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I. Vidaller and J. Revuelto are both co-first authors.

Key Points:

- The glacierized area shrank by 23.2% and thickness decreased on average by 6.3 m during the 2011–2020 period
- There is no sign of slowdown in glacier shrinkage respect to previous decades
- The smaller Pyrenean glaciers are influenced by local topography as they show highly contrasted evolution under the same climatic conditions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Toward an Ice-Free Mountain Range: Demise of Pyrenean Glaciers During 2011–2020

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Abstract Pyrenean glaciers are the largest in southern Europe. Their survival is threatened by climate change, highlighting the significance of their study. This research presents an assessment of changes in the glacierized area and thickness of Pyrenean glaciers from 2011 to 2020, using high-resolution optical satellite, airborne lidar and UAV images. The total glacierized area has shrunk by 23.2% and thickness has decreased on average by 6.3 m. These two variables show no correlation for individual glaciers. Although climatic conditions do not vary much among glaciers, their evolution was heterogeneous during the study period. The smaller glaciers (<10 ha) show a higher variability in their area decrease and thickness loss whereas the four largest glaciers (>10 ha) have a more homogeneous response. This can be attributed to the generally larger influence of local topography on the response of the smaller Pyrenean glaciers. There is no sign of slowdown in glacier shrinkage respect to previous decades.

Plain Language Summary Pyrenean glaciers are the largest in southern Europe. Their survival is threatened by climate change, highlighting the significance and relevance of their study. This study presents an assessment of changes in the glacierized area and thickness of Pyrenean glaciers during 2011–2020 based on UAV, optical satellite imagery and lidar observations. In this period, their total area shrank by 23.2% and thickness decreased by 6.3 m on average. Although climatic conditions do not vary much among glaciers, their evolution was heterogeneous during the observed period. The smaller Pyrenean glaciers (area <10 ha) are highly controlled by local topography, whereas the largest glaciers are predominantly influenced by regional climate forcing. There is no sign of slowdown in shrinkage of Pyrenean glaciers respect to previous decades. This indicates the continuous decline of Pyrenean glaciers toward an ice-free mountain range in the coming decades.

1. Introduction

Glacier mass balance evolution depends on snow accumulation and snow, firn and ice melt during the cold and warm seasons respectively and is thus considered a reliable indicator of climate fluctuations (Braithwaite & Hughes, 2020). The Little Ice Age (LIA, between the 14th and 19th centuries) represents the last global advance phase for the majority of mountain glaciers around the world (Solomina et al., 2016). Since then, the decline of glaciers has been almost continuous, only interrupted by short stabilization periods (Zemp et al., 2015). Several studies identify the 1980s as a "tipping point in global glacier evolution," followed by accelerated glacier shrinkage (Beniston et al., 2018; Huss & Hock, 2018).

Very small glaciers (<0.5 km^2) predominate in number in the northern hemisphere mountain ranges at temperate latitudes, since more than 80% of glaciers in these mountains are beneath this area threshold (Huss & Fischer, 2016). Shrinkage of very small glaciers occurred more rapidly by the late 20th and early 21st centuries than in earlier decades (Bahr & Radić, 2012; Parkes & Marzeion, 2018). This fast shrinkage is explained by their generally low accumulation area ratio, which is mainly driven by the observed global temperature increase (Zemp et al., 2015). However, some of these very small glaciers, when constrained to the most elevated and sheltered areas, start to attenuate their response to regional climate evolution, and local topographic factors influence their mass balance, leading to the so-called topoclimatic control (Fischer, 2018; Florentine et al., 2018, 2020; Huss & Fischer, 2016). Under these circumstances a small fraction of very small glaciers still persist at relatively low elevation, often below the regional equilibrium-line altitude (ELA; Grunewald et al., 2006; Hughes & Woodward, 2009), demonstrating that they are decoupled from regional climate forcing (Fischer, 2018).

The southernmost glaciers in Europe are located in the Pyrenees, Apennines and Balkan Peninsula at latitudes between 41°N and 43°N and elevations between 2,000 and 3,300 m above sea level (a.s.l.) (Grunewald & Scheithauer, 2010) and can all be classified as very small glaciers as all of them are smaller than 0.5 km^2. Since the LIA maximum during the 19th century, these glaciers have lost 30%–100% of their volume (Hughes, 2018). In southern Europe, glaciers larger than 0.05 km^2 (5 ha) are only found in the Pyrenees. The Pyrenean glaciers are in extreme jeopardy and could disappear or become residual ice patches in about 20 years from now (López-Moreno, García-Ruiz et al., 2020). This kind of process has already been observed in other southern European mountain ranges (Carturan et al., 2013) or in tropical areas such as the Santa Isabel Mountains (Colombia) and the Puncak Jaya Mountains (Indonesia) where glacier extinction is imminent (Morán-Tejeda et al., 2018).

In the Pyrenees, temperature has increased by more than 1.5°C since the LIA (Cuadrat et al., 2018). For high-elevation areas, this warming has been especially marked during the summer and shoulder seasons (López-Moreno et al., 2019). Snow depth observations in the Spanish Pyrenees started in mid 1980s and exhibit a significant decline, especially in spring at elevations above 2,000 m a.s.l. (López-Moreno, 2005). Analyses of long-term (1958–2017) trends in snow cover duration and depth by López-Moreno, Soubeyroux et al. (2020) confirmed the significant decrease in snow depth especially at high elevation sites of the French and Spanish Pyrenees during spring time. These trends led to a marked area shrinkage of the Pyrenean glaciers, from 2,060 ha in 1,850 to 810.3 ha in 1984 (a loss of 60.7%) to 242.0 ha in 2016 (a loss of 88.3% compared to 1,850) and the number of glaciers has decreased accordingly, from 52 (in 1850) to 39 (1984) to 19 (2016) (according to Rico et al., 2017). The main question to be answered about the evolution of Pyrenean glaciers is whether they are still controlled by regional climatic conditions and still show accelerated shrinkage and wastage, or whether glacier changes are increasingly controlled by topographic factors that might attenuate their response to temperature increase. Whereas the latter behavior has been observed for glaciers in other Mediterranean regions (Hughes, 2018), the attempt to answer this question for the Pyrenees has been hampered by the scarcity of mass balance/volume estimations available to date, since there are only observations from Ossoue (René, 2014), Maladeta (Pastor-Argüello, 2013) and Monte Perdido (López-Moreno et al., 2019) glaciers for limited time periods.

In this study, we report and analyse glacier area, surface elevation and thickness changes for Pyrenean glaciers from 2011 to 2020. Glacier area changes have been determined for the 24 remaining Pyrenean glaciers in 2011 from high spatial resolution satellite imagery and field surveys. Additionally, glacier volume changes have been determined from 3D point clouds derived from close-range remote-sensing techniques for 17 of the 24 remaining glaciers. This data set contributes to identifying the most important driving factors of recent glacier evolution all along the Pyrenean mountain range and, hence, determining whether these glaciers are responding homogeneously to climatic changes or whether topographic factors are significantly affecting and influencing their response.

2. Data and Methods

2.1. Study Area

Glaciers in the Pyrenees are located only in the central and highest massifs. Glaciers of the *Infiernos, Monte Perdido, Posets* and *Maladeta* massifs are located in Spain, while glaciers in *Balaitous*, *Vignemale, Gavarnie*, *La Munia, Perdiguero* and *Mont Valier* massifs are in France (Figure S1). The estimated mean annual elevation of the 0°C isotherm ranges between 2,700 and 3,000 m a.s.l. (Jomelli et al., 2020). At the highest elevations, the mean annual precipitation exceeds 2,000 mm, winter and spring being the most humid seasons (Buisan et al., 2015).

2.2. Computation of Glacier Thickness Change

2.2.1. Acquisitions of Consecutive Glacier Surface Elevation Information

Glacier surface elevation data were obtained from different close-range remote-sensing devices. In 2011, glacier surface elevation information was acquired with airborne lidar, known to produce high-resolution input data for glacier surface elevation changes (Hopkinson & Demuth, 2006). Between October and November 2011 (October 17–21 for western parts of the study area and November 4–9 for eastern parts of the study area) the Spanish National Geographic Institute (IGN, last accessed May 2021: http://centrodedescargas.cnig.es/CentroDescargas/index.jsp) conducted several airborne lidar flights over the Pyrenees to generate a high spatial resolution Digital Elevation Model (DEM). The instrument used was a Leica ALS60, which has a diode-pumped transmitter and a large-aperture low-inertia/high-speed scan mirror working with a wavelength of 1,064 nm. The airborne lidar surveys generated point clouds with an average density of 0.5 pts/m^2.

In 2020, glacier surface elevation information was obtained with three different UAVs (according to the logistic requirements of the sites: two fixed-wing UAVs (*SenseFly eBee-Plus* and *eBee-X*) and a quad-copter UAV [*DJI Mavic Pro 2*]; Table S1) in several field campaigns between late August and early October. The fixed-wing UAVs are equipped with a *SenseFly* S.O.D.A. digital camera (20Mp resolution), with GPS receivers allowing RTK (Real Time Kinematic) or PPK (Post-Processed Kinematic) positioning systems (positioning accuracy <0.05 m). The quad-copter also has a camera of 20Mp resolution and a GPS with a positioning accuracy >5 m.

The overlaps of the UAV images (always higher than 70%), together with the ground sampling distance (GSD) of about 2.8 cm/px defined by the UAV flight elevation, allowed to generate dense 3D point clouds of the study areas using the Structure from Motion (SfM) algorithm (Forlani et al., 2018). The SfM software used to process all images and create the point clouds was *Pix4Dmapper (Pix4D)*. The images acquired and the Pix4D point cloud densification algorithms allowed generation of 3D point clouds with an average resolution of 4 pts/m^2.

The *Monte Perdido* glacier surface was surveyed in 2011 and 2020 (both in early October) with a long-range Terrestrial Laser Scanner (TLS). The device, a RIEGL LPM-321, uses lidar time-of-flight (at 905 nm wavelength) to generate a 3D point cloud (Revuelto et al., 2014). Details of the acquisition procedure and point cloud generation with this device can be found in López-Moreno et al. (2019).

2.2.2. Point Cloud Geolocation and Glacier Thickness Change Computation

The images obtained with the two fixed-wing UAVs allowed an accurate geolocation due to the RTK-PPK GPS options. By contrast, in the case of quad-copter UAVs, images were geolocated with the standard GPS geolocation error (~5 m), and thus the point clouds generated with this UAV had a lower 3D positional accuracy. These point clouds were co-registered with the airborne lidar point clouds in *Cloud Compare* (Girardeau-Montaut, 2016) to allow the later assessment of glacier surface elevation changes. First, several areas of stable terrain around the glaciers (at least seven ice-free patches covering all directions) with no expected changes in surface elevation during the study period (ridge, peaks, etc.,) were selected in both point clouds to align the UAV to the lidar point cloud. Afterward, these areas of stable terrain were used to compute a rotation and translation matrix with the iterative closest point algorithm (Rajendra et al., 2014). Finally, this matrix was applied to the entire point clouds of the quad-copters (see the Root Mean Squared Error (RMSE) values in Table S1).

Point clouds differences over glacierized areas (glacier thickness change) between 2011 and 2020 point clouds were obtained with the *M3C2* tool (James, 2017) of *Cloud Compare*. Then, these differences were rasterized for further analysis. Glacier surface elevation changes was calculated over the glacierized area existing in 2020. Readers are referred to the "Uncertainty of the changes observed" included in the Supporting Information S1.

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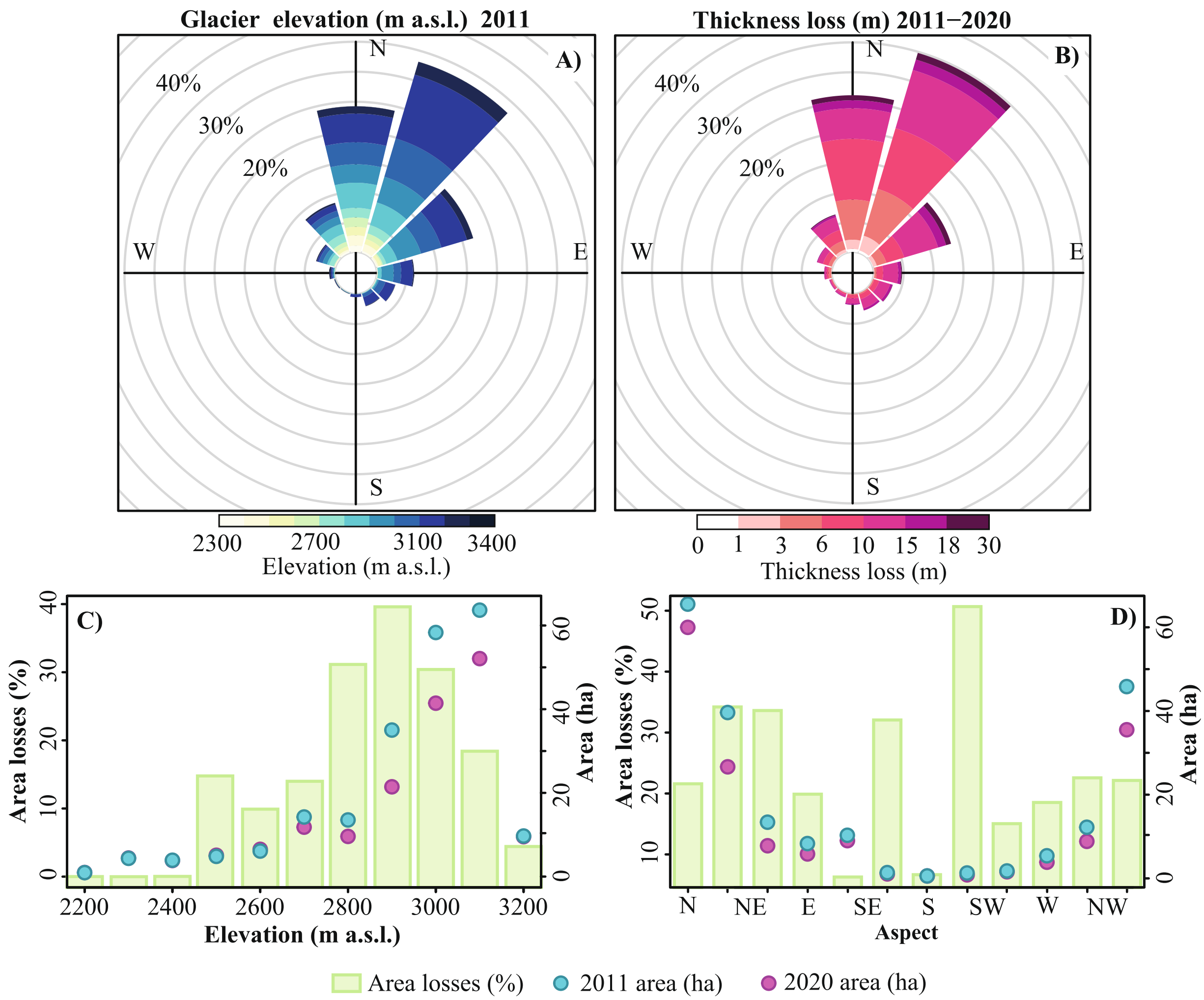

Figure 1. (a) Distribution of glacier elevations in 2011 categorized by aspect. (b) Distribution of thickness losses by aspect. The size of each sector on upper graphs corresponds to the percentage of the total glaciated area. The color scales show entire elevation range (a) or thickness loss (b and c) Altitudinal distribution of relative area loss (light green bars) and glaciated area in 2011 (blue points) and 2020 (pink points). (d) Distribution of relative area loss and glaciated area in 2011 and 2020.

2.3. Glacier Area Delimitation

Glacier delimitation was made using manual on screen tracing of ice margins in both 2011 and 2020. For 2011, glacier outlines were delimited from RapidEye satellite images, which were acquired between September and October and validated against the glaciers outlines from Marti, Gascoin, Houet, Ribière, et al., 2015 and Marti, Houet et al., 2015. For 2020 glacier outlines, high-resolution imagery derived from the UAVs and field survey with a handheld GPS was used for the manual delimitation of glaciers boundaries. For both datasets of glacier outlines (2011 and 2020), the projected glacier surface in a 2D horizontal plane and the 3D representation were computed. For the latter, glacier extents were calculated from the 3D UAV, the TLS or lidar surveys of the glaciers' surface topography. Information about the uncertainty of glacier area delimitation is included in the Supporting Information S1: "Uncertainty of the changes observed."

3. Results and Discussion

Based on high spatial resolution remote-sensing imagery from satellites and field surveys, 24 glaciers were mapped for 2011, covering a 2D area of 293.9 ha (2.93 km^2) which corresponds to a 3D surface of 338.9 ha (3.39 km^2) (hereafter called 3D area; Figure 1; Table S2). In 2020, three ice bodies (*Coronas*, *Pailla East* and

Maupas) showed no sign of movement or their surface area was smaller than 2 ha, so these were not considered to be glaciers anymore but ice patches (Leigh et al., 2019). Several very small glaciers showed very weak movement features in 2020 (e.g., *La Paul*, *Tempestades*), symptomatic of their close demise. One of the three largest glaciers (*Aneto*) was divided into two separate ice bodies during the study period. The total glacierized area was reduced to 229.2 ha (257 ha 3D area), representing a loss of 23.2% (24.2% 3D area) in the 9 years of the study period, i.e., an average area loss of 2.6% per year. The area-weighted mean ice thickness loss was 6.3 ± 0.4 m (0.70 m yr^{-1}), equivalent to a specific mass balance loss rate of 0.59 m w. e. yr^{-1} (Table S2), assuming a density conversion factor of 850 kg/m^3 (Huss, 2013). Many glaciers have shown zones where ice thickness decreased by more than 20 m. Despite these marked changes in glacier thickness the glacierized surface hypsography did not show strong variations, during the nine years of the study period.

The RMSE of glacier thickness change (Table S1 and Figure S4) shows that confidence in the ice loss estimation is high: in all cases, the RMSE is at least one order of magnitude lower than the mean glacier thickness change. However, some glaciers show higher uncertainties, mainly because of the lack of fixed common ground control points during glacier surface elevation acquisitions (in 2011 lidar flights and in 2020 in the UAV), potential surface elevation changes around glaciated areas being highly difficult to identify (debris falls, buried ice melting, etc.,), and in some glaciers the presence of a shallow snowpack (Fischer et al., 2016). On average, the residuals outside the glaciers (Figure S5) are below 0.4 m (accepted here as the uncertainty of thickness loss, see Supporting Information S1), an order of magnitude smaller than glacier-wide surface elevation changes which exceeded 6 m. This uncertainty (0.4 m) is assigned to the comparison of the two acquisition techniques as hardly any changes in surface elevation over stable terrain occurred during the observed period.

In 2011, the mean orientation of Pyrenean glaciers was concentrated between N and NE aspects (77% of the total), and their mean elevation above 2700 m a.s.l. (Figure 1a). A similar pattern persists in 2020 as N and NE aspects account for 60% of the glacierized area. However, glaciers with N aspect (respectively NE aspect) exhibited a relative area reduction of 22% (resp. 33%) from 2010 to 2020. In 2020, N and NNE aspect classes concentrate the highest fraction of glacierized area, and also show the largest thickness losses (>20 m at some locations, Figure 1b).

Below 2,400 m a.s.l., glacier area did not change significantly. At elevations from 2,400 to 2,700 m a.s.l., glaciers exhibited little shrinkage (~10%), whereas glacier area shrinkage was much higher (>30%) between 2800 and 3,000 m a.s.l. (Figure 1c). Such difference in glacier surfaces shrinkage is causing an increase in the average glacier slopes (López-Moreno et al., 2019). This could cause a decrease in snow accumulation, which is known to decline over 25–30° slopes due to gravitational displacement of fresh fallen snow (López-Moreno et al., 2017). Considering aspects, the largest relative area changes occurred in the SW aspect (−50%), while the largest absolute area losses were observed for the aspect class N. This is because on S slopes glaciers covered only a few hectares, so small area changes led to large relative losses (Figure 1d).

In Figure 2, the lack of a clear relation between ice thickness loss and loss of glacierized area for each individual glacier is striking. Nor is any clear relationship evident between glacier shrinkage and glacier aspect, mean elevation or size in 2011, also glacier hypsography did not change significantly between 2011 and 2020. Only the four largest Pyrenean glaciers (larger than 10 ha in 2020: *Aneto*, *Ossoue*, *Monte Perdido* and *Maladeta*, which represent 60.2% of the total 2020 area) show a positive correlation between area decrease and thickness loss. *Ossoue*, which shows an ESE aspect and a moderate mean elevation (3,068 m a.s.l), experienced the largest losses (25.7% area change and 10.9 m average thickness change), followed by *Aneto* (24.4% and 8.5 m) and *Maladeta* glaciers (18.4% and 7.4 m). *Monte Perdido* exhibited reduced area losses but similar ice thickness loss (12.9% and 7.5 m). For three out of this four glaciers, yearly surface mass balances (Lopez-Moreno et al., 2019; Pastor-Argüello 2013; René, 2014) show that these glaciers are mainly controlled by the mean climatic conditions of the year (snow accumulation in winter and air temperatures in summer). Smaller glaciers (area <10 ha) exhibited strongly contrasting area and thickness loss. Among these latter glaciers, three classes can be distinguished. A first group of glaciers (4–10 ha) surrounded by rock walls facing N and NE, shows small area and thickness loss, including *Infierno*, *Oulettes*, *Tempestades*, and *La Paul* glaciers, characterized by very heterogeneous local conditions (summit altitudes and ice thickness, height of rock walls, lithology). These glaciers are also the least dynamic glaciers. The second class also corresponds to glaciers in the size range of 4–10 ha but with very high thickness loss and low area loss (*Seil*

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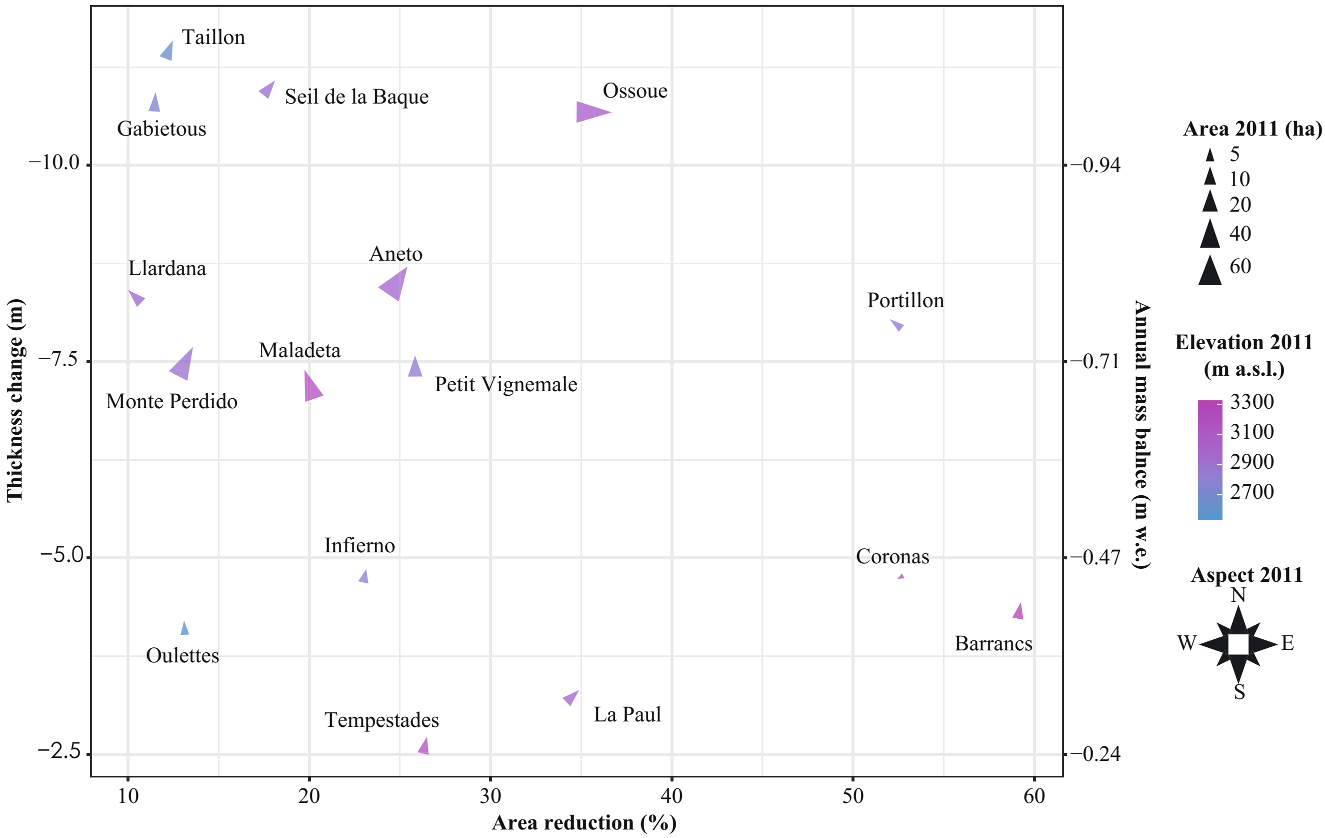

Figure 2. Relationship between thickness loss (m) and glacierized area reduction (%). Triangle size represents 2011 area, the color scale represents the mean glacier elevation and the orientation of the triangles refers to the mean aspect of the glacier.

de la Baque, *Taillon*, *Gabietous*, and *Llardana*). These glaciers have moderate elevations but are situated in narrow cirques surrounded by nearly vertical rock walls with distinct main aspect classes and thus local topographical conditions are decisive for their strong mass loss. The third class is formed by the smallest Pyrenean glaciers (<4 ha) and ice patches located at high elevation with high area loss and moderate thickness loss, located in open morphology (i.e., not protected against solar radiation by narrow cirques or rock walls) with moderately steep rocks walls in granitic massifs.

These results highlight the marked variability in thickness loss among glaciers. Figures 3, S2 and S3 illustrate that in most cases the maximum thinning is found in the lower-lying and middle part of the glaciers, while the upper parts exhibit an attenuated wastage or even elevation changes close to zero (the largest reductions in ice thickness are observed at the elevations with the largest percentage of total glacier cover). Glaciers that are split into two different ice bodies (i.e., *Monte Perdido* and *Taillon*) show a bimodal distribution of ice thickness loss with elevation.

Although Pyrenean glaciers have already retreated to the most elevated and protected cirques (Rico et al., 2017), they are still in clear imbalance with the current climate in the Pyrenees. As this work shows, the reach of a new equilibrium that could be expected in the evolution of very small and marginal glaciers (Carturan et al., 2013) has not yet occurred in the Pyrenees. This may cause the complete disappearance of most Pyrenean glaciers in the coming decades. Indeed, the loss of 23.2% (2.60% per year) of the glacierized area in the period 2011–2020 is similar to the rates of loss of 2.93% per year and 2.59% per year reported for the periods 2008–2016 (Rico et al., 2017) and 1984–2008 (Rico, 2019), respectively. The mass balances of −0.70 and −1.03 m w. e. yr^{-1} for *Maladeta* and *Ossoue* glaciers do not differ substantially from previously reported mass balances (Gascoin & René, 2018; Marti, Gascoin, Houet, Laffly, et al., 2015). Also, the area-weighted mean ice thickness loss of 0.70 m yr^{-1} reported here is somewhat smaller but in the same order of magnitude compared to values reported by Hugonnet et al. (2021) in Central Europe (−1.00/−1.11 ± 0.23/0.26 m

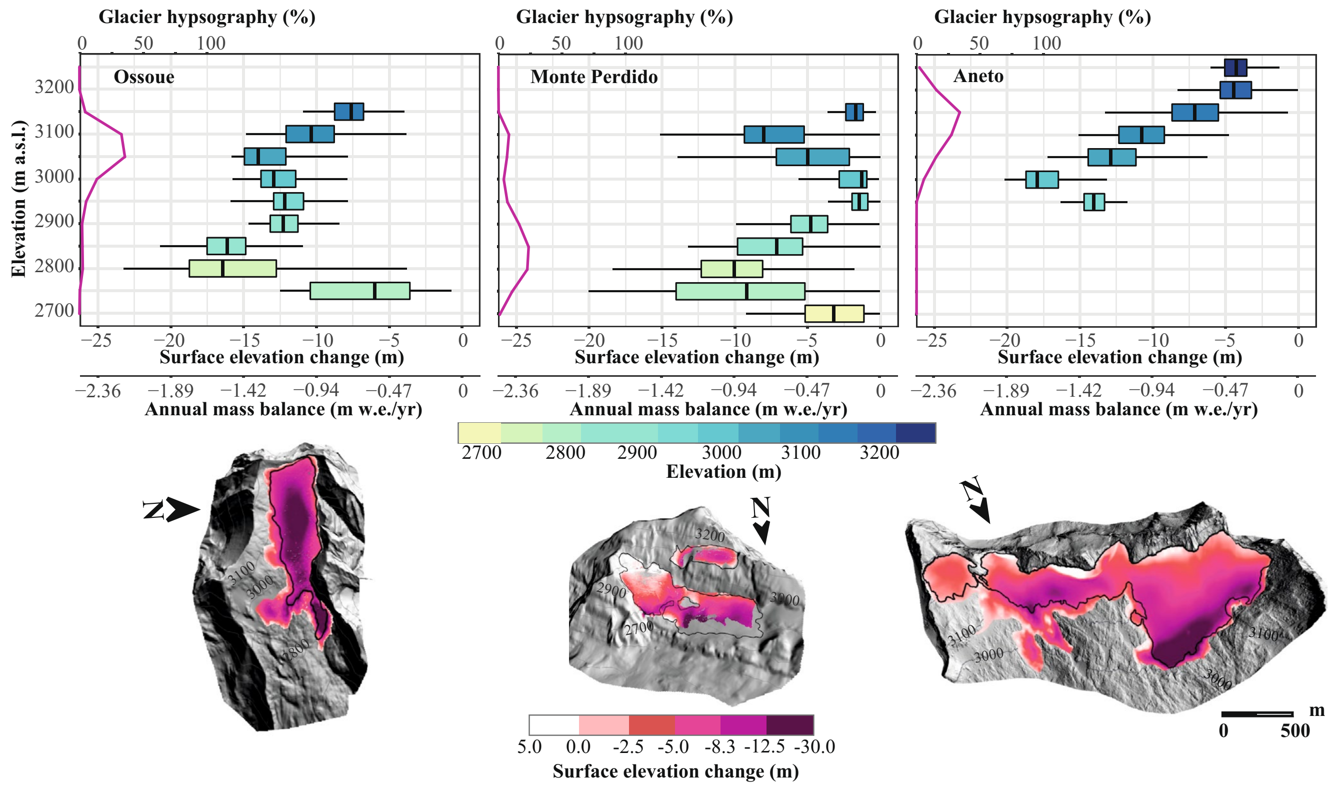

Figure 3. Lower panel: 3D views depict surface elevation change for the three largest glaciers in the Pyrenees during 2011–2020 (from left to right: *Ossoue, Monte Perdido* and *Aneto*). The black line in the three maps delineates the 2020 glacier area. Upper panel: boxplots show the mean surface elevation change for each elevation band; the pink line shows the distribution of glacier area with elevation. Since the 3D views show a frontal view of glaciers, each image has in the upper part an arrow indicating the North direction.

yr^{-1} in the periods 2010–2014/2015–2019, respectively for a much wider region). Nonetheless, high spatial resolution observations of glacier evolution presented here show differences when compared with coarser-resolution studies (Fischer et al., 2016). Thus, the surface elevation change reported in two 1° × 1° grids for the Pyrenees glaciers (42°N, 0°E and 42°N, 1°W) shows a mean ice thickness change of -0.96 m yr^{-1} over a long time period (2000–2019; considering the glaciated area inside each 1° size pixel of the Pyrenees; Hugonnet et al., 2021), contrasting with the -0.70 m yr^{-1} observed here. Despite the uncertainties in both works (0.07 and 0.04 m yr^{-1} respectively) and also the differing study periods, the difference in mean values is not negligible. This shows the importance of in-situ observations, which are needed to correct glacier elevation or ice thickness changes derived by coarser satellite imagery.

Temperature and precipitation anomalies from ERA5 reanalysis data (Hersbach et al., 2020) for the study period 2011–2020, compared to a reference period from 1980 to 2010 (total precipitation from November to May and average temperature from June to September), showed that precipitation was slightly higher (+9%) and temperature warmer (+0.7°C on average) during the study period (Figure S4). However, these changes in climatic conditions were similar for all glaciers and their response to these variations was highly variable. A strong variability in area and thickness loss is observed among the smallest glaciers. This variable response to similar climatic conditions strongly suggests that local topographic conditions are becoming more important and climate evolution may have a lesser impact on glacier dynamics (Fischer, 2018; Hughes, 2018; Huss & Fischer, 2016; Rico, 2019). Moreover, the variability in glacier area decrease and thickness loss is more pronounced among the smallest Pyrenean glaciers which, probably highlights that, the smaller a very small glacier becomes, the higher the influence of local topography on its evolution. Recent glacier changes are related to the cirque characteristics of each glacier, such as shadowing from neighboring slopes, glacier slope, position relative to dominant blowing snow direction, and snow avalanche deposition. This result agrees with previous studies that point out that small glaciers have an exacerbated spread in response to regional climate fluctuations (DeBeer & Sharp, 2009; Fischer et al., 2014, 2015). Conversely, the four largest

Pyrenean glaciers exhibited changes more consistent with each other, with a much smaller range of variability in area and thickness losses than when all ice bodies are compared to the entire sample of Pyrenean glaciers. This suggests that the evolution of these four glaciers are still primarily influenced by the regional climate signal. However, some differences in the behavior of these larger glaciers appear, such as the larger losses of ice of *Ossoue* glacier (10.9 m of mean thickness loss and 25.7% of area reduction) compared to *Monte Perdido* glacier (7.5 m mean thickness loss and 12.9% area decrease) that, could be explained by their highly contrasted potential incoming solar radiation (respectively, mean daily radiation of 0.17 and 0.12 kW m^{-2} from early June to late September). *Ossoue* glacier is located inside a topographic depression where there are no large slopes, hence cirque walls do not protect it from direct solar radiation.

Glacierized area losses and thickness loss for the different glaciers are highly heterogeneous, confirming that glacier area cannot be used as a proxy for mass balance (Huss & Fischer, 2016). As recent research and the results of this study demonstrate, TLS surveys (Fischer et al., 2016; López-Moreno et al., 2019), UAV surveys (Gaffey & Bhardwaj, 2020; Revuelto et al., 2021) and new emerging remote-sensing products such as high resolution satellite stereo imagery (Gascoin & René, 2018) are efficient tools for analyzing the evolution of very small glaciers. The increased use of optical satellite imagery with enhanced resolution and frequency may permit better delimitation of glacierized areas, and the identification of crevasses, debris cover and the evolution of the ELA, finally allowing an improved monitoring of even very small glaciers (Marti, Gascoin, Houet, Laffly, et al., 2015).

Available estimations from ground-penetrating radar surveys suggest that the maximum ice thickness of Pyrenean glaciers rarely exceeds 30 m and most of the glacierized areas are less than 15 m thick (Del Rio et al., 2014; Jiménez-Vaquero, 2016; López-Moreno et al., 2019). When these values are contrasted to ice losses reported in this study for the last 9 years, we can argue with confidence that Pyrenean glaciers are in extreme jeopardy and could disappear or become residual ice patches in about two decades.

4. Conclusions

From 2011 to 2020, the glacierized area of the Pyrenees has been reduced from 293.9 to 229.2 ha (−23.2%) and three glaciers have disappeared. The area-weighted mean ice thickness loss was 6.3 m, which is equivalent to an area-weighted specific mass balance of −0.59 m w. e. yr^{-1}. The annual rate of glacierized area loss reported in the study period is similar to that observed since the 1980s. This indicates that glacier shrinkage in the Pyrenees and wastage have not slowed down in the last few years. However, the individual values of glacier shrinkage and area reduction vary significantly among glaciers. Moreover, these two variables are poorly correlated, suggesting that change in surface area is a poor proxy for mass balance in this region. The four largest Pyrenean glaciers have exhibited strong losses in area and ice thickness, causing important changes in their slope and mean elevation. The other glaciers (those covering less than 10 ha) are all losing area and thickness but at variable rates, suggesting that local topographic factors affecting solar radiation (shadowing) or preferential snow accumulation areas may play an important role in explaining recent changes. In general, the regional climate conditions (which are the same for all surveyed glaciers) primarily still control the evolution of glaciers in the Pyrenees. Nonetheless, the considerable variability in glacier area and ice thickness losses observed among individual glaciers points to the importance of local topography on glacier mass balance and evolution as well. The results of this study indicate that Pyrenean glaciers are in a clear imbalance with the regional climate and will likely disappear in the next few decades.

Acknowledgments

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Data Availability Statement

At the time of publication, the database of glacier thickness changes and glacier delimitation in 2011 and 2020 will be available through this URL: https://doi.org/10.5281/zenodo.4756351.

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