

Responses to Anonymous Referee #1

This study presents a detailed analysis of ice loss in A294 Ice Cave over the last 12 years (2009–2021), with implications for climate change impacts on cave ice deposits. The authors use a combination of temperature monitoring, precipitation data, and ice loss measurements from historical cave surveys, offering valuable insights into the unprecedented nature of recent melting. The authors successfully place their results within the broader framework of climate reconstructions and ice retreat trends in the Pyrenees.

We thank referee #1 for reviewing the manuscript and comments. Below we respond to the suggestions (text in green).

Suggestions for areas of improvements:

1) The temperature reconstruction method using quantile-based gap-filling should include a validation step against external datasets beyond Góriz and La Renclusa stations.

The authors consider it unnecessary to test additional stations beyond those used in this study, given the very low percentage of missing data in the series (<1%) and the strong performance observed during the independent validation period. In fact, Barca et al. (2024) emphasized that the method used to fill temperature gaps has a minimal impact when data gaps are below 5%, even in analyses of extreme events.

2) More details on uncertainties associated with ice retreat rates would be helpful. For example, specifying potential sources of error in survey comparisons (e.g., instrument precision, human factors) would strengthen confidence in the retreat estimates.

In the case of the speleological survey from 2019, the precision associated with each measurement (n=68) is ± 1.5 mm (Leica Disto X310). In contrast to clean congelation ice, where the laser can penetrate the ice over several meters (e.g., Bartolomé et al., 2023) our measurements indicate this is not the case in firn. The points from which the measurements were taken are well identified in the field, but potential errors may arise from the inclination of the laser line when taking the measurement. Normally, several measurements are taken to ensure that there are no major variations. This human error could result in inaccuracies of up to 5 cm, which, for distances greater than 10 m, would represent less than 0.5% error (measurements from Northern (1) and Ice Front (3), Fig. 3d in the manuscript), and slightly more for Rock Corner (2).

Luetscher et al. (2005) used a comparison of historical surveys to highlight changes over time, as it is a simple method to observe ice changes. Of course, surveys carried out by different individuals may vary slightly depending on the level of detail, the skill of the surveyor, and human measurement error. In fact, in the 1974 topography, we noticed an error in the orientation of the north arrow. However, the ice loss is so evident that even when considering only a rough outline of the cave, the measurements taken in successive surveys are consistent with those reported by Belmonte et al. and with the ice retreat measured in this study. We will add some sentences about the uncertainties of measurements.

3) Some sections, particularly those discussing temperature trends and ice retreat, could benefit from a clearer distinction between observed data and modeled inferences. For instance, in section 5.1, the link between external temperature anomalies and ice melting rates could be more explicitly quantified. Including R-squared values or additional statistical measures would strengthen the argument.

We agree on this point; however, due to the resolution of the measurements and the comparison of surveys (n=3), it was difficult to obtain the same year-by-year resolution for melt rates and the increase in temperature/precipitation. This limits our ability to perform correlations similar to those established with other parameters derived from the weather station and the cave's internal sensors. In this sense, the discussion on this topic could only be linked to what is addressed between lines 416 and 426 of the manuscript, in section 5.1, regarding melting rates depending on the sector of the cave. Without consistent resolution in both measurements and environmental parameters, it is challenging to establish any correlation beyond indicating that melting rates have increased in recent years. We will add a few lines in the Methods section specifying which annual rates were inferred from cave surveys and which were obtained from direct measurements inside the cave.

4) Linking the cave's ice retreat to regional hydrology or ecosystem impacts could provide further relevance beyond cryosphere studies.

Thank you for this suggestion. However, the retreat or even the complete disappearance of this or all ice caves in the Pyrenees, would not have a significant impact on the local and regional hydrology. In fact, López-Moreno et al., (2020) calculated the water storage capacity of Pyrenean glaciers (Rico et al., 2017) and estimated that their contribution represents only 0.02% of the 3000 hm³ storage capacity of the 13 major dams built in the Central Pyrenees (López-Moreno et al., 2008); 0.04% of the 1500 hm³ annual average of water stored as snow in the Central Spanish Pyrenees; and less than 0.01% of the 7300 hm³ long-term mean annual runoff (1950–2006) from the main Pyrenean tributaries (López-Moreno et al., 2011). Thus, the hydrological contribution of Pyrenean glaciers is minimal, and their disappearance would not impose a significant additional pressure on water resources. Ice caves represent only a very small percentage of the cryosphere in the Pyrenees.

Regarding the ecological impact, it primarily occurs at the cave ecosystem level. Ruiz-Blas et al. (2023) identified the prokaryotic and eukaryotic microbial communities inhabiting the ice in A294 at different ages of ice deposition. This study simulated the in vivo effects of climate change, examining how a 4°C temperature increase would affect microbial populations. The results revealed molecular modifications, identified several proteins and enzymes associated with cellular adaptation to higher temperatures, documented the influence of temperature rise on biogeochemical cycles, and detected proteins expressed at elevated temperatures that could serve as climate change indicators. All this information will be briefly included in Section 5.3 of the manuscript.

Figures & visual presentation

Figure 3: The cave survey should have clearer legends to indicate differences in retreat rates across different sectors of the cave. In panel (d) the ice limit for 2011 is shown but not for 2012. Why there are no plan views for all ice deposit limits shown in (d)?

We outline this suggestion below.

“The cave survey should have clearer legends to indicate differences in retreat rates across different sectors of the cave.”

We will enlarge the legend and add more information. Additionally, in the topographic maps, we will enlarge the red lines that indicate the measured points.

“In panel (d) the ice limit for 2011 is shown but not for 2012.”

The positions in Figure 3d have been approximately reconstructed based on the topographic surveys conducted in 1974, 2012, and 2019, as well as photographic sequences. To avoid overcrowding the figure with additional lines, and given that the position of the deposit in 2011 and 2012 was very similar, we will add a label "2011–2012" to the pink line.

“Why there are no plan views for all ice deposit limits shown in (d)?”

No additional topographic surveys were carried out during these monitoring years; only those from 1974, 2012, and the most recent one from 2019 exist. We conducted the 2019 survey after learning about the existence of the 1974 topography, considering it would be valuable to have a new survey for comparison purposes.

Figure 4: I suggest using “Twelve years ...” instead of “12 years...”

We will change 12 years by twelve years

Figure 8: (a) The caption is unclear. Light blue bars are visible in other months than April to November. The dark blue lines are intended to represent the number of rainy days (April to November), but the curve includes data from months outside this period. The same applies to the total rainfall. Why are the Y-axes titled “April–November” when the plots show wider intervals? Are the last two plots (nr of rainy days and total rainfall) depicted in Fig. 8a necessary, given that they are also shown in Fig. 8b and in panel (a) there is a lack of correlation?

We will clarify the footnote. We will add dashed vertical lines in the figure to clearly separate the April–November periods, and we will double-check the dates for both series.

Regarding the second point, we plotted both curves together with the temperature during the closed phase and the Thaw Index, to visually show the increase in temperature (closed phase), and the rise in both the amount and frequency of precipitation during the monitored period. Given the inflow of liquid water into the cave during the closed phase is the main mechanism driving ice melt and the increase in cave temperature, we would like to keep the figure as it was.

Figure 9: Enhance text visibility in panels (e) and (f) by employing larger white font.

We will increase the font size of the text in figures (e) and (f).

Figure 11 is highly informative, but it is quite dense. Can you think of some changes that might improve readability? For (h), orange (Fall) is not the best color as is almost impossible distinguish from red.

We will adjust the colors for fall, summer, and annual in Fig. 11h to enhance readability. To simplify and reduce the number of curves, only the moving averages will be retained in Fig. 11f.

Minor editorial issues:

Lines 80-82: Several additional factors influence cave temperature during the “closed” phase, not solely the heat exchange during winter. The sentence requires revision for clarity, considering the information provided in lines 82-85.

We will rephrase the lines 80-82 taking into account the lines 82-85

Line 183: The (dd/mm/aa) format is used, but at line 187, authors use the (dd/mm/yy) format. Choose and maintain one format consistently.

We will check the consistency along the text and we will homogenize the format

Line 594 (Acknowledgements): should be “... foe for ..” or it should only be “for”

We will delete “foe”

References: There are minor formatting inconsistencies in the list, which should be checked for uniformity.

We will correct the inconsistencies in the reference list.

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