Reviewer #1

Dear Editor, Dear Authors,

The manuscript (egusphere-2022-349) presents a detailed speleoclimate monitoring in a mountain permafrost area and a unique cryomineral association. The study is principally well-written, follows a logical structure and the illustration material is of high-quality. The study provides the first report about the co-occurrence of cryogenic calcite and gypsum and the presented $\delta^{34}S$ data of cryogenic gypsum are also novel. Therefore, I strongly support the publication of the study following some minor revision.

- ➔ We thank referee #1 for the detailed review and the positive comments on the manuscript. We add here our responses while the modifications to the text and figures according to reviewers' comments will be in the track-changes version of the manuscript after the editor's decision.

Major comments:

The title of sub-section 3.3 needs revision. The current title is misleading. The section is not about sampling but about the methodology of the applied mineralogical and geochemical analyses.

- ➔ We will change the title of sub-section 3.3 from "Mineralogy, water and mineral sampling" to "X-ray diffraction, ion chromatography, and sulphur isotopes"

Done (Line 231). We have changed the title of sub-section 3.3 by "X-ray diffraction, ion chromatography and sulfur isotopes".

It is also quite strange that there is not any reference for the applied methods. Please consider citing the proper references in the revised manuscript.

- ➔ In general, these methods are all well established. Nonetheless, we will include in the revised manuscript some papers using the same methodology for X-ray diffraction (e.g. Rodríguez-Salgado et al., 2021) and sulphur isotopes (e.g. Giesemann et al., 1994).

Done (Lines 237 and 245). We have added the cite of Rodríguez-Salgado et al., 2021 that used the same X-ray diffraction method, and Grieseman et al., (1994).

An additional related comment is that it is stated in section 4.4.2 that "*XRD analyses yielded ...gypsum, calcite, ... pyrite and goethite,*" however no evidence is presented. I suggest adding some annotated diffractograms (at least in a supplementary document) in the revised version.

- ➔ We will include the XRD results in a supplementary document of the revised version and the figure will be referenced in the text.

Done. We have included a supplementary material with the diffractograms, and we cited that material in line 235 ("Fig. S1")

Minor comments:

lines 73-78: This sentence somehow doesn’t fit to the other parts of this paragraph. Please consider omitting it or moving it to another place where it fits better.

- ➔ The sentence will be moved to the end of line 67 and re-phrased. On the other hand, we will update this section with recent publications.

Done. We have moved the sentence to line 70-75: “Temporal and spatial changes in past permafrost distribution have been identified using speleothems (stalagmites, flowstones) in high-latitude and polar regions (e.g., Vaks et al., 2013, 2020; Moseley et al., 2021; Li et al., 2021) as well as in mid-latitude regions (e.g., Lundberg and McFarlane, 2007; Fankhauser et al., 2016; Lechleitner et al., 2020)”, and we added a new cite (Li et al., 2021)

line 210: I suggest expressing the lapse rate as 5.5°C km^{-1} because the current expression is confusing. It suggests 0.55°C change by 0.01 m.

- ➔ We will change the expression as suggested.

Done (Line 222): We have changed the expression by 5.5 °C km^{-1}.

line 214: Please capitalize “Midi”

- ➔ We will capitalize it.

Done (Line 227)

line 244: Maybe “Bragg-Brentano geometry” or “θ/2θ-mode” would be the appropriate expression.

- ➔ We will change as suggested.

Done (Line 237)

line 290: Please explain it a bit more what is “an increase of ~+1.5 ºC”. A trend value? or the difference between the mean of a certain period at the beginning and at the end of the record? or what?

- ➔ The temperature increase refers to the trend of the temperature series since beginning of the record. We will rephrase this sentence to *“The PMBS MAAT record (Fig. 3b) shows a warming of +1.5 ºC since the beginning of the measurements in 1882”.*

Done (Line 304-305). We have rephrased the sentence by “The PMBS MAAT record (Fig. 3b) shows a warming trend of around +1.5 ºC since the beginning of the measurements in 1882.”

line 299: Please check the dimension.

- ➔ We will change “kh/m^2” by “kWh/m^2”

Done (Line 313)

lines 321-329: I cannot see the usefulness or necessity presenting the correlation year-by-year in these lines? I suggest simplifying this part similarly to lines 334-337.

- ➔ The text about correlations will be simplified in the revised manuscript (lines 322-331) but we prefer to keep the seasonal correlations since there are important differences between winter and summer regarding the synchronicity of external and internal temperatures.

Done (Lines 334-343). We have simplified the paragraph "Sensor T5air (2017-2021, Fig. 5d) in room B also shows a high correlation and significant correlation (0.82, $p<0.0005$) with the outside temperature. During the major cave cooling that takes place between the end of October and May and the correlation is significant and ranges between 0.68 to 0.84. During summer and part of fall, the correlation decreases notably (-0.23 to 0.76). Sensor T11air (2018-2021, Fig. 5d) is partly protected from the air flow and shows lower a correlation (0.69, $p<0.001$) despite being located in a well-ventilated gallery (SPD room). Also during the winter months, the correlations are lower (0.49-0.62, $p<0.001$) than in T5air."

line 346: I suggest replacing "small" with "weak".

- ➔ We will include this change.

Done (Line 372)

line 511: I suggest replacing the term "beginning of the Industrial Era" with "late 19th century". As far as I know the Industrial Era begun much earlier than the PMBS record.

- ➔ We will change it to "late 19th century".

Done (Line 556)

lines 546-552: Discordancy without visible detrital layer could also indicate unconformity. A nice example can be found in Fig5 of Hercman et al., 2010 (http://www.geochronometria.pl/pdf/geo_36/Geo36_05.pdf). This type of discordancy/unconformity could be also considered in this part of the discussion.

- ➔ We agree with that observation, thanks for pointing it out. We will add the reference to the discussion section. We are currently working on detailed stratigraphic descriptions, isotopic trends, and the chronology of these deposits to fully understand the meaning of these unconformities and the history of the deposits and this information will be part of a separate publication. At this point of the research, we prefer establishing a robust chronology before discussing the meaning of the unconformities.

Done (Line 593). We have added the reference (Hercman et al., 2012).

line 554: Maybe "These" instead of "Our".

- ➔ Will be changed.

Done (Line 599)

lines 574-575: I suggest omitting the bracketed comment.

- ➔ Will be changed.

Done (Line 621). We omitted it.

lines 676-679: I think that this info could be moved forward in the section.

- ➔ We think these lines are in coherence with the text but more information about mineralogy in the Results section (4.4.2 Mineral deposit) will be added. Besides, lines 676-679 will be rephrased.

In the result section, in the line 497-498 we have added the sentence "Gypsum coating walls or ceilings was not observed."

We also have rephrased the sentence in lines 723-725 by "On the other hand, the absence of gypsum growing on the ceiling or on the walls allows to discard its formation from seepage water followed by precipitation due to evaporation in the cave (e.g., Gázquez et al., 2017, 2020).."

line 723: Please consider adding "ice mass" between the word large and loss to clarify the meaning of the sentence.

- ➔ We will add it.

Done (Line 769).

line 816: I think "Minimax Workshop" should be deleted here.

- ➔ We will remove it.

Done (Lines 858-859).

line 854: Please capitalize the name of the ice cave.

- ➔ We will capitalize it.

Done (Lines 896-897)

line 1034: Please correct the publication date of this paper. 2014 instead of 2013.

- ➔ We will correct it.

Done (Line 1087).

References

Giesemann, A., Jaeger, H.-J., Norman, A. L., Krouse, H. R., and Brand, W. A.: Online Sulfur-Isotope Determination Using an Elemental Analyzer Coupled to a Mass Spectrometer, Anal. Chem., 66, 2816–2819, https://doi.org/10.1021/ac00090a005, 1994.

Rodríguez-Salgado, P., Oms, O., Ibáñez-Insa, J., Anadón, P., Gómez de Soler, B., Campeny, G., and Agustí, J.: Mineralogical proxies of a Pliocene maar lake recording changes in precipitation at the Camp dels Ninots (Pliocene, NE Iberia), Sediment. Geol., 418, 105910, https://doi.org/10.1016/j.sedgeo.2021.105910, 2021.

Reviewer #2

Overall evaluation

The present study documents the presence of mountain permafrost in a cave of the Pyrenees, in a region where it is generally absent. The authors set out to characterise the permafrost conditions in Devaux ice cave and make a well-structured argument for the occurrence of past and present permafrost in a high elevation cave of the Pyrenees, and this assertion is well supported by adequate monitoring and observations of cryogenic cave sediment or morphologies.

The authors present a clear inventory of cryogenic and ice-related geomorphological features in a glaciated cave and attempt to link their spatial distribution to the various microclimatic or hydrological dynamics of the respective chambers/galleries. Substantial conclusions are reached on the causative mechanisms controlling the different ice morphologies reported in specific regions of the cave. To achieve this the authors use a combination of air, rock and water temperature monitoring to demonstrate the influence seasonal ventilation and hydrological activity in cave sector on the resulting cave ice morphologies. The monitoring set up adequately addresses the complex geometry of the cave, identifying both ventilated and poorly ventilated sections, and the attendant air and rock temperature patterns.

Additionally, the authors successfully demonstrate the cryogenic origin of several types of cave minerals using appropriate major ion geochemical analyses and stable isotope geochemistry. With special emphasis on cave gypsum, the authors explore the spatial relationships of the gypsum crystals with surrounding ice and cryogenic carbonate at both macro- and micro-scale, and provide a convincing first report of cryogenic gypsum in a limestone-bedrock cave.

Overall, the authors present a consistent and well-rounded study highlighting the localised nature of mountain permafrost, and those interpretations are well supported by figures of consistently high quality. This study is timely, it fits within the scope of the cryosphere and should be published with minor corrections, as outlined below.

- ➔ We thank referee #2 for the detailed review and the positive comments. We add here our responses while the modifications to the text and figures according to the reviewers' comments will appear in the track-changes version of the manuscript.

Minor comments

A) l90-91: I think this statement could be clarified or rephrased. Because one could argue that ice is also still being preserved at lower elevation sites due to the ventilation-driven thermal anomalies. In the frame of the present study, the main contrast between the mid and high elevation/latitude sites appears to be the contribution of heat conduction to the thermal balance of the cave (positive for the former, negative for the latter).

- ➔ Yes, we agree with the reviewer. The A294 ice cave (cited in the text in the next lines) is a relatively low-elevation cave in the Pyrenees, where the ventilation regime leads to a thermal anomaly that is the cause of the preservation of the ice deposit (Belmonte-Ribas et al., 2014; Sancho et al., 2018). We will rewrite the sentence indicating that ice in high-altitude and high-latitude caves can be preserved also by the presence of permafrost.

Line 99: we have added "by the presence of permafrost" in the sentence.

B) l98-99: The authors mention a little earlier that often ice caves do not inform about the wider thermal characteristics of the bedrock. When citing the example of ice cave A-294 (Sancho et al., 2018), which is located at an elevation of 2238 m asl with positive MAAT at the entrance, the authors could perhaps point out that this is another observation of sporadic permafrost, driven by the cave geometry, rather than by mountain permafrost as in the sense of this study. I would also suggest rephrasing this sentence (see technical comments).

- ➔ We will modify the sentence to stress that the A294 ice cave as well as the other Pyrenean caves represent sporadic permafrost occurrences.

Lines 106-108: We have included the suggestions and rephrase the sentence→ "...and the presence of a few ice caves has only recently been documented (e.g. Sancho et al., 2018a; Serrano et al., 2018) informing about the occurrence of sporadic permafrost. ."

C) l83 - here there could be some additional quantitative description of the cave geometries for the reader unfamiliar with cave exploration (include perhaps cross-section dimensions when mentioning narrow passages?). Figure 2B is good, but the blue-grey bedrock colouring is not included in the legend. For the reader, it could be helpful to add items in the legend, and perhaps colour coding the parts of the cave influenced by different thermal regimes, the outer sector and the inner one.

- ➔ We thank the reviewer for his suggestion to improve Fig 2. We will add the approximate dimensions of the chambers and passages named in the text. We will include the cross-section of some passages in the cave survey. We will remove the grey bedrock colour, will not saturate the figure with colours and we will add colours or symbols for the different thermal regimes. We will also add the limit of active layer, and the possible extension of permafrost from the entrance to the inner part of the cave.

Done. The suggestions were incorporated in the Fig.2

D) l506-513, high thermal inertia - how long does it take to erase a climate signal from about 150 years ago, is the bedrock temperature consistent with the approx 1.5°C temperature rise since 1881 at Bigorre station?

- ➔ Coupling all thermal processes involved in heat propagation through the karst system, including diffusive and advective fluxes, is part of our ongoing research and beyond the scope of this article. Assuming heat transfer by diffusion alone, an external warming trend of c. 0.01°C a-1 would rise the cave temperature 200 m below the surface by c. 0.2°C after 150 years, depending on the boundary conditions and physical properties of the rock. These values are remarkably consistent with the Devaux rock temperature of -1.25°C measured at 60 cm depth in the poorly ventilated room D.

Although the calculations above are consistent, we prefer not to include sentences about this, since permafrost in Devaux cave is a combination of cave ventilation and permafrost inherited from the past. Maybe in the future a heat-flow model that couples heat and mass transfer between rock and air in ventilated caves (Sedaghatkish et al., 2022) allow us to better understand and quantity all the factors that contribute to the permafrost in Devaux.

E) l315 - figure 5d, the air temperature variations at T11 and T5 (and T2) could be discussed in additional detail (at line 481 for instance). I think that, in summer, the lower correlation between the (T) loggers and the outside air (T) can also be explained by the influence of the outward air flow, whereby air temperature variations are more muted than during the winter inward air flow regime. Could the authors comment on this?

- ➔ We agree with this comment. During summer, the cold and dense air flows out of the cave due to the temperature difference between outside and inside air. Moreover, the heat supplied to the cave by the river can also modify the cave air temperature, lowering the correlation between both temperature sensors. In winter, although we do not have observations, a chimney effect is expected and relatively warm air masses with respect to the external temperature move towards hypothetic shafts located at higher elevations than the cave entrance, in the southern face of the Monte Perdido massif. Thus, this process drags cold outside air into the cave. Also, the absence of liquid water in the river reduces thermal disturbances. We will add a sentence about this issue as suggested by the reviewer.

We have introduced these changes in the lines 517-524. We added the following text "Devaux cave is characterized by mean air and rock temperatures lower than the external mean annual temperature (Fig. 5). The low cave temperatures in winter lead to an inward airflow and an associated negative thermal anomaly behind the entrance zone. On the contrary, during summer the cold and dense air flows out of the cave due to the temperature difference between outside and inside air. The heat supplied to the cave by the river also influences the cave air temperature by exporting thermal energy from the cave during winter."

F) l315 - rock temperature sensor R2 is included in the results and discussion with 'well ventilated' parts of the cave, yet it lies in the vicinity of a massive ice body, near the Terminus Devaux, suggesting that there is perhaps little air flow there. Indeed, at line 331, the authors mention that the chamber morphology shields them from the air flow. Perhaps the discussion of its record could be moved to the 'poorly ventilated' section?. Could the authors comment on the lag between the seasonal tock temperature maxima and minima compared to the external and cave air temperature? Given the thermal conductivity of limestone and a sensor depth of 60 cm, does the record support a simple heat conduction model?

- ➔ Temperatures recorded by the R2rock sensor are significantly higher and more variable than in the poorly ventilated room D. These data are also consistent with the measured cave air temperatures and suggest that the cave's ventilation dynamics may affect this area more strongly than anticipated.
- ➔ Regarding the lags between cave air, rock, and external temperatures, it is important to note that in room K (Terminus Devaux), maximum temperatures recorded by the T12air sensor show a lag with respect to the outside maximum temperature ranging from ~31 to ~51 days, while sensor R2rock records the maximum temperature 44 to 82 days later than in the outside atmosphere. For minimum temperatures, the lag recorded by sensor T12air is ~10 to ~123 days while for sensor R2rock the lag with respect to the minimum outside temperature is ~20 to ~123 days. However, the R2rock sensor reaches minimum temperatures around 34 and 62 days before the minimum temperature at the site of sensor T12air. This suggests a complex temperature pattern and a possible lag of more than a year between cave air temperature in room K and rock temperature, calling for extended monitoring to understand how the different heat sources control the temperature variations in Devaux cave.

We have moved the text from R2 rock sensor from well-ventilated to poorly ventilated parts, and also in coherence the text of T12air (Lines 392-400). Also we have adjusted the text in lines 326-327, 329-331 and 382.

G) l518 - the only place where perennial hoarfrost is indicated on figure 2B is a small recess appears to be surrounded by ventilated galleries containing seasonal hoarfrost, and as mentioned adjacent to a small ice body of room SPD. This certainly speaks to the frozen nature of the bedrock in this part of the cave, and demonstrates the clear effect of the negative thermal anomaly brought about by the ventilation pattern in the surrounding galleries. But if this is the case, could the authors comment on why there is no perennial hoarfrost in the galleries leading to room D, where such hoarfrost could also have developed?

- ➔ A possible explanation for the absence of hoarfrost in rooms D (and also G) is that these chambers are insufficiently ventilated. Devaux (1929) indicated the presence of ice crystals on the ceiling at the entrance of room D. In the same way, du Cailar and Dubois (1953) showed a schematic cross-section of room D, where ice crystals are present to the mercury thermometers (Fig 1). These historical reports suggest that these chambers were probably more ventilated in the past, possibly related to a major rise of the water level (later freezing) due to the blockage of the Brulle spring. Those seasonal changes of the river base level might have favoured air circulation towards room D. The blockage of the Brulle spring, as well as the elevation of the base level, provoked seasonal changes of the passages. This situation might have favoured a more intensive ventilation of room D.

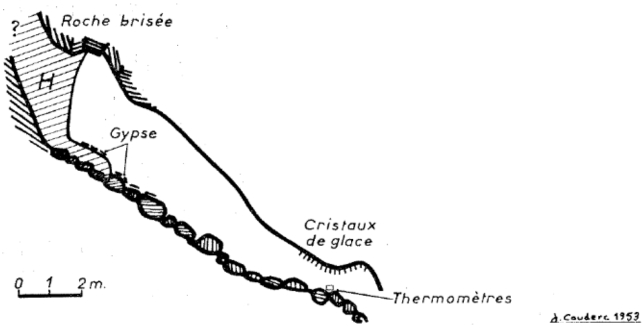

Figure 1: Schematic cross-section of room D, where hoarfrost (Cristaux de glace) appears to form close to mercury thermometres. Modified from du Cailar and Dubois (1953)

We have added some lines about the presence of hoarfrost in room D suggesting major ventilation in that areas than today. **Line 573**: "Devaux (1929) indicated the presence of ice crystals on the ceiling at the entrance of room D. In the same way, du Cailar and Dubois (1953) showed a schematic cross-section of room D, where ice crystals are present at the beginning of the room. These historical reports suggest these areas were probably more ventilated in the past, which favoured the hoarfrost formation."

H) Could the authors elaborate on why CCC or CCG related ice, rich in air inclusions could be related to the formation in a subaqueous environment?

➔ Cryogenic cave carbonates (CCC) are crystals that form when water freezes inside caves (e.g. Žák et al., 2004, 2012). At low freezing rates, water ponds start to freeze from the surface, thus isolating and preserving liquid water in a closed system (pool-model) (Žák et al., 2004). The progessive freezing of the pond provokes the loss of CO_2 and the segregation of solutes (Killawee et al., 1998). Once supersaturation is reached, CCC start to crystallize. Thus, liquid water is necessary for CCC formation. CCC are characterized by a different isotopic composition ($\delta^{13}C$, $\delta^{18}O$) than regular speleothems (e.g., stalagmites). We are currently working on the characterization of CCC from Devaux and our preliminary observations show that the CCC morphologies show the same shapes as those found in other ice caves (e.g. Luetscher et al., 2013; Žák et al., 2012, 2018). Also, we find these carbonates trapped within the ice, indicating a subaqueous environment of formation as suggested by earlier studies (Bartolomé et al., 2015; Colucci et al., 2017).

The relation between CCC and ice rich in air inclusions (bubbles) is difficult to study in comparison with other caves containing CCC since only very few sites are known where CCC are still present within the ice and detailed studies are lacking. Most of the CCC were found on blocks long after the ice had disappeared (e.g. Koltai et al., 2020; Spötl et al., 2021; among others). In Sarrios 6 ice cave (southern slope of the Monte Perdido massif), CCC were found within the ice (Bartolomé et al., 2015), and the CCC are also surrounded by bubbles (Fig.2a in Bartolomé et al., 2015), similar to those found in Devaux. The forthcoming analyses of these gas inclusions may provide additional information with respect to CO_2 degassing during the freezing process, leading to the precipitation of CCC. On the other hand, gypsum crystals appear as single crystals and also used CCC as nucleation points.

We think that the response of this question is well solved along the point 5.3 (Cryogenic cave minerals). For example: in line 685, we already indicated that CCG appear together with CCC_{coarse}, thus informing about the subaqueous environment. In the line 692 we indicated how the CCC_{coarse} form. In line 736 we discuss why the gypsum formation suggest a subaqueous formation. The relation with bubbles is explained in the line 731. Here we have added a sentence about this process in agreement with reviewer comments (**Line 739**) "Similar to that, CCC were found within the ice and surrounded by bubbles in Sarrios 6 ice cave (Bartolomé et al., 2015). However, the scarce presence of CCC within the ice today, together with the very few sites where this topic is investigated, leads to a lack of studies about gas inclusions and CO_2 degassing during CCC formation."

I) l689: the authors mention that 'exceptional insights' into the origin of mountain permafrost are gained by the study of the Devaux ice cave deposit. In this study, three potential mechanisms are put forward, which all go some way to explain the permafrost conditions at the site. 1) negative thermal anomalies due to cold air advection in winter, 2) negative radiative anomaly due to the mountain topography/orientation and 3) inherited past cold climate signals, not entirely erased by current warming due to thermal inertia. In the discussion, the authors could comment on a ways to quantify the potential contributions of each to the current thermal state of the cave?

- ➔ That is an interesting point but exceeds the scope of this paper. Quantifying every factor that influences the thermal state of the cave is a multifaceted issue that would require a heat-flow model coupling heat and mass transfer between rock and air in ventilated caves (Sedaghatkish et al., 2022). Eventually, once the age of the ice bodies has been determined, the relative importance of the individual processes may become clearer and help reconstructing the thermal history of the inherited permafrost. We will add a sentence indicating these points in the conclusions to discern the contribution of the different factors in the modern permafrost.

Technical comments (T: suggested typographic correction, R: suggested rephrasing)

- ➔ We will include all technical comments suggested below.

l55-57: (R) snow cover distribution and thickness, topography, water availability, surface and rock temperature all influence the spatial distribution of mountain permafrost

Done (lines 56-58): We have changed " They influence the spatial distribution of mountain permafrost, including snow cover distribution and thickness, topography, water availability, and surface temperature and rock temperature (Gruber and Haeberli, 2009) " by "Snow cover distribution and thickness, topography, water availability, and surface and rock temperature influence the spatial distribution of mountain permafrost (Gruber and Haeberli, 2009). "

l57-61: (R) In light of these processes, [...] are needed to gain a comprehensive understanding of mountain permafrost.

Done (Line 59): We have changed it by "In light of these processes, multidisciplinary studies including, among others, measurements of rock temperature in boreholes and bottom temperatures of snow cover (BTS), geophysical techniques, and detailed mapping (geomorphology, thermal) are needed to gain a comprehensive understanding of mountain permafrost (e.g. Lewkowicz and Ednie, 2004; Serrano et al., 2019; Biskaborn et al., 2019)".

l98-99: (T) the presence of a few ice caves has only recently been documented

Done (Line 107-108): We have changed it by "the presence of a few ice caves has only recently been documented (e.g. Sancho et al., 2018a; Serrano et al., 2018) informing about sporadic permafrost "

l315: I think this could be reformulated, as the authors list water, and rock T sensors together with the air T sensors.

Done (Lines 329-331): We have changed by "Air (T2air, T5air, T10air, T11air) and water (W6water, W7water) temperature data show large seasonal oscillations."

l357: I think R1 could be dropped from the list in parentheses, as it is not an air temperature sensor.

Done (Line 381): We have modified the sentence: "Air temperature sensors located in rooms D (T3air, T4air, T8air), G (T9air), K (T12air,) and rock temperature (R1rock, R2rock) show a weak and/or insignificant correlation with the external temperature."

l396: (T) transparent and massive ice (~15.5 m above the Brulle spring) currently fills a cupula or chimney

Done (Line 431): We have changed it by "transparent and massive ice (~15.5 m above the Brulle spring) currently fills a cupula or chimney"

l452: (T, American English spelling) millilitre

Done (Line 487): "Millilitre" was not correct. We wanted to refer to "SUB-MILLIMETRE SIZE". We have corrected it.

l453: (T) in room SPD, CCC and CCG

Done (Line 488): We have added the comma.

l456: for the sake of consistency, I would drop the s at the end of CCC here.

Done (Line 491). We have removed the "s" from CCC.

l501: (T) with more continuous permafrost starting at 2900 m asl

Done (Line 544): we have added "starting" in the sentence.

l535-536: massive ice is formed by slow freezing - there should perhaps be a reference here.

Line 589-590. Line 589-590. CCC_{coarse} requires low freezing rates (Žak et al., (2004). We have added "as well as the presence of CCC, which formation require low congelation rates (Žák et al., (2004)".

l568: (T) The cave ice bodies [...] therefore represent

Done (Line 612). "S" has been removed.

l596: (T) which contrasts with

Done (640). We have changed "to" by "with"

l615: for the sake of consistency, drop s at the end of CCG here.

Done. We have removed the "s" in lines 659-660-667-669

l636: (T) related to hydrocarbons

Done (Line 680).

l666-667: (T) is the size and well-developed shape of the crystals

Done (Line 711)

l718: (T) rich in air inclusions

Done (Line 762)

l724: (T) in Devaux cave

Done (Line 768)

Figure 2A: could it be helpful to indicate on the cross-section the assumed extent of mountain permafrost (200 m thick, over 350 m in an E-W direction)?

Done. We have added the assumed extent of mountain permafrost and modified the figure caption consequentially. Also we have also corrected the reference about figure 7, by figure 6. That now is correct.

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Here we reply to an email received with some questions about the manuscript:

Regarding precipitation, I noticed a small error in your manuscript "annual precipitation next to the cave may exceed 2500 mm, as the snow depth measured in early May exceeds on average 3 m"
3 m snow depth is not 2500 mm precip (water equivalent) but rather 1000-1500 mm w.e. even at the end of winter when the snowpack is dense.
Note that there are winter precipitation measurements (i.e. coincident snow depth and density measurements) done by Moraine in late May on Ossoue glacier, the average over a 21 year period is 2700 mm w.e. (max 2000 mm w.e., min 3700 mm w.e.)

- ➔ These precipitation data are derived from measurements performed at the end of April, when snow depth was ~3.2 m on average and snow density was close to 450 kg/m^3. The average snow depth could even be larger due to the strong winds that remobilize and compact the snow during winter in this sector. These measurements would thus represent a minimum amount of 1500 mm w.e (López-Moreno et al., 2019), while the rest of the precipitation would correspond with rainfall between May and October. Data from Góriz hut (2150 m a.s.l, 1984-2020), located in the South face of the Monte Perdido massif, indicate the total precipitation between May to October ranges from 331 to 1415 mm, with a mean of 884 mm. Moreover, this precipitation would increase with altitude. We will rephrase the sentence in the revised version, to clearly indicate which part of the total precipitation comes from snow and which one from rainfall.

Done (Lines 168-172). We have rephrased the sentence. " However, mass balance calculations of the nearby Monte Perdido glacier, where more than 3 m of snow (density 450 kg/m^3) accumulates between November to April, indicates a minimum amount of 1500 mm water equivalent, therefore the total annual precipitation in high parts of the massif exceeds 2500 mm (López-Moreno et al., 2019).".

Recompute the radiation map with a better digital elevation model, there are weird staircase-like artefacts on Fig 4.

- ➔ We computed the radiation map using a 5 m resolution DEM from the Aragón Service of Cartography (https://boletinagrario.com/f296,sitar-sistema-informacion-territorial-aragon.html, last visit 21/09/2022). To our knowledge this is one of the most accurate DEM available for the Pyrenees. Those staircase-like artefacts may be due to the extreme slope that forms the Gavarnie cirque. We are confident that the use of a different DEM would not affect the main message of this figure which is to indicate the great radiation anomaly in the Gavarnie cirque.

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