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THE PYRENEES WITHOUT GLACIERS?

The disappearance of the La Paúl Glacier at the Posets massif

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The La Paúl Glacier, located in the central Pyrenees, developed during the Little Ice Age. Historical documents, orthophotographs, the application of geomatic techniques and ground penetrating radar sounding have since then made it possible to monitor the glacier and reconstruct its evolution. In the 19th century, it began to lose mass and became an ice patch. Glacier mass loss occurred throughout the 20th century, but it accelerated in the 1990s due to anthropogenic climate change. The ablation rate further increased in the 21st century. From 2013 onwards, a series of warm summers and processes of ice collapse caused the glacier to disappear, leaving behind relict ice.

Keywords: **glaciers**, **glaciology**, **extinction**, **climate change**, **Pyrenees**.

THE DECLINE OF GLACIERS

The Earth's glaciers have been retreating and thinning at different rates in all the world's mountains since the late 19th century. Since the 1990s, the loss of the cryosphere has increased and the disappearance of glaciers has accelerated. Mountain deglaciation is attributed to anthropogenic causes, such as rising temperatures above certain thermal thresholds and ice ablation (Marzeion et al., 2014).

Deglaciation accelerates due to a succession of warm summers that melt the winter snows and prevent ice from accumulating. As glaciers retreat, a new environment is created, called a *paraglacial environment*. It is characterised by intense processes that transform the environment and new ecosystems that replace glacial environments. Temperate mountains are very sensitive to climatic and environmental changes, and their glaciers respond quickly to temperature rises and changes in precipitation.

«Temperate mountains are very sensitive to climatic and environmental changes, and their glaciers respond quickly to temperature rises»

In the Iberian Peninsula the only glaciers are the Pyrenees, a legacy of the Holocene and, most especially, of the Little Ice Age, a brief cooling by 1 °C between the 14th and mid-19th centuries that led to important changes all over the planet and whose main repercussion was the generation of new glaciers and the growth of existing ones in most places on Earth. Since 1890, the increase in temperature in the Pyrenees has been greater than 0.9 °C and several estimates point to the disappearance of glaciers by 2050. During the Little Ice Age (according to

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measurements made in 1884 by the French pyreneiste, geographer, and mountaineer Franz Schrader) the Pyrenean glaciers occupied more than 3,300 ha. However, approximately 88% of their extension has been lost since then and in 2023, they only occupied 143.2 ha, distributed among 15 glaciers (Izagirre, Revuelto et al., 2024). In recent years, the process has accelerated; in 2020 there were still 23 glaciers occupying 238 ha, but in 2022 only 18, occupying 172.6 ha, were inventoried, and in 2023, only 15 glaciers remained, occupying 143.2 ha. In other words, in three years, eight ice masses ceased to be glaciers and those with an area of less than 10 ha are in a critical situation. At present, most of them persist due to topoclimatic conditions, such as low solar radiation originating from the protection of the surrounding mountain walls, their northern orientation, snow feeding due to avalanches and clast coverings (after landslides), and water streams that favour ice protection (Izagirre, Palacios et al., 2024; Izagirre, Revuelto et al., 2024; Rico et al., 2017; Serrano, 2022; Vidaller et al., 2021).

Following the disappearance of the glaciers, only their morphological remains, such as moraines, polished rocks, and lake basins, can still be found. While these features are highly visible and have significant educational value, they also bear the cultural imprint of mountaineers, naturalists, cartographers, and artists, which endures over time. In the following section, we will analyse one of these disappearances.

THE LA PAÚL GLACIER AND ITS DISAPPEARANCE

The La Paúl Glacier was located on the northwest slope of the Posets or Llardana peak (3,360 m above sea level, 42° 39’N, 0° 36’E) in the Posets massif (Huesca Pyrenees). The glacier was born and grew during the Little Ice Age in a glacial cirque surrounded by steep 300-metre-high walls. It was located in a valley surrounded by peaks, where a granite batholith met a metamorphic halo formed from Palaeozoic shales and schists at the summit and along the main ridges. The relief is the result of the tectonic processes of the axial zone of the Pyrenees and the subsequent action of the Quaternary glaciers that occupied the High Pyrenees until approximately 12,000 years ago.

During the Little Ice Age, the Posets massif was home to three glaciers: the first to disappear was the Posets Glacier, sometime in the 1980s, then the La Paúl Glacier. Today there is only one small glacier left, the Llardana, on the western slope. The present-day ice patches, the remains of the Posets and Paúl glaciers, are all that is left from the last historic glaciation.

When the ice disappears, a *paraglacial* environment is generated, characterised by the erosion of proglacial lakes and appearance of snowmelt waters, the action of cold on the substrate and the relaxation of stresses due to the disappearance of the ice. All this leads to increased slope instability and hydrological changes with ecological consequences and indirect impacts such as the extinction of extremophile species, colonisation by new species, and variations in the ecosystem services of high mountains.

The first protection for the glacier was the enactment of Law 2/1990 on the declaration of the Pyrenean glaciers as Natural Monuments, followed by the declaration of the Natural Park of Posets–Maladeta in 1994. In 2002, Decree 271/2002 of the Government of Aragon extended the protected area to the space occupied during the Little Ice Age; the Natural Monument Protection Plan (PRUG) was also approved, and Decree 216/2007 finally inventoried the La Paúl Glacier as such. Its heritage designation did not come in time, as the loss of the glacier was already irreversible in terms of its natural significance (Serrano, 2023).

«Several estimates point to the disappearance of glaciers by 2050»

THE STUDY OF THE LA PAÚL GLACIER

The evolution of the La Paúl Glacier can be reconstructed, from the end of the Little Ice Age to its extinction, using historical sources, existing aerial photographs (available from 1957), orthophotographs, recent geomorphological and glaciological studies, and the application of techniques from geophysics and geomatics.

The lack of information on La Paúl, absent from the works of Schrader in 1884 to those of the ERHIN programme in the 1980s (Martínez de Pisón & Arenillas, 1988), has been complemented with geomorphological data and historical documentary records (photographs taken prior to the first studies, accounts by Pyrenees climbers, and written documents). This method is common in the Alps, where we have extensive documentation which has proven both useful and accurate (Zumbühl et al., 2008) for understanding glaciers since the Little Ice Age.

Digital elevation models (DEM) have been used to calculate and reconstruct the state of the glacier in different phases, as well as its surface. These models were created using existing orthophotographs and data obtained through novel techniques such as terrestrial

Figure 1. Images showing the evolution of the La Paúl Glacier between 1910 and 2021. The loss of surface area accelerated in the 1990s.

Year	1910	1935	1956	1983	1994	1997	2002	2006	2013
Area (ha)	19.8	19.5	13.4	12.9	12	10.3	8	7.5	6.7

Table 1. Evolution of the extension of the La Paúl Glacier during the 20th century and the first years of the 21st century.

laser scanning, georadar, and drone flights. The techniques applied on the La Paúl Glacier have also evolved alongside technological advances, allowing for greater accuracy and ease in collecting field data, as well as greater precision in measuring annual changes.

At the La Paúl Glacier, measurements have been taken for 14 years without interruption, which has made it possible to produce digital elevation models and to reconstruct the different phases of the glacier's retreat, as well as its surface. The studies began by using global positioning systems (GPS) with three objectives: to delimit the outline of the glacier (using Global Navigation Satellite System–Real-Time Kinematic techniques); to support the data from the total station with laser scanner (TLS) information, and to give precise points on the vertical photos obtained with aerial photogrammetry with an unmanned aerial vehicle (AP-UAV). The total station equipped with a laser scanner provided digital elevation models from 2009 to 2020, and the drone has been used for the last four years, facilitating the acquisition of orthophotographs. All measurements were taken with centimetre accuracy using GPS. By comparing digital elevation models, we can gain insight into changes in the glacier surface and relief, obtain ice profiles, and calculate ice thinning and surface loss. Finally, in 2010 and 2017, vertical profiles were created using ground penetrating radar (GPR) to determine the internal structure of the glacier and the thickness of its ice. Comparing the profiles shows the changes in ice thickness in the different years.

DEGLACIATION AND DISAPPEARANCE OF THE GLACIER BY 2022

The Paúl Valley was covered in ice during the glacial maximum of the Pleistocene, which fed the large glaciers of the Last Glacial Maximum over 20,000 years ago, and again by smaller glaciers in the cirques around 14,000–12,000 years ago, during the so-called Younger Dryas. Subsequently, the glaciers disappeared. During the Little Ice Age, a new glacier occupied the cirque and reached a maximum area of 32 ha in the 18th century. Franz Schrader mapped the Posets and La Paúl glaciers together in the 19th century, but we now know that they were two separate glaciers. A period of glacial equilibrium in which the glacier measured 23.5 ha, generated the bulky internal frontal moraines in the 19th century.

Existing images show the glacier retreat between the early 20th century and 2021 (Table 1; Figure 1). During the early decades of the 20th century, the glacier's snout was bulging, and numerous crevasses were visible on its surface. It was a very stable glacier that retreated only slightly and lost less than one hectare in area. In this period, it was difficult to calculate the loss of thickness. The decline in surface area accelerated from the late 1990s, when it lost 4.5 ha in 10 years and became significantly thinner (Figure 1). In 2001, the glacier had a bevelled snout and a debris cover already showing signs of degradation, but it still retained traction crevasses, which are indicators of its activity (Serrano et al., 2002).

The accelerated loss of ice thickness coincided with exceptionally hot summers and low winter precipitation, as evidenced by data from 2010 and 2011, which recorded average losses of –128 cm and –146 cm, respectively. Although between 2008 and 2016 the decrease in area was moderate at 0.12 ha a^{-1} (Rico et al., 2018), the thickness experienced a sharp decrease between 2010 and 2017, losing –100/150 cm in the upper section and –150/300 cm in the lower one, with an average loss of –17.5 cm a^{-1}. In 2018, the maximum ice thickness was 13 m in the upper section and 3 m in the lower section. Thinning was consistently greater in the lower areas of the glacier, with cumulative thickness losses of up to 350 cm between 2010 and 2017. In contrast, the upper areas experienced losses of about 250 cm during the same period. The mean annual thickness loss along the glacier centreline was 50 cm a^{-1} in the lower areas and 35.7 cm a^{-1} in the upper areas (Figure 2). With a thickness of less than 10 m in 2010 and the rates indicated above, the glacier would have disappeared in 20 years, but it actually disappeared only 12 years later, which points to an increase in annual melting between 2017 and 2022.

From 2013 onwards, rapid thinning, retreat, and void formation began. In the upper section, the bedrock became exposed and the glacier divided into two separate fragments: to the east, a mass of ice showing no flow and a snout between 2,990 and 3,020 m, and to the west, a tiny glacier with tensional crevasses and a snout at 2,890 m. This process creates voids within the ice and rapid retreats due to the collapse of those voids.

In 2021 and 2022 the western body became compartmentalised. The cracks disappeared and there was no longer any movement due to internal deformation (Figure 3). It transformed into an ice patch, a mass of ice of glacial origin broken into small blocks that disappeared over the following two summers.

In 2022, the glacier no longer existed and the ice patch was fractured into small relict ice lenses, which no longer functioned as accumulation areas and were disconnected from the upper sections. The glacier had disappeared, although rapidly disappearing ice patches remained attached to the slopes.

CLIMATE CHANGE AND THE ACCELERATION OF THESE PROCESSES

The La Paúl Glacier has been retreating since the end of the Little Ice Age, with moderate losses in thickness and surface area associated with climate warming. However, it was in the 20th century that the gradual increase in temperature affected the behaviour of the ice, accelerating the loss of mass until the glacier disappeared completely (Table 2; Figures 4 and 5). In the decades of the 1910s and 1920s, there was a moderate thermal rise that implied a small reduction in the glacier area and a limited retreat of the snout. This thermal increase continued in the 1940s and 1950s, but the glacier responded with a decrease in surface area, and its snout was lodged at the upper threshold of the cirque. Between the 1960s and the 1980s, the Iberian Peninsula experienced 25 years (1965–1986) of negative thermal anomalies with values ranging from –0.5 °C to –1.5 °C (Domínguez et al., 2024). This period brought a glacial equilibrium that kept the surface stable, although there could have been a loss of thickness not supported by available data. At that time, the glacier appeared to be in equilibrium with the local climatic conditions.

Between 1986 and 1998 there were irregular years with alternating positive and negative anomalies. The latter were predominant, always within moderate

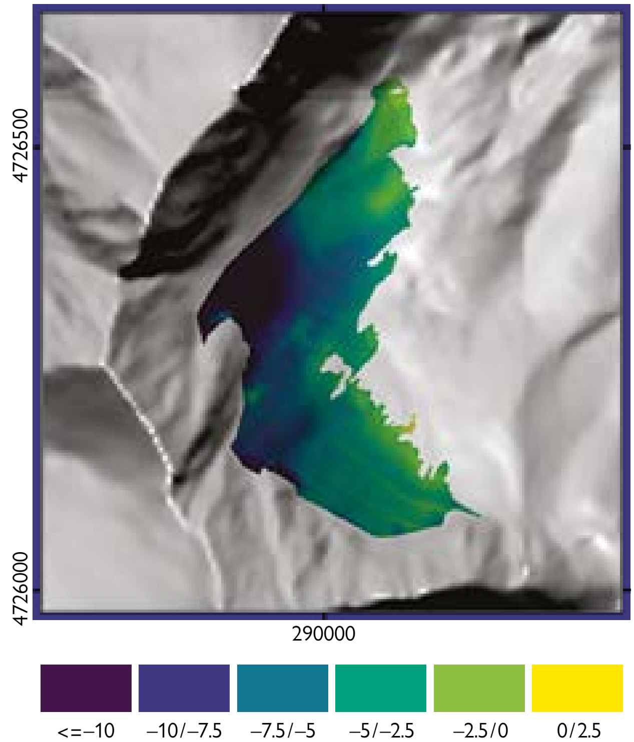

Figure 2. Glacier thinning between 2010 and 2017. Figures are provided in metres.

«The accelerated loss of ice thickness coincided with exceptionally hot summers and low winter precipitation, as evidenced by data from 2010 and 2011»

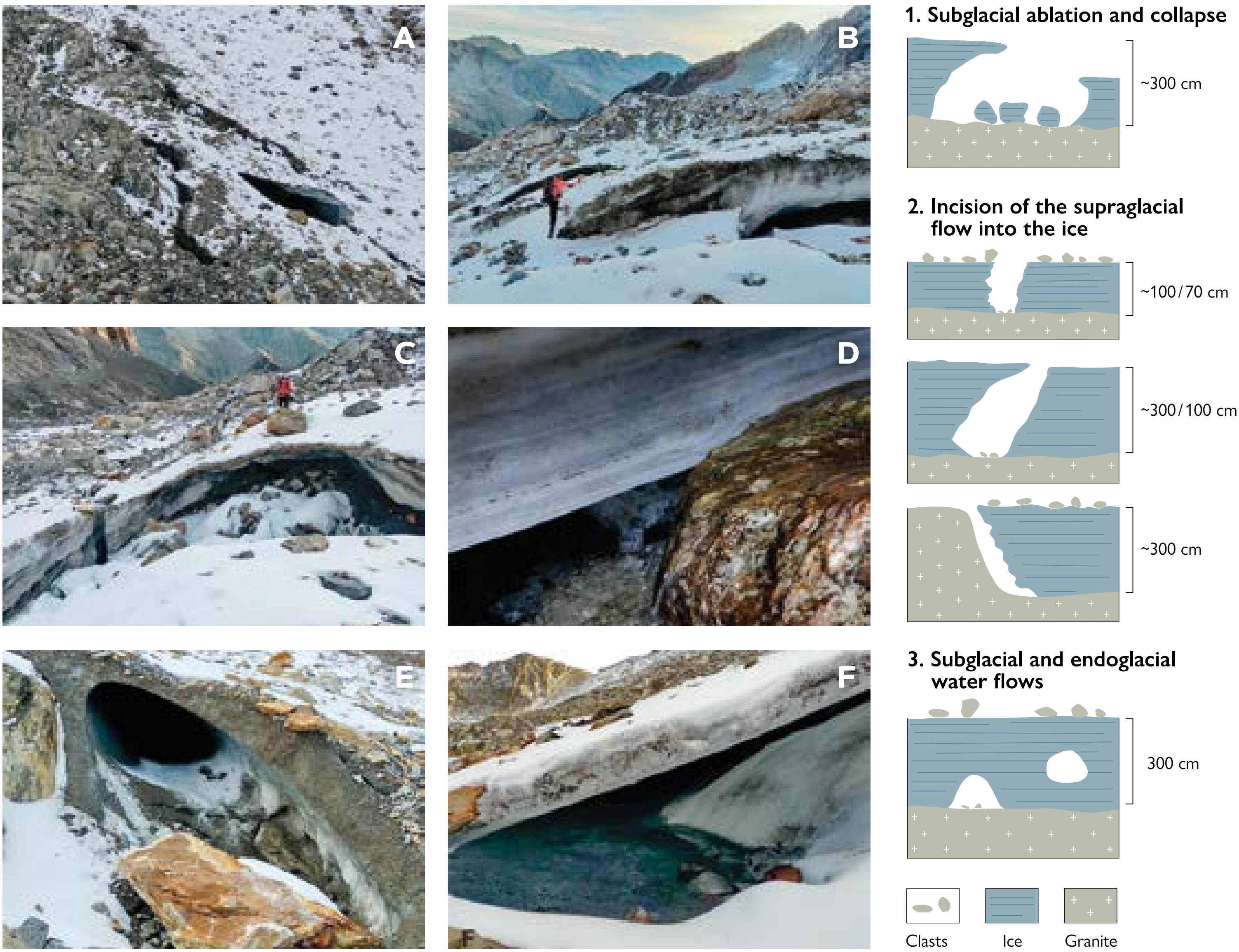

Figure 3. Ablation and fracture processes in the final stage of the glacier decline: **A**) Cracking and collapse, 2023. **B**) and **C**) Detail of the collapse and incision to the bedrock, 2023. **D**) Subglacial void formation with ice flow, 2018. **E**) Englacial conduits, 2023. **F**) Subglacial void formation with no ice flow.

«At the La Paúl Glacier, measurements have been taken for 14 years, which has made it possible to reconstruct the different phases of the glacier's retreat»

values. During this stage the glacier lost thickness and the surface decline accelerated (Rico et al. 2016; Serrano et al. 2002). It also responded to topoclimatic conditions to a greater extent than to climatic conditions, and the thinning exceeded the loss of surface area until the late 1990s.

In the 21st century, temperatures increased and there were warmer summers. The glacier, however, adapted to the topoclimatic conditions and maintained a constant and moderate loss of surface area. Nevertheless, thinning was still high during the first decades of the 21st century (Figure 6). The glacier lost an average thickness of 50 cm between 2009 and 2010,

Phase		Period	Processes
1	Glacier maximum	Little Ice Age (17th–early 18th century)	Maximum historical extent. Outer frontal moraines.
2	Secondary advance	19th century	Short, fast advance.
3	Glacier retreat	Late 19th century–1910	Loss of 26.3 % of its surface area.
4	Glacier balance	1910–1930s	Stable front, losing 1.2 % of its surface area.
5	Continuous retreat	1935–1960s	Loss of 31.5 % of its surface area.
6	Slow retreat	1960s, 1970s, and 1980s	Moderate volume loss, surface reduction by 3.1 %.
7	Drastic retreat	Late 1980s–2013	Loss of mass and surface area by 60.8 %.
8	Collapse	2013–2020	Thinning, retreat, and void formation.
9	Transformation into ice patches	2021–2022	Compartmentalisation and lack of movement.

Table 2. Dynamic phases of the La Paúl Glacier.

and of 143 cm between 2010 and 2011 – almost two metres in two years, a very rapid thinning. Between 2008 and 2016, it lost around 0.12 ha a^{-1}, more than in any previous period.

Starting in 2013, the ice mass presented only a few small cracks at the top. It was already below the regional glacier equilibrium line altitude (ELA = 3,075 m) and conditions were very unfavourable for accumulation. During this time, the dynamics of the glacier were primarily influenced by topographic factors, which were crucial for explaining its continued existence. From 2014 onwards, there was an increase in temperatures, with nine years of positive anomalies and values greater than 0.5 °C, mostly between 1 °C and 1.5 °C. This rapid thermal increase in successive hot summers with strong heat waves in the Pyrenees accelerated the loss of surface area and thinning. The topoclimatic conditions were insufficient to preserve the ice, and the warm air masses in summer resulted in high ablation rates. Given the small volume of ice, this led to a rapid loss of ice.

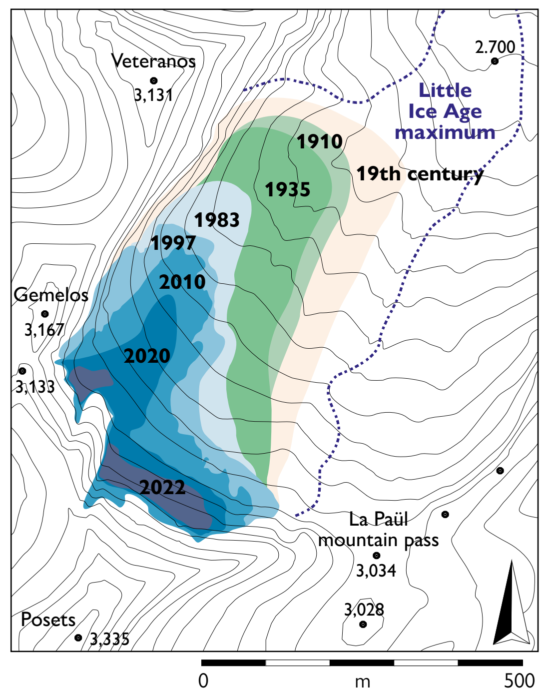

Figure 4. Reconstruction of the evolution of the glacier surface from the Little Ice Age to 2022.

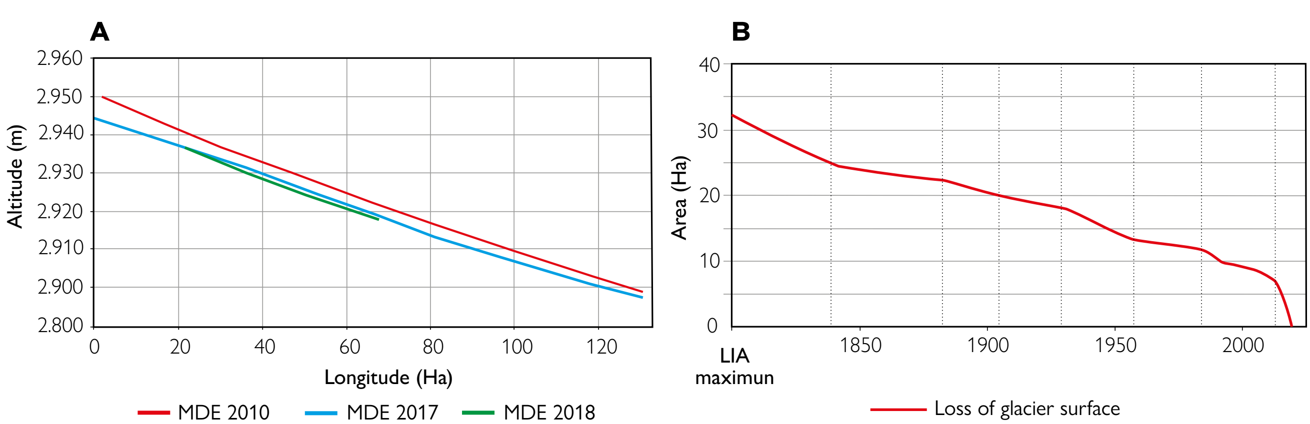

Figure 5. **A**) Thinning between 2010, 2017, and 2018, from digital elevation model (DEM) data. **B**) Loss of surface area of the La Paúl Glacier from its Little Ice Age (LIA) maximum to the present. This loss of surface area is particularly clear in the 20th century.

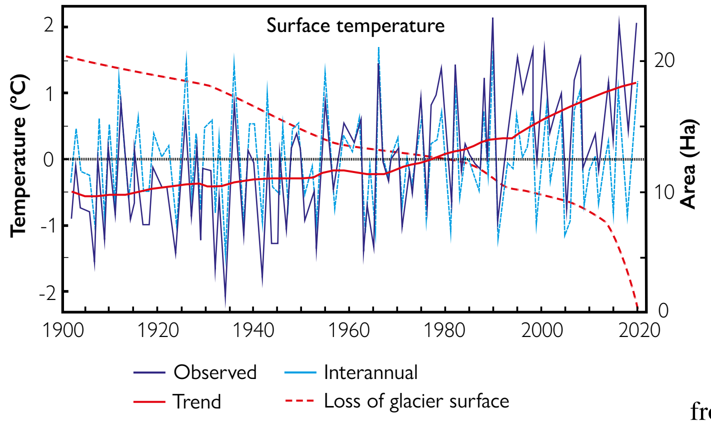

Figure 6. Relationship between thermal anomalies (Domínguez et al., 2024) and the loss of surface area of the La Paúl Glacier. The thinning of the glacier was very marked in the first decades of the 21st century.

«It was in the 20th century that the gradual increase in temperature accelerated the loss of mass until the La Paúl Glacier disappeared completely»

In 2016, the period of collapse began, due to lack of accumulation and predominance of ablation, and the equilibrium line altitude remained above the upper limit of the glacier for nine years. From this point onwards, ablation processes dominated and deformation was attenuated. Runoff, whether supraglacial, endoglacial, or subglacial, became the dominant active process. All of this resulted in glacier stagnation due to mass loss, the formation of subglacial voids, ice calving, and ultimately, the disappearance of the glacier within five years. It was transformed into two small ice patches attached to the northern faces, which have steep slopes and receive almost no sunshine. These patches still persist thanks to topoclimatic conditions (Figure 7).

A CIRQUE AND THE PYRENEES WITHOUT GLACIERS

The evolution and disappearance of the La Paúl Glacier shows how quickly they respond to climatic variations and highlights the importance of Pyrenean glaciers as very sensitive geo-indicators of global change.

Environmental conditions on the La Paúl Glacier have worsened discontinuously since the end of the Little Ice Age. Geomorphological evidence and historical photographs allow us to reconstruct its evolution until the middle of the 20th century. From this date onwards, aerial photography, satellite images, previous glaciological studies, and the application of techniques from geomatics and geophysics allowed us to establish nine stages of glacial retreat until it finally became extinct. These stages are characterised by alternating periods of stability and retreat and, starting with the 21st century, an accelerated retreat clearly driven by climate change.

Terrestrial laser scanner and ground penetrating radar measurements showed a glacier suffering from rapid mass loss, accelerated thinning, and stagnation, which survived until the second decade of the 21st century thanks to topoclimatic conditions. When the topoclimatic conditions were no longer a sufficiently strong influence because of rising summer temperatures, the system collapsed and the glacier rapidly disappeared.

The study of the disappearance of the La Paúl Glacier shows how rapidly the glacier responded to climatic conditions. Processes accelerated in response to successive warm summers that generated a loss of mass that could not be reversed, due to the momentum derived from the lack of snow supply, and despite the

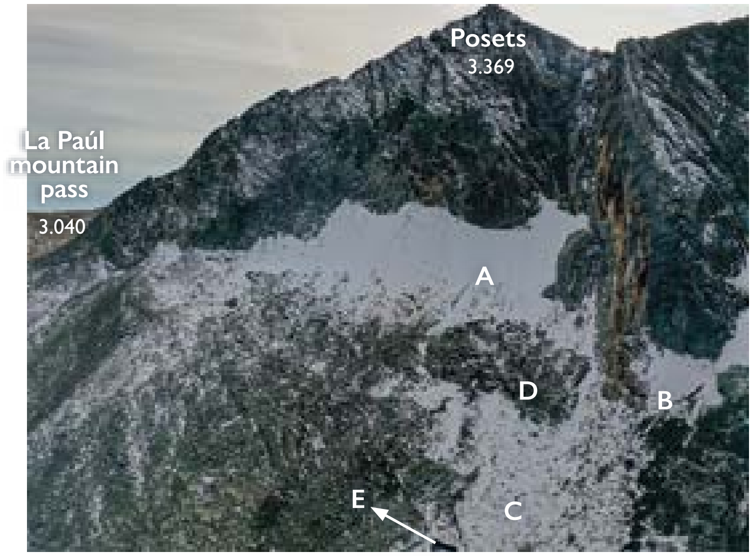

Figure 7. La Paúl ice patch in 2023 (it lost its glacier status in 2022). **A**) Eastern ice patch. **B**) Western ice patch. **C**) Residual ice. **D**) Rocky threshold. **E**) Ice collapse.

«The disappearance of the La Paúl Glacier highlights the importance of Pyrenean glaciers as very sensitive geo-indicators of global change»

fact that some years recorded positive anomalies. All this ultimately led to a rapid disappearance.

The rapid decline of the glacier occurred when it became disconnected from the climatic conditions, first in general and then also from topoclimatic conditions. When this occurred, the glacier collapsed following a number of internal processes that anticipated the immediate end: cracking unrelated to ice movement; void formation at the snout and middle section (which, on steep glaciers, can lead to dangerous natural hazards); stagnation and lack of tensile crevasses; and surface meltwater runoff incising to the glacier bedrock.

The study of the La Paúl Glacier shows that small glaciers respond first to retreat and thinning processes (climatic period), then to thinning with moderate surface loss (topoclimatic period), and finally to rapid disappearance processes. In La Paúl, this process was faster than initially estimated from the loss of mass (both in surface area and in depth), and the collapse and disappearance came earlier than expected.

Based on calculations from the 1990s and 2000s, current models estimate that the last alpine glaciers in the Pyrenees will disappear by around 2050. However, specific cases such as La Paúl, as well as the accelerated pace of glaciological processes, suggest their loss could occur decades earlier (during the 2020s–2030s). The Pyrenees would thus end up completely free of glaciers. This has been the case in previous periods, but the current process of deglaciation is very rapid and will have repercussions for high mountain ecosystems.

The disappearance of glaciers leads to hydrological changes and the replacement of ecosystems. This causes species that depend on glacial environments to disappear, while new environments emerge, characterised by paraglacial (associated with slope instability and torrential dynamics) and periglacial (associated with changes in the state of water in the soil) processes. However, traces of both their physical presence – the glacial morphology of the Little Ice Age – and their cultural impact will remain, proof and legacy of the relationship between humans and glaciers. ⊕

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