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 IGM) 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.

Keywords: Glaciers, Climate Change, Instructed Glacier Model (IGM), Pyrenees

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 (2025–2034). 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 ºC per year) (Rounce and others, 2023).

Since 1950 temperature of the Pyrenees has risen more than 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 ten 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 2010-2020 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 analysed 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 smaller than 0.1 km^2, and have shown clear signs of stagnation in the last years (Izagirre and others, 2024a).

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 et al., 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 (2006-2011; -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 2011-2020 (Vidaller and others, 2021) and 2020-2023 (Izagirre and others, 2024a) were then applied to the base maps. The ice thickness reconstructions were updated to 2024 using UAV surveys in September/October 2024, using the same procedure as in the previously published studies. An average thinning of -0.7 ma^{-1} for 2023-2024 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 (2010–2020), we used the SAFRAN reanalysis dataset. This dataset is based on ARPEGE (2002 to 2023) 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 2006-2023 period.

The Instructed Glacier Model (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 2010–2020 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 (0.20ºC) 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/day, 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/day mm/°C/day to reduce the mismatch between observations and IGM simulations. In the extreme temperature year, melt rates were set to 6 mm/°C/day for Monte Perdido and Aneto, and 4.5 mm/°C/day 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 3m. Temperature downscaled using a lapse rate of -0.6ºC per 100 m, and precipitation downscaled using a vertical gradient of 35 mm per 100 m. The surface mass balance simulations are subtracted from the original ice thickness distribution to obtain a yearly estimate of future ice-loss.

RESULTS AND DISCUSSION

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The estimated average thickness of the glaciers Aneto, Monte Perdido and Ossoue in October 2024 is 11.6, 15.0 and 15.1 meters, respectively. Only below 24.1% of the total area of these glaciers is the ice more than 20 meters thick, while below 36.4% of the area has an ice thickness of less than 10 meters (Figure 1). Since 2011, the area with a thickness of more than 20 meters 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 et al., 2024b), that indicate transformation to glacial stagnation.

-FIGURE 1 NEAR HERE-

Using the Instructed Glacier Model, the expected lifetimes of these Pyrenean glaciers were quite similar when using a replica of the observed climate data of the 2010-2020 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 (Figure 2a). For the later scenario and this time period (2024-2030), the Aneto Glacier is the only glacier that will have any glacier area thicker than 20 m (Figure 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 less than 2 ha, and no single ice body will exceed 1 ha (Figures 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 climatic conditions of 2022 show that the RCP 4.5 scenario for 2034 will be reached within only 3 to 4 years from 2024 (Figure 2). Even assuming inherent uncertainties of the modelling 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 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 favourable conditions for the glaciers could potentially delay the hopeless projections presented in this study.

-FIGURE 2 NEAR HERE-

Pyrenean glaciers have survived the Roman and Medieval Warm Periods (Moreno et al., 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 43º 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 et al., 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.

- FIGURE 3 NEAR HERE-

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

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glaciers have a thickness of more than 20 meters, with large areas not even reaching 10 meters. The average ice thickness loss on the three glaciers since 2011 is more than 15 meters, underlining their critical state. Simulations of glacier mass balance and evolution under three different scenarios indicate that within the next 5 to 10 years, most likely none of the largest Pyrenean glaciers will retain enough mass or dynamic movement to be classified as glaciers. Moreover, just three 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.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author [JILM].

Acknowledgements

REFERENCES

Biemans H and 7 others (2019) Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. **Nat Sustain** 2, 594–601. doi:10.1038/s41893-019-0305-3

Clason C and 7 others (2022) Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities. **Annals Glaciology** 63, 73–78. doi:10.1017/aog.2023.14

Copland L (2022) 4.04 - Properties of Glacial Ice and Glacier Classification, in: Shroder, J. (Jack) F.B.T.-T. on G. (Second E. (Ed.). Academic Press, Oxford, pp. 52–62. doi:10.1016/B978-0-12-818234-5.00014-6

Herman F, De Doncker F, Delaney I, Prasicek G and Koppes, M (2021) The impact of glaciers on mountain erosion. **Nat Rev Earth Environ** 2, 422–435. doi:10.1038/s43017-021-00165-9

Hock R (2003) Temperature index melt modelling in mountain areas. **J Hydrol** 282, 1, 104–15, doi:10.1016/s0022-1694(03)00257-9

Hock R and 7 others (2019) GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. **J. Glaciol** 65, 453–467. doi:10.1017/jog.2019.22

Huber CJ and 7 others (2024). High-altitude glacier archives lost due to climate change-related melting. **Nat Geosci** 17, 110–113. doi: 10.1038/s41561-023-01366-1

Hugonnet R and 10 others (2021) Accelerated global glacier mass loss in the early twenty-first century. **Nature** 592, 726–731. doi: 10.1038/s41586-021-03436-z

Izagirre E and 10 others (2024a). Pyrenean glaciers are disappearing fast: state of the glaciers after the extreme mass losses in 2022 and 2023. **Reg Environ Change** 24, 172. doi:10.1007/s10113-024-02333-1

Izagirre E and 7 others (2024b). A variable increase of debris cover on Pyrenean glaciers from 2000 to 2022. **Medit Geosci Rev.** doi:10.1007/s42990-024-00149-z

Jouvet G and Cordonnier G (2023) Ice-flow model emulator based on physics-informed deep learning. **J. Glaciol** 1–15. doi: 10.1017/jog.2023.73

Jouvet G, Cordonnier G, Kim B, Lüthi M, Vieli A and Aschwanden A (2022) Deep learning speeds up ice flow modelling by several orders of magnitude. **J Glaciol** 68, 651–664. doi:10.1017/jog.2021.120

López-Moreno JI and 14 others (2019). Ground-based remote-sensing techniques for diagnosis of the current state and recent evolution of the Monte Perdido Glacier, Spanish Pyrenees. **J Glaciol** 65. doi:10.1017/jog.2018.96

Marti R and 11 others (2015). Evolution of Ossoue Glacier (French Pyrenees) since the end of the Little Ice Age. **The Cryosphere** 9, 1773–1795. doi:10.5194/tc-9-1773-2015

Moreno A and 23 others (2021). The case of a southern European glacier which survived Roman and medieval warm periods but is disappearing under recent warming. **The Cryosphere** 15, 1157–1172. doi: 10.5194/tc-15-1157-2021

Quintana-Seguí P, Turco M, Herrera S and Miguez-Macho G (2017) Validation of a new SAFRAN-based gridded precipitation product for Spain and comparisons to Spain02 and ERA-Interim. **Hydrol Earth Syst Sci** 21, 2187–2201. doi:10.5194/hess-21-2187-2017

Rounce DR and 10 others (2023) Global glacier change in the 21st century: Every increase in temperature matters. **Science** (1979) 379, 78–83. doi: 10.1126/science.abo1324

Taylor C, Robinson, TR, Dunning S, Carr JR and Westoby M (2023) Glacial lake outburst floods threaten millions globally. **Nat Commun** 14, 487. doi: 10.1038/s41467-023-36033-x

Vidaller I and 12 others (2021) Toward an Ice-Free Mountain Range: Demise of Pyrenean Glaciers During 2011–2020. **Geophys Res Lett** 48, e2021GL094339. doi:10.1029/2021GL094339

Vidaller I and 8 others (2023) The Aneto glacier's (Central Pyrenees) evolution from 1981 to 2022: ice loss observed from historic aerial image photogrammetry and remote sensing techniques. **The Cryosphere** 17, 3177–3192. doi:10.5194/tc-17-3177-2023.

Figure captions

Figure 1. Current spatial distribution of glaciers in central and southern Europe (a). Reconstructed ice thickness of the Aneto, Monte Perdido, and Ossoue glaciers during 2024 (b). Areas of these glaciers that had thickness less than 10 m, 10 to 20 m, and more than 20 m during 2011, 2020 and 2024 (c). 3D orthoimages are derived from point clouds obtained with Unmanned Aerial Vehicles in 2024.

Figure 2. 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 Figure S1 to S3 (a). Present and predicted glacier areas under two scenarios (committed ice loss, RCP4.5) (b). Present and predicted distributions of ice thickness under the RCP4.5 scenario. (c). Predicted ice thickness changes (%) relative to 2024 under three scenarios (committed ice loss, RCP4.5, and extreme temperature year) (d).

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.
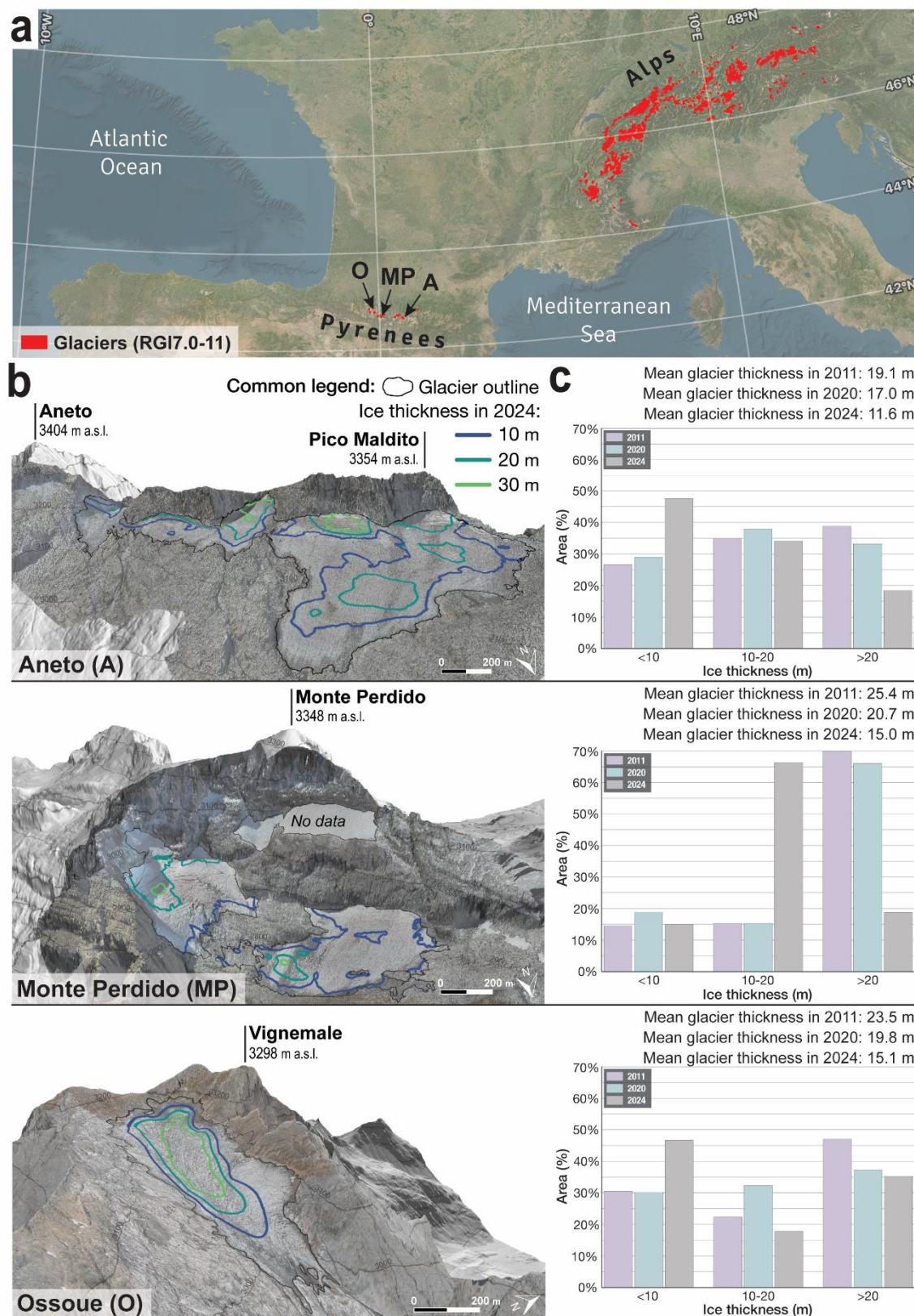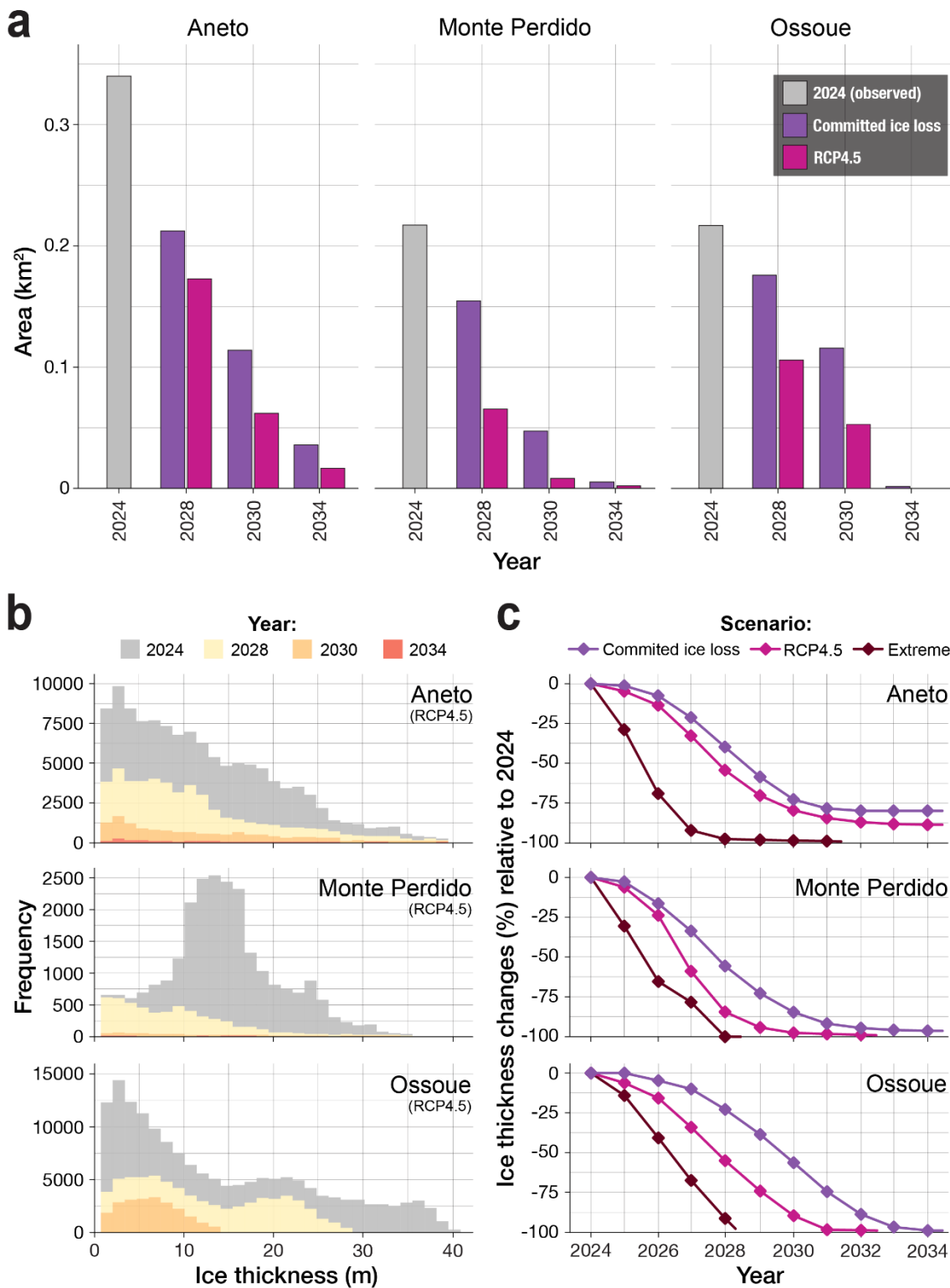
Figure 1

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Figure 2

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