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INDICE

Responses to Climatic Changes since the Little Ice Age on La Paul Glacier (Central Pyrenees)

Ibai Rico, Enrique Serrano, Jose Juan de Sanjosé, Mariano del Rioi

1. **Introduction.**

The glaciers and ice-patches located in the southwestern European mountains receive more and more attention due to ongoing global warming. These ice-masses are facing continuous negative mass-balance since several decades (Grove 2004). Nevertheless, due to their smaller size, low altitude and their location (at the interface of the Atlantic and the Mediterranean environments), these glaciers are being recognized as highly sensitive geo-indicators of climatic variations (Grunewald and Scheithauer 2010; Serrano *et al*. 2010; Serrano *et al*. 2011). Thus, the interest and studies focused on these ice-masses is growing very rapidly.

In the southern Europe's mountains, between 44º N and 41ºN, glaciers and relict ice still survive in relatively low ranges such as in the Pyrenees, Cantabrian Mountains, Maritime Alps, Italian Apennines and the mountains of the Balkan Peninsula. All these glaciers are a legacy of the Little Ice Age (LIA) and they survive in a relatively warm environment (mean annual temperature 0 ºC to + 1 ºC) due to topographic factors and accumulation by avalanche and snowdrift. Recent works estimate that since the end of LIA in the 19th century all south European glaciers have retreated (or disappeared) losing 30-100% of their volume (Hughes *et al*. 2006, González-Trueba et al., 2008; Steiner *et al*., 2008a; Grunewald and Scheithauer, 2010).

Small glaciers are a very common feature in all mountains and high latitudes of the world and these are often confused with ice-patches, relict glacier ice without movement or internal motion (Serrano *et al*., 2011). However, despite of their small size, these glaciers still show internal motion and ice deformation and are therefore considered true glaciers.

In the Iberian Peninsula today glaciers only exist in the Pyrenees. These have been studied during the last decades (Martinez de Pisón and Arenillas, 1988; Martinez de Pisón *et al*., 1995, 1997; Copons and Bordonau, 1994; López Moreno, 2000; Cancer *et al*., 2001;

Serrano *et al* 2002; González-Trueba, 2006, Chueca *et al.,* 2007; González-Trueba *et al.*, 2008; René, 2003, 2010). At the present there are 21 glaciers, 10 on the Spanish side and 11 on the French side, with a current glacier area of about 450 Ha. From 1880 to 1980 at least 94 glaciers disappeared in both Spanish and French Pyrenees and 17 glaciers have disappeared on the Spanish side since 1980 (Martinez de Pisón *et al*.1997). In the Iberian high mountains the rise of ELAs from the last glacial maximum from the LIA to the present day allows the calculation of a mean temperature increment of around 0.9ºC. The 19 current glaciers are now showing severe loss in mass and length, burials, and some show a progressive transformation into motionless ice patches (González Trueba *et al*. 2008).

This paper studies the recent evolution and current dynamic of the La Paul glacier (Posets massif), in the Central Pyrenees (NE Spain). Focus is given to the morphodynamic surface transformations since the end of LIA to the present and their relation to climatic variations. Eveentually, current state is described based on recent observations and quantitative data from previous studies in this glacier (Rico *et al*.2012).

2. Geographical setting.

La Paul glacier is located in the NW side of the Posets or Llardana peak (3360 m a.s.l, 42º 39´N, 0º 36´E) in the Posets Massif (Central Spanish Pyrenees) (Fig. 1). The bedrock beneath the glacial sediment accumulations consists of a granitic batholit. Hornfels resulting from contact metamorphism of palaeozoic shales surrounds the igneous intrusion and forms most of the Posets peak faces overhanging both glacier cirques. The relief is the result of tectonic, glacial and periglacial Quaternary processes. Annual rainfall is between 2000 and 2300 mm. The 0 ºC isotherm is situated near to 2700 m a.s.l. and the regional ELA for the massif around 3075 m (Serrano *et al*. 2002; Lugon *et al*. 2004).

La Paul glacier (like the Pyrenean glaciers) was originated and developed during the LIA (González *et al*. 2008, Martinez de Pisón *et al*. 2007) and therefore the remaining ice is an heritance of this last historical glaciations.

Currently, the Posets massifs houses two small glaciers (Llardana glacier and La Paul glacier), a relict glacial ice mass (the former Posets glacier) and three active rock glaciers (Fig.1). All of them are located above 2700 m a.s.l in glacial cirques of diverse orientations (Martínez de Pisón y Arenillas 1988; Serrano *et al*. 2002; Lugon *et al*. 2004; Serrano *et al*. 2010).

La Paul glacial cirque is formed by steep NW orientated cirque walls of 300 m. LIA moraines are relatively well preserved except on the frontal section where the runoff stream coming from the glacier has eroded these landforms. The deglaciated area between the LIA moraines and the current ice is nowadays occupied by sub-glacial till, abraded surfaces and periglacial landforms. Today this glacier occupies 7.3 ha. with an altitude front located at 2878m whilst the higher top of the accumulation area is at 3115 m (Differential Global Positioning System - DGPS - measurements in 2010 and 2011).

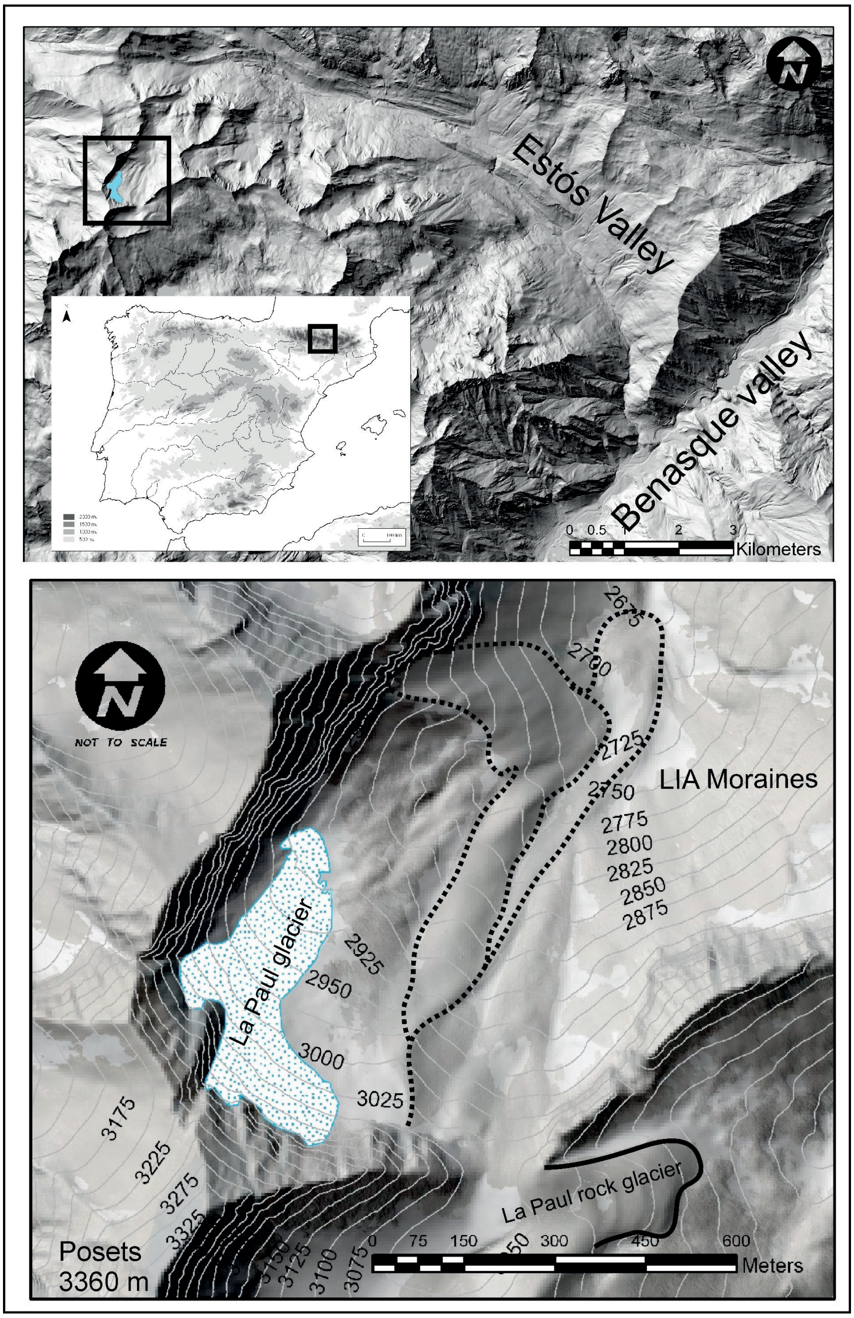

Figure 1. Location of the La Paul Glacier

3. Methods.

In order to infer the variation and evolution of the glacier we have used the analysis of previous geomorphological and historical data and geophysical and geomatic techniques. Historical and recent documentary records (photographs and written documents) of the LIA glacier and its evolution during the 20th century were useful sources of information. The use of historical pictures, photographs and testimonies for the reconstruction of glacier evolution has been previously developed (Steiner *et al.* 2008b; Strelin and Iturraspe 2007; Zumbühl *et al.* 2008) proving its efficacy and accuracy. Review of the existing geomorphological maps and documents was also carried out in order to determine the phases and maximum extent of the glacier during the LIA. Digital Elevation Models (DEM) and orthophotographs of the area combined in a Geography Information System (GIS) were the basis for the glacier surface reconstruction and calculation.

Current state and dynamics of the glacier are inferred from recent works on the glacier (Rico *et al.*2012) where Terrestrial Laser Scanner (TLS) and Ground Penetrating Radar (GPR) were applied.

4. Results.

Historical scientific sources, testimonies of climbers and mountaineers, aerial photographs and recent geomorphological studies enable the reconstruction of the glacial evolution of La Paul glacier since the end of the LIA to the present (Table 1). Despite the increase of studies since the 70´s to the present, there´s a general lack of information about La Paul glacier (and the Pyrenean glaciers as a whole) since the observations of Schrader in 1884 (Schrader 1936).

The LIA glacier evolution has been well documented (Alonso *et al*. 1983; Martinez de Pisón and Arenillas 1988; Serrano *et al*. 2002; Lugon *et al*. 2004; Gonzalez Trueba *et al*. 2008). Maximum extension of the ice during the LIA period is marked by the position of the external moraine, reaching an area of 32.04 Ha. This moraine, with an extension of 1 Km is adjacent in its upper part to the La Paul Rock Glacier. On the other hand, according to Schrader (1936) both Posets and La Paul glaciers were joined through the La Paul coll reaching a surface of 132 ha in 1894. However, since the external moraine of La Paul glacier is limiting with the La Paul rock glacier (Serrano et al. 2002; Lugon *et al*. 2004; Serrano and Agudo 2004) if both Posets and La Paul glaciers were joined at that time, no rock glacier could exist from La Paul coll towards la Paul glacier. Therefore, we assume that the observations of Schrader in 1866 could have been distorted by high amounts of seasonal snow giving the appearance of glacier ice flowing across the mentioned coll.

Serrano *et al*., (2002) estimate that during the maximum LIA advance (17th century) the glacier left the external moraine complexes. This was followed by a general retreat phase and a minor but fast re-advance, which built up internal moraines and deformed deposits in the 19th century. Reconstruction of the glacier surface for that period yields 23.59 Ha. After that, geomorphological evidences of re-advances don´t appear and a global recession period started with the beginning of the 20th century.

The available quantitative data about the glacial evolution during the 20th century is very scarce; thus surface changes can only be estimated through the use of historical or aerial images. In the first decades of the 20th century the glacier still showed a remarkable size and

AREA CHANGES IN LA PAUL GLACIER											
	LIA Max.(1)	**XIX century (1)**	**1910(1)**	**1935(1)**	**1956(1)**	**1983(1)**	**1993(2)**	**1997(1)**	**2002(2)**	**2006(1)**	**2013(1**
Surface (Ha.)	32.0	23.5	19.8	19.5	13.4	12.9	12.0	10.3	8.0	7.5	6.7
Surface loss since LIA (%)	-	-26.3	-38.0	-38.8	-58.1	-59,4	-62,5	-67,	-75.0	-76,4	-79,0
Surface loss con- pared to previous phase(%)	-	-26.3	-15.8	-1.2	-31.5	-3,1	-7.5	-13.5	-29.7	-5.8	-10.6
Glacier Longitude (m)	1036.8	775.3	719.6	713.7	609.4	593.9	-	496.1	-	475.5	464.6
Front altitude (m)	2678.5	2778.7	2796.1	2799.2	2839.0	2844.5	-	2874.1	-	2884.3	2890.4

Table 1 Area changes in La Paul glacier. (1) Surface estimations using historical documents and GIS. (2) Surface data from other studies

volume, numerous crevasses and a snout only several dozens of metres away from the internal moraines of the 19th century glacier moraines (Fig.3). Glacier area for 1910 is estimated in 19.8 ha from an historical photograph made from the north (Clarabide Peak). In the same way the surface in 1935 is inferred from another picture (Spanish State Tourist Department) and calculated in 19.5 Ha. This shows that the glacier remained very stable during the first decades of the 20th century. Later in 1956 (American flight 1956) the ice had thinned and the position of the front had retreated considerably (13.4 Ha.). Until the beginning of the 80´s the glacier retreated continuously but at a relatively slow speed with 12.9 ha in 1983. This last data has been inferred from the vertical photograph taken by INEGLA (Former Spanish Glaciology Institute) in 1983.

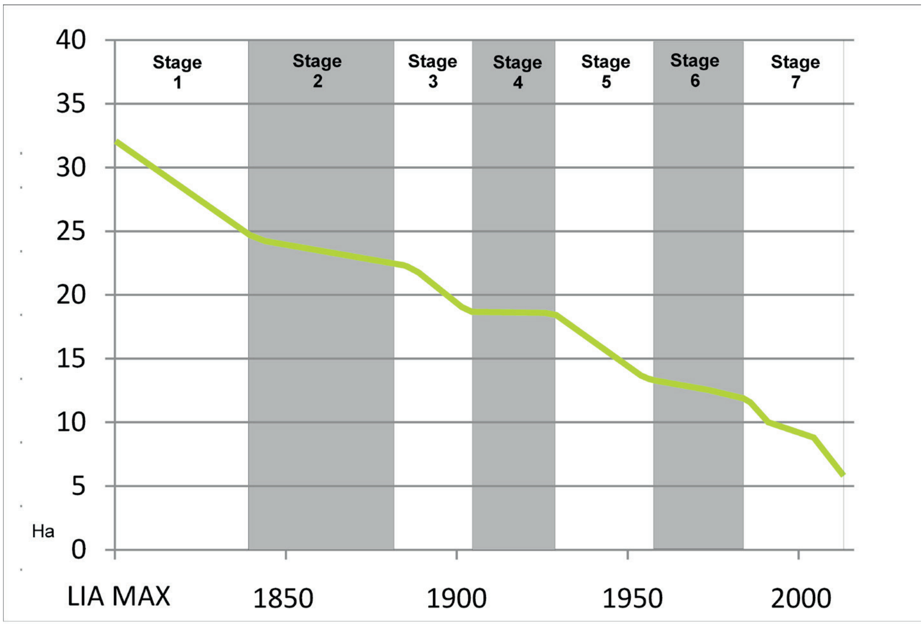

Figure 2. Glacier surface evolution since LIA Maximum to the present and main glacial stages

Glaciological observations and measurements started at the beginning of the 80´s decade. In 1983 the INEGLA (Former Spanish Glaciology Institute) visited the glacier and also flew above it reporting that the glacier showed crevasses proving the movement of the ice and estimated an area of 13ha. Besides, it was reported that the ice-mass showed debris coverage in the upper part and a bevelled front. Moreover they highlighted that the glacier had already retracted to the accumulation area of the cirque and that the rock-step covered by the ice just two decades ago was free of ice.

A decade later, according to the ERHIN program (Evaluation of Water Resources from Snowfall) observations the glacier looked very similar but with a slight frontal retreat; 12 Ha. (Martínez de Pisón *et al*. 1995). The glacier terminus kept retreating and orthophotographs from 1997 (SITAR, Sistema de Información Geográfica de Aragón, 1997) allow us to estimate an 10.3 Ha. area for this year.

With the beginning of the new century Cancer *et al* (2001) report an ice surface of 12.2 Ha. Later, Serrano (2002) remark that La Paul glacier showed a belleveled front with debris coverage and in the middle section a system of various traction crevasses and one longitudinal crevasse reflecting its active movement. On the other hand the observations of the EHRIN in 2002 (Arenillas Parra *et al*. 2008) group yield a 8 ha. area. The disagreement is also notable with other recent data available for this glacier: in 2007 ERHIN pointed out a glaciated surface of 6 ha. for La Paul glacier whilst Gonzalez Trueba (2008) estimates 11.3 ha. Such different estimations may be explained by the presence of a distorting debris cover, making difficult the identification of the glacier outline. Thanks to the high resolution 2006 orthophotograph we estimate that the glacier surface area in this year was close to 7.5 ha.

DGPS measurements made in 2013 provide a 6.7 ha. surface for this glacier (Fig.3). At the present, the remaining ice mass shows now very little internal motion (very few crevasses) and is partially buried with clast.

Between 2009 and 2011 TLS and GPR techniques were applied to the glacier. Laser Scanner results yield a thickness average loose of up to -1.28 m for the 2009-2010 and -1,46 for the 2010-2011 period. Both years were characterized by high temperatures and low precipitations, and the glacier followed the tinning trend of the last decades (Rico *et al.*2012).

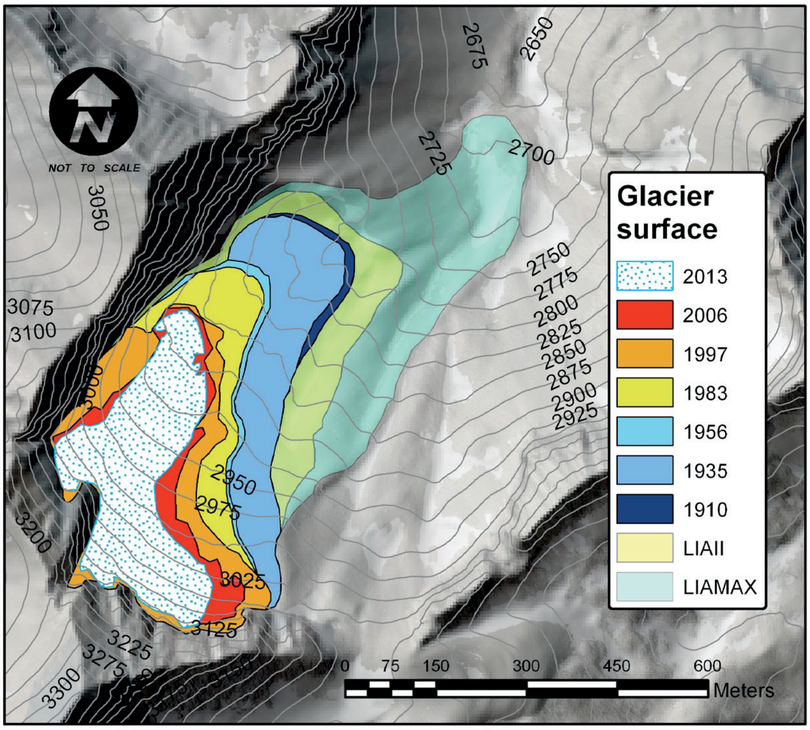

Figure 3. Changes in La Paul glacier since Little Ice Age

The GPR measurements in 2012 (Rico *et al.*2012) showed a three-layer internal structure. From top to bottom, (1) a nevé and firm later mixed with rock fragments and debris; (2) a layer composed mostly by glacier ice and some scattered rocks; and (3) a mixed detrital layer formed by till, ice and water. The maximum depth of the glacier is determined in 19-20 m (Rico *et al.*2012).

The ice mass is losing signs of internal glacial flow, despite some small transversal crevasses still appear at the upper part and is partially being covered by clast. This is linked with the general lack of snow feed and subsequent ice formation. In this regard, the glacier is located just below the regional Equilibrium Line Altitude (ELA, 3075 m) and therefore under very unfavorable conditions for the development of glacial processes. Thus, the influence of topographic factors such as snow accumulation by windblown snow and avalanches, the steep north facing cirque walls and the protection offered by the debris cover are key to understand the persistence of such glacial body.

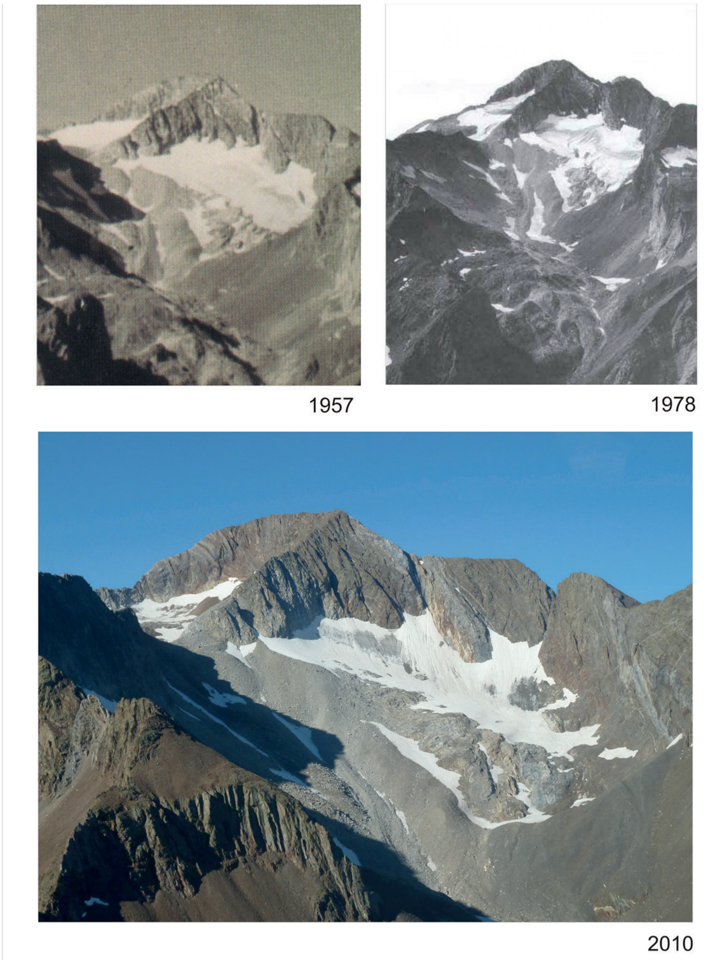

Figure 4. Surface changes in La Paul glacier in 1957 (A. Jolis), 1978 (unknown author) and 2010 (Enrique Serrano)

The analysis of historical documents and photographs, geomorphologic studies and glaciological observations allow us to identify seven glacial stages for La Paul glacier (Fig.2):

(1) *Little Ice Age glacial maximum:* Between the last decades of the 17^{th} century and the first decades of the $18^{th\ c}$ century the glacier reached its maximum historical extent. This is represented by the lowest external moraines.
(2) *Secondary 19^{th} Advance:* During the 19th century a short and fast re-advance took place in La Paul glacier. This re-advance is responsible of the secondary lateral moraines.
(3) *Glacier retreat*: From the last decades of the 19th century and up to 1910 the glacier separated from the secondary moraines losing 26.3 % of its area.
(4) *Glacier Equilibrium:* La Paul glacier remained relatively stable from 1910 to the 30´s with very little change in area (-1.2 %) and front position.

(5) *Continuous retreat:* Since 1935 to the 60´s the glacier lost 31.5 % in respect to its surface.
(6) *Slow retreat:* During the decades from 1960´s to late 1980´s the glacier again remained relatively stable, losing volume but not reducing significantly its surface area (-3.1 %).
(7) *Drastic Retreat:* From the late 1980´s to 2013, the glacier began a sudden loss of mass. In the last two decades the glacier has lost 60.83 % in respect of its glaciated area.

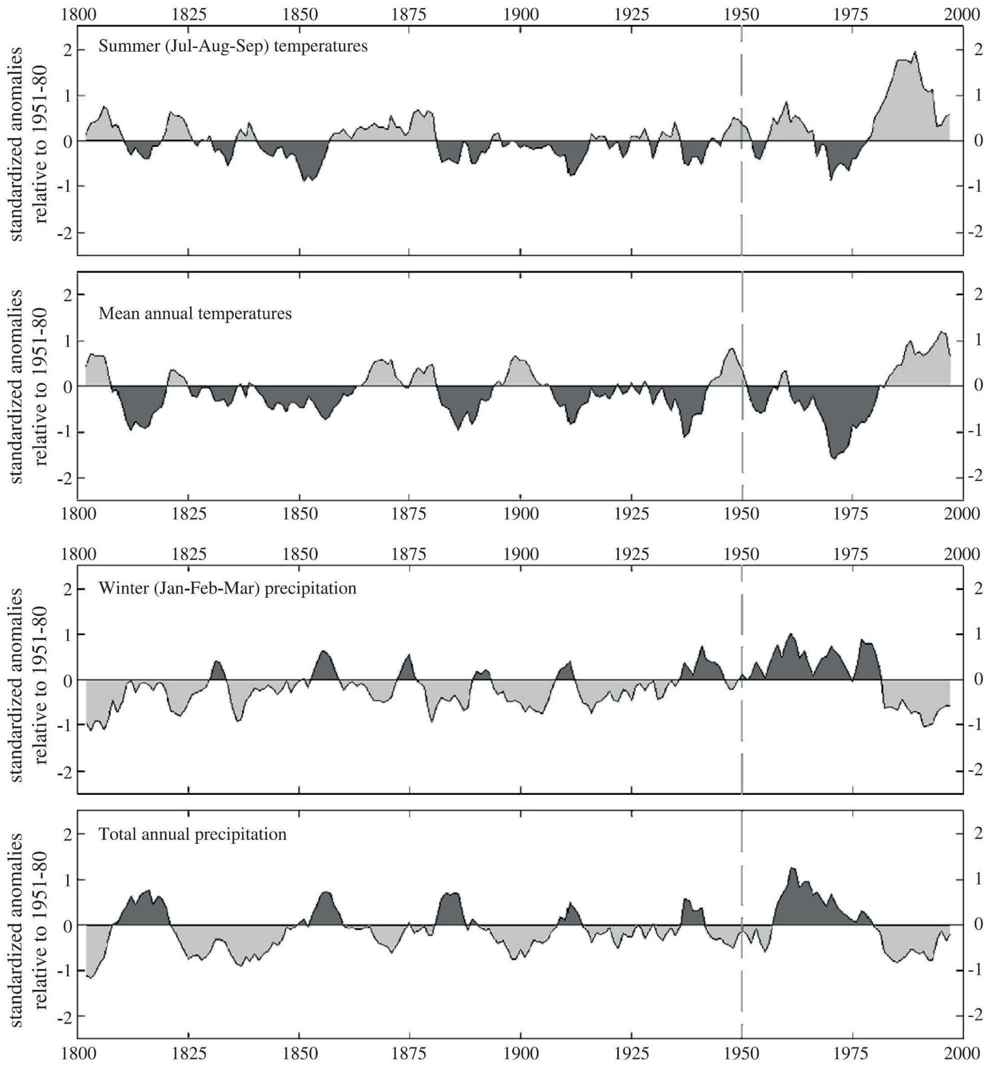

Figure 5. Climatic data from Capdella station and instrumental data from AEMET in Aragon (Chueca, et al 2007).

Figure 6. General view and current state of the glacier; 2. Higher section with debris cover and 3. Glacier front in 2010

Correlation of the identified stages with climatic variation (Figure 5) is high: Stage 2 of Secondary Advance was the response of the glacier to the climatic cooling and relative increase in precipitations until late 19th century and beginning of the 20th with dryer and warmer conditions for a few decades. Equilibrium and retreat stages intertwine until 1950 with a peak in warm temperatures and a drop in precipitation (stage 5), followed by a coolder and more humid period in the 80 s (stage 6). Since then, climatic data trend are clearly showing an unprecedented and dramatic warming and decrease of precipitations (stage 7).

5. Conclusions.

Evolution of La Paul glacier has been studied since the LIA, showing a very rapid response to climate variations and highlights the importance of the Pyrenean glacier as sensitive geo-indicators of global change.

Environmental conditions for glacial dynamics in La Paul glacier have been worsening discontinuously since the end of the LIA in the 19th century. The use of historic photographs, aerial and satellite images and geomorphological evidence has allowed to establish seven different stages for this glacier: 1. *Little Ice Age glacial maximum; 2. Secondary 19th century Advance; 3. Glacier retreat (Late 19th century-1910); 4. Glacier Equilibrium (1910-1930);*

5. Continuous retreat (1935-1960); 6. Slow retreat (1960-1980); 7. Drastic Retreat (1980-2010). Glacial evolution since the 19th century has been characterized by periods of stability and periods of shrinking. The glacier has lost around 77 % of its surface since the LIA with particularly rapid melting loose since 1990.

TLS and GPR measurements (Rico, et al 2012) showed that the glacier is suffering intensive wastage, thinning, scree cover and loss of motion in recent years. Still the glacier remains due to snow accumulation by windblown snow and avalanches, the steep north facing cirque walls and the protection offered by the debris cover. These topoclimatic factors will in the short term control the dynamic of the glacier, whilst climate and environmental changes will determine its survival in the long term.

La Paul glacier is therefore in disequilibrium with present day environmental conditions given in the Posets massif and the Pyrenees as a whole. This glacial mass has now a marginal status surviving only due to the effects of topoclimatic factors whilst periglacial and cryogenic processes domain the current high mountain environment in the Posets massif. In this regard, if the ice mass continues losing the dynamic characteristics of a glacier, its adscription from glacier to ice patch will soon have to be considered.

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