il en résulte que leur morphologie subit des modifications et leur division engendre de nouveaux petits glaciers tout à fait indépendants des bassins dont jadis ils faisaient partie.

En partant de ces considérations, nous allons examiner les évolutions morphologiques des glaciers de Lex Blanche, Miage, Brenva, Frebouzie, Triolet et Prè-de-Bard. D'après les données de l'observatoire météorologique du Grand-Saint-Bernard, nous étudierons les relations entre les changements climatiques et ceux des glaciers. La hausse de la température, qui s'est intensifiée après 1986, a provoqué l'élévation d'environ 250 mètres de la limite climatique des neiges et, par conséquent, les glaciers du Mont Blanc ont perdu environ 50% de leur aire d'alimentation par rapport à 1975.

MOT CLES: Massif du Mont Blanc, Fluctuations glaciaires, Dynamique glaciaire, Limites des neiges, Phases climatiques.

INTRODUCTION AND METHOD

Most part of the mountain glaciers all over the world and, in particular, in the Alps, experienced a sensible retreat since the end of the Little Ice Age (LIA). Terminus

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fluctuations of the alpine glaciers, measured since the end of the XIX century, show an almost constant retreat trend, with some significant interruptions, the last one of which took place between 1950 and 1990, when a small advance phase was recorded (Cerutti 1971, 1992; Patzelt, 1985; Wood, 1988). After this limited advance, glaciers retreat in the Western Alps started again and lasting even faster until the present day (Hoelzle & *alii* 2003, Citterio & *alii* 2007; Federici & Pappalardo 1995, 2010; Zemp, 2006).

Glaciers evolution of the Aosta Valley follows the pattern of regression trend that began at the end of the XX century (Cerutti 1985; 2002; Vanuzzo, 2005; Diolaiuti & *alii*, 2012).

The analysis of the glacial variations of the Mont Blanc massif is particularly interesting because they are causing significant morphological and typological changes.

In 1975, on the Italian side of Mont Blanc, there were four valley glaciers: Lex Blanche, Miage and Brenva, flowing on the valley bottom of Veny valley, and Prè-de-Bard flowing on the Val Ferret. Today, with the exception of the Miage, these glaciers withdrew their fronts onto the threshold of the accumulation cirque, losing the characteristic that made them valley glaciers.

To highlight those transformations, the present study will use the data collected in three documents: the *Catasto dei Ghiacciai Italiani (Inventory of Italian Glaciers)* (CGI-CNR, 1959-1962), the *Catasto dei ghiacciai e delle nevi perenni in Valle d'Aosta su aerofotogrammetria 1975* (Inventory of the glaciers and perennial snow in the Aosta Valley, based on the aerial survey of 1975) edited by F. Secchieri and printed on the occasion of the World Glacier Inventory (CGI-RAVA, 1986, unpublished), the *Catasto on-line dei ghiacciai della Regione Autonoma Valle d'Aosta su aerofotogrammetria (Online Invntory of the Glaciers of the Autonomous Region of Aosta Valley, based on data collected through aerophotogrammetry in 2005* (RAVA, 2007).

The 1959-1962 inventory is based on the 1:25,000 topographical map of the Italian Military Geographic Institute (IGM), compiled using data collected through an aerial survey done in 1947 and updated with information collected in other glaciological campaigns of the same institute. The information reported in the inventory probably refers to the 1957-1958 period. The document records the conditions of the glaciers at the end of a long retreat phase started in 1924. The *Inventory* edited by Secchieri using data collected by the aerial survey of 1975 was compiled during the above-specified advance phase. The 2005 inventory reports the condition of the glaciers after about twenty years of retreat.

A comparison between the three inventories listed above allows a first draft quantitative comparison of the effects of the glaciers evolution. However, the three inventories were compiled using very different methods. Data comparison cannot therefore be considered really accurate and representative of real changes.

After 2005, glaciers shrinking continued; recently the reduction in length and surface has been accompanied by the separation of different ice flows in the high basins.

RECENT VARIATIONS OF THE GLACIERS OF THE MONT BLANC MASSIF

Glaciers of the Veny Valley

This section of the paper analyses the recent variations of the three major glaciers of the Veny Valley: Lex Blanche, Miage, and Brenva.

Lex Blanche Glacier

Lex Blanche glacier, reaching maximum altitude 3910 m, is located near the head of the Veny Valley, lying in the wide cirque between the Aiguille des Glaciers (3817 m) and the peaks of the Trèlatête (3920 m). The glacier result from three ice flows converging in one basin, the western one coming down from the Aiguille des Glaciers, the second from the Aiguille de Lex Blanche (3686 m) and the third from the Petit Mont Blanc peak; the last originates at the altitude of 3910 m from the saddle dividing the northern peak of the Trèlatête Group from the central one. This glacier merges in the basin of the Lex Blanche at about 2750 m carrying a considerable volume of ice into the accumulation basin during positive mass balance phases, thus contributing to the growth of the main glacier.

When the equilibrium line rises significantly over 2800 m, the accumulation brought by the ice flow is reduced or interrupted, with serious consequences on the valley tongue of the Lex Blanche Glacier. The valley tongue, is shortened or lengthened drastically according to the different climatic phases, as can be seen in table 1.

TABLE 1 - Lex Blanche Glacier Variations

Survey	Surface (ha)	Length (m)	Front altitude (m)
1975 Inventory	433	3600	2065
2005 Inventory	352	2844	2400

The CGI Inventory describes the situation of the glacier during of maximum retreat phase after the LIA, when its front was at 2200 m.

An inversion started in the late 1950s. The aerial photographs of 1975 show, on the Lex Blanche Glacier, a surface increase of 63 ha compared to the 1957 data, the front reaching 2065 m. The expansion phase continued until 1988-89 (fig. 1-2).

The whole glacier entered then a dramatic retreat phase. The ortophotographs taken in 2005 show a surface loss of 81 ha since 1975. Most part of this loss affects the valley tongue. Today the front reaches 2400 m asl, on the threshold of the feeding basin, and consequently the valley tongue completely disappeared. In plan, the glacier is now 756 meters shorter but actually, because of the morphological characteristics of the area, the length loss is more than 1000 meters (fig. 3).

FIG. 1 - Lex Blanche Glacier in 1959 from Mont Fortin (2752 m). The photo shows the glacier at the beginning of the advance phase that involved all the glaciers of the Italian side of Mont Blanc at the end of the 1950s (photo A.V. Cerutti).

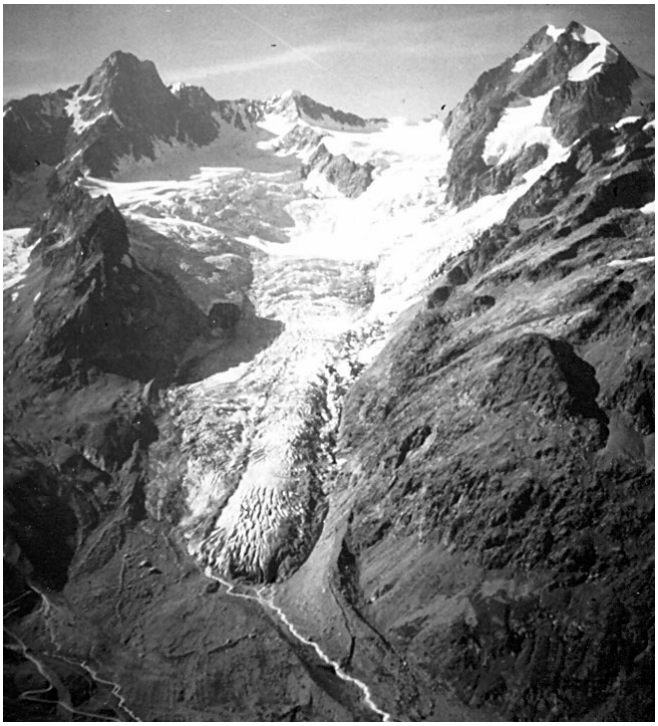

FIG. 2 - Lex Blanche Glacier in 1985, from the same point of view of fig. 1, in expansion phase. Because of that, between 1959 and 1988, the glacier advanced of 750 m (photo A.V. Cerutti).

FIG. 3 - Lex Blanche Glacier in 2012 from Mont Fortin. The great retreat, started on 1989, led to the almost total disappearance of the valley tongue (photo A. Fusinaz).

The fact that the inflow from the «Little Mont Blanc» has greatly diminished in the past 20 years has contributed significantly to this reduction in area and length.

Miage Glacier

Miage is the largest glacier, and the only one on the Italian side of Mont Blanc and the only one that belongs to the category of compound valley glaciers. The snow cap of Mont Blanc and the wide glacial ridge that departs from the highest peak of the massif and remains constantly above 4000 m, running westward for four kilometres to reach the Col de Bionassay are both part of its basin. From this ridge three big glacial flows furrowed by majestic crevasses flow down, bringing a massive inflow from this elevated altitude. The hanging glaciers of Col du Miage (3356 m) and Dôme de Miage, (3668 m) discharge their ice on the main basin in form of avalanches (fig. 4). All these confluences create a valley tongue more than 6 km long, covered mainly by a thick layer of debris and embedded in a deep valley, whose average width is 600 meters. At the end of the valley, the valley tongue bends eastward, towards the Veny Valley and divides itself into three lobes.

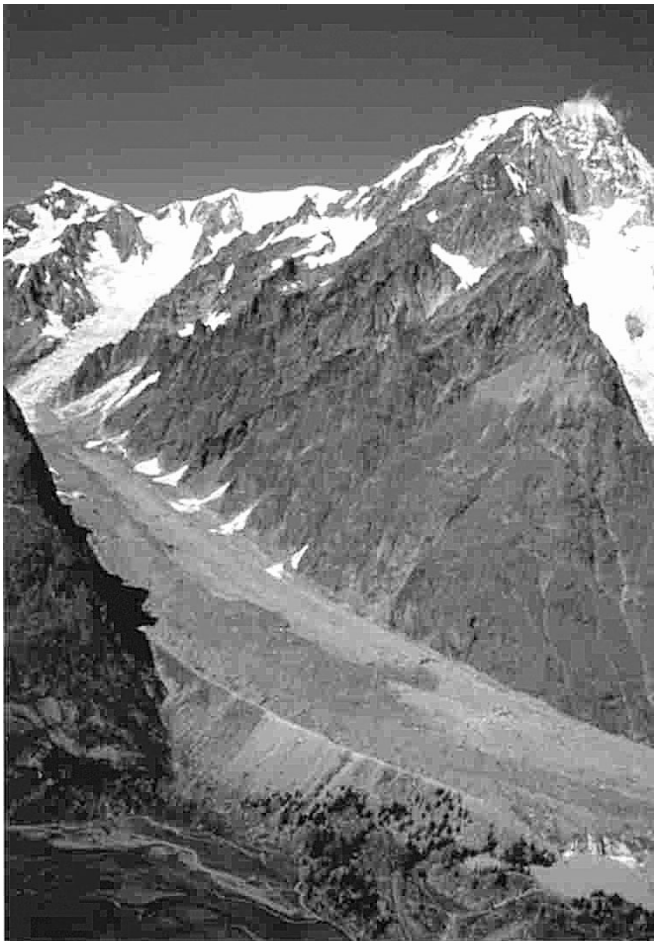

FIG. 4 - The Miage glacier in 1994, from Mont Fortin. The glacier is fed by several powerful tributaries flowing down from the domed summit of Mont Blanc and gathered in a large valley tongue debris covered reaching Veny Valley. With a total surface area of almost 1.100 ha, is the largest glacier on the Italian side of Mont Blanc. It, of the entire massif, is the only one to have preserved an almost unchanged shape from the maximum of Little Ice Age (LIA), despite the succession, during the last two centuries, of climatic periods more or less unfavorable to the development of the glacier (photo A.V. Cerutti).

The right lobe is the longest and nowadays its debris-covered ice front reaches 1720 m.

In recent decades, the glacier has kept a constant length of about 10.3 km, showing both positive and negative variations corresponding to about 1% of its overall length. The study of the deposited moraines leads us to estimate the distance of the flow front from the frontal moraines of the LIA to be less than one hundred metres (Bertolo & Pollicini, 2003).

This is an exceptional phenomenon: all the other glaciers of Mont Blanc have been subject to considerable contraction in the last 150 years. The overall reduction of the glacial covering of the massif has been estimated at about 34% of the surface reported in 1856 in the *Carta degli stati Stati Sardi in Terraferma - Foglio XXI* (Map of the mainland Sardinian States - Table XXI) (Smiraglia, ed., 2006).

The unusual behaviour of the Miage glacier can be explained taking into account both its abundant accumulation, coming from the highest snow peaks of Mont Blanc, and its thick debris cover, that protects the most part of its valley tongue by reducing melting rate of the underlying ice (tab. 2). This process has been described by Østrem, 1959; Nakawo & Young, 1981; Nakawo & Takahashi, 1982; Nakawo & Rana, 1999 and others.

TABLE 2 - Variations of the Miage Glacier

Survey	Surface (ha)	Length (m)	Front altitude (m)
1975 Inventory	1302	10350	1720
2005 Inventory	1080	10300	1719

Brenva Glacier

This glacier is located near the end of the Veny Valley, on whose bed its valley tongue flows, reaching about 1400 m. Thanks to its easy accessibility it is the best-known and most studied among the glaciers of Mont Blanc. Its front was the lowest of all Italian glaciers until 2004.

Like Miage Glacier, the highest point of Brenva Glacier is the ice cap of Mont Blanc (4810 m); its wide accumulation cirque opens on the south-western side of the peak and then widens eastward, joining Mont Maudit 4468 m) and continuing to the Tour Ronde (3792 m). It is divided into two sectors: the widest one is dominated by the peaks of Mont Blanc and of Mont Maudit; the other one, below the Tour Ronde, consists of a wide slope, surrounding a rocky outcrop and then converging in the central sector. This high-altitude basin is about 1.5 kilometres wide. From this wide cirque, the glacier flows toward its terminus, sited at about 2400 m. Below this point, the slope is interrupted by an enormous rocky cliff called Pierre à Moulin. Despite the steepness of the cliff, the glacier, until some years ago, was able to overcome the obstacle maintaining its unity and formed a majestic valley tongue more than two kilometres long.

Between 1920 and 1941 a wide advance is recorded, despite the warm climate period: this was probably due to an huge rock avalanche occurred in November 1920 that covered the valley tongue with a thick debris layer.

The glacier then underwent a phase of intense contraction between 1942 and 1960 that caused the retreat of the front up to 1550 m, as recorded in the *Catasto dei ghiacciai Italiani, 1957-58 (Inventory of Italian Glaciers, 1957-58).*

After this date, a documented advance phase started (Lesca, 1972). In 1975 the aerial photography survey highlights a widening of 75 ha of the glacier surface and a linear advance of 940 meters. The advance continued for the following fourteen years: in 1987 the front widened so much, near the Planponquet plane, that it dammed the river Dora flowing in the Veny Valley, forcing the stream to form a tunnel under the glacier to allow its water to flow (Cerutti, 1988). This situation has been recorded and

mapped in the satellite update of the 1:25,000 Mont Blanc table, printed in the same year by the Italian Military Geographic Institute (IGM). In this official cartographic document, the front of the glacier is reported at 1379 m; this means that the frontal cliff was at a distance of about 40 meters from the frontal moraine arch deposited in 1820, during the maximum expansion of the LIA. The arch is still clearly visible.

It is evident that for a long time the Brenva Glacier, like the Miage but with much more pronounced variations, maintained the conditions it reached in the phase of maximum expansion during the LIA, (for a synthesis of the volumetric variations that occurred in the second half of the XX century, see D'Agata & *alii*, 2005) (fig. 5-6).

A significant shrinking phase started at the beginning of 1989. The phenomenon became evident in the seracs fall connecting the upper basin with the valley tongue, covering the very steep rocky cliff of Pierre à Moulin. In this seracs fall some openings started to appear, gradually uncovering the underlying rock and becoming wider and

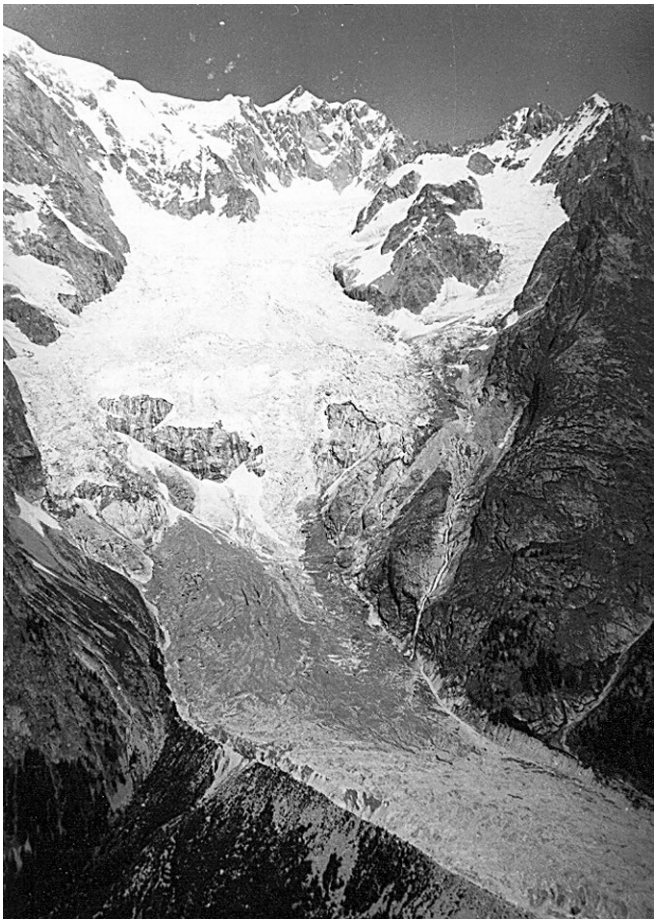

FIG. 5 - The Brenva Glacier in 1981, from Mont Chetif (2342 m) in full expansion. During 1989 it was almost 7900 m long with his terminus in Veny Valley at 1384 m of altitude. Please note the clear and large accumulation basin with the support, in the orographic left, of the ice flows flowing down from the Tour Ronde (photo A.V. Cerutti).

FIG. 6 - Since 2004, the Brenva is no longer a valley glacier. It suffered a retreat strong enough to cut off the ice flow that connected the accumulation basin with the valley tongue. The phenomenon is evident in the photo of summer 2012 from Pré de Pascal (1900 m), the terminus is lying on the threshold of the cirque without any contact with the valley tongue abandoned like a big pile of fossil ice (photo A.V. Cerutti).

wider. The situation got worse in the winter of 1997 when, from the Brenva outcrop (3557 m) a big rock landslide detached, crushing large ice volumes, in particular ones hanging on the Pierre à Moulin rockwall. (Cerutti, 1997; Deline 2003, 2008). After this event, the continuity between the higher basin and the valley tongue depended on a thin and precarious seracs fall. The valley tongue acquired the characteristics of a regenerated glacier, mainly fed by the ice avalanches falling from the cirque limit.

In 2004 the two units were connected only by a thin ice strip that broke at the end of September (Cerutti, 2005). The active front of the glacier set on at 2400 m asl on the threshold of the Pierre à Moulin; From this moment Brenva is no more considered a valley glacier but switched category, becoming a more Smaller cirque glacier.

The remaining part of the valley tongue, disconnected from the upper basin, lies on the valley bottom in the shape of a huge mass of fossil ice, covered by a very thick debris layer. This thick covering, that protects the underlying ice from solar radiation, is the cause of the slowness of the melting of this portion of the glacier. In the fall of

2012, after a negative phase that lasted for twenty-three years, the front of what once was the valley tongue of the glacier, on the valley bottom of the Veny Valley, at 1470 m asl, had the shape of a high cliff of black ice, and was no more than 300 meters far from the frontal moraine arch deposited in 1989.

The loss of the valley tongue has been a significant mutilation for the Brenva Glacier, but it is not the only one that affected the glacier. In the accumulation basin, the flow coming from the Tour Ronde that joined the central sector of the glacier at 2700 m, no longer reaches this altitude because its accumulation has diminished drastically (tab. 3). The active front of this ice flow settled at 2850 m, losing every connection with the Brenva basin and becoming an independent glacier.

TABLE 3 - Variations of the Brenva Glacier

Survey	Area (ha)	Length (m)	Front altitude (m)
1975 Inventory	805	7640	1415
2005 Inventory	577	3606	2420

THE GLACIERS OF THE FERRET VALLEY

During the LIA there were three valley glaciers in the Ferret Valley: Frebouzie, Triolet and Prè-de-Bard. Only the last one has maintained this characteristic until recent times, but what is left of its valley tongue today is just a thin line of seracs that, as of September 2012, is interrupted before reaching the valley bottom. All these glaciers, moreover, show, in their upper basin, fractures similar to the one described in the paragraph about the Brenva Glacier.

Frebouzie Glacier

Frebouzie Glacier, reaching maximum altitude 3750 m flows down from the western side of the Aiguille Leschaux and is enclosed between the crests starting from this peak and the eastern walls of the Grandes Jorasses (4206 m); from the round-shaped basin some rocky crests emerge and divide it into several sectors. The different ice flows join in a plateau, about 2600 m.

During the LIA, the Frebouzie Glacier was a valley glacier and its tongue reached the valley bottom of the Ferret Valley.

In 1957 its surface had shrunk down to 239 ha, but in 1975 it had regained 17 ha and its frontal lobes flowed below the cirque threshold reaching 2350 m altitude. (tab. 4). The ice mass advanced originating ice avalanches that formed slabs of regenerated ice at the foot of the rocky cliff (fig. 8-9).

TABLE 4 - Variations of the Frebouzie Glacier

Survey	Surface (ha)	Length (m)	Front altitude (m)
1975 Inventory	256	2200	2350
2005 Inventory	210	1746	2430

The situation recorded in 2005 is very different: the accumulation flows are particularly poor and, the plateau sited at 2600 m, because of the rise of equilibrium line, is part of the ablation zone.

In the right bank area, the ice flow coming down from the eastern walls of the Grandes Jorasses no longer reaches the confluence area and its front hangs on a rocky outcrop at 2700 m, completely independent from the remaining glacier basin.

FIG. 8 - The Frebouzie Glacier in 1982, from an altitude of 1740 m in the high Ferret Valley. It was then booming and overflowed from the threshold of the cirque with frequent ice avalanches that formed, at the foot of the walls that hold up the threshold, an important plaque of regenerated ice (photo A.V. Cerutti).

FIG. 9 - The terminus of Frebouzie, from the same point of view of the photo of fig. 8, in 2013, after almost thirty years of retreat, appears to be strongly retracted, settled upstream of the threshold of the cirque (photo A.V. Cerutti).

Triolet Glacier

The Triolet glacier lies between the eastern walls of the crest Aiguille Lescaux (3759 m) - Mont Gruettaz (3684 m) and the western walls of the Aiguille du Triolet (3870 m) - Mont Rouge de Triolet (3432 m), descending to a level of 3600 m. It results from merging of four different, almost parallel flows, joining onto a plateau, at 2700 m.

During the LIA, the Triolet Glacier had a long valley tongue that, during the period of greatest expansion as shown by its moraines, flowed down to 1790 m on the floor of the Ferret Valley.

It remained a valley glacier until 1937, despite strong progressive shrinking (fig. 11-12).

The advance of 1960-1988 did not allow the Triolet Glacier to re-join the old valley tongue, but the suspended front took the form of a high cliff and reached an altitude of 2350 m, discharging ice avalanches on the fossil tongue below (Cerutti, 1982).

In 1975 the glacier surface added 70 ha to its extension but the retreat phase that started after 1989 made the glacier lose slightly less than 100 ha. This considerable shrinkage is a consequence of the separation of the flows that form the glacier. Among the four glacial flows that formed

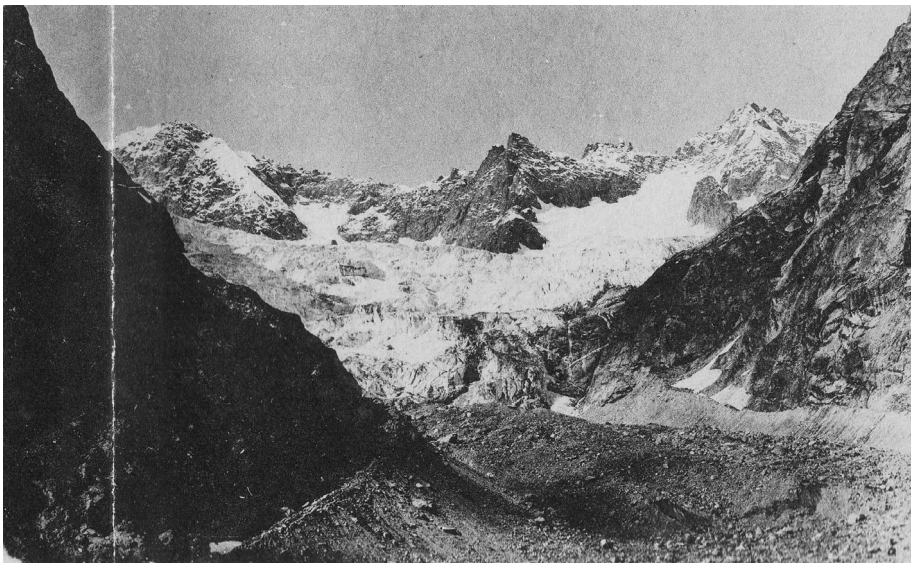

FIG. 11 - The Triolet Glacier in 1914, from the altitude of about 1850 m in the high Ferret Valley. It was then a mighty valley glacier; at the maximum of the LIA was more than 4 km long, bringing its historical moraines to occupy a great part of the bottom of the high Ferret Valley (photo Alaria).

FIG. 12 - The Triolet Glacier, as a consequence of global warming, suffered a drastic retreat. Around 1934 stopped the supply of the valley tongue and turned into a cirque glacier, gradually retreated further up the broad hanging terminus. The photo, taken in Summer 2013 from the same point of view of that of 1914 shows it inside the cirque at the height of around 2600 m (photo A.V. Cerutti).

the glacier, the two central ones, flowing down respectively from the eastern and from the western side of the southern crest of the Aiguille Savoie, did not reach the plateau at 2700 m for some years. The active front of the western flow is now about 150 metres far from the confluence site, while the eastern flow is so shortened that it no longer reaches the altitude of 2900 m and is now completely independent from the Triolet Glacier (tab. 5).

The wide plateau at 2700 m is now reached only by the western flow flowing down from Aiguille de l'Eboulement (3601 m) and the eastern one coming down from the Aiguille du Triolet (3874 m) but both those flow are in very unstable conditions and are barely able to feed the main front that now is at an altitude of 2640 m, that is getting weaker and is even more distant from the limit of the cliff that separates the wide cirque from the deep glacier bed below in which the valley tongue flowed in the past (fig. 13).

TABLE 5 - Variations of the Triolet Glacier

Survey	Surface (ha)	Length (m)	Front altitude (m)
1975 Inventory	460	2500	2350
2005 Inventory	364	2443	2640

[1] The morphology of the Triolet Glacier, composed by four almost parallel flows, makes it difficult to measure the glacier in plan, because the length may vary if it is measured parallel to the direction of the valleys or along the line connecting the highest altitude of the glacier to the front.

[2] This figure is probably a printing error because it is not consistent with the position of the front which, at 2400 m, allows only an overall length of the glacier of less than 2500 meters.

FIG. 13 - The ice flows feeding the Triolet Glacier, seen from the 2100 m of the Belle Combe Valley. In this photo of 2011 at least two ice flows do not reach anymore the confluence area and consequently appear as small separated glaciers (photo A. Roveyaz).

The Prè-de-Bard Glacier

This glacier lies near the head of the Ferret Valley, east of the Triolet Glacier, from which it is divided by the rocky crest of Mont Rouge de Triolet that is connected with the Aiguille du Triolet (3872 m). The Prè-de-Bard basin is fed by a 1500 m wide cirque that lies between Aiguille de Triolet and Mont Dolent (3819 m) and reaches the maximum altitude of 3750 m. From the accumulation zone, a valley tongue flows into the deep valley below. In the past, this valley tongue had an enormous flow rate.

This glacier tongue reached massive dimensions during the LIA: it occupied the whole valley, overflowing from it and then running along a long part of the main axis of the Ferret Valley, stopping its descent at 1860 m, only a few dozen metres away from the left border of the Triolet Glacier.

The survey done in 1957-58 to update the Inventory of Italian Glaciers reports the altitude of 2200 m for the Prè-de-Bard front but the contemporary photographs show it at a much lower altitude, (below 2100 m): probably the figure published was the result of a printing mistake (fig. 14-15).

The advance phase recorded between 1962 and 1989 brought an increase both in surface and length of the glacier, that pushed its front down at the altitude of 2055 m (Cerutti & *alii*, 2008).

FIG. 14 - The Prè-de-Bard Glacier in 1955, from the Rifugio Elena (2060 m). Since more than 30 years it was in retreat and then appeared flattened and much shortened (photo Agostino Cerutti).

FIG. 15 - The Prè-de-Bard Glacier in 1988, from the same point of view of fig. 14, at the peak of the advance phase began in 1962. In 26 years of growth, the glacier became almost 300m longer. The terminus, fed by a magnificent cascade of seracs, became a large bulk of white ice and assumed a smart fox-tail shape (photo A.V. Cerutti).

Between 1975 and 2005 the whole glacier retreated rapidly, losing more than 46 ha, especially in its valley tongue that, until about ten years ago, was a large bulk of white ice in a smart fox- tail shape. In these last years it has drastically reduced its length and width to become a plate of fossil ice covered by a large quantity of debris. At the same time, the seracs fall that descended from the upper basin reduced both its length and its flow rate, resulting in a thin icy line; finally, in September 2012, the connection with the valley tongue broken at an altitude of 2170 m. Nowadays, this thin ice strip frozen to the rock wall is all what remains of what once was the valley tongue (tab. 6).

TABLE 6 - Variations of the Pré-de-Bard Glacier

Survey	Surface (ha)	Length (m)	Front altitude (m)
1975 Inventory	352	3930	2075
2005 Inventory	306	3305	2170

Surveys carried out by «Fondazione Montagna sicura» since 1997 shows constantly negative mass balance results, reporting a total loss almost 5 metres water equivalent (fig. 16-17).

The melt rate on the steep Mont Dolent SW rockwall is quite amazing. Until some years ago, all the area was covered in ice; now, between the altitudes of 3000 and 3200 m some large openings have appeared, splitting the ice cover and separating the ice flow lying below Mont Grapillon.

CLIMATE EVOLUTION AND ITS EFFECTS ON GLACIERS

In previous papers (Cerutti, 1977; 1985; 2001) the correlation between Mont Blanc glaciers evolution and climate trend was established using meteorological data collected in stations located in the territory of Courmayeur, close to the Mont Blanc Massif. Unfortunately, these stations are no longer in service. The best data source providing useful data about the climate and its evolution on Mont Blanc is the Gran S. Bernardo Hospice weather station. This station has been in use since 1818 and is located at 2470 m, in Swiss territory, about ten kilometres far from the west side of the Mont Blanc.

Both Mont Blanc and Gran S. Bernardo climate is regulated by Atlantic winds and, as a consequence, the climate quality resulting from the data record of the Gran S. Bernardo weather station is similar to the Mont Blanc environment, even if the higher altitude of the latter massif makes a difference from the values collected on the Gran S. Bernardo Pass.

The climate evolution of the Gran S. Bernardo up to 1965 was studied by Janin, 1970, while the average values of the data of the 1971-2000 period (the standard 30-year period established by the International Meteorological Organization) are reported in Mercalli, 2003.

The Atlantic winds bring a large quantity of precipitations both to the head of the Dora Baltea Valley, where Mont Blanc stands, and to the head of the Buthier Valley, where the Gran S. Bernardo pass begins. The annual average precipitation recorded by the Gran S. Bernardo weather station between 1851 and 2011 is around 2000 mm. However, variations are wide, ranging from minimum values just below 800 mm, and peak values largely above 2500 mm (Janin, 1970; Mercalli, 2003).

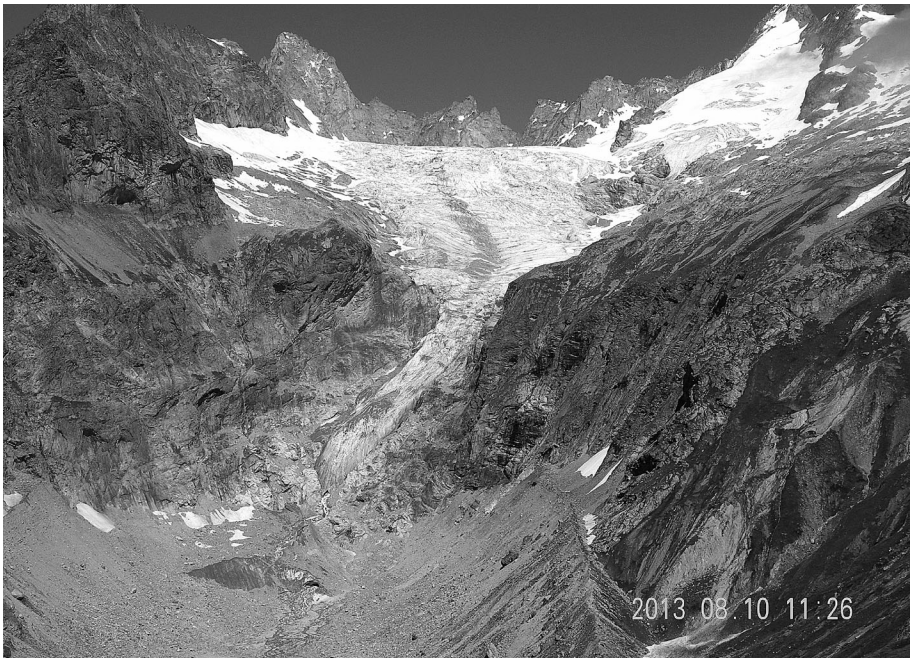

FIG. 16 - The Prè-de-Bard Glacier, in 2013, from the Rifugio Elena. Practically it is unrecognizable: the valley tongue is reduced to a plate of ice covered with abundant debris, the cascade of seracs that fed it has turned into a slender cord that stops along the rocky wall (photo A. Franchino).

FIG. 17 - The Mont Dolent and the highest part of Prè-de-Bard in the Summer of 2012 seen from the altitude of 1990 m of the historical moraines of the LIA. Until a few years ago, the Prè-de-Bard descended from the summit of Mont Dolent as a single large mantle; please note that now, a few hundred meters below the summit, large openings have appeared, splitting the ice cover (photo A.V. Cerutti).

Precipitation is useful for the glaciers accumulation only in the form of snowfalls. At the high Mont Blanc altitude the snowfall coefficient is 100%, i.e. all the atmospheric precipitations occur in form of snowfall. Below 3000 m the situation changes, even though there are, or there used to be, wide accumulation basins. On the Gran S. Bernardo, at 2470 m, the yearly snowfall coefficient from 1851 to 1981 was 66% of the annual total of atmospheric precipitations.

A more direct indication of the snowfall is the average annual snowfall thickness. During the 130 years measurement, the average annual snow depth was 1465 cm (Mercalli, 2003), ranging from minimum values of less than 900 cm in the second half of XIX Century to maximum values of about 1900 cm in the first decades of XX century.

Temperatures show significant variations too. The annual average value in the 1818-1965 period was –1.5°C (Janin, 1970), while in the 1971-2000 period it was –0.6°C (Mercalli, 2003). This variation of less than one degree Celsius should imply the rise of about 150 metres of the Equilibrium Line Altitude, obviously resulting in serious consequences on glaciers accumulation.

Table 7 (from Cerutti, 2002) points out the close relationship between variations in temperature and snowfall, recorded by the Gran S. Bernardo weather station, and the linear variations of the Mont Blanc glaciers. starting from the first decades of XIX century, Table is updated to 2011 for the meteorological data and to 2005 for the glacier lengths.

From the information collected since 1818, we can deduce that the Mont Blanc glaciers had six retreat phases. Each one of these phases began 4 or 5 years after the average temperature on the Gran S. Bernardo stabilized above –1.5°C and the depth of the annual snowfall was below 1500 cm.

The advance phases that followed the retreat became evident only 7/8 years after the setting a glaciers-favourable climate trend. During the advance phases the average annual temperature was below –1.5°C (sometimes even lower than –1.9°C) in the 1837-1853 and 1905-1915 periods. The depth of the annual snowfall, in these phases, was above 1500 cm and it reached 1870 cm in the 1905-1919 interval.

TABLE 7 - Climatic and glacial phases on Mont Blanc from 1818 to 2011

Climatic phases at the weather station of the Gran San Bernardo	**Length in metres at the peaks of the glaciers advance or retreat phases[1]**		
T: Annual average temperature °C P: Average annual precipitations mm H: Average annual snow depth cm	**Lex Blanche (L)** **Brenva (B)** **Pré de Bard (P)**		
Before 1818: data missing	1820: Maximum LIA historical advance.		
1818-1836: unfavourable to glacialism T: – 1,3	1822-1842: retreat of unknown entity		
1837-1853: favourable to glacialism T: – 1,9	1843-1860: advance L: 4300	B:.7900	P: 5040
1854.1874: significant temperature rise, end of LIA. T: – 1,4; P:1503; H: 890	1861.1882: retreat L: ?	B: 6980	P: 4200
1875- 1896: favourable to glacialism T: – 1,8; P: 1903; H: 1590	1883-1897: advance L: ?	B: 7300	P: 4400
1897-1904: unfavourable to glacialism T: – 1,3; P: 1920; H: 1429	1898-1912: retreat L: 3750	B: 7080	P: 4250
1905-1919: favourable to glacialism T: – 1,9; P: 2240; H: 1870	1913-1923: advance L: 4050	B: 7310	P: 4500
1920-1934: unfavourable to glacialism T: – 1,2; P: 2016; H: 1500	1924-1939: retreat L: 3950	B: 7795	P: 4250
1935-1941: favourable to glacialism T: – 1,7; P: 2426; H: 1740	1940-1945: advance L: 3940	B: 7795	P: 4310
1942-1954: unfavourable to glacialism T: – 0,8; Prev.: 1908; H: 1040	1946-1962: retreat L: 3100	B: 7440	P: 3810
1955-1985: favourable to glacialism T: – 1,0: P: 2160; H: 1530	1963-1989: advance L: 3850	B: 7940	P: 4060
1986-2011: unfavourable to glacialism T: – 0,4; P: 2329	1990-2005: retreat L: 2844	B: 3606	P: 3305

[1] The length of the glaciers in the different periods have been taken from the following sources: 1918: Bertolo & Pollicini (2003), 1860: Mieullet (1865), 1882: Topographic map: IGM (1882), 1897: Porro (1902), 1912: Sacco (1919), 1923: Topographic map of Italy, IGM (1929).

The 1963-1989 advance phase is somewhat abnormal, because the annual snowfall depth, in this period, was similar to one of the two previous advance phases, but the annual average temperature was –1.0°C, at least 0.5 degrees warmer than the previous expansion phases.

Notwithstanding the unusual condition, during this 26-year-long phase, the valley tongue of the Lex Blanche Glacier increased 750 metres in length, the Brenva Valley tongue 500 metres and the the Prè-de-Bard Valley tongue 250. All these valley tongue increased their width as well and the ice mass of all the glaciers experienced a significant volume increase. (Cerutti, 1992).

Temperature data of the Gran S. Bernardo weather station, (tab. 7), show that the actual climatic phase, from 1986 to the present day, is the warmest of the last two centuries. Actually, the annual average temperature of the last 26 years is –0.4°C. The temperature increase is 1.1°C compared to the 1818-1965 period, but 0.6°C compared to the 30-year period 1955-1985.

In the last 20 years precipitations seem to be much higher than for the past but, unfortunately, the Gran S. Bernardo weather station has not recorded the snowfall coefficient and the annual snowfall thickness since 1981.

We can observe, however, that May and October, whose precipitations sum represent about 20% of the annual total (Mercalli, 2003) had, in the past, an average temperature below 0°C: as a consequence, more than a half of the precipitation was snow: The snowfall coefficient was thus 57% in May and 51% in October (Janin, 1970).

In the last decades, the average temperature of May and October was above 0°C. We can therefore assume that almost all the atmospheric precipitations consisted of rainfall.

At high altitudes, moreover, the rise in temperatures in spring and fall causes precipitation to take the form of rainfall, so that they don't contribute to the snow accumulation on glaciers but, on the contrary, accelerate melting. This process causes the climatic snow limit to rise much higher than what should be expected taking into account the temperature rise alone. The temperature difference between the actual phase and the previous one is 0.6°C which, according to the theoretical thermal gradient, should bring about a rise of the climatic snow limit of about 100 metres.

The climatic snow limit, that in our climatic zone corresponds more or less to the Equilibrium Line Altitude (ELA), determines the surface areas of the respective basins: the bigger the accumulation basins, the more snow accumulates, then the more ice forms and, as a consequence, the whole glacier expands.

The opposite process occurs when the temperature rises, as well as the climatic snowline, thus reducing the surface of the accumulation basins and leaving more space for the ablation basins.

Unfortunately, ELA has seldom been recorded in glacier studies.

A reliable approximation was recorded in the Inventory of Glaciers and Perennial Snows (*Catasto dei ghiacciai e delle nevi perenni*) CGI-RAVA, drawn from the aerial photos taken in September 1975. In this survey, for each one of the 200 glaciers of the Aosta Valley region, the altitude of the climatic snowline is reported. These figures vary from a minimum of 2650 m to a maximum of 3250 m with a difference of 600 metres.

The lowest altitudes are registered on La Thuile Valley glaciers (Mont Valesan, Paramont and Arguerey) and Veny Valley glaciers (Estellette, Brenva and Entreves). The first group faces northwards and the second southwards, but all of them are influenced by Atlantic moisture flow. In the areas not reached by these winds, such as the Monte Rosa and the Gran Paradiso massifs, the climatic snow limit is at a considerable altitude. In September 1975, in the Cogne Valley, on the northern side of the Gran Paradiso, the limit of persistent snow on the large "Tribolazione" and surrounding glaciers was at 3220 m, although they face north-westwards. It can therefore be deduced that the altitude at which the persistent snow limit settles, does not depend on the intensity of solar radiation, but on the exposure to humid winds that bring the snowfalls.

According to the 1975 Inventory, in the Mont Blanc glaciers which all face south but are reached by the humid winds coming from the Atlantic Ocean, the altitude of the persistent snow limit varies from 2630 m on the Estellette Glacier (the westernmost and therefore the most exposed to the oceanic winds), to the altitude of 3025 m of the Pré de Bard Glacier, the easternmost, reached by the Atlantic winds when they have already lost part of their moisture.

In the inventory, the area of each ablation basin has been calculated taking into account the above-specified altitude values.

Subtracting the surface obtained from the calculation specified from the total surface of each glacier, it is possible to work out the extent of the accumulation basins in 1975 and to compare them with today's situation.

Recent, although general, information on the altitude of perennial snows have been collected by the Fondazione Montagna Sicura of Courmayeur. This information shows the situation as it was at the end of Summer 2008: Mont Blanc Massif, 3050 m; Matterhorn Massif, 3250 m, Monte Rosa Massif, 3300 m (FMS, 2008).

In 2010 the residual snow cover altitude showed strong variations. In south-facing basins, the snow limits have been recorded at rather high altitudes (above 3300 m), while in the basins north-facing they are usually at a lower altitude (3100 m) (FMS, 2010).

Table n. 8 shows variations of accumulation zones in the last 4 decades, on the basis of above data. The situa-

TABLE 8 - Variations of the accumulation areas of Mont Blanc from 1975 to 2010 (LPS: Limit of Persistent Snow, in m; AA: Accumulation area, in ha)

Glacier	LPS 1975	AA 1975	LPS 2010	AA 2010	Variations in ha (%)
Lex Blanche	2820	317	3100	181	-136 (-43%)
Miage	2870	719	3100	508	-211 (-29%)
Brenva	2725	514	3100	278	-236 (-46%)
Frebouzie	2780	195	3100	69	-126 (-65%)
Triolet	2845	312	3100	69	-243 (-77%)
Pré-de-Bard	3035	211	3100	137	-74 (-35%)

tion of 2010 has been calculated on the basis of the width of the glaciated altitude ranges (Capello, 1936) above 3100 m, that is, the actual estimated altitude of the limit of persistent snows.

The altitude values of the persistent snow limit have been obtained using non-comparable methods, above all because an average value has been used for the year 2010. The comparison, can nevertheless provide some general information on the reduction of the accumulation areas, that is more accentuated when the altitude of the glacier is higher.

The Miage Glacier, for instance, has a range width of 66 ha and an altitude of more than 4000 m and is the one that suffered least from the raise of the climatic snow limit. The dimensions of the accumulation basin reduced by 29%. The case of the Brenva Glacier is different because its maximum altitude coincides with the top of Mont Blanc, at 4810 m, but its part above 4000 m has a more limited surface than the Miage Glacier, this means that its accumulation area was reduced by 46%.

The Frebouzie and the Triolet glaciers are in even worse conditions, their maximum altitudes are, respectively, 3750 and 3600 m and their accumulation basins have shrunk respectively by 65% and 75% since 1975. These figures show clearly the reason for the on-going dramatic contraction of the glaciers that, in some cases lead to the separation of the accumulation flows (fig. 7-10).

FIG. 7 - The eastern flow of the Brenva Glacier in 2013, from Fodze at 1700 m, coming down from the Tour Ronde, shows such a strong linear shrinkage that does not reach anymore the main large glacier. This flow from the Tou Ronde is now an independent unity (photo A.V. Cerutti).

FIG. 10 - The accumulation basin of Frebouzie, since some years, is no longer unitary; in the photo of summer 2013 from an altitude of 1760 m in the high Val Ferret is clear that the ice flow that comes down from the foot of the Grandes Jorasses east face was shortened so as not to reach anymore the main body of the glacier and now constitute new small glaciers totally independent from the original basin (photo A.V. Cerutti).

CONCLUSIONS

The comparison between the variations of the main glaciers on the Italian side of Mont Blanc, based on the data of the 1957-58, 1975 and 2005 Inventories highlights a surface and length increase in 1957-58 and 1975, followed by a substantial decrease in the following period, that coincided with a rise of the front altitude. The only glacier that has preserved its nature of valley glacier is the Miage. This is due to the high altitude of the collection basin of this glacier, and, by consequence, to the abundant snow accumulation in the upper basin. Furthermore, the debris cover protect its valley tongue from ablation.

The recent general shrinking caused strong variations in the morphology of these glaciers. Lex Blanche and Brenva glaciers have lost their valley tongue and have become cirque glaciers. The case of the Brenva is remarkable. In 2004 its valley tongue detached completely from the accumulation basin and now, having lost every form of accumulation, it is slowly melting away, protected only by its debris cover.

By comparing and analysing temperature, precipitations and snow-cover thickness data, collected since 1818 by the of the Gran S. Bernardo weather station, we can observe a good correlation between climatic evolution and the variations of the glaciers of the Italian side of the Mont Blanc. Glacial retreat phases occur 4-5 years after the average temperature is stabilised above –1.5°C and the annual snowfall does not reach 1500 cm. The comparison between the altitude of the perennial snow limits in 1975 and 2010 respectively, and the subsequent variations of the accumulation basins, points out that the latter were considerably reduced; this reduction is more evident in glaciers reaching a lower maximum altitude, such as Frebouzie or Triolet glaciers.

The actual dramatic shrinking of the Mont Blanc glaciers, with the consequent morphological changes, is therefore the consequence of the interaction, at high altitudes, of the snowfall and of the temperature variations, where an increase in temperature causes reduction of the accumulation zones and intense melting of the snowpack and ice in the ablation basins (fig. 18).

FIG. 18 - This photo of October 2013 from the Combal Lake shore, reflect the history of the Lex Blanche Glacier during the last 200 years. The photo lower part clearly shows the moraine amphitheater at the maximum of the LIA, between 1820 and 1850. Along the slope is evident the trail left by the highly developed valley tongue abrasion, during the expansion from 1950 to 1988. In the upper part, the snow clearly exhibit the apparatus, whose terminus is retracted on the threshold of the cirque feeder (photo A.V. Cerutti).

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