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No hope for Pyrenean glaciers

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Abstract

Updated estimates of 2024 ice thickness, the surface elevation losses in the last years and simulations of mass balance and evolution (using the Instructed Glacier Model) for the three largest Pyrenean glaciers strongly suggest that by 2034 the Pyrenees will be ice-free. If extreme summers like 2022 and 2023 recur, this could happen even earlier. We show that by 2030, 94% (from 0.22 to 0.01 km^2) of the ice in Monte Perdido, 91% (from 0.22 to 0.05 km^2) of the ice in Ossoue and 79% of the ice in Aneto (from 0.34 to 0.06 km^2) will have melted under the RCP4.5 scenario; these numbers are 83%, 72% and 57% under a committed ice loss scenario, meaning that only 0.05, 0.12 and 0.12 km^2 of ice will remain, respectively. In 2034, most likely they will have completely disappeared under the three considered scenarios (RCP 4.5, 'committed ice loss' and extreme 2022 year in a loop). The loss of these glaciers is a harbinger for what will happen in many other mountain regions.

1. Introduction

The United Nations has declared 2025 as the International Year of Glaciers' Preservation and the start of the Decade of Action for Cryospheric Sciences (2025–34). The aim of these initiatives is to raise global awareness of the importance of glaciers as unique landscape features and critical sources of freshwater that are rapidly disappearing, and to urge governments, corporations and individuals to take urgent actions that mitigate climate change. Climate change has affected glaciers around the world, and many glaciers will disappear in the very near future. In fact, a recent study projected that half of the existing world's glaciers will vanish by the year 2100, even with a conservative estimate of global warming (1.5°C per year) (Rounce and others, 2023).

Since 1950, temperature of the Pyrenees has risen >1.5°C causing a progressive shrink of their glaciers that has accelerated in the 21st century. By the end of 2023, the Pyrenees had only 15 ice bodies and a total ice area of 143.2 ha (Izagirre and others, 2024a). This was a significant decrease compared to 2011 (27 ice bodies, 3.02 km^2) and 2020 (24 ice bodies, 2.38 km^2) (Vidaller and others, 2021). Currently, all remaining glaciers in the Pyrenees are in a critical state, and there is recent evidence that glacier shrinkage and melting rate are accelerating (Vidaller and others, 2021). Over the last 10 years, scientists studying the Pyrenean glaciers have warned that these glaciers could disappear within a few decades. However, the climatic extremes of 2022 and 2023 led to drastic decline of ice and a tripling of the annual thinning rates observed during the previous decade (Izagirre and others, 2024a). This suggests that the Pyrenean glaciers could disappear in just a few years.

In this study, we first reconstructed the remaining ice thickness of the three largest Pyrenean glaciers. Second, we used the Instructed Glacier Model (IGM) (Jouvet and others, 2022) to simulate the mass balance of these three glaciers, using the ice volumes at the end of 2024 as the baseline conditions for the next 10 years under three different scenarios: RCP 4.5, 'committed ice loss' based on the climate conditions observed in the Pyrenees during the period 2010–20 and the 'extreme' based on the extremely warm and dry year 2022 as a loop. This approach makes it possible to assess whether the Pyrenean glaciers will still exist in 2034.

The glaciers analyzed are Aneto (0.34 km^2), Monte Perdido (0.27 km^2) and Ossoue (0.22 km^2). These three larger glaciers together represent 62% of the total glacierized area in the Pyrenees and still show signs of ice movement. The rest of the Pyrenean glaciers are <0.1 km^2 and have shown clear signs of stagnation in the last years (Izagirre and others, 2024a).

2. Data and methods

A total of 11.4 km of ground-penetrating radar (GPR) profiles were recorded for the three largest glaciers in the Pyrenees; 2.6 km on Ossoue in late summer 2006 (Marti and others, 2015), 2 km on Monte Perdido in early fall 2016 (López-Moreno and others, 2019) and 6.8 km on Aneto in early summer 2020 (Vidaller and others, 2023). To obtain continuous ice thickness maps from the sometimes sparsely collected GPR profiles, we applied an interpolation method using the radial basis function (RBF) kernel to generate the baseline ice thickness maps for Ossoue (2006), Monte Perdido (2016) and Aneto (2020; Vidaller and others, 2023). The Ossoue survey (2006) covered ∼50% of the glacier's area in 2006 (Marti and others, 2015); to account for sparse coverage and after subtracting elevation losses (2006–11; −8.2 m in total), we applied RBF interpolation constrained by bedrock topography from LIDAR data (Marti and others, 2015; Vidaller and others, 2021). The cross-validation resulted in a mean ice thickness error of ±1.2 m compared to the validated GPR transects. In the Monte Perdido survey (2016), there is a risk of signal attenuation due to liquid water in the fall surveys, but a residual uncertainty of ±5 m is assumed in water-rich sectors (López-Moreno and others, 2019). In the Aneto survey (2020), the dense 6.8 km transects provided high-resolution data and the interpolation uncertainty (±0.3 m) was validated using a randomly selected 30% (test) of the GPR data (Vidaller and others, 2023).

To estimate the ice thickness distribution in intermediate years (2011, 2020 and 2024), the published surface elevation changes for the periods 2011–20 (Vidaller and others, 2021) and 2020–23 (Izagirre and others, 2024a) were then applied to the base maps. The ice thickness reconstructions were updated to 2024 using unmanned aerial vehicles surveys in September/October 2024, using the same procedure as in the previously published studies. An average thinning of -0.7 ma^{-1} for 2023–24 was calculated for the three glaciers studied.

Future air temperature and precipitation data are based on CMIP5 scenarios from the CNRM-CM5 model, downscaled to 2.5 km using the SAFRAN atmospheric model (available at https://digital.csic.es/handle/10261/271116, accessed on 26/10/2024). The historical climate period, from 1960 to 2006, was data-assimilated with meteorological observations from the mountain range. Climate projections were bias-corrected using the analog method (Quintana-Seguí and others, 2017). To estimate committed future ice loss due following the current trend (2010–20), we used the SAFRAN reanalysis dataset. This dataset is based on ARPEGE (2002–23) models corrected with in situ meteorological observations for the mountain range. A moderate greenhouse gas emission scenario (RCP4.5) was also considered to assess the response of Pyrenean glaciers to a slightly warmer climate (+0.2°C) beyond the committed ice loss (FS3). The 2022 extreme ablation year was simulated by identifying the 2022 temperature anomalies during the 2006–23 period.

The IGM simulates the evolution of ice thickness, extent and velocity based on ice mass conservation, surface mass balance (SMB) and ice-flow physics (Jouvet and others, 2022). Ice flow is modeled using a convolutional neural network (CNN) trained on land-terminating alpine glaciers (Jouvet and Cordonnier, 2023). This CNN emulator replicates the full-Stokes equations at a reduced computational cost (Jouvet and others, 2022). The IGM is driven by air temperature and precipitation data. SMB is estimated using a monthly positive degree-day (PDD) model (Hock and others, 2019). The PDD melt rate factor is calibrated to match with in-situ observed SMB data from 2015 to 2022 (FS 4) and the extreme temperature year (FS5). Three simulations were performed to estimate (i) the committed future loss, regardless of future climate scenarios, based on the 2010–20 climate period (committed ice loss), (ii) future loss for an extreme temperature year (2022) in a loop (extreme) and (iii) future loss for a moderate emissions scenario (RCP4.5). RCP4.5 represents slightly warmer (0.20°C) conditions than those of the committed period and is used as an upper bound for temperature scenarios (FS3). We conducted a calibration process to tune the PDD melt rate factor using literature values ranging from 4 to 7 mm °C^{-1} d^{-1}, consistent with similar values reported in the literature (Hock, 2005). For the future and committed future scenarios, the melt rate was set to 4 mm °C^{-1} d^{-1} to reduce the mismatch between observations and IGM simulations. In the extreme temperature year, melt rates were set to 6 mm °C^{-1} d^{-1} for Monte Perdido and Aneto, and 4.5 mm °C^{-1} d^{-1} for Ossoue, (FS5), based on the SMB and melt rate sensitivity during extreme temperature conditions. This sensitivity analysis is also compared with OGGM's calibration included in the IGM SMB module, as described in the OGGM documentation (https://docs.oggm.org/en/v1.1/mass-balance.html#calibration), which showed that a PDD melt rate factor of 5 aligns the SMB with the geodetic mass balance for each glacier (RGI6.0 level, Hugonnet and others, 2021).

The IGM is forced using a high-resolution DEM acquired from at a resolution of 3 m. Temperature downscaled using a lapse rate of −0.6°C per 100 m, and precipitation downscaled using a vertical gradient of 35 mm per 100 m. The SMB simulations are subtracted from the original ice thickness distribution to obtain a yearly estimate of future ice loss.

3. Results and discussion

The estimated average thickness of the glaciers Aneto, Monte Perdido and Ossoue in October 2024 is 11.6, 15.0 and 15.1 m, respectively. Only below 24.1% of the total area of these glaciers is the ice >20 m thick, while below 36.4% of the area has an ice thickness of <10 m (Fig. 1). Since 2011, the area with a thickness of >20 m was reduced in average by 33% on average. The largest decrease was reconstructed for the Monte Perdido glacier (from 70% to 19%). Estimated thicknesses must be considered together with the thinning rates for these glaciers from 2011 to 2024 (Aneto: 16.4 m, 1.26 m a^{-1}; Monte Perdido: 15.8 m, 1.22 m a^{-1}; Ossoue: 21 m, 1.61 m a^{-1}). Ice thickness losses are accompanied by other concerning signs, such as the collapse and fragmentation of ice bodies and the rapid increase in debris cover (Izagirre and others, 2024b), that indicate transformation to glacial stagnation.

Using the IGM, the expected lifetimes of these Pyrenean glaciers were quite similar when using a replica of the observed climate data of the 2010–20 period (committed ice loss) and using climate projections under the RCP4.5 scenario. By 2030, 94% of the ice of Monte Perdido, 91% of the ice of Ossoue and 79% of the ice of Aneto will have melted under the RCP4.5 scenario; these numbers are 83%, 72% and 57% under the committed ice loss scenario (Fig. 2a). For the later scenario and this time period (2024–30), the Aneto Glacier is the only glacier that will have any glacier area thicker than 20 m (Fig. 3), and the probability of glaciers to show distinct ice motion (a defining characteristic of glaciers) is minimal based on Copland (2022). By 2030, the total ice area of Aneto will decline to 0.06 km^2, Ossoue to 0.05 km^2 and Monte Perdido to 0.01 km^2 under the RCP4.5 scenario. By 2034 (the end of the UN Decade of Action for Cryospheric Sciences), there will be little or no remaining ice in Monte Perdido and Ossoue; and Aneto will fragment into small patches with a total glacier area <2 ha, and no single ice body will exceed 1 ha (Figs 2b and 3 and FS1 and FS2).

The glacier areas under the committed ice loss scenario are only slightly larger. Interestingly, simulations that replicate the

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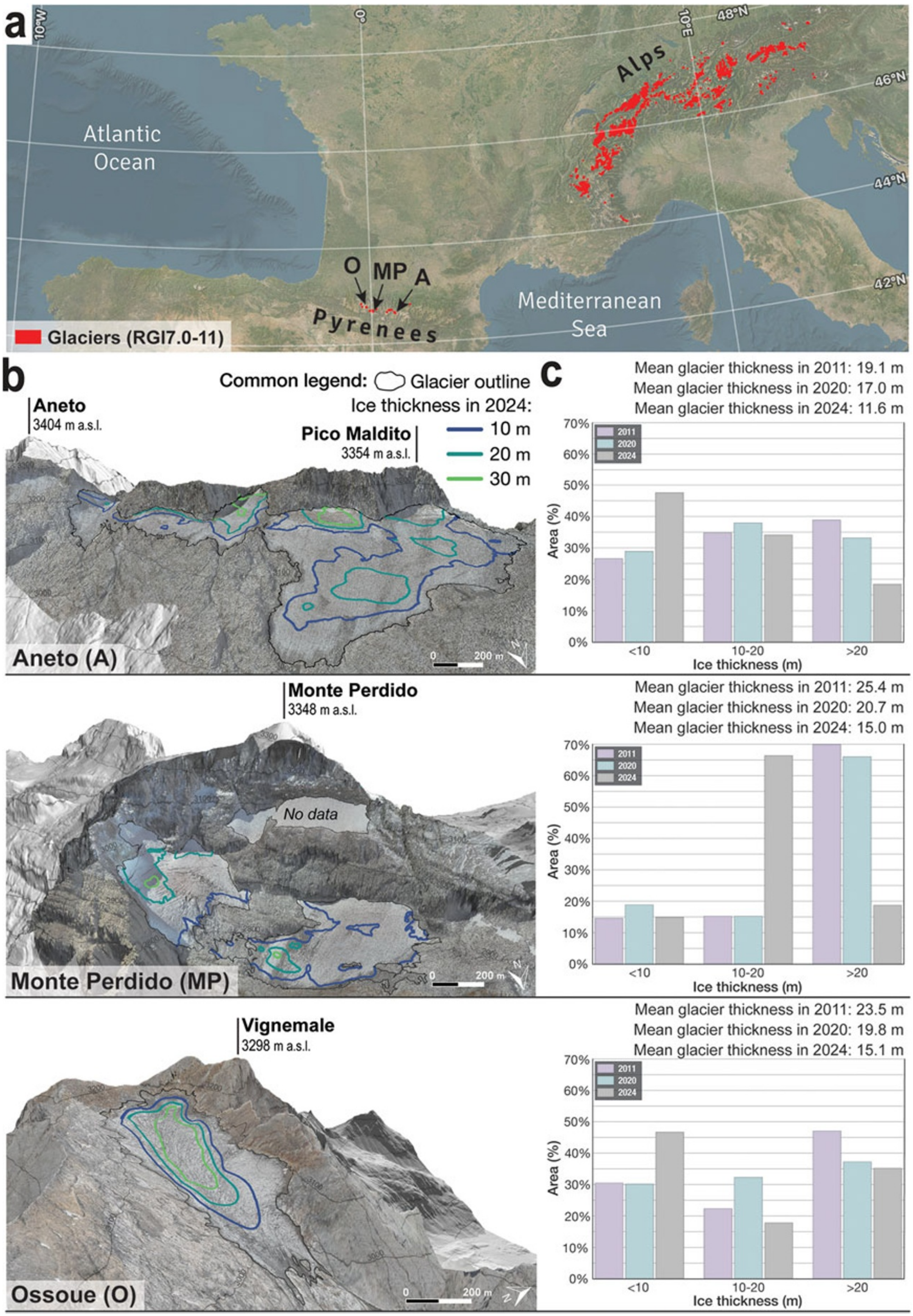

Figure 1. (a) Current spatial distribution of glaciers in central and southern Europe. (b) Reconstructed ice thickness of the Aneto, Monte Perdido, and Ossoue glaciers during 2024. (c) Areas of these glaciers that had thickness <10 m, 10–20 m and > 20 m during 2011, 2020 and 2024. 3D orthoimages are derived from point clouds obtained with unmanned aerial vehicles in 2024.

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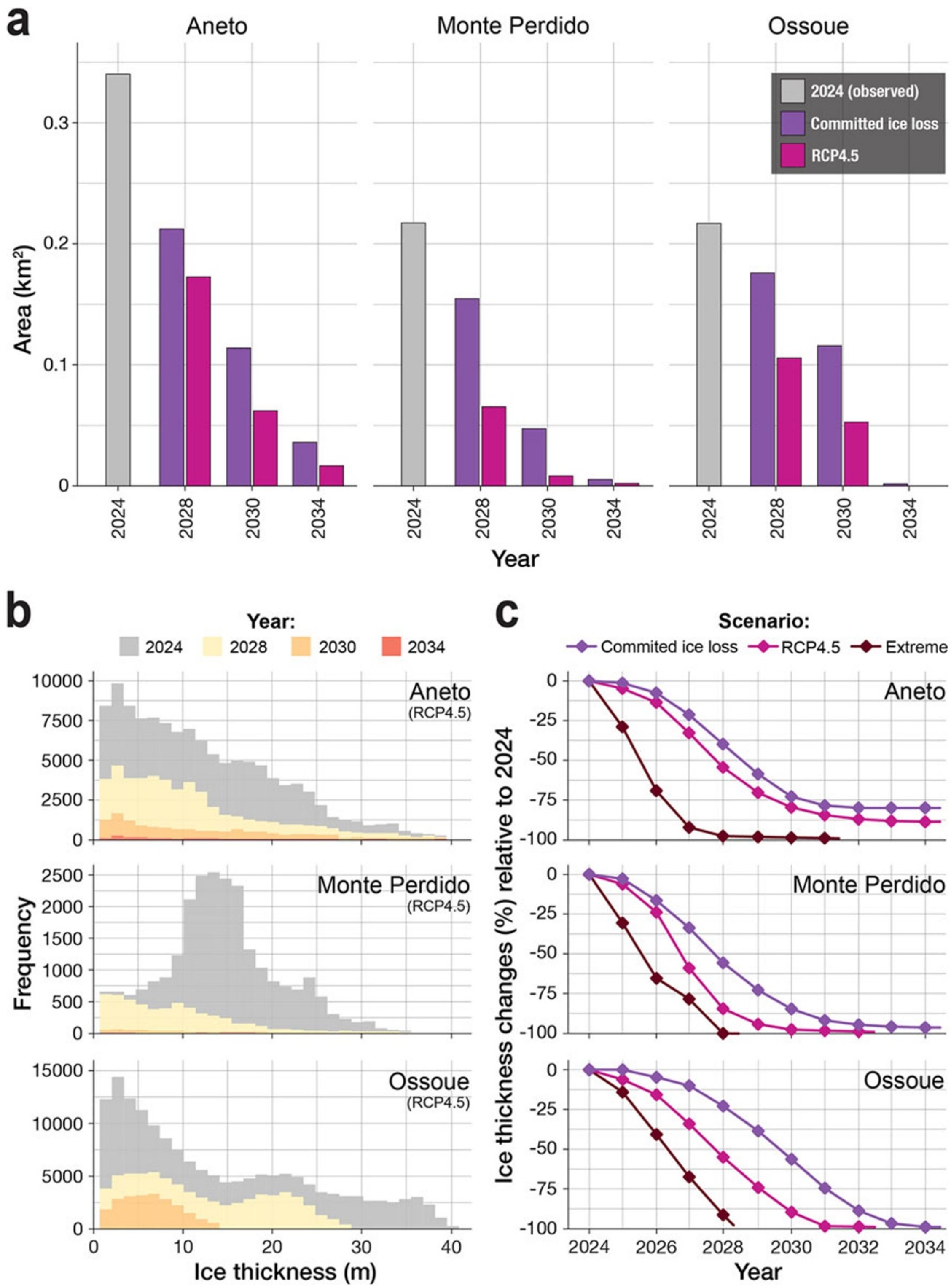

Figure 2. (a) Reconstructed glacier area and ice thickness during 2024 and predictions for 2030 under two scenarios (committed ice loss, RCP4.5) for the Aneto, Monte Perdido, and Ossoue glaciers, with details in Figures S1–S3. (b) Present and predicted glacier areas under two scenarios (committed ice loss, RCP4.5). (c) Present and predicted distributions of ice thickness under the RCP4.5 scenario. (d) Predicted ice thickness changes (%) relative to 2024 under three scenarios (committed ice loss, RCP4.5 and extreme temperature year).

climatic conditions of 2022 show that the RCP 4.5 scenario for 2034 will be reached within only 3–4 years from 2024 (Fig. 2). Even assuming inherent uncertainties of the modeling approach and data used, results of this study confirm that the current climate in the Pyrenees is incompatible with the existence of glaciers, and that this region will be one the next mountain ranges to be

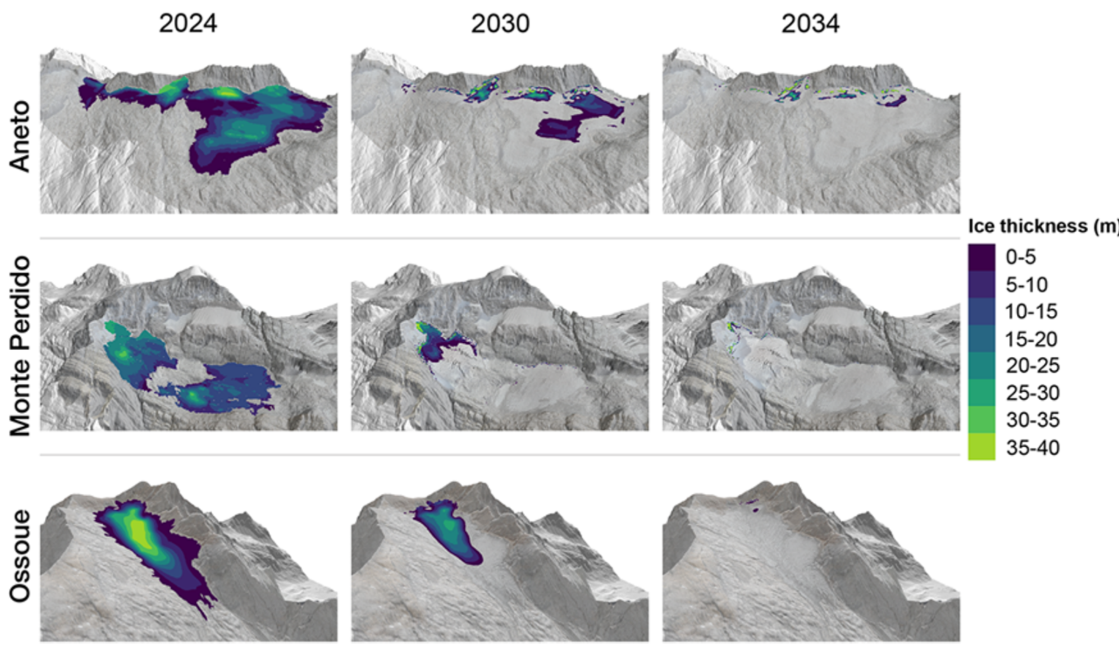

Figure 3. Spatio-temporal distribution of ice thickness in 2024 (reconstructed) and predictions for 2030 and 2034 under the committed ice loss scenario for the Aneto, Monte Perdido and Ossoue glaciers.

declassified as 'glacierized'. Only a significant and unlikely shift in the current climatic conditions could prolong the duration of the glaciers over time. In the past 14 years, there have been instances of neutral or even slight snow accumulation on the glaciers, as observed in the geodetic mass balance of the Monte Perdido glacier (López-Moreno and others, 2019). However, these years represent an outlier compared to those with a negative mass balance, and the positive effects have not been sufficient to counteract the substantial ice losses documented above. Only an improbable sequence of years with favorable conditions for the glaciers could potentially delay the hopeless projections presented in this study.

Pyrenean glaciers have survived the Roman and Medieval Warm Periods (Moreno and others, 2021), but the current warming seems to be too much for them. The disappearance of Pyrenean glaciers means there will be no mountain ranges in southern Europe (below 43° N latitude) with active glaciers, making this event a 'canary in the coal mine' warning that similar outcomes will occur in many other mountain ranges around the world (Rounce and others, 2023). The loss of the small glaciers of the Pyrenees will generally have no significant hydrological or environmental consequences compared to other mountain ranges in terms of water availability, energy and food production, natural hazards and mountain erosion (Biemans and others, 2019; Herman and others, 2021; Clason and others, 2022; Taylor and others, 2023). However, the loss of these small glaciers means the disappearance of a unique landscape feature, and this will prevent studies of important paleoenvironmental and microbiological information that is unique to these glaciers (Huber and others, 2024). There is also evidence that the disappearance of small glaciers can alter the cultural identity and landscape perception for inhabitants and tourists. It may be hoped that the disappearance of the Pyrenean glaciers will send a clear message to the immediately affected societies and to the world at large, which should then take urgent actions to mitigate the effects of climate change.

4. Conclusions

This study shows that the Pyrenean glaciers are at high risk of completely disappearing in the coming years. The reconstructed ice thickness data for the Aneto, Monte Perdido and Ossoue glaciers in October 2024 show that only a small part of these glaciers have a thickness of >20 m, with large areas not even reaching 10 m. The average ice thickness loss on the three glaciers since 2011 is >15 m, underlining their critical state. Simulations of glacier mass balance and evolution under three different scenarios indicate that within the next 5–10 years, most likely none of the largest Pyrenean glaciers will retain enough mass or dynamic movement to be classified as glaciers. Moreover, just 3 years of extreme climatic conditions, such as those observed in 2022 and 2023, could be enough to trigger their ultimate disappearance. The situation in the Pyrenees is a clear warning signal for other mountain regions that are likely to experience similar trends as temperatures continue to rise. This observation should serve as a call to action and underline the urgent need to reduce greenhouse gas emissions and mitigate the rates of warming predicted for the second half of this century.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/aog.2025.10015.

Data availability statement. The data that support the findings of this study are available on request from the corresponding author (JILM).

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Competing interests. The authors declare that they have no conflict of interest.

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