Dear Editor, dear Reviewers:

We are pleased to submit a revised version of our manuscript entitled "The Aneto Glacier (Central Pyrenees) evolution from 1981 to 2022: ice loss observed from historic aerial image photogrammetry and remote sensing techniques" by Vidaller et al where we have incorporated your suggestions and corrections. We thank you very much for the valuable comments that certainly helped to improve our manuscript. Please, note that we have also simplified the title by removing the term "recent" as this was not informative nor accurate enough.

Below we provide a point-by-point response to all comments raised in the reviews. We hope that the revised manuscript now meets the quality standards of *The Cryosphere*. I will be happy to answer any question you might have regarding this study.

We look forward to hearing from you.

Sincerely,

Ixeia Vidaller and co-authors

<u>Referee 1 Evaluations (hereafter RC1):</u>

General comments

I find this paper to be a convincing contribution to the current state and recent evolution of the Aneto glacier in the Pyrenees. This is a well-studied glacier, with many previous studies, but the current paper puts together an impressive and updated series of datasets. The work is nicely and extensively illustrated as well.

The methods are consistently explained and documented.

On the hind side, I think the results read with some difficulties due to the emphasis in including lots of data for each statement. The text could be made simpler by making better use and focusing on the trends shown by the figures. If needed, the detailed data of area, thickness and depth changes can be included in tables in the supplementary material.

From a methodological point of view, this work integrates data from gridded data sets (DEM), point clouds (UAV DEM) and transects (GPR) with variable spatial footprints. Maybe consider a resampling of the different datasets to a common gridded base, which would make the integration easier, both in terms of the representation of the results in the figures and maps, and in the explanations in the results and discussion sections.

I consider the paper would benefit from minor correction prior to publication.

Answer (hereafter A):

We thank RC 1 for a very constructive and positive review of the manuscript. Indeed, there are lots of data for each stamen, so to avoid repeat these data in the text and in table, we have move surface and thickness changes to the *Supplementary material*.

Also, we certainly agree on the limitations resulting from the different spatial resolution of the methods used in this study. Thus, and with the aim of avoiding possible misunderstandings, we have modified some figures to facilitate their interpretation. Please review Figures 2, 3 and 5 on this regard. Following the RC1 recommendation about the text in figure captions, we have better described the results of the hypsography changes in Figure 3 caption:

> *"Figure 3: (A) Thickness loss of Aneto Glacier from 1981 to 2022. In the upper map, the black line delineates the glacier in 2022 while grey line represents the glacier in 1981. The arrow indicates the north direction. (B) Distribution of thickness loss considering elevation bands of 20 m."*

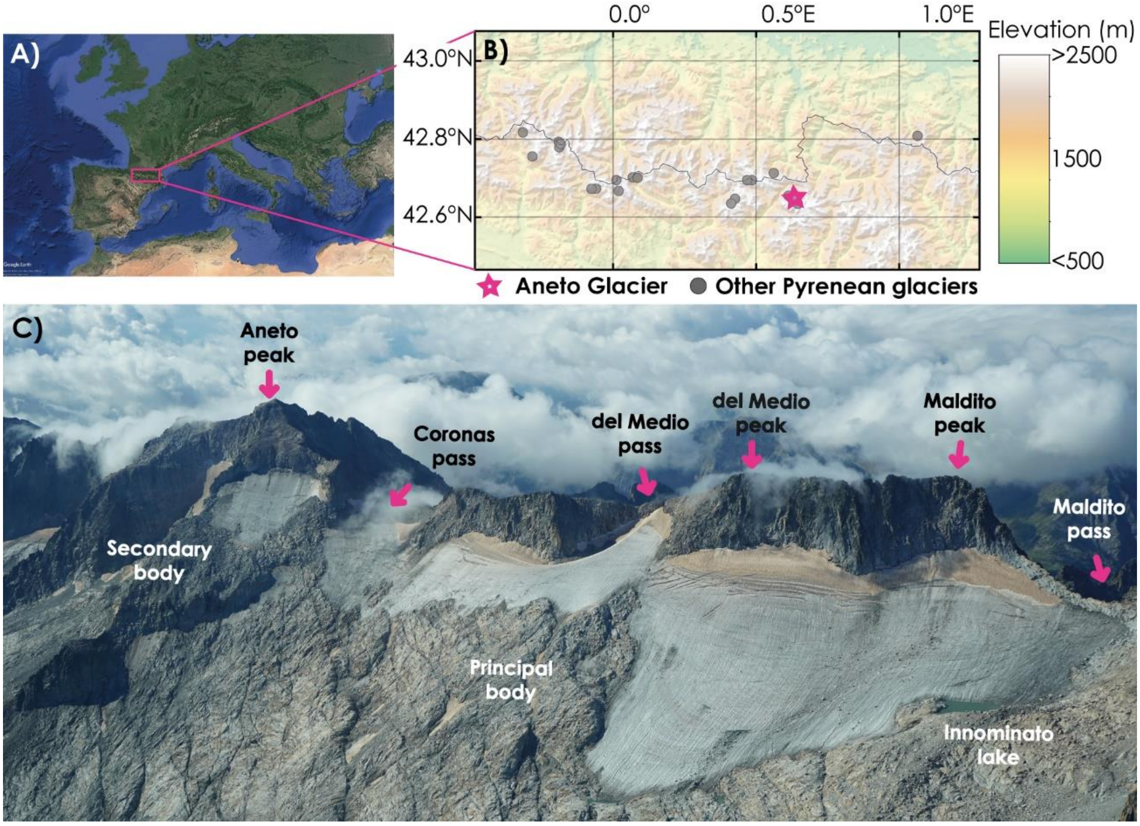
In-line comments

Line 47. Here and elsewhere glacier areas should be expressed in km^2 (WGMS, 2009). While it is not incorrect to use ha, km^2 communicates the relative size of the studied glacier

A: Thank you for the appreciation. Due to the small size of all Pyrenean glaciers, it is common to use ha as the unit of measure, as in Rico et al. (2017) and Vidaller et al. (2021), for example. However, in light of your comment, we have included the area in km^2 in parentheses, to make it easily comparable to other previous published data.

Figure 1. I suggest including political boundaries in A) and keep the same line type in B). In B) increase the hillshadding so that the relief is highlighted. Also, I would expect glacier outlines rather than point indicating glacier position here (handle line thickness to make glacier visible at this scale). I think C) is a nice and very clear way to indicate the main geographic features of the study area.

A: We discard adding political boundaries since they could overload the map of Europe too much and compromise the clarity. Therefore, we prefer not to include them in A). Nevertheless, Figure 1B) includes the Spanish-French border. However, if RC1 still thinks that borders are needed in A), we are open to focus this map on a smaller area. Since the glaciers of the Pyrenees are too small (all <50 ha), we decided to assign points to each site instead of marking their surfaces to better identify their location in a 50 x 200 km map.



"Figure 1: Location of the Aneto Glacier. (A) Map of Europe, with the pink rectangle delimiting the central part of the Pyrenees. © Google Maps (B) Topographic map of the central Pyrenees; the glaciers in this area are marked with grey dots and the location of the Aneto Glacier is marked with a pink star. (C) An aerial photo of Aneto Glacier in summer 2021. The main reliefs surrounding the glacier are indicated."

Line 108. I suppose this is the mean annual isotherm, please clarify. Consider including a climograph with the station data. This kind of graph clearly shows the magnitude and seasonality of the main climatic variables. Finally plot the stations location in Figure 1 B).

A: Amended as suggested. The Renclusa station is not visible in Figure 1C and, due to the extent of map in Figure 1B, the location of this station overlaps with the location of the glacier. In such a situation, we cannot plot the Renclusa station location.

On the other hand, we have finally decided not to include climate diagrams as an additional figure since the number of figures in the manuscript is already too large. However, in response to a comment made by RC2, we have enlarged the text with climatic information to fill the indicated gap. Still, the altitude difference between the Renclusa station and the glacier and the short period when observations are available in the Aneto station (2018-2022 years), precluded an in-depth analysis of these climatologies. Therefore, we focus our attention on the evolution of the glacier. This is show in the main manuscript as (L127-130):

"Mean annual temperature for the period 2007-2022 was 4.6 ºC at the weather station of Renclusa hut (2,140 m a.s.l.), meanwhile the mean temperature for the same period in the ablation season (June-September) was 11.6 ºC. 2022 was an especially warm year, in which annual mean temperature was 5.2 ºC and the summer mean temperature was 12.1 ºC (data from the AEMET database)."

Line 162. Do you mean mountain areas? Or heterogenous in terms of ground cover? Please clarify.

A: Thank you for the appreciation. We mean mountain areas, in terms that is an irregular terrain with changes in elevation and slopes.

For clarification, we have reworded the text as follows:

"shows equivalent accuracies for working in highly heterogeneous areas" → *"shows equivalent accuracies to work in this area".*

Line 204-208. While a glacier "true" area is better approximated by a 3D approach, most glaciers inventories report projected areas and this is the standard approach (WGMS, 2009) so, by making this choice you make your data harder to integrate with most other regional and global datasets.

A: We agree with this comment and understand the difficulty to integrate our data with global datasets but, at the same time, the small size of Pyrenean glaciers forced us to use the 3D area, thus gaining a more accurate representation of their real surface. To facilitate comparison with other datasets and following this reviewer suggestion, we have included in Table 1 (now in the *Supplementary Material Table S5*) another column with the 2D area data.

Table S5: Main characteristics of the Aneto Glacier over the years of the study.

Year		Area 3D (ha/km^2)	Area 2D (ha/km^2)	Glacier front (m a.s.l.)	Area changes since 1981 (%)	Area changes since 1981 (% yr^{-1})
1981		135.7/1.36	115.49/1.15	2,828	–	–
2011		69.3/0.69	62.59/0.63	2,939	−49.0	−1.6
2020	Principal	43.97/0.44	47.8/0.48	3,011	−61.7	−1.6
	Secondary	3.82/0.38	4.2/0.04	3,170		
2021	Principal	41.99/0.42	46.1/0.46	3,014	−63.1	−1.6
	Secondary	3.44/0.03	3.9/0.04	3,170		
2022	Principal	38.29/0.38	44.6/0.45	3,026	−64.7	−1.6
	Secondary	2.9/0.03	3.52/0.03	3,170		

Line 219-221. Again, not the most standard approach. Because mountain glaciers usually shrink in area as they thin, it is customary to use the mean area of the period to convert the volume loss into mean thickness change (e.g.: Berthier and others, 2004; Falaschi and others, 2022).

A: This point led us to interesting discussions. We agree that glaciers generally shrink in area as they thin. As in a recent previous work carried out in the Pyrenees (Vidaller et al., 2021), we intend here to determine the mean ice thickness loss considered only changes within the most recent surface. For example, for the period 1981-2022, we had only considered ice thickness loss within 2022 surface, to avoid overestimations. If we considered the glacier extent at the beginning (or mean extent) of these periods, we would take into account ice loss in areas where no ice was present during the whole period when calculating mean ice thickness.

Table 1. I would place this table in supplementary material and include an area, or even better a cumulative area change plot in Figure 2.

A: Amended as suggested as Table S5. Also, a cumulative area change plot in Figure 2.

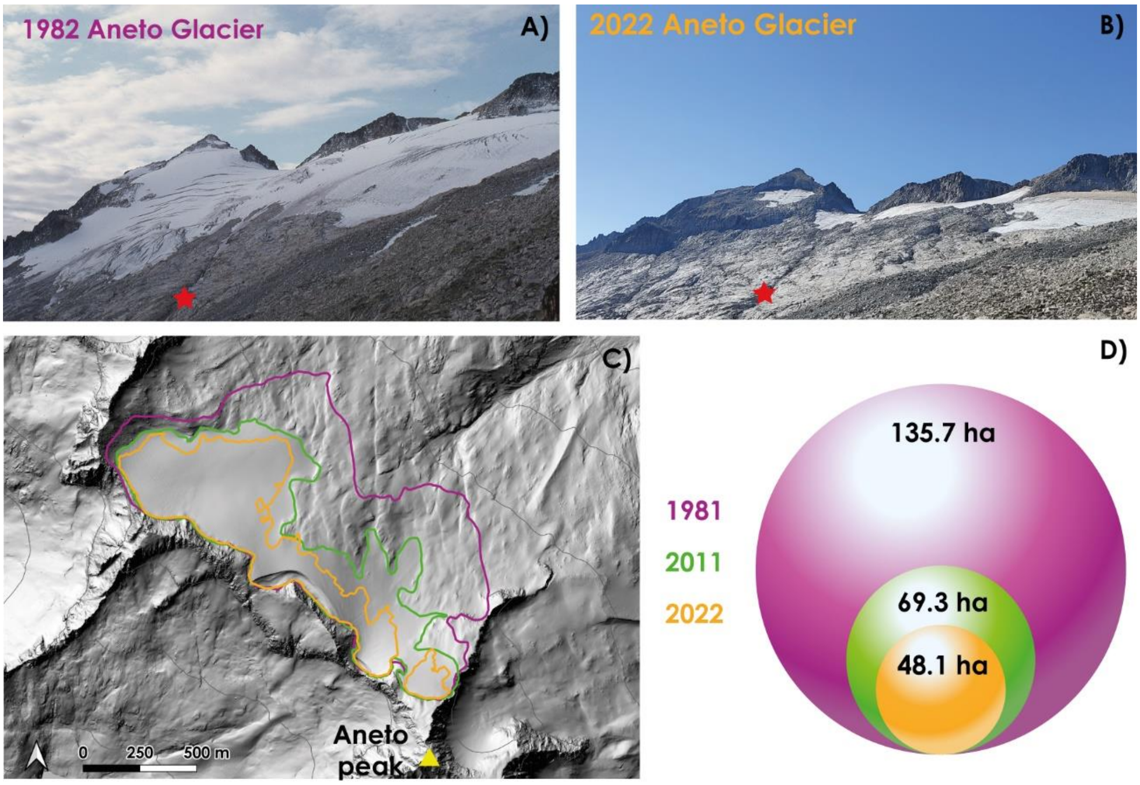


Figure 2: Appearance of the Aneto Glacier during the study period. (A) Photo (Fernando Biarge, Fototeca DPH) corresponding to Aneto Glacier in 1982. (B) Photo corresponding to Aneto Glacier in 2022. The red stars refer to the same location in both photos. (C) Map showing differences in the area of the glacier during the study period; the purple line delineates the extent of the glacier in 1981, the green line in 2011, and the orange line in

2020. The shading of the terrain was calculated from the 2011 LiDAR. The yellow triangle represents the summit of Aneto peak. (D) Cumulative area change plot of the Aneto Glacier for the years 1981 (purple), 2011 (green) and 2022 (orange).

Figure 2. B) I would invert the position or the year labels on top so that they follow the glacier recession as represented in the map (2022 2011 1981). There appears to be a moraine in front of the glacier, probably a LIA feature marking the glacier extent. With a slight offset to the west of the represented area, you could include the entire area encompassed by this moraine and put in even larger perspective the recent area loss.

A: Yes, that is the LIA moraine and since it appears clearly in Figure 2C that covers a larger area than Figure 2B. The glacier extent lost since the LIA is well documented in the Pyrenees in Rico et al. (2017) and summarized in lines 415-417 as follows:

> *"Although this work focuses on the period 1981-2022, the glaciers of the Aneto-Maladeta massif had about 610 ha at the end of the LIA, so they lost about 338 ha from 1850 to 1984 (Rico et al., 2017)."*

Line 265. I made a general comment regarding the different footprints of your data. If you use uniform grid base for your data this sentence could simply read: "Between 1981 and 2022 the mean ice thickness loss was 30.51 m". Also, if you use mean area (see comment of Line 219-221), you can remove the line between brackets.

A: Instead of using raster data, which would require either filling gaps in areas without observations or reducing the size of raster cells to achieve the same resolution as coarser observations, we compared 3D point clouds directly with CloudCompare's M2C3 tool. In addition, as we calculate ice thickness differences within the smallest surface (the most recent surface of the study period in each case), we prefer to keep the information in parentheses. Therefore, the readers will be aware about ice thickness differences considering the biggest glacier surface (the oldest surface of the study period in each case) of each period are taken into account. Also, this information was show in Table S6 in *Supplementary Material* as:

Table S6: Glacier thickness change over the year of the study.

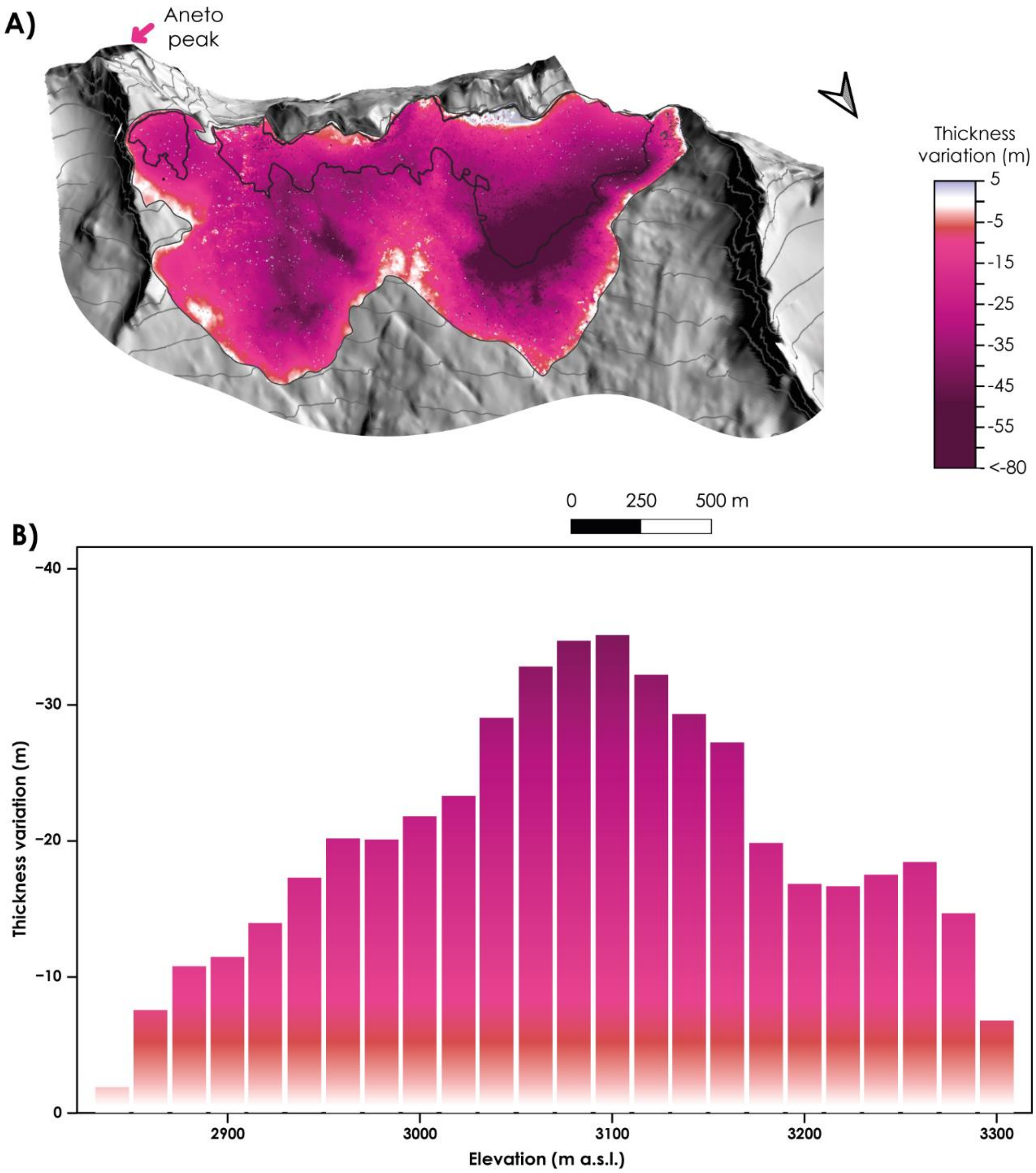
Method of calculation	1981-2022 (m / m yr^{-1})	1981-2011 (m / m yr^{-1})	2011-2022 (m / m yr^{-1})	2020-2021 (m)	2021-2022 (m)
Slope-perpendicular	-30.5 / -0.7	-17.8 / -0.6	-12.6 / -1.1	-1.5	-2.7
Height change	-45.3 / -1.1	-26.5 / -0.9	-18.6 / -1.7	-2.2	-4.8

Line 275-277. This line could be removed if you include a mass balance time series graph in Fig. 3.

A: We preferred to keep this sentence and not include the mass balance time series graph because it could span over periods of varying duration, which would hinder realistic identification of temporal trends. Therefore, we haven't made any change in this regard.

Figure 3. Your color scale is not very good here. I think you should use a single color ramp, with linear intervals, from white to dark (0 to -80 m). B) I would recommend a longitudinal profile from the headwall to the glacier front, rather than a frequency distribution.

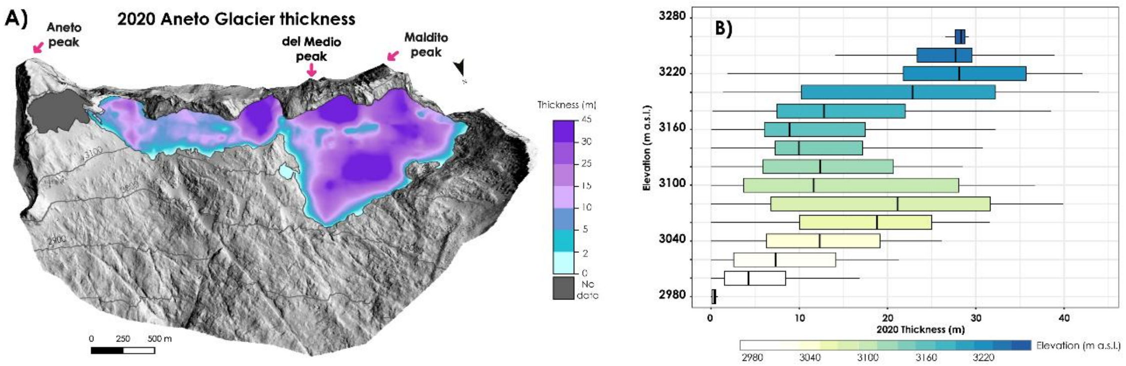
A: The change in B) was included as suggested. In contrast, we did not change the colour scale in A) since we prefer want to keep the same colour scale as in previous work (Vidaller et al., 2021). In this way, the colour scale represents in white the zone without changes, red colours when the differences in thickness go from -5 to -7 m, and a colour ramp from red to dark purple when the differences are among -7 to -80 m.



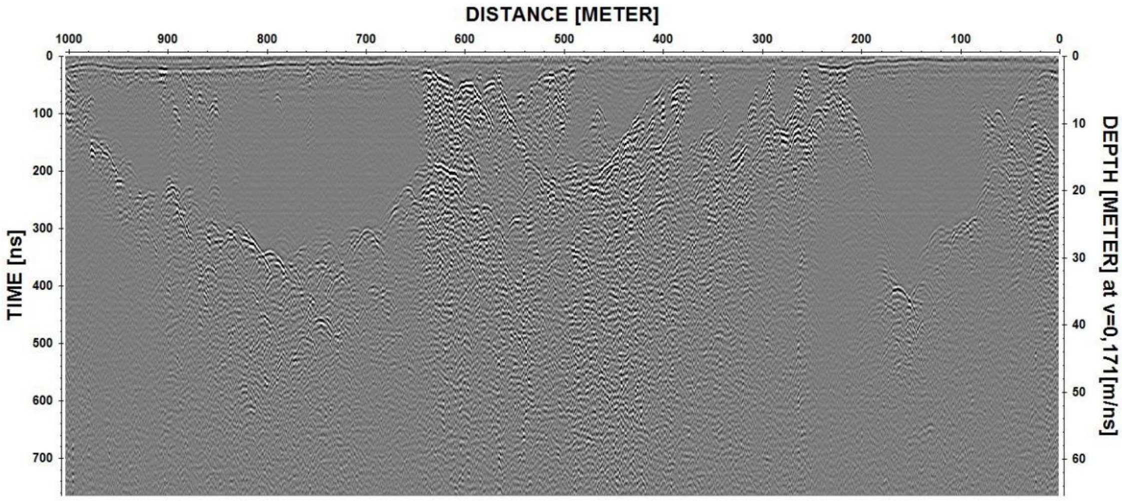
“Figure 3: (A) Thickness loss of Aneto Glacier from 1981 to 2022. In the upper map, the black line delineates the glacier in 2022 while grey line represents the glacier in 1981. The arrow indicates the north direction (see Supplementary Material Figure S3 the maps for each period of the UAV surveys). (B) Distribution of thickness loss considering elevation bands (mean of each band) of 20 m.”

Figure 4. A) Again colorscale. You have a linear variable from 0 to 45 m. The most appropriate approach is a single color, linear, color ramp. By using several colors, you make the interpretation harder. Two colors would be useful if you had positive and negative values, which is not the case here. B) Again consider using a longitudinal profile here. Note you would share a distance axis and could even combine both plots in a single graph.

A: Similar to Figure 3, we retained the colour scale, this time with different colours, due to in Figure 3 we show ice thickness loss, meanwhile in Figure 4 we represent remaining ice thickness. This colour scale is informative in terms of ice accumulation and corresponds to snow depth cartographies in mountain areas (Revuelto et al., 2014). We consider that using multiple colours helps potential readers to easily identify areas with different ice depths. Regarding the use of longitudinal profile, we think that, given the shape of the glacier with much shorter distances to the east than to the west, that type of representation could be a source of confusion. In any case, and considering recommendations of RC2, Figure 4B is now changed to a boxplot that shows mean ice thickness loss in each altitudinal band. We have also included a representative GPR profile in *Supplementary Material* (Figure S5) to support this figure.



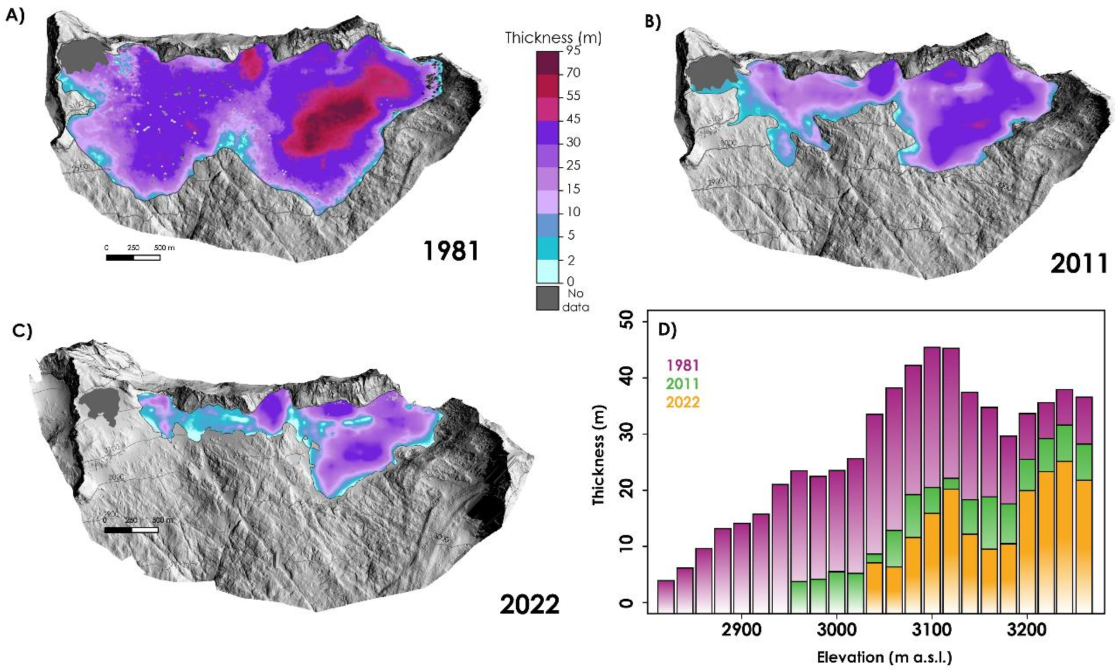
"Figure 4: Ice thickness of Aneto Glacier in 2020. In map (A), the blue colour represents the zones of lesser ice thickness that are about to disappear, in contrast to the purple colours that represent the greatest ice thickness. The secondary body of the Aneto Glacier is coloured grey because no data are available for this glacier body and therefore no interpolation is possible. The boxplot (B) shows the mean glacier thickness in 2020 for each elevation band (20 m). A GPR profile is show in Supplementary Material as example of longitudinal radargram (SE-NW) of the glacier (Figure S5 in Supplementary Material)."



"Figure S5: Radargram 1062, representative of the western area. The radargram is represented from SE (0 m) to NW (1000 m), so, from the high part to the lower part of the glacier."

Figure 5. Consider longitudinal profile here too. A stack of the three thickness profiles is the simplest way of showing the absolute and relative thinning. See comment in Fig. 4 regarding colorscale.

A: See previous comment about the appropriateness of a longitudinal profile. We have completed this Figure by adding a plot that represents the mean ice thickness loss for each altitudinal band for 1981, 2022 and 2022 years to better compare the changes in ice thickness among the three studied years (now Figure 5D).



"Figure 5: Reconstruction of the ice thickness of Aneto Glacier at different times during the study period. (A) shows the thickness in 1981, (B) shows the thickness in 2011, and (C) shows the thickness in 2022. The blue colour represents the zones of lower ice thickness that are about to disappear, in contrast to the red colours that represent the greatest ice thickness. The secondary body of the Aneto Glacier is coloured grey because no data are available for this glacier body and therefore no interpolation is possible. (D) Comparison of the thickness of Aneto Glacier in 1981, 2011 and 2022, structures in elevation bands of 20 m."

Line 318. Remove "as is well known" and consider including a reference for this statement.

A: Amended as suggested. Added reference: Palacios et al. (2022). Now the sentence is shown as (L372-373):

"Glaciers erode the surface beneath the ice mass so that the subglacial topography is not a flat surface (Palacios et al, 2020)."

Line 324-328. Note how your first sentence is part of methods and the rest discussion or methdos. This paragraph of the results should start in line 328.

A: Amended as suggested. These lines have been moved to the methods and adapted to the text.

Line 336. "The rate of area loss was uniform over time". Maybe use an average here? Also note the number of figures between lines 336 and 343. A multiple line plot could do the job here.

A: Following this recommendation, we now report the average value of area loss as follows:

"(−2.2 ha yr−1, −2.2 ha yr−1, −2.1 ha yr−1, and –2.1 ha yr−1 from 1981 to 2011, 2020, 2021, and 2022, respectively)" → *"(-2.2 ha yr^{-1})"*

Since the total number of figures in the manuscript and the supplementary material is already 10, we prefer including these numerical values in the text instead a new plot, as they equally provide information about the observed temporal trends.

Lines 348-537. Consider a synthesis plot here (i.e.: Fig. 3 in Dussaillant and others, 2019), which allows the comparison of several datasets with different observational periods.

A: In these lines we wanted to discuss the specific glacier mass balance values observed in the Pyrenees with different techniques and time periods compared to the specific mass balance of the Aneto Glacier. Synthesis plots such as the one presented by Dussaillant et al. (2019) for the Andes, would be useful in a "regional" Pyrenean mass balance analysis but not necessary for a detailed study on a single glacier.

References

Berthier E, Arnaud Y, Baratoux D, Vincent C and Rémy F (2004) Recent rapid thinning of the "Mer de Glace" glacier derived from satellite optical images. Geophysical Research Letters 31(17). doi:10.1029/2004GL020706.

Dussaillant I and others (2019) Two decades of glacier mass loss along the Andes. Nature Geoscience 12, 802–808. doi:10.1038/s41561-019-0432-5.

Falaschi D and others (2022) Increased mass loss of glaciers in Volcán Domuyo (Argentinian Andes) between 1962 and 2020, revealed by aerial photos and satellite stereo imagery. Journal of Glaciology, 1–17. doi:10.1017/jog.2022.43.

WGMS (2009) Attribute description. World Glacier Monitoring Service, Zurich, Switzerland.

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