 doi:10.20944/preprints202212.0113.v1

Article

The *Infierno* Glacier (Pyrenees, Aragon, Spain): Evolution 2016-2022

Luis Cancer-Pomar [1], Gonzalo Fernández-Jarne [2] and José Antonio Cuchi [3], and Javier del Valle-Melendo [4] *

[1] Department of Physical Geography and CEACTEMA. University of Jaén. 23071, Jaén, Spain; lcancer@ujaen.es
[2] Department of Geography, St. Ignatius of Loyola High School, 31004 Pamplona; gonzalofernandez@jesuitaspamplona.org
[3] University of Zaragoza. Politechnic School of Huesca, 22007, Huesca, Spain; cuchi@unizar.es
[4] Centro Universitario de la Defensa de Zaragoza. 50090 Saragossa, Spain, and National University of Distance Education (UNED); delvalle@unizar.es
* Correspondence: lcancer@ujaen.es

Abstract: The *Infierno* glacier is located in Aragon (Spain), Pyrenees mountain range, southern slope, the only one in this country that still preserves white glaciers. These are the southernmost glaciers in Europe and are currently in rapid regression. The work analyzes the evolution of the glacier between 2016 and 2022 (taking as "year zero" or starting point, 2015). In addition to the observations on the glacier itself, the variables (precipitation, temperatures, snow volumes and thicknesses) that allow understanding this evolution are studied. The results offer strong regression, with thickness losses in that period of 4.6 m and retreat of its front of 14.9 m. The evolution has frequent trend changes, linked to the interannual climatic irregularity characteristic of this mountain range. The main explanatory factor is the thermal increase. The thermal anomalies with respect to the average reference values have increased, in this period, +0.55° C. The year 2022 has been particularly warm and has recorded the greatest regression of the glacier (between May and August, the thermal anomalies were between +4° C and +2° C). Regarding precipitations, they have irregular tendencies and show a decreasing trend (-9% in the same period of time).

Keywords: Pyrenees; *Infierno* glacier; glacial evolution; climate and hydrological analyses

1. Introduction

The Pyrenees mountain range is home to the only glaciers in Spain. All of them are located in the region of Aragon, province of Huesca. Its environmental interest is enormous, since they are the most southern glaciers of Europe. They are in a situation that is limit for the ice persistence due to different factors as the strong Mediterranean influences in the climate environment, the southern latitude (between 42° 37' and 42° 50' N) and moderate altitudes, in bulks that surpass the 3000 m above sea level (a.s.l.), being the Aneto (3404 m a.s.l.) the culminating point. In the last decades, due to temperature increase, glaciers are experiencing fast losses of surface and volume. Assuming that these climatic conditions will continue, these ice masses would completely disappear. The first reviews of these glaciers were published in the early nineteenth century and are due to enlightened explorers [1]. Later, at the end of the nineteenth and early twentieth centuries, naturalists, geographers and geologists presented them [2-6]. At a later time, in the last decades of the 20th century, there was a surge of interest in the glaciers of this mountain range, when several authors carried out specific studies and general surveys [7-20].

The retreat of the Spanish Pyrenean glaciers is too evident. Their estimated surface area in the mid-19th century, at the end of the Little Ice Age, was 1291 ha. In 1980, 641 ha were measured, representing a loss of 50%. In 2012 there were just 160 ha left, distributed among 10 small glaciers, representing a 75% regression in three decades. Altogether, the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

losses of surface area between the mid-19th century and 2012 was 87.5% [16]. For the glaciers of the French side of this mountain range, the global data are similar [21-23]. For 2016, 242 ha are calculated on both sides of the Pyrenees (Spain + France), distributed between 19 glaciers [24]. In recent years, the strongly regressive trend has continued, with glacier area decreasing by more than 20% between 2011 and 2020 [25]. This evolution can be related to the one observed in the French Alps, located at a more northerly latitude and altitudes above 4000 m a.s.l., which have lost over 40% of their surface area since the end of the Little Ice Age and up to the beginning of the 21st century [26]. The global loss from 1980 to the middle of the last decade is somewhere just over 25 and 40%, with significant variations depending on sectors [27-29], similar values to those registered in the Italian Alps [30-31]. Mass loss rates in the Alps, although high, are much lower than those reported for the Pyrenees.

The western sector of the Spanish Pyrenean glaciers is located in the upper valley of the Gállego River. This is a mountainous area with several peaks over 3000 m a.s.l. in altitude (*Balaitus*, 3151 m a.s.l., *Infierno*, 3082 m a.s.l., etc.), in which the *Infierno* glacier is located (Figure 1).

Figure 1. Location of the *Infierno* glacier. Upper Gállego River valley, northern of the Huesca province (Aragon, Spain). Own elaboration.

The *Infierno* mountain is made up of metamorphic materials, mainly limestone, quartzite and marbles from the Devonian, which overlie the Cauterets-Panticosa granitic batholith. The *Infierno* glacier is located in a deep cirque on the north-northeast slope, between the Central (3082 m a.s.l.) and Western (3075 m a.s.l.) peaks of the *Infierno*, and flanked by two ridges that separate it from two other glacial cirques (Figure 2). Very close to the glacier there are several dead ice (from the ancient glaciers that disappeared in recent decades) and a large rocky glacier of 14 ha. The *Infierno* glacier has been specifically studied [32-35].

Figure 2. View of the *Infierno* mountain. *Infierno* glacier (central position), former eastern glaciers (left) and western (right), now just become dead ice-snow patch. September 20, 2018. Photo by the authors.

This glacier is now a small mass of ice that has experienced a significant shrinkage: from 40 ha in the Little Ice Age to 14 ha in 1980 [16]. Since this date, the shrinkage has continued at an accelerated rate, reaching just 5.52 ha at the end of the summer of 2022, between 2929 m a.s.l. and 2698 m a.s.l. elevations, with an average slope value close to 50%. The length of the ice mass is 477 m, with a maximum width of 231 m. These measurements have been assessed by means of images captured from drones, in which we can see -as in the walk along the glacier itself- a profile that is becoming more concave every year, which indicates significant losses of power in the ice body. The cross-slope profiles of the glacier, made from drone images, confirm this view. The lower level is the lowest of all the Spanish Pyrenean glaciers. At present, despite its small surface and its concave and beveled appearance, some rims and crevasses persist. The surface measured in 2022 is smaller than the one the glacier had in the immediately previous years (7.06 ha al the end of summer 2020), as can be seen in Figure 3. 2022 have been catastrophic year for Pyrenean glaciers, with extremely high temperatures in crucial months for their evolution, notably between May and August, that were highly warm, resulting in early fusion of the nival cover and strong ablation of the ice glacier. The high temperatures, with values well above the reference averages, have extended throughout October, as has similarly occurred in other European mountain ranges, like in the Alps.

 doi:10.20944/preprints202212.0113.v1

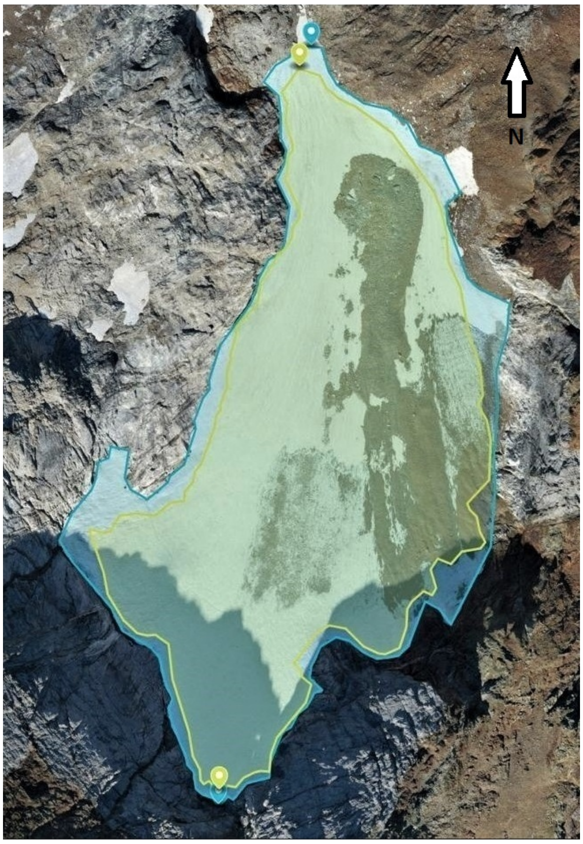


Figure 3. Aerial view of the *Infierno* glacier, August 31, 2020, outline in blue. In yellow, outline of the glacier on August 30, 2022. Photo and composition by Carlos Martín.

Owing to the mountain range location, between the Cantabrian and Mediterranean seas, the climatic conditions reflect the transition from Atlantic to Mediterranean climate, yet altered by the altitude and locally modified by the orientation. There are no meteorological data for the glacier altitude in this area. Establishing the altitude-temperature correlations analysed for other sites in the High Pyrenees [36-38], an approximate average temperature of 0° C and a precipitation over 2300 mm in the central area of the *Infierno* glacier, at the 2850 m a.s.l. can be estimated -according to the logarithmic correlation calculated [39]-. Around 65% of this precipitation would fall in the form of snow, which makes it possible to calculate an annual snow addition to the glacier of 1516 mm of equivalent water.

Along with the significant loss of surface that the glacier has experienced in recent decades, over the past few years a progressive covering of rocks has been observed. This covering has partially affected the surface of the ice, largely in its eastern third and in its middle-bottom side, as well as in other quite dispersed sectors. The average percentage of glacier cover, which varies every year, can be considered around 1/4 -1/3 of the surface of the glacier, and is certainly increasing over the last few years. This phenomenon might be related to the progressive melting of permafrost at these altitudes and to increasing periglaciar dynamics (Figure 4). It is acknowledged that the upper covers of washout located at some centimeters isolate the ice and reduce the melting process [40-44]. In spite of it, these glaciers are becoming thinner, their velocity is modified, and it has been observed a compression of the ice through the weight of the melt [45]. This dynamic leads to expect an evolution of the *Infierno* glacier -or part of it- towards a black glacier, as noted in [34]; a fact that we are able to confirm now, five years later. Either way, despite the general trend indicated here, this evolution is not uniform, since some years the white glacier recovers part of its domain. This was the case, for example, in 2018 and 2020.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

Figure 4. Eastern sector of the *Infierno* glacier, with progressive rock cover. September 5, 2021. Photo by the authors.

In the last years, the surface of the glacier may be considered divided in four sectors, when this one reaches the annual minimums, normally in the last days of August-first of September, the usual summer-autumn transition dates at these high Pyrenean altitudes. The four sectors indicated are presented below, with their approximate percentage value. 1: High area of snow accumulation, which marks the area of glacial equilibrium range (20%). 2 and 3: Intermediate area of outcropping ice (40%) and rock cover (30%). 4: Low area with lower slope and covered with firn (10%). This division into subunits is the most common in recent years of observations. However, the significant inter-annual variability in the state of the glacier causes frequent changes from year to year into this structuring "type", which is strongly influenced by the changing volume of protective snow cover at the indicated dates. This can be seen in Figure 5, with just one year difference (2020-2021).

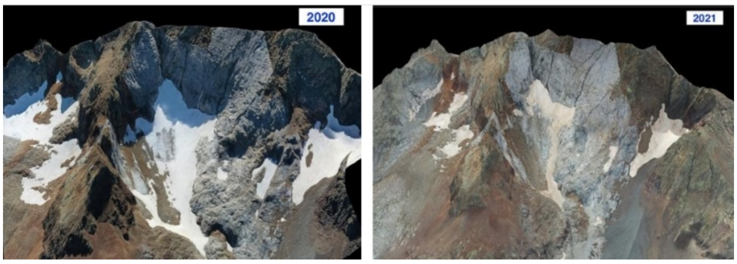


Figure 5. Aerial view of the *Infierno* glacier, August 31, 2020 (left) and September 5, 2021 (right). Snow-firn cover is very different between two successive years. Photos by Carlos Martín.

The *Infierno* glacier is part of a Protected Natural Space ("Natural Monuments of the Pyrenean Glaciers") since 1990, due to its high scientific, cultural and landscaping interest and aiming to protect those ice mass sourroundings [46]. At the present time, the regulation of uses of this Natural Space is determined by the "Master Plan for the Use and Management of Natural Monuments of the Pyrenean Glaciers", issued in 2020.

We would like to emphasize the idea that the study of the Inferno glacier is of great scientific interest. It entails to study a glacier set in the Pyrenees mountain range, where

 doi:10.20944/preprints202212.0113.v1

the most southerly glaciers in Europe are located. Many have already been lost. The few remaining Pyrenean glaciers are absolutely unique ice masses.

Our starting hypothesis is well known today: these are glaciers in rapid retreat and are expected to have an end in sight. Acknowledging they are located in the south of Europe, within a physical space and meteorological limited conditions for the existence of these ice masses, the aim of this study is to be able to validate this hypothesis by means of an "in situ" study of the *Infierno* glacier. To this end, annual monitoring campaigns have been carried out. This paper synthesizes the achieved results in the last years the glacier has been monitored (between 2016 and 2022) and analyzes its evolution in relation to climatic, hydrological and nivological data. The results confirm a rapid regression of the glacier, which is clearly related to an upward trend in temperatures affecting this area.

2. Materials and Methods

This study aims to examine the evolution of the *Infierno* glacier. The study has been carried out by this team since 1998 till the end of 2022.The categories of basic numerical reference data used, and their source are listed below:

- Meteorological data: *Agencia Estatal de Meteorología (AEMET)* - (State Meteorological Agency of Spain) [47, 48].

- Hydrological data: *Confederación Hidrográfica del Ebro-Sistema Automático de Información Hidrológica (CHE-SAIH)* - (Hydrographic Confederation of the Ebro River-Automatic Hydrological Information System) [49].

- Snow data: CHE-SAIH and AEMET [49, 50].

There is neither climatological nor a nivological station in the glacier area or in its immediate surroundings, therefore different proxy data have been used:

- Rainfall and thermal anomalies, accumulated snow volumes and persistence of snow cover. In all cases, the territorial reference framework is the upper basin of the Gállego River, up to the Búbal reservoir (to which the *Infierno* glacier belongs).

- Evolution of snow cover thicknesses, in two mountain refuges close to the glacier, as well as in the upper basin of the Gállego River.

Rainfall and temperature evolution -monthly deviations from normal reference values- (DRV-Deviation from Reference Values-, from here), are shown in Figures 6 and 7. The data come from the monthly climate summaries issued by AEMET [47, 48]. The volumes of snow accumulation (expressed in hm^3 of water equivalent) and its evolution over the hydrological years (1 October to 30 September), allow to approximate the snow accumulation rates on the glacier (Figure 8). The persistence of snow cover should be considered another salient variable for the analysis of glacier behavior. Figure 9 and table 1 show the duration of the annual period with more than 10 hm^3. The data are from the CHE-SAIH -snow measuring network- [49]. This temporal duration can be cross-checked with the snow accumulation volume. The result is shown in Figure 10.

A complementary nivological variable is the evolution of snowpack of layer thickness. Based on hydrological years, data are presented for two mountain refuges, with altitudes ranging between 1636 m a.s.l. and 2200 m a.s.l. These data are managed by AEMET [50] and the results are shown in Figures 11 and 12.

The glaciological observations and measurements carried out in situ on the *Infierno* glacier are a key part in this study. For this purpose, the glacier was visited between 1998 and 2022. In the first year, 1998, two topographic control stations were set up, using fixed measurement positions installed on stable rocks, right on the sides of the ice mass. These stations enable to estimate the glacier fluctuations (ice plus snow cover, if any). In the indicated period, the measurements were taken in the days of climatic transition from summer to autumn. In the high Pyrenees, this usually occurs in late August and early September, when the ice masses reach the annual minimum, and immediately before the coming autumn brings snow precipitation again to these high altitudes.

The distance to the glacier surface is measured from these two topographical stations. One of the stations is located at the end of the glacier tongue ("glacier front", meaning the ice front or firn/snow -depending on the year- at the end of the glacier area). Its measurements indicate the longitudinal changes of the tongue. This tongue, in previous years, was embedded in a narrow glacio-karstic canyon (less than 5 m wide), but in 2022 it has receded and it is above. The second station is located on the right-east margin of the glacier ("lateral glacier"), at the height of its lower third, and the measurements taken from here are used to assess the variations in glacier thickness (or power). These measurement results and the annual variations, are shown in Table 2 and Figures 15 and 16.

In this study, we present evolution data of the *Infierno* glacier for the period 2016-2022. Results from previous years, since 1998, were published [35].

3. Results

3.1. Climatic analysis

Figures 6 and 7 show the inter- and intra-annual rainfall and thermal irregularity, characteristic of the climate with strong Mediterranean influences that affects the Spanish or southern slope of the Central Pyrenees. Both express the DRV values. The data come from AEMET [47, 48]. The period analyzed comprises from September 2015 to September 2022. Its detail allows us to appreciate the rhythms of the different hydrological years.

Figure 6 reflects very pronounced DRVs, ranging from 25% to 200% (over 100% mean value), with values from 50% to 150%-175% being very common. The lowest DRV values, 25%, are spread over most of the years, but increase from 2021. The highest DRV values, 175%, only occur from 2016 to 2018, although the peak, 200% is obtained later (2020). The DRV trend line was declining, with a variation of -9%, within a period of time of seven years.

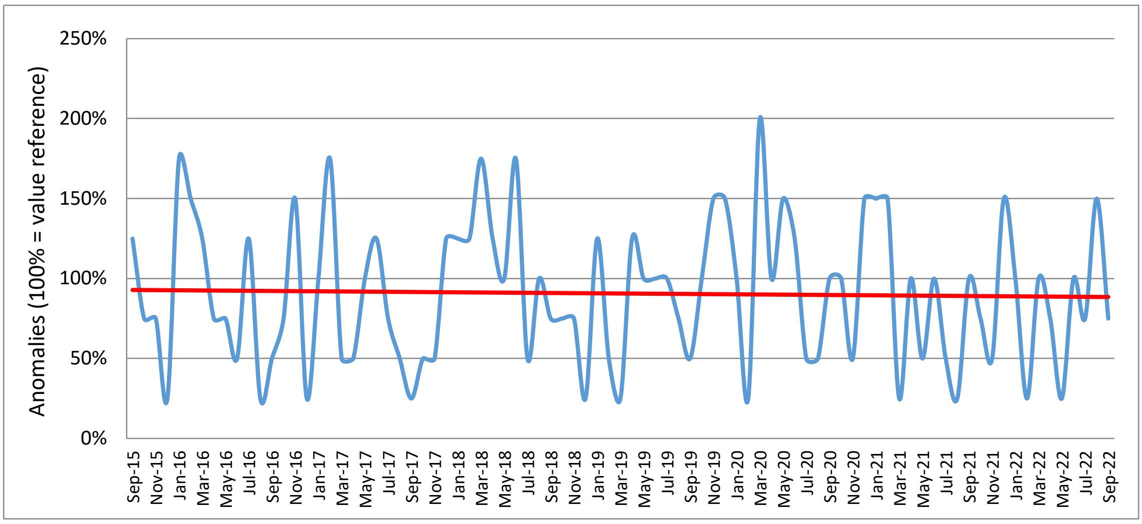


Figure 6. Rainfall anomalies in the upper Gállego River basin. September 2015-September 2022 (over 1981-2010 reference period, as determined by AEMET for these comparisons). Trend line. Data source: AEMET [47, 48]. Own elaboration.

Figure 7 is very expressive: the months with positive thermal DRV are much more abundant than the months with negative DRV. And the positive DRV are of greater importance than the negative ones. Among the positive DRV, the value DRV +3° C appears on several occasions, and in one case (May 2022), DRV +4° C is reached (record in our series). DRV +2° C and +1° C are very abundant. In the case of negative DRV, the values are more moderate. There is no DRV -3° C, the top values are DRV -2° C, which are repeated with some frequency (although to a lesser extent than DRV +2° C). And DRV -1° C are also less frequent than DRV +1° C. The DRV trend line is clearly upward, with a variation that reaches +0.55° C in a period of seven years. This evolution is very negative for the survival of the Infierno glacier, as it increases the energy available for nival and glacial ice ablation [51].

 doi:10.20944/preprints202212.0113.v1

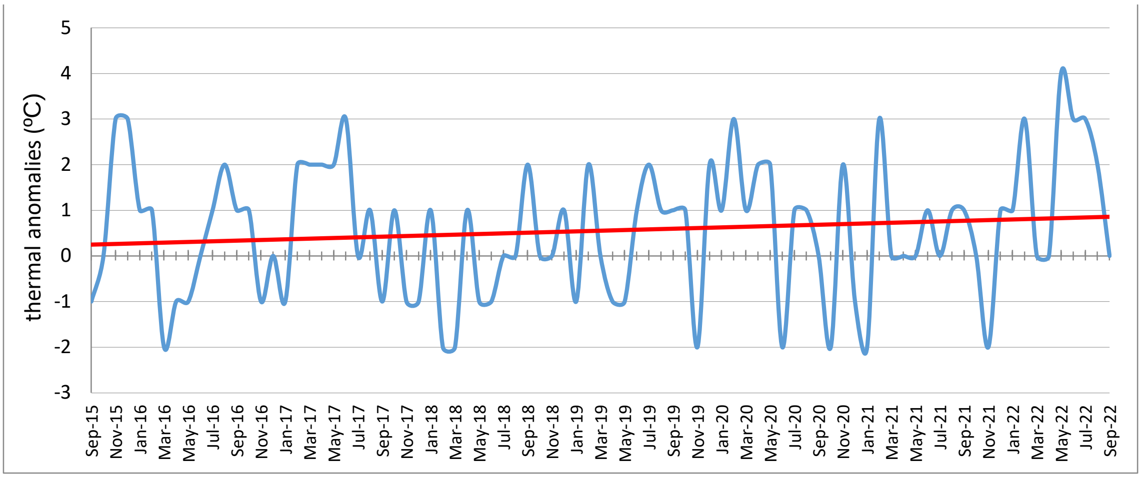


Figure 7. Thermal anomalies in the upper Gállego River basin. September 2015-September 2022 (over 1981-2010 reference period, as determined by AEMET for these comparisons). Trend line. Data source: AEMET [47, 48]. Own elaboration.

3.2. Snow analysis

Based on data series provided by the CHE-SAIH [49] and by AEMET [50], the graphs included in this section have been prepared, which refer to snow accumulations (equivalent volumes of water) in the upper Gállego River basin, up to the Búbal reservoir, and to snow column thicknesses in two mountain refuges, located in different places of the head of this basin.

The volumes and thicknesses of snow shown in these graphs indicate variations of great magnitude, which are the result of different interrelated meteorological variables: dates and volumes of snowfall -and liquid precipitation, rain is a factor that accelerates snowmelt-, temperatures, their respective behaviors throughout the year, dates on which certain meteorological events occur (such as heat or cold waves), episodes of intense precipitation or prolonged droughts... In short, these graphs are indicative of the remarkable interannual climatic irregularity in the mountains of the southern slope of the central Pyrenees.

Figure 8 shows the snow accumulation in the upper basin of the Gállego River. Its detail allows us to appreciate the rhythms of the different hydrological years, between 2015/2016 and 2021/2022. Three periods can be roughly discriminated: a) 2015/2016 and 2016/2017; b) 2017/2018 to 2019/2020; c) 2020/2021 and 2021/2022.

In the first, the maximum snow volumes are of the order of 120 hm^3. In the second, there are the two best years of our series (2017/2018 and 2019/2020), with values exceeding 180 hm^3 and 160 hm^3, respectively, but separated by a year (2018/2019) that is worse, in which 100 hm^3 is narrowly exceeded. Finally, the third is very similar to the first. The trend line indicates an increase in snow accumulation in the upper basin of the Gállego River, within the period analyzed. It is the years 2018 and 2020 that explain this upward trend, while four years of the seven included in this time series, show very stable values.

The general trend of precipitations shows a decreasing trend in precipitations (Figure 6). This difference with respect to the variable volumes of snow -with an upward trend- is due to the fact that during the period of our study, the driest months have been mainly registered over the summer. On the contrary, there have been significant cases of cold months (with snow precipitation), in which precipitation has been recorded well above normal values.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

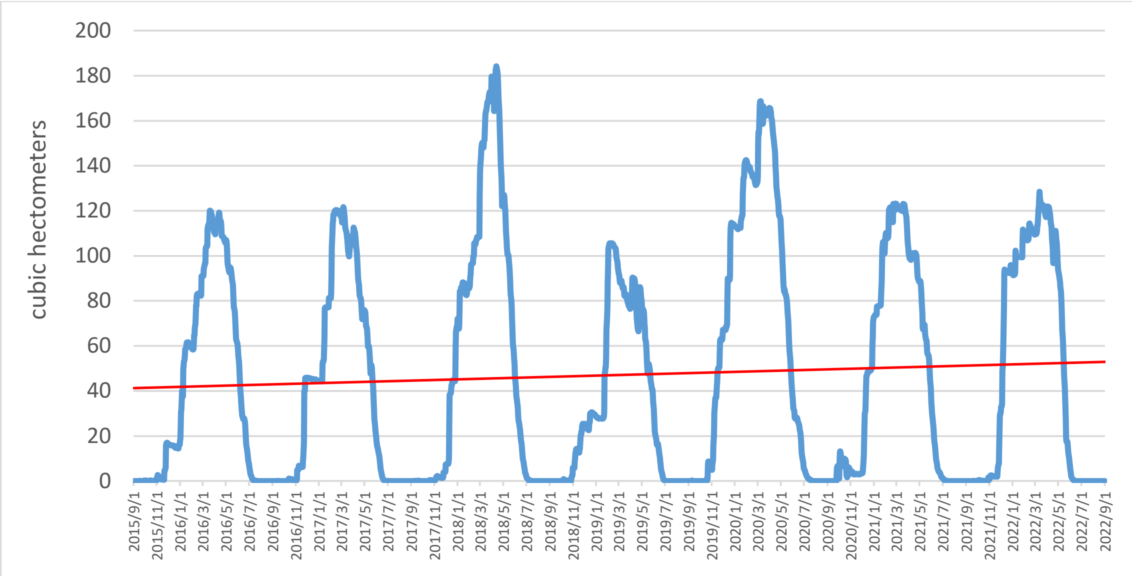


Figure 8. Evolution of accumulated snow in the upper Gállego River basin (up to the Búbal reservoir). September 2015-September 2022. Trend line. Base data: weekly snow volumes, expressed in hm³ (equivalent water volume). Data source: CHE-SAIH [49]. Own elaboration.

On the other hand, Figure 9 shows the duration expressed in number of days of the annual period with snow accumulation greater than 10 hm³ in this basin, by hydrological years. It is between 184 and 235 days. The trend line is slightly negative, with the last two years (2020/2021 and -with the lowest value, 2021/2022-) having the worst records, while 2019/2020 has the best.

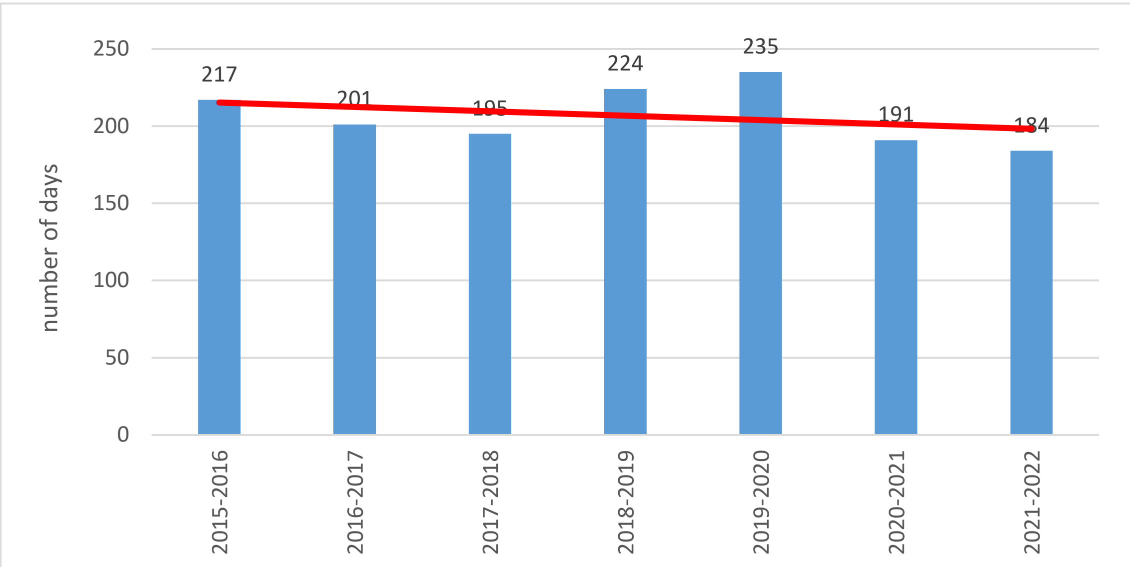


Figure 9. Number of days with snow accumulation higher than 10 hm³ (equivalent water volume) in the upper Gállego River basin (up to the Búbal reservoir), by hydrological years. 2015/2016 to 2021/2022. Trend line. Data source: CHE-SAIH [49]. Own elaboration.

In addition to Figure 9, Table 1 shows additional data: as a complement to the number of days with uninterrupted snow accumulations greater than hm³ (equivalent volume of water), this table includes the dates of the beginning and end of this period, the maximum value reached for each hydrological year and the date on which this value occurs. Normally, this reference value is exceeded between November and June, but -as in the other variables analyzed above- there is marked interannual variability, with two years in which the start of the period is delayed until December and one in which the end is brought forward to May. The start dates range from November 5, 2019, to December 9, 2017. As for the end dates, they range from May 29, 2022, to June 28, 2016. In 2019/2020,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

with 235 days, the start date is the earliest in the series (November 5) and the end date is the second latest (June 26). In 2021/2022, with 184 days, the start date is the third latest in the series (November 27) and the final is the earliest (May 29).

Table 1. Start and end dates of uninterrupted accumulations of more than 10 hm^3 of snow (equivalent water volume) in the upper Gállego basin River (up to the Búbal reservoir), by hydrological years. 2015/2016 to 2021/2022. Includes number of days for each hydrological year, value and date of maximum accumulation. Data source: CHE-SAIH [49]. Own elaboration.

Hydrologic year	Start	End	Total days	Date of maximun and volume of equivalent water
2015-2016	November 25	June 28	217	March 21 119,9 hm^3
2016-2017	November 21	June 9	201	March 6 121,7 hm^3
2017-2018	December 9	June 21	195	April 13 184,1 hm^3
2018-2019	November 6	June 17	224	February 5 to 12 105,6 hm^3
2019-2020	November 5	June 26	235	March 9 168,7 hm^3
2020-2021	December 5	June 13	191	February 27 123,2 hm^3
2021-2022	November 27	May 29	184	March 13 128,5 hm^3

The number of days with snow accumulations greater than 10 hm^3 (equivalent water volume) has greater interannual stability than the nivological variable of accumulated snow volume. This conclusion is derived from their respective analyses by hydrological years (Figures 8 and 9, Table 1). The visual comparison of both variables is shown in Figure 10, in which the number of days and volumes of more than 10 hm^3 are compared. Years with very little accumulated snow, such as 2018/2019, present a greater volumetric variation, with respect to the best years of snow accumulation, than that derived from the respective comparisons referring to the number of days with more than 10 hm^3. There is also the paradox that there is not always a direct relationship between these two variables. There are years with large volumes of snow, but which have a moderate number of days with more than 10 hm^3, such as 2017/2018. There is also the opposite situation. The reasons have to do with the pluviometric and thermal rhythms of each hydrological year. All this is reflected in the interannual behavior of the Infierno glacier.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

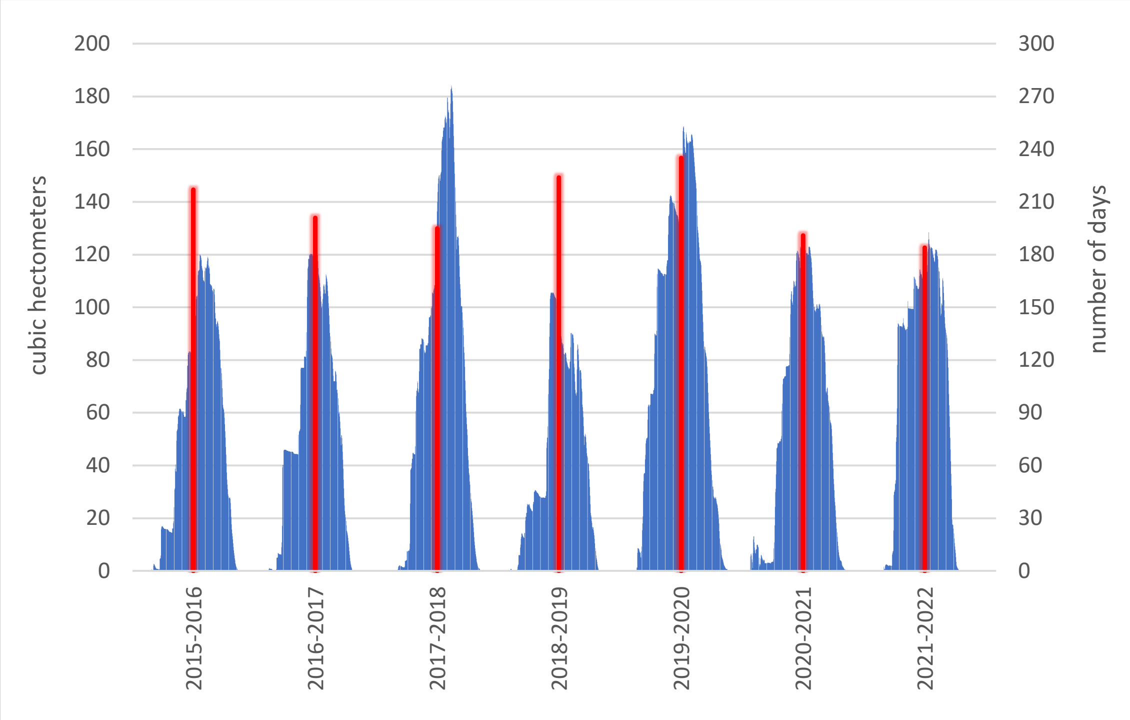


Figure 10. Comparative study between the evolution of accumulated snow and the number of days with snow accumulation higher than 10 hm³, in the upper Gállego River basin (up to the Búbal reservoir), by hydrological years. 2015/2016 to 2021/2022. Base data: weekly snow volumes, expressed in hm³ (equivalent water volume). Blue: snow volume; red: number of days. Data source: CHE-SAIH [49]. Own elaboration.

Another nivological variable of great glaciological interest is the evolution of the thickness of the snowpack. For its study in the upper Gállego River basin, data have been taken from meteorological stations that systematically measure this variable and that have acceptably long time series of data. The chosen stations are two, located in mountain refuges owned by the Aragonese Mountaineering Federation, whose meteorological data are managed by AEMET. The two stations are located in the fluvial basin of the Caldarés River, a tributary of the Gállego River at its headwaters: Casa de Piedra (1636 m a.s.l.) and Bachimaña (2200 m a.s.l.). Figures 11 and 12 show data, respectively, from both stations. Their detail allows us to appreciate the rhythms of the different hydrological years, between 2015/2016 and 2021/2022.

Despite the geographical proximity of the two stations (only 2.25 km in a straight line), they show annual rhythms that are not always homogeneous, with both similarities and differences depending on the year. Such behavior should not be surprising: on the one hand, the notable variation in elevation between the two refuges, close to 600 m; on the other hand, the topographic characteristics of their respective enclaves. Casa de Piedra occupies the bottom of a deep glacial cirque; Bachimaña is more exposed to strong winds and snow sweep. The varied nivological conditions of the Pyrenees and their pronounced interannual variability have been studied in different studies [52-56].

The inter and intra-annual evolution of snow thicknesses for the indicated period, in the two stations, certifies important variations both in maximum thicknesses and in the shape of the curve. There are years with long periods of snow on the ground, others are much shorter. There are years in which high thicknesses are reached, but which quickly melt (as in 2021/2022); in other years, with lower thicknesses, snow persistence is more prolonged (as in the cases of 2017/2018 or 2019/2020). The trend of snow thicknesses for this period, is slightly upwards (in accordance whit the trend of snow volumes, Figure 8).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

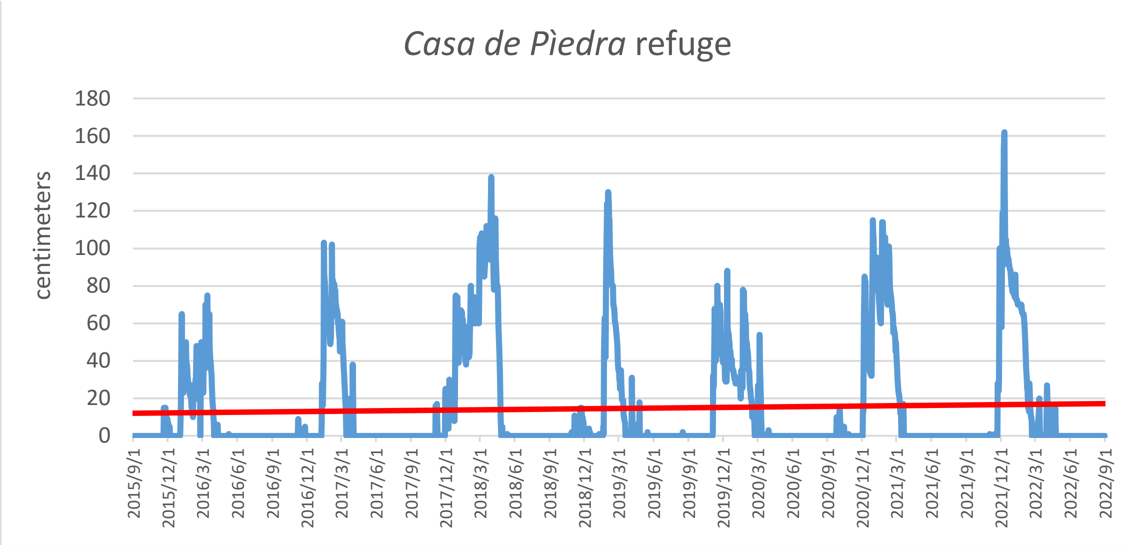


Figure 11. Evolution of snowpack thickness at the *Casa de Piedra* Refuge, weather station (1636 m a.s.l.). September 2015-September 2022. Trend line. Base data: daily columns of snow accumulation. Pyrenean mountain refuges. Data source: AEMET [50]. Own elaboration.

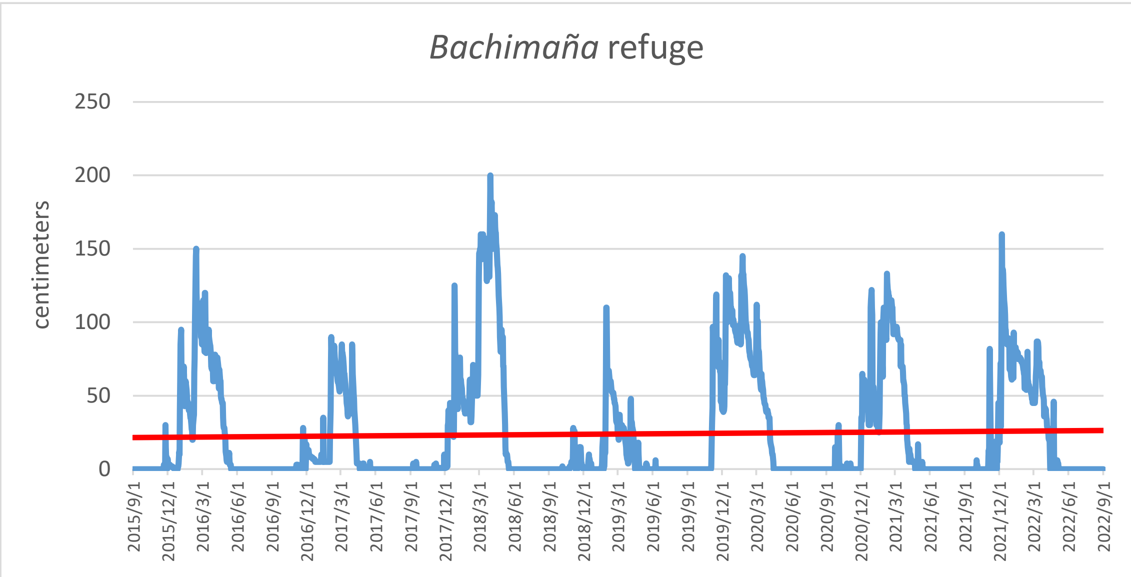


Figure 12. Evolution of snowpack thickness at the *Bachimaña* Refuge, weather station (2200 m a.s.l.). September 2015-September 2022. Trend line. Base data: daily snow accumulation columns. Pyrenean mountain refuges. Data source: AEMET [50]. Own elaboration.

The variables presented in the preceding sections (precipitation and temperature anomalies, accumulated snow volumes, snow thickness), are detailed in terms of their annual behavior in the 3.3. Subsection, “Glacier evolution”, below.

3.3. Glacier evolution

The evolution of the Infierno glacier can be seen in table 2 and figures 15 and 16. The measurements carried out at the two monitoring stations described above are shown: glacier front and glacier side. These data (retreats/advances of the glacier front and losses/gain of thickness/power at the lateral station) have been analyzed in relation to the monthly climatological summaries of AEMET [47, 48] and with the snow data series of CHE-SAIH [49] and AEMET [50], as detailed in figures 6 to 12 and table 1. We present below the evolution of the glacier during the period 2016-2022. The starting data ("zero" position) is the situation of the previous year, 2015.

The mentions of the seasons of the year, refer to the climatic seasons, not astronomical ones. For the present work, season are grouped as presented: Spring (March to May); Summer (June to August); Fall (September to November); Winter (December to February).

Before analyzing the 2016-2022 period, we should point out that, as mentioned in section 2 (Materials and Methods), we have monitored the evolution of the Infierno glacier from 1998 to 2022. We note here briefly that during this 25-year period there are numerous fluctuations and interesting changes in trend, with predominantly years of retreat and also years of advance. But the overall result is one of clear recession. In 2022, the glacier front has retreated 38.8 m with respect to the 1998 position, while the thickness/power loss at the side station has been 8.7 m. The evolution data for the period 1998-2015 indicate 2006, 2012 and 2015 as the years of greatest losses. While the most outstanding positive balances occurred in 2013 and 2014 [35], years in which the glacial ice remained protected by continuous snow cover, until the end of summer and the beginning of the climatic fall (first days of September).

However, 2015 shows a very bad evolution for the Infierno glacier. In 2015 (date of measurements: September 5), the positive balance gained in the previous two years was lost. The ice is exposed on most of the glacier surface and there are significant retreats in the glacier front and thickness losses (-3.1 m) laterally, compared to 2014 (date of measurements: September 3). The entire month of March at July 2015 period was very dry, with little snowfall and low snow accumulation. The same period, extended until August, was also very warm (April, May and July, extraordinarily warm, +3º C DRV). All this caused particularly intense melting processes of the snow cover and of the glacier ice itself. This dismal year 2015 for the evolution of the Infierno glacier is in line with the situation of other Pyrenean glaciers. The Maladeta glacier can serve as a comparative reference: in this year, it presents the third most negative mass balance since 1991/1992 [57].

Between 2016 and 2020, the dynamics of the glacier certify an extreme interannual irregularity. There is a continuous succession, year after year, of trend changes. A good year is systematically followed by a bad one, and vice versa.

Year 2016. Date of measurements: September 3.

The situation is better than in 2015. The glacier gains (+18.4 m and +2 m, compared to our "year zero", in frontal and lateral measurements, respectively). The January-March quarter was very wet (150% DRV), although the rest of the spring proved dry (75% DRV). The March-May period was cold (March, very cold, -2° C DRV), followed by normal June and warm July and August (August, very warm, +2° C DRV). The rainfall behavior of the winter and early spring, with heavy snow accumulations, as well as low temperatures and a normal June (which delayed snowmelt), even though the summer was warm, explain the gain of the glacier compared to a previous very bad year.

The values of snow thicknesses in the mountain refuges are in accordance with these rainfall and thermal rhythms. In Casa de Piedra, the greatest thickness of the entire 2015/2016 hydrological year is reached in mid-March. And so are the volumes of accumulated snow in the upper basin of the Gállego River, which reaches its highest values for the hydrological year between late February and mid-May, recording a moderate maximum value (119.9 hm^3), but with the particularity that is reached on March 21, the second latest date in our series, with a secondary maximum in mid-April. This behavior is reflected in the number of days (217) with snow accumulations higher than 10 hm^3 for the hydrological year, the third highest value of our study period, highlighting that the final day in which this value is reached is very late (June 28, the most advanced of our series), so that in the full of the climatic summer, there were still important volumes of snow at high altitudes.

Year 2017. Date of measurements: September 2.

It is a bad year for the glacier, with marked losses compared to 2016. The glacier front has retreated (-12 m), and the loss of thickness at the side station is strong (-2.2 m). Relative to "year zero" 2015, the position is respectively +6.4 m and -0.2 m. November 2016 and

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

February 2017 proved to be very wet, with strong snow inflows (150% and 175% DRV, respectively), although, in between, December was extraordinarily dry (25% DVR) and January, normal. On the other hand, the period from November to January was predominantly cold (November and January, -1° C DRV). However, the subsequent months are adverse for the glacier: spring is dry (close to 70% DRV), while February and the whole spring are very warm (+2° C DRV), followed by an extraordinarily warm early summer (June, +3° C DRV), normal July and warm August. As a result, there was little snowfall since March, accompanied by high temperatures that caused snowmelt at high altitudes from mid-spring, accelerated by a very warm start to the summer. All this explains a situation of the glacier significantly worse than that of the previous year.

Snow thicknesses in the mountain refuges reflect this meteorological behavior. At Casa de Piedra, snow thicknesses are higher than in the previous year in January and February, but in March the opposite happens, with a strong decrease in snow cover. In Bachimaña, the decrease in snow cover in April is much faster than in 2016. The accumulated snow volumes in the upper basin of the Gállego River are also in line with these behaviors. Moderate maximun value (121.7 hm^3), reached early (March 6), with rapid declines from the first decade of April. This has its correspondence with the number of days (201) with snow accumulations higher than 10 hm^3 for the hydrological year, but especially with an end date for this value, June 9, which is 19 days earlier than that of the previous year, indicative of faster snowmelt processes.

Year 2018. Date of measurements: September 1

In this year, the trend of 2017 is broken and the glacier has net gains at its two monitoring stations (+29.7 m at the front station and +2.3 m at the side station, compared to 2017). The comparative balance with "year zero" 2015 is as follows: +36.1 m and +2.1 m, respectively. Winter 2017/2018, spring and early summer were very wet, predominantly wet months since December (125% DRV), with March and June reaching 175% DRV. A similar period, from November to June, was cold on average. Only January and April had above average temperatures (+1° C DRV). But all the others were cold (-1° C DRV), with February and March being very cold (-2° C DRV). The rest of the summer (July and August) was not hot either, with normal temperatures (0° C DRV). The coincidence from late autumn to early summer of a long wet and cold period, causes significant snowfall and late melting of snow. This results in a positive glacial evolution.

Figure 8, allusive to the accumulated snow in the upper basin of the Gállego River, corroborates this assessment, being 2017/2018 the best year of our series, with maximum values of volumes that exceed the average by 30%, reaching the top (184.1 hm^3) on April 13, the latest in the series. This very good year of snowpack reserves has no correspondence with the number of days (195) with snow accumulations higher than 10 hm^3 for the hydrological year, a low value in the series as a whole, which has its explanation in the initial date on which it was reached, December 9, the latest in this series of years, due to a very dry September-November quarter (40% DRV), with weak snowfall. On the other hand, the final date for the 10 hm^3 value, June 21, is among the latest in the series. The snow thicknesses in the reference mountain refuges are in agreement with the data presented so far. Casa de Piedra shows clearly higher values than in previous years, with a maximum at the end of March and high accumulations until the third week of April. Bachimaña, on the other hand, presents higher values than in any other year of the serie, in a period that goes from the beginning of March to the middle of April. Figure 13 shows the state of the glacier on September 1, 2018.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

Figure 13. Detail of the Infierno glacier. September 1, 2018. Most of the surface is covered with firn. Photo by the authors.

Year 2019. Date of measurements: August 31.

This year turns out to be very negative for the evolution of the glacier. Everything gained in 2018, and more, is lost. In the frontal station there is a big retreat (-32.9 m), and in the lateral, the loss of thickness is also strong (-2.6 m), in both cases with respect to 2018. The balance with the "year zero" 2015 indicates a thickness loss (-0.5 m), leaving the frontal measurement at +3.2 m. These are the worst records since 2016, remaining even, in the case of the lateral thickness measurement, below the "year zero", which corroborates a negative trend that, despite its notable irregularities, is evident.

In the fall, winter and early spring of the 2018/2019 hydrological year, almost all months are dry. Indeed, between September and March, only January is wet (125% DRV), the others being dry and even extraordinarily dry (December and March, 25% DRV; February, 50% DRV). The rest of spring and summer are predominantly normal. During the autumn, winter and spring, temperatures are very variable, with normal, cold and warm months, without following clear patterns. However, summer is warm-to very warm (July, +2° C DRV; June and August, +1° C DRV). The predominance of dry months in key periods for snow accumulation and the melting derived from a warm summer, lead to the negative situation described.

The snow accumulated in the upper basin of the Gállego is in accordance with these weak snow inflows, with the lowest values of all our series. In addition, the date on which the annual maximum is reached is the earliest of the entire series (February 5 to 12, with a poor 105.6 hm^3). From here, a progressive decrease in volumes begins, which only slightly goes up again in some phases of April, to fall again rapidly from the end of this month. As for the period with snow accumulations above 10 hm^3, the values recorded are surprising in a first reading, since it covers 224 days, a high figure for this variable, which is due to a very premature start (November 6, the second earliest in the series). Although October and November were on average dry (75% DRV in both cases), from mid-October and during the first week of November there were several episodes of intense precipitation, accompanied by low temperatures, which were snowy at medium and high altitudes. Thus, on November 6, in the refuges of Bachimaña and Casa de Piedra, snow precipita-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

tions of 40.5 mm and 38 mm were recorded, leaving thicknesses of 26 cm and 42 cm, respectively (the lower value of Bachimaña is due to its windy location). This episode, together with those that have occurred since mid-October, explain the early date on which the aforementioned value of 10 hm^3 was reached.

It should be added in this respect that, subsequently, snow accumulations were very scarce in the Alto Gállego basin. It does not reach up to a modest 26 hm^3 until December 14 (on that date, in the 2016/2017 hydrological year, which was also bad for the glacier, there were already 40 hm^3); while the 2017/2018 hydrological year, qualified as good for the glacier, on November 30 had already reached 67 hm^3). The snow thicknesses recorded in the mountain refuges and their rates of evolution certify the above data. Bachimaña yields the lowest thickness values of all our series, which are also reached very early, at the end of January, to drop rapidly in February and March. There are only slight recoveries at the beginning of April, to drop again to values close to 0 cm during the rest of the spring. Casa de Piedra reaches a normal maximum value, similar to that of other years, but at a very early date (beginning of February), starting a rapid decline since then.

Year 2020. Date of measurements: August 31.

2020 again represents a change in the behavior of the glacier in relation to the previous year. It advances at the front station (+11.3 m) and gains of thickness at the side station (+1.9 m), compared to 2019. Its comparative position with respect to "year zero" 2015 is as follows: +14.5 m (frontal) and +1.4 m (lateral). In the 2019/2020 hydrological year, after a normal October, November and December were very wet (150% DRV), as was March (200% DRV), with January normal, but February proved extra dry (25% DRV). After a normal April, May and June were again very wet (150% and 125% DRV, respectively). There were, therefore, strong snow inflows from late autumn to late spring. On the other hand, the thermal rhythms show clear predominance of warm months during a long stretch spanning autumn, winter and spring. Except for November, which was very cold (-2° C DRV), the other months were warm or very warm (+2° C December, April and May; February +3° C DRV). But June was very cold (-2° C DRV), although the rest of the summer was warm (+1° C DRV). Despite the high temperatures, heavy precipitation during many months (snow, at these high altitudes) caused high accumulations of snow on the glacier.

A key to this good year for the glacier is the thermal and pluviometric behavior of the months of May and June. The first month had high precipitation and was very warm, despite the fact that, at the glacier's heights, most of the precipitation was snow, at least during the first fortnight, the wettest. And June was very cold. That is to say, in May there was still snow accumulation on the glacier and in June the losses were weak.

The rainfall and thermal rhythms just described are reflected in the accumulated snow reserve in the upper Gállego River basin, which reaches 168.7 hm^3 (the second highest value in our series). It is interesting to add that the number of days in which the 10 hm^3 of water reserve in the form of snow is exceeded in this basin is very high (235), being this the highest value of the series, which was due to the date (5 November) on which this volume was reached, being the earliest date of all our series for this variable. In addition, the final date for this volume, June 26, is also very late, the second in the series. The result is the presence of important volumes of snow at high altitudes at the beginning of the climatic summer.

The snow thickness curves in the mountain refuges are in accordance with the previous data. Bachimaña, at 2200 m a.s.l., is characterized by the width of the period of maximum snow accumulations, from the beginning of November to the beginning of March, with maximum thicknesses in the range of the good years of our series. The case of Casa de Piedra is different. The curve is more irregular, with maximums between the beginning of November and the end of January (but with frequent changes of rhythm), and modest values of maximum thicknesses. This was undoubtedly influenced by the moderate altitude of this refuge (1636 m a.s.l.), where, despite the numerous snowfalls recorded, the high temperatures during most of the months of the hydrological year caused rapid snowmelt.

After the five-year period 2016-2020 just analyzed, characterized by annual trend changes, we enter the last two years of our study period (2021 and 2022). Both present very negative dynamics for the evolution of the glacier.

Year 2021. Date of measurements: September 5.

Ice losses at both monitoring stations are strong and much of the previous year's gain has been lost. The glacier retreats at front station (-11.7 m) and loses thickness at side station (-1.2 m), with respect to 2020. Its comparative measurements with our "year zero" 2015 give these values: +2.8 m frontal and +0.2 m lateral. The 2020/2021 hydrological year is characterized by strong contrasts in monthly precipitation values. After normal October and very dry November (50% DRV), there are three consecutive very wet months with high snow input: December, January and February (150% DRV). In contrast, spring is dry. Only April is normal, but March and May are extremely-very dry (25% DRV and 50% DRV, respectively). After normal June, the rest of the summer is very dry. As for temperatures, after a very warm late autumn (November, +2° C DRV), winter starts cold (December and January, -1° C DRV and -2° C DRV, respectively), but February is extraordinarily warm (+3° C DRV). Spring is normal in temperatures, but summer is warm, with June and August +1° C DRV. The regressive behavior of the glacier is explained by the low snowfall in spring and the rapid summer melting.

The hydrological year yielded normal values in snow reserves, with a maximum of 123.2 hm^3, which was reached early, on February 27, although it remained at similar values over a long period from February 10 to March 25. This was undoubtedly due to the strong winter snow input. On the other hand, we are in the second worst year of our series in terms of the number of days (191) with snow accumulation higher than 10 hm^3. In fact, the starting date on which this value is reached is the second latest in our series (December 5, derived from a very dry November), while the final date is somewhat early (June 13). Snow thicknesses in the mountain refuges are in accordance with the precipitation rates described. Maximum values reached between the end of December and the end of February for Bachimaña, while in Casa de Piedra the final date of maximum values is brought forward to the first decade of February, due to the high temperatures of this month and the greater effect of these on the moderate elevation of this refuge (1636 m a.s.l.).

Year 2022. Date of measurements: 30 August.

The last year of our series of observations has been by far the worst for the evolution of the glacier. Strong retreat at the front station (-17.7 m) and large thickness loss at the side station (-4.8 m). In both cases with respect to the previous year. Taking as reference our "year zero" 2015, the losses are largest (-14.9 m and -4.6 m, respectively). If we focus the analysis on the worst year of our series from 2016 to 2021, which was 2019 for the lateral station, the glacier has lost -4.1 m of thickness. These are dramatic values, which not only affect this glacier, but the whole Pyrenean mountain range. The result for the Infierno glacier is a considerable reduction in surface area, being 5.52 ha at our measurement date (August 30, 2022), when only two years earlier, on date August 31 2020, it was 7.06 ha (Figure 3).

The 2021/2022 hydrological year was predominantly dry, although with several wet and normal months on key dates for snow accumulation. After a dry autumn, the winter was, on average, normal, but with notable internal variations. December started out very wet (150% DRV) and January was normal. But February was extra dry (25% DRV). And in early spring, March was normal. The rest of the spring, dry (May, extra dry, 25% DRV). We have three months (December, January and March) with snow accumulations, on average, higher average. The result is snow volumes in the upper basin of the Gállego River reach normal maximums for our series (128.5 hm^3) on March 13, in the usual range for this variable, and that remain at relatively high values until the end of April, to begin a rapid decline during May, to the point that at the end of this month, less than 10 hm^3 remain. The number of days with snow accumulation higher than 10 hm^3 is in accordance with this behavior. The result is 184 days, the lowest in our series, due to a late start date (27 November, after a dry autumn) and an end date that is the earliest in the series (29 May),

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

a date that is explained by the low precipitation in April and May and by the very high temperatures of this month.

The main factor explaining the very bad year 2022 was undoubtedly thermal. The very high temperatures in key months for the evolution of the glacier are behind the result explained above. In the hydrological year as a whole, there was only one year below the average (November, very cold, -2° C DRV). The rest were normal (in only three cases: October, March, April) and, mostly, warm-very warm, with several records of +3° C DRV. After the very cold November, the whole winter was warm (December and January, +1° DRV), but February reached extraordinary values (+3° C DRV). The spring began normal (March and April), followed by an ultra-warm May (+4° C DRV). The summer continued with extraordinary hot values (June and July, +3° C DRV; August, +2° C DRV). That is, between May and August, without interruption, it is between +4° C and +2° C DRV. These very high and persistent temperatures caused rapid melting of the glacier snow cover and, once lost, of the glacier ice itself. Yet another factor further contributed to this process: August was not only very warm; but also very wet (150% DRV), and liquid precipitation on the glacier ice accelerated its melting.

The evolution rhythms of snow thicknesses in the mountain refuges support the behavior of the preceding variables. The highest values are reached in mid-December, due to intense precipitation between the end of November and mid-December. Casa de Piedra exceeded 320 mm (not all in the form of snow, there were days of rain), giving high thicknesses for the moderate elevation of this refuge (1636 m a.s.l.): more than 100 cm between 9 and 18 December, with a peak of 162 cm on the 11th. Bachimaña has a similar behavior (peak, 160 cm, December 8). This is in accordance with a very wet December (150% DRV). However, this good start of the winter season in terms of snow accumulations was quickly truncated. January was a normal month, but from the first ten days of February onwards, at Casa de Piedra, the thicknesses are less than 20 cm, except for occasional moments. The curve of maximums is very narrow, indicative of rapid melting due to the adverse rainfall and thermal conditions described above. Bachimaña maintains acceptable thicknesses until mid-March (the altitude factor, 2200 m a.s.l., is noticeable), with a curve in which there are alternating losses and gains. But from this moment on, except for an occasional increase (April 23, 46 cm), the losses are sharp, quickly reaching zero from the beginning of May.

Figure 14 shows the state of the glacier on August 30, 2022.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

Figure 14. Mid-upper sector of the Infierno glacier. August 30, 2022. Stones cover most of the surface. Ice emerges.

Table 2. Evolution of the Infierno glacier (front and lateral), period 2016-2022. References over position in 2015 and over the previous year. Data in meters. Glacier front: longitudinal variation. Lateral glacier: thickness variation. Reference to surface prevalence of ice or firn. Data provided by the writing team. Own elaboration.

Year/date measurementes	Glacier front (value reference 2015=0)	Glacier front (over previous year)	Lateral glacier (value reference 2015=0)	Lateral glacier (over previous year)	Ice/ firn (predominance)
2015/09/05	0	0	0	0	ice
2016/09/03	+18.4	+18.4	+2	+2	firn
2017/09/02	+6.4	-12	-0.2	-2.2	ice
2018/09/01	+36.1	+29.7	+2.1	+2.3	firn
2019/08/31	+3.2	-32.9	-0.5	-2.6	ice
2020/08/31	+14.5	+11.3	+1.4	+1.9	firn
2021/09/05	+2.8	-11.7	+0.2	-1.2	firn
2022/08/30	-14.9	-17.7	-4.6	-4.8	ice

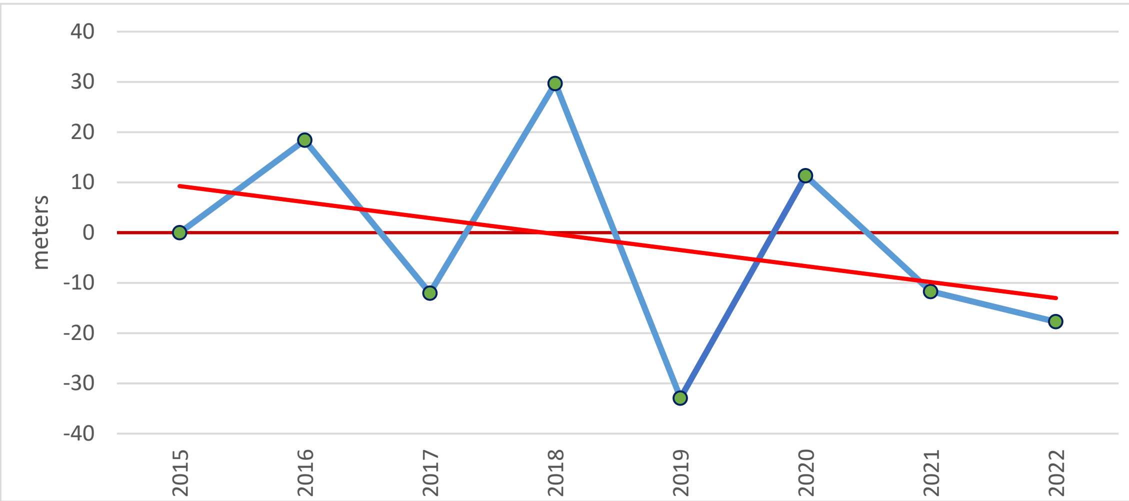


Figure 15. Evolution of the *Infierno* Glacier (glacier front). Period 2016-2022. Longitudinal variation, data in meters. References on position in 2015 and trend line. Data from the writing team. Own elaboration.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

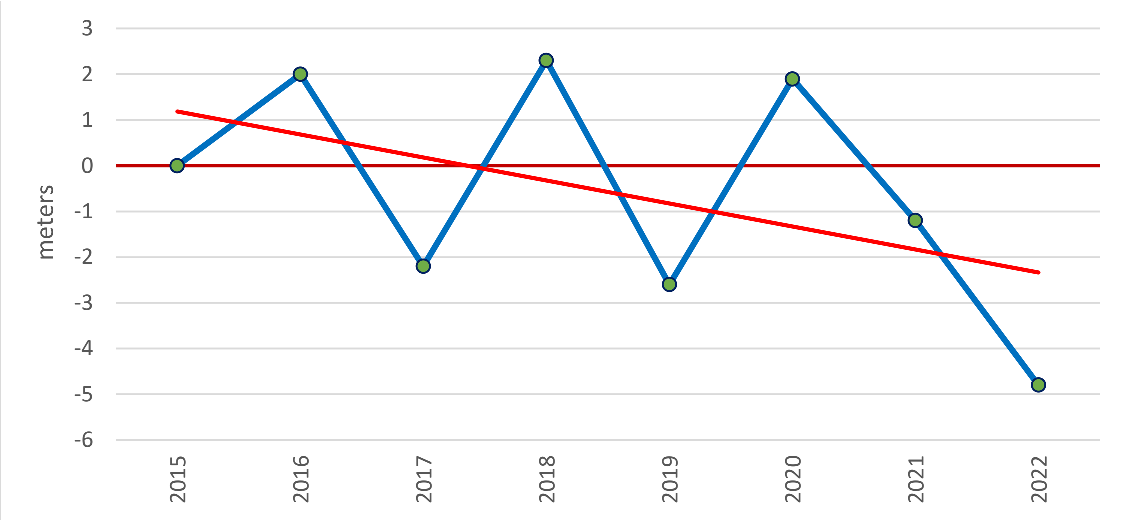


Figure 16. Evolution of the *Infierno* Glacier (glacier side). Period 2016-2022. Thickness variation, data in meters. References on position in 2015 and trend line. Data from the writing team. Own elaboration.

4. Discussion

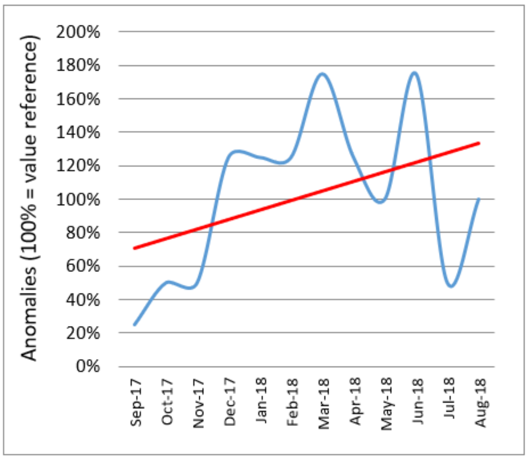
The evolution of the *Infierno* glacier shows a clearly regressive trend in the period 2016-2022. The loss of 4.6 m in thickness and 14.9 m in length with respect to the "year zero" of our work, 2015, is significant. But if we extend the comparison to 1998, when we started measurements on this glacier, the values are even more striking: loss of 8.7 m in thickness and 38.8 m in length.

This regressive dynamic has not followed a regular pattern. On the contrary, trend changes have been the norm. Between 2016 and 2020, each year has had opposite behavior with respect to the previous one. A year of gains has been followed by a year of losses. Only in 2021 and 2022 has the loss trend remained stable. This has much to do with the inter-annual (and intra-annual) climatic irregularity characteristic of the climate of much of the Spanish Pyrenees, also of the upper basin of the Gállego River, where the glacier is located, with strong Mediterranean influences. The years in which the glacier has had gains with respect to the immediately preceding one have been 2016, 2018 and 2020. The years of losses, 2017, 2019, 2021 and 2022.

The annual evolution of the glacier has been analyzed according to the meteorological conditions. The relationship has been clear. In this sense, two years are particularly significant, as they represent the extremes in the highly variable behavior of the glacier. They are 2018 and 2022. The first is the one with the greatest gains in our series; the second, the one with the greatest losses. 2018 had a long period (winter, spring and early summer) very wet and -also including November- cold, with the rest of the summer normal in temperatures. The coincidence from late autumn to early summer of a long wet and cold period led to significant snow inflows and late snowmelt. The result was a positive glacial balance. In the case of 2022, conditions were very different. There was no serious deficit of snow inflows, as several months of the winter and spring had normal or even high precipitation. Others in the same period, however, were very dry. But the key factor this year has been the high temperatures in many months: winter, late spring, summer, with in many cases extraordinary values. The result is a rapid snowmelt, followed by mass loss of glacial ice, with the most pronounced negative glacier balance of our entire series.

Several graphs help to understand this very different behavior between 2018 and 2022. For the respective hydrological years, the precipitation curves -according to DRV values- are significant, with records well above average in 2018 since December, being clearly lower in 2022 (Figures 17 and 18). As for temperatures -DRV values- while low records predominate in 2018, the positive deviation for 2022, since December, is extraordinary, with progressive increase as the hydrological year progresses (figures 19 and 20).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1



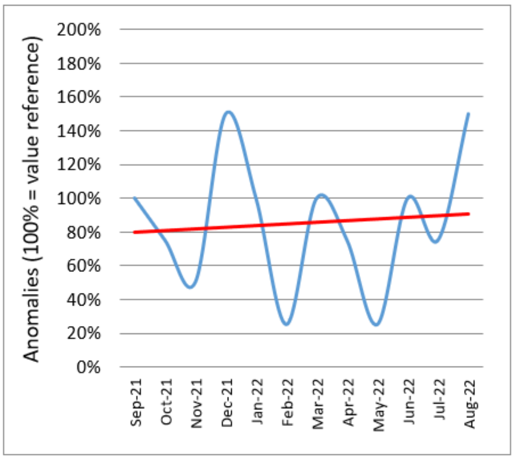
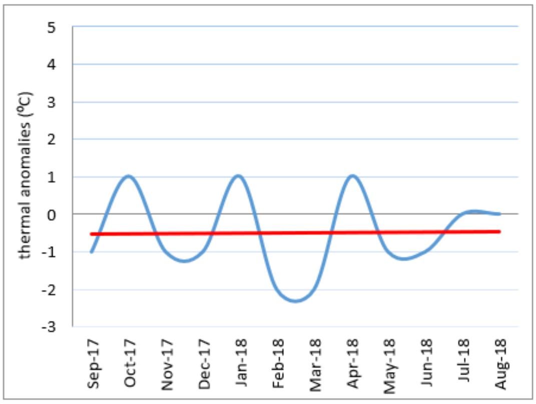


Figure 17 (Left) - Figure 18 (Rigt). Rainfall anomalies in the upper Gállego River basin. Hydrological year **2017/2018 (left)** and **2021-2022 (right).** Over reference period 1981-2010, as determined by AEMET for these comparisons. Data source: AEMET [47, 48]. Own elaboration.



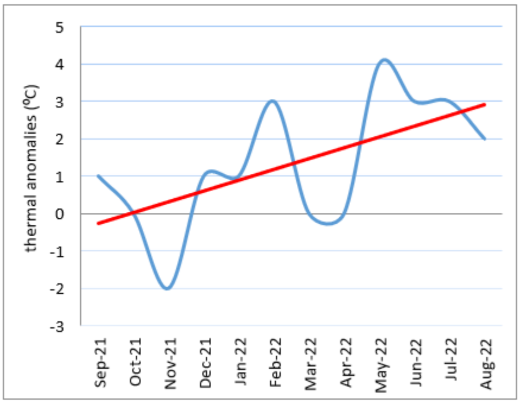
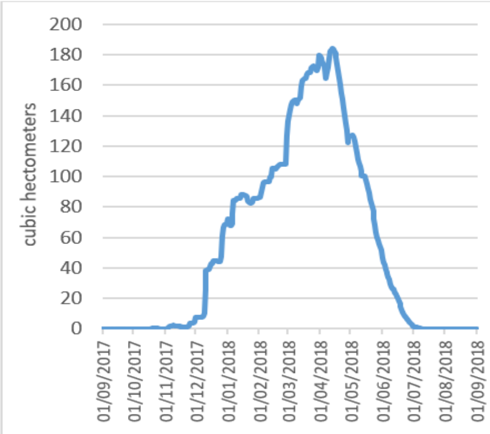


Figure 19 (Left) - Figure 20 (Rigt). Thermal anomalies in the upper Gállego River basin. Hydrological year **2017/2018 (left)** and **2021-2022 (right).** Over reference period 1981-2010, as determined by AEMET for these comparisons. Data source: AEMET [47, 48]. Own elaboration.

Another key variable to understand these 2018-2022 differences is the volume of snowpack reserves in the upper basin of the Gállego River (Figures 21 and 22). In the former, it is difficult to reach high volumes, in the vicinity of 100 hm^3, until the beginning of February, but then very high values are reached, exceeding 180 hm^3, and in early June still exceed 40 hm^3. In 2022, on the other hand, 100 hm^3 are reached one month earlier, but the maximum is just over 120 hm^3. And although the values remain acceptable until the end of April, the decline is very rapid, and from the beginning of June the reserve is zero. Some significant data help to understand the differences: April 13, 2018: 184 hm^3; April 13, 2022: 113 hm^3. May 15, 2018: 100 hm^3; May 15, 2022: 54 hm^3.



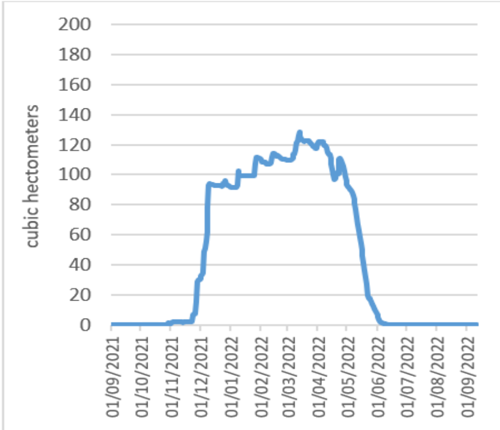
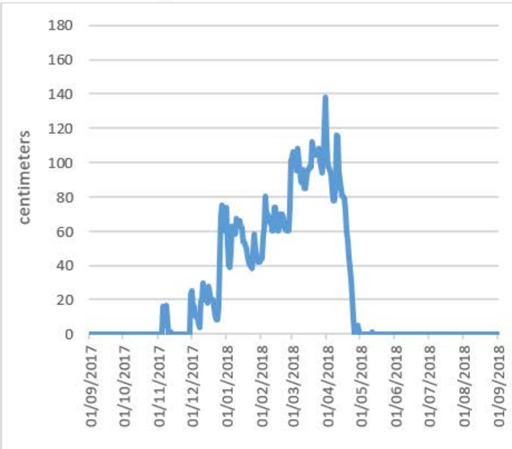


Figure 21 (Left) - Figure 22 (Rigt). Evolution of accumulated snow in the upper Gállego River basin (up to the Búbal reservoir). Hydrological year **2017/2018 (left)** and **2021-2022 (right).** Base data, weekly snow volumes, expressed in hm^3 (equivalent volume of water). Data source: CHE-SAIH [49]. Own elaboration.

As a final variable in our 2018-2022 comparison, we include snow thicknesses at the *Casa de Piedra* mountain refuge. (Figures 23 and 24). Recall that it is located at a moderate altitude (1636 m a.s.l.), which makes it difficult for the snowpack to persist for prolonged periods. Despite this, in 2018, from the end of December to the third week of April, 40 cm are exceeded. The maximum value, although high (138 cm, March 31) is, however, lower than that of 2022 (162 cm on December 11). But the former is reached well into spring, while the latter is at the beginning of winter. And in 2022, at the beginning of February, it drops below 40 cm, a value that is not recovered again during the whole season and decreases rapidly.



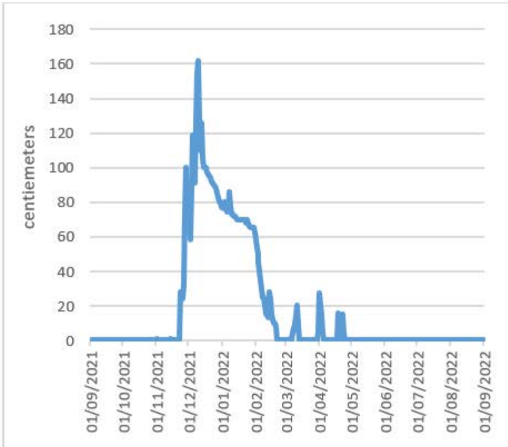


Figure 23 (Left) - Figure 24 (Rigt). Evolution of snowpack thickness at the *Casa de Piedra* Refuge, weather station (1636 m a.s.l.). Hydrological year **2017/2018 (left)** and **2021-2022 (right).** Base data, daily columns of snow accumulation (in meters). Pyrenean mountain refuges. Data source: AEMET [50]. Own elaboration.

A very important aspect for the analysis of the evolution of the *Infierno* glacier is the comparison between the values recorded at the two monitoring stations: frontal and lateral. There are logical coherences between the two, but also some differences. In this regard, we should point out several interesting details.

The years that offer advances in the front station with respect to their respective preceding years (2016, 2018 and 2020), have been characterized by an aspect of the glacier

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2022 doi:10.20944/preprints202212.0113.v1

that still retained snow cover (firn) on an important part of its surface, on the dates of climatic summer-autumn transit. This was reflected in the lateral season, with increases in thickness between +1.4 and +2.1 m (not so much of glacier ice, but of firn).

In the case of the years that have recorded net losses in the terminal tongue with respect to their preceding years (2017, 2019, 2021 and 2022), it should be noted that the comparison with our "year zero" 2015 yields mostly positive values. The only year with regression respect to 2015 is 2022. But it should be noted at this point that 2015 was a very special year, to the point that in the entire 1998-2015 period of monitoring of the *Infierno* glacier, 2015 was the most regressive. However, the side station measurements do not follow identical pattern. In all the years noted, there are thickness losses relative to 2015 (except in 2021, with a negligible gain). The losses in 2017 and 2019 are minor (-0.2 and -0.5 m, respectively), with the loss in 2022 being much larger (-4.6 m). These data confirm the progressive ablation of the glacier ice mass. From this we can infer that the evolution measured at the lateral control station seems to us to be more in line with the real behavior of the *Infierno* glacier, showing a regressive trend. The frontal position, on the other hand, is more conditioned by variations in snow cover (snow or firn, depending on the year), with greater interannual variability.

A complementary data for the analysis of the evolution of the *Infierno* glacier, is the confirmation of the last date of each hydrological year in which snow accumulation of more than 10 hm^3 is still measured in the upper basin of the Gállego River, up to the Búbal reservoir. In the 2016/2022 period, this date is in June, except for one year (2021/2022), the year of greatest glacier regression, when it was on May 29. We can appreciate that in the three years of positive evolution (2016, 2018, 2020), that date occurs at the end of the month (June 28, 21 and 26, respectively). But in the years of negative evolution, the date is earlier (between the end of May and mid-June), according to CHE-SAIH data [49].

5. Conclusions

The *Infierno* glacier presents a clear regressive dynamic, within the general context of the Pyrenean glaciers. Its behavior in the 2016/2022 period certifies this.

There is a remarkable correlation between the annual climatic conditions (temperatures and precipitation recorded in weather stations near the glacier) and the behavior of the glacier. It can be affirmed that the latter has very variable rhythms, often even opposite, between successive years. In the study area, thermal and pluviometric anomalies are common, both intra and inter-annual. This behavior is directly reflected in the glacier and explains the interesting variations between the years analyzed.

The thermal anomalies (DRV) show a clear upward trend in this seven years period. The thermal value has increased by +0.55° C. With regard to precipitations, their anomalies (DRV) show very irregular trends. Precipitations data show a decreasing trend (-9% in the same period of time), having rainfalls a higher influence than snowfalls (with an upward trend of the snow accumulation volumes).

It is therefore the temperature factor that best explains the regression suffered by the *Infierno* glacier, which can be seen throughout our 2016/2022 series, but especially in the last year, 2022, with an exceptionally warm late spring and summer. The result is that the glacier has lost 4.6 m in thickness with respect to 2015 (and 8.7 m with respect to 1998, the year when our work on this glacier began).

The analysis of snow accumulation rates and monthly thermal irregularities has allowed us to understand the behavior of the glacier in each year. There are winters with heavy snowfall, followed by warm springs and summers, which make these winter snow thicknesses disappear rapidly, resulting in the retreat of the glacier. In a different sense, heavy snowfall in late spring can explain a good year for the glacier, sometimes being more decisive than winter snowfall, because it helps to protect the ice mass during the period of high summer temperatures (although it is difficult to transform it into ice and incorporate it into a positive balance of glacier ice).

 doi:10.20944/preprints202212.0113.v1

Author Contributions: Conceptualization, methodology, writing original draft, review and editing, supervision, LCP; collected data, GFJ; data curation, GFJ, investigation, LCP, GFJ, JAC, JDVM; analyzed and interpreted results, LCP, GFJ. All authors have readand agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable" here.

Acknowledgments: We are grateful for the support of the Board the "Natural Monuments of the Pyrenean Glaciers", the drive and fundamental participation of Fernando Lampre-Vitaller in the "Infierno Glacier" project since its inception in 1998, the collaboration of Carlos Martín since 2020 with his images captured from drones, the attention and information of the guards of the *Casa de Piedra* and *Bachimaña* refuges, the help of friends who have accompanied us on many of our climbs to the glacier.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ramond, L.F. Voyages au Mont-Perdu et dans la partie adjacente des Hautes-Pyrénées. Belin, Paris, France, 1801. 392 p.
2. Mallada, L. Breve reseña geológica de la provincia de Huesca. An. Soc. Esp. Hist. Nat, 1875, IV, 169-232.
3. Mallada, L. Descripción física y geológica de la provincia de Huesca. Memorias de la Comisión del Mapa Geológico de España. Imprenta y Fundición de Manuel Tello. Madrid, Spain, 1878. 439 p.
4. Russell, H. Souvenirs d'un montagnard. 1ª ed.; Del Gave, Pau France, 1878. 416 p.
5. Russell, H. Souvenirs d'un montagnard. Vignancour, Pau, France, 1908. 738 p.
6. Schrader, F. Pyrénées. I. Courses et ascensions. Édouard Privat. Toulouse, France, 1936. 350 p.
7. Arenillas, M.; Martínez Costa, R.; Martínez de Pisón, E. El estado de los glaciares españoles en 1991. Ería, 1992, 28, 176-182. https://doi.org/10.17811/er.0.1992.176-182.
8. Arenillas, M.; Martínez de Pisón, E.; Martínez Costa, R.; Navarro, J. Los glaciares actuales y la nieve en el Pirineo español. In Las huellas glaciares de las montañas españolas Gómez Ortiz, A. Pérez Alberti, A. Eds.; Universidade de Santiago de Compostela, Santiago de Compostela, Spain; 1998. pp. 329-346.
9. Chueca, J.; Lampre-Vitaller, F. Los glaciares del Alto Aragón. Instituto de Estudios Altoaragoneses, Huesca, Spain, 1994. https://www.iea.es/documents/449827/510304/Los+glaciares+en+el+Altoarag%C3%B3n.pdf/be9c8cec-5ae2-5f1a-d259-d205e16cd79f?t=1565783407735
10. Martínez de Pisón, E.; Arenillas, M. Los glaciares actuales del Pirineo Español. In La nieve en el Pirineo Español. Ministerio de Obras Públicas y Urbanismo, Madrid, Spain, 1998. Pp. 29-98
11. Cancer-Pomar, L.; Lampre-Vitaller, F.; Ollero, A. Glaciares actuales del Pirineo español. Catálogo de masas y aproximación hidrológica. Treb. Soc. Cat. de Geogr, 2001, 52, 165–193. http://revistes.iec.cat/index.php/TSCG/article/view/37264/37247
12. Julián, A.; Chueca, J.; Peña, J.L.; López, I.; Lapeña, A. Dinámica de los glaciares del Pirineo aragonés: resultado de la campaña glaciológica del año 1999. Boletín Glaciológico Aragonés, 2001. 2, 13–36. https://www.cervantesvirtual.com/nd/ark:/59851/bmcht309
13. Biarge, F.; Chueca, J.; Julián, A. Los glaciares pirenaicos aragoneses. Evolución. Fotografías 1880–1999. Boletín Glaciológico Aragonés. 2002. Special number.
14. Mora, J.; Arenillas, M.; Cobos, G.; Navarro, J. Évolution récente des glaciers des Pyrénées espagnoles. La Houille Blanche, 2006, 3, 65–70. doi.org/10.1051/lhb:200603010
15. González Trueba, J.J.; Martín Moreno, R.; Serrano, E. Little Ice Age, glaciation and current glaciers in the Iberian Península. The Holocene, 2008, 18 (4)., 551–568. Doi.org/ 10.1177/0959683608089209
16. Lampre-Vitaller, F. Situación actual de los glaciares pirenaicos aragoneses. Patronato de los Monumentos Naturales de los Glaciares Pirenaicos, Zaragoza, Spain. (Unpublished report). 2016.
17. Rico, I.; Izagirre, E.; Serrano, E.; López-Moreno, J.I. Current glacier area in the Pyrenees: an updated assessment. 2016. Pirineos, 2017. 172, e029. doi.org/10.3989/Pirineos.2017.172004
18. Camins, J. Pirineos, glaciares desde el aire. Inventario y catalogación. 2017. Besa & Keops, Igualada, Spain, 2018; 96 pp.
19. García Ruiz, J.M.; López Moreno, J.I. Los glaciares cuaternarios y actuales: agentes de la evolución del relieve y ejemplos de los grandes cambios climáticos. In Del Pirineo al estudio de las montañas del mundo: 75 Aniversario del Instituto Pirenaico de Ecología; Lasanta Martínez, T., Pueyo, Y.; CSIC, Madrid, Spain. 2018, pp. 165-175.
20. Sánchez Miravalles, A.; Cortada Ibañez, U., Ratko Vasiljevic, R. Los glaciares pirenaicos. Tierra y Tecnología, 2020, 56, dx.doi.org/10.21028/asm.2020.12.03
21. René, P. Glaciers des Pyrénées. Le réchauffement climatique en images. Cairn Éditions, Pau, France, 2013. 167 p.
22. René, P. Le suivi des glaciers dans les Pyrénées françaises. La Météo, 2014, 85, 27–34. DOI: 10.4267/2042/53748.
23. René, P. Les glaciers des Pyrénées francaises: Cycle glaciaire 2015-16. Association Moraine, Luchon, France, 2016.

24. Rico, I.; Izagirre, E.; Serrano, E.; López-Moreno, J.I. Current glacier area in the Pyrenees: an updated assessment 2016. Pirineos, 2017, 172: e029. doi.org/10.3989/Pirineos.2017.172004
25. Vidaller, I.; Revuelto, J.; Izaguirre, E.; Alonso González, A.; Gascoin, S.; René, P.; Berthier, E.; Rojas, F.; Rico Lozano, I.; Moreno, A.; López Moreno, J.A. La respuesta heterogénea de los glaciares pirenaicos entre 2011 y 2020. Geotemas, 2021, 18, 1038. https://sge.usal.es/archivos/GEO_TEMAS/Geo_temas18.pdf
26. Francou, B., Vincent, C. Les glaciers à l'épreuve du climat. IRD Éditions et Belin, Paris, 2007. 274 p. DOI : 10.4000/books.irdeditions.9972
27. Gardent, M. Inventaire et retrait des glaciers dans les Alpes françaises depuis la fin du Petit Âge Glaciaire. Thèse de doctorat, Université de Grenoble, Grenoble, France, 2014. 443 p.
28. Schoeneich, P. Tournée IGS-SAO 2016. La Bérade-vallée du Vénéon. 25–28 août 2016. International Glaciological Society, Section des Alpes Occidentales. Internal paper. 2016.
29. Vincent, C.; Peyaud, V.; Laarman, O.; Six, D.; Gilbert, A.; Gillet-Chaulet, F.; Berthier, E.; Morin, S.; Verfaillie, D.; Rabatel, A.; Jourdain, B.; Bolibar, J. Déclin des deux plus grands glaciers des Alpes françaises au cours du XXIe siècle: Argentière et Mer de Glace. La Météo., 2019, 106, 49-58. DOI: 10.4267/2042/70369
30. Smiraglia, C.; Diolauti, G. Eds. Il nuovo catastro dei Ghiacciai Italiani. Università degli Studi di Milano, 2016, Milano, Italy
31. Diolaiuti, A.G; Azzoni, R.S; D'Agata, C; Maragno, D.; Fugazza, D.; Vagliasindi, M.; Mortara, G.; Perotti, L.; Bondesan. A; Carton. A.; Pecci, M.; Dinale, R.; Trenti, A.; Christian, C.; Colucci. R.R.; Cagnati, A.; Crepaz, A.; Smiraglia, C. Present extent, features and regional distribution of Italian glaciers. La Houille Blanche, 2019, 5-6, 159–175. https://doi.org/10.1051/lhb/2019035
32. Serrano, E. Geomorfología del Alto Gállego. Pirineo Aragonés. Institución Fernando el Católico, Zaragoza, Spain, 1984. 501 p.
33. Serrano, E. Glacial evolution of the Upper Gállego valley (Panticosa mountains and ribera de Biescas, Aragonese Pyrenees, Spain). Pirineos, 1991, 138, 83–78. DOI: https://doi.org/10.3989/pirineos.1991.v138.191
34. Cuchí, J.A.; Cancer-Pomar, L.; del Valle-Melendo, J.; Lampre-Vitaller, F.; Fernández-Jarne, G. Evolución reciente del glaciar del Infierno (Panticosa, Huesca). Lucas Mallada, 2017, 19, 323-340. https://revistas.iea.es/index.php/LUMALL/article/view/2694
35. Cancer-Pomar, L.; Cuchí, J.A.; Lampre-Vitaller, F.; del Valle-Melendo; J., Fernández-Jarne, G. Observations glaciologiques (1998–2015) sur le glacier d'Infierno (Pyrénées, Espagne). La Houille Blanche, 2020, 1, 84–91. doi.org/10.1051/lhb/2019060.
36. Lampre-Vitaller, F. Clima de alta montaña y sistemas morfoclimáticos fríos en el macizo de La Maladeta (PirineoAragonés). Treballs de la Societat Catalana de Geografía, 2001, 52, 195–231. http://revistes.iec.cat/index.php/TSCG/article/view/37263/37246
37. Cancer-Pomar, L.; Lampre-Vitaller, F.; del Valle-Melendo, J. Análisis de los primeros datos de la estación meteorológica del Aneto (3.050 m, macizo de la Maladeta, Pirineo aragonés). Su interés glaciológico. In Clima, sociedad y medio ambiente; Cuadrat, J.M. et al. Eds.; Asociación Española de Climatología, Madrid, Spain, 2006; pp.541–551.
38. Del Valle-Melendo, J.; Cancer-Pomar, L. Análisis de los datos climáticos de la estación del Aneto (Pirineo aragonés, 3050 m) durante el verano de 2009. Proceedings Congreso Nacional de Medio Ambiente, Madrid., Spain, 2012. DVD.
39. Del Valle-Melendo, J. La precipitación media anual en el sector alto de la cuenca del Cinca (Pirineo aragonés, España). Pirineos, 1997, 149–150, 121–144. DOI: https://doi.org/10.3989/pirineos.1997.v149-150.130.
40. Östrem, G. Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges. Geogr. Ann., 1959, 41, 228–230.
41. Mattson, L. (1993). Ablation on Debris Covered Glaciers: an Example from the Rakhiot Glacier, Punjab, Himalaya. Proc. Int. Assoc. Hydrol. Sci., 1993, 218, 289–296.
42. Nicholson, L.: Benn, D. I. Properties of Natural Supraglacial Debris in Relation to Modelling Sub-debris Ice Ablation. Earth Surf. Process. Landforms, 2013, 38, 490–501. Doi: 10.1002/esp.3299. https://doi.org/10.1002/esp.3299.
43. Evatt, G. W.; Abrahams, I. D.; Heil, M.; Mayer, C.; Kingslake, J.; Mitchell, S.L.; Fowler, A.C.; Clark, C. D. Glacial melt under a porous debris layer. J. Glaciol. 2015, 61, 825–836. doi: 10.3189/2015JoG14J235
44. Herreid S. What can thermal imagery tell us about glacier melt below rock debris? Front. Earth Sci. 2021, 9, 681059. doi: 10.3389/feart.2021.681059
45. Anderson, L.S.; Armstrong, W.H.; Anderson, R. S; Scherler, D; Petersen, E. The Causes of debris-covered glacier thinning: Evidence for the importance of ice dynamics from Kennicott glacier, Alaska. Front. Earth Sci. 2021, 9, 680995. doi: 10.3389/feart.2021.680995
46. Lampre-Vitaller, F. Monumento Natural de los Glaciares Pirenaicos. Colección Espacios Naturales Protegidos. Gobierno de Aragón, Departamento de Agricultura y Medio Ambiente. Zaragoza, Spain, 2003.
47. AEMET. Resúmenes climatológicos. España. Gobierno de España, Ministerio para la Transición Ecológica y el Reto Demográfico. Agencia Estatal de Meteorología. Web site http://www.aemet.es/es/serviciosclimaticos/vigilancia_clima/resumenes: (Accessed on September-November, 2022).
48. AEMET. Resúmenes climatológicos. Aragón. Gobierno de España, Ministerio para la Transición Ecológica y el Reto Demográfico. Agencia Estatal de Meteorología. Web site:http://www.aemet.es/es/serviciosclimaticos/vigilancia_clima/resumenes?w=1&k=arn (Accesed on September-November, 2022).
49. CHE-SAIH. Evolución de la nieve acumulada en la cuenca del Alto Gállego. Gobierno de España, Ministerio para la Transición Ecológica y el Reto Demográfico. Confederación Hidrográfica del Ebro-Sistema Automático de Información Hidrológica. Web site: http://oph.chebro.es (Accesed on September-November, 2022).

50. AEMET. Datos diarios de acumulación nival. Refugios de montaña pirenaicos. Gobierno de España, Ministerio para la Transición Ecológica y el Reto Demográfico. Agencia Estatal de Meteorología. Internal report. 2022.
51. Bonsoms, J.; López-Moreno, J.I.; González, S.; Oliva, M. Increase of the energy available for snow ablation in the Pyrenees (1959–2020) and its relation to atmospheric circulation. Atm. Res., 2022, 106228. doi.org/10.1016/j.atmosres.2022.
52. López-Moreno, JI. Recent variations of snowpack depth in the Central Spanish Pyrenees. Arct. Antarct. Alp Res., 2005. 37 (2), 253-260. doi.org/10.1657/1523-0430/2005)/037[0253:RVOSDIJ2.0.CO;2
53. Añel, J.A.; López-Moreno, J.I.; Otto, F,E.; Vicente Serrano, S.M.; Schaller, N.: Massey, N.; Buisán, S.; Allen, M.R. The extreme snow accumulation in the western Spanish Pyrenees during winter and spring 2013. Bull. Am. Meteorol. Soc, 2014, 95 (9), Special supl. S73-S76
54. Buisán, S.T.; López-Moreno, J.; Saz, M.A.; Kochendorfer, J. Impact of weather type variability on winter precipitation, temperature and annual snowpack in the Spanish Pyrenees. Clim. Res., 2016, 69 (1), 79-92. doi: 10.3354/cr01391
55. Navarro, F.; López-Moreno, J.L. Spatio-temporal analysis of snowfall events in the Spanish Pyrenees and their relationship to atmospheric circulation. Cuad. inv. Geográf., 2017, 43 (1), 233-254. doi.org/10.18172/cig.3042
56. López-Moreno, J.I.; Soubeyroux, J.M.; Gascoin, S.; Alonso-Gonzalez, E.; Durán-Gómez, N.; Lafaysse, M.; Vernay, M.; Carmagnola, C.; Morin, S. Long-term trends (1958–2017) in snow cover duration and depth in the Pyrenees. Int. J. Climatol, 2020, 40 (14), 6122-6136. doi.org/10.1002/joc.6571
57. CHE. Determinación del balance anual de masa y movimiento del hielo en el glaciar de la Maladeta. Año hidrológico 2014–2015. Gobierno de España, Ministerio de Agricultura, Alimentación y Medio Ambiente. Confederación Hidrográfica del Ebro, 59 p. (Internal report. Informe Técnico del Programa ERHIN: Evaluación de los Recursos Hídricos procedentes de la Innivación). 2015.