Ana Moreno Caballud
INSTITUTO PIRENAICO DE ECOLOGÍA (CSIC)
Zaragoza. (Spain)
☎ *976 369 393 (ext 880049)* 💻 *amoreno@ipe.csic.es*

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Dear Dr. Farinotti,

I am submitting the revised version of our TC-2020-107 manuscript entitled "**The case of a southern European glacier which survived Roman and Medieval warm periods but is disappearing under recent warming**", co-authored by myself and colleagues, to be considered for publication in *The Cryosphere.*

In this new version we have incorporated the minor changes indicated by the two reviewers and provide a response to their main concerns that can be summarized as follows:

- Rev1 pointed to the lack of any value of 210Pb or 137Cs from other sites to be compared with ours. This is corrected and comparison is now much clear. Table 1 and 2 are also corrected following Rev1 comments.
- Rev1 was concern about our presentation of the principal result of this manuscript (the lack of ice from last 600 years) as a fact and not as an interpretation. We have carefully changed those sentences and, in general, our arguments in that regard have been moderated in this revised version.
- Rev2 was concern about the glacier bed structure in our Figs 2A and 5. This is changed since we don't have any information about the bedrock under the current ice and any idea of possible old ice trapped on "overdeepenings" is removed. Fig. 5 is also modified according Rev2 comments regarding the representation of different glacier stages, particularly we tried to reflect that the new ice pushes older ice masses from the accumulation to the ablation area where they may ablate.
- Rev2 noted that only 35 samples were analysed for trace elements, so their ID (position in the sequence) should be incorporated into Fig. 4 to make clear we don't observe the increase of Pb/Al or Hg associated to the Industrial Era. Since the incorporation of that information in Fig. 4 was difficult and made the figure less clear, we have included a new table with the sample IDs (Table 5).

We hope this new version was suitable for *The Cryosphere*, and hope that it will fulfil your expectations. I will be happy to answer any question you might have regarding this study.

Yours sincerely,

Ana Moreno Caballud

Answers to tc-2020-107 RC1 “The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods”.

Note: Reviewer 1 comments start with RC1 while author responses start with AR.

RC1. General comments
The revised manuscript reads more clearly and progresses in a more structured way than did the original version. The background and sampling strategy are also improved, and the rationale for sample exclusion/selection is included. Thus, the manuscript is greatly improved but I still have a couple of general concerns and requests, as well as a few specific ones (outlined below).

AR We greatly appreciate the comments made by Rev1 about the improvement of this version.

RC1. My first general comment is that the very low concentrations of Cs and Pb are taken as evidence that the ice being sampled is not recent – and that there is therefore a hiatus in the record and thus that modern ice, including that assumed to have formed during the LIA, has ablated. Given the sampling strategy I’m now ok with this argument – but it is missing one crucial element: that the Cs and Pb concentrations in recent ice elsewhere across southern Europe (or farther afield if none is available) are not summarized and presented for comparison. In other words, how do we know that the levels expected in recent ice are higher than those measured in MPG? I believe this step in the argument needs presenting formally, supported with data from other studies.

AR We agree about this issue. It is true that values from other locations were not included in the manuscript and the comparison with our values was then difficult. We have included now reference to other ice cores in European glaciers where ^{210}Pb and ^{137}Cs were measured to facilitate the comparison. In fact, all glacier surface samples across the European Alps present a similar ^{210}Pb activity concentrations, on average 86 ± 16 mBq kg^{-1} (Gäggeler et al., 2020), while ours are most of them below MDA and when is measurable is lower than 20 mBq kg^{-1}. Regarding Cs values, MPG samples are all below MDA, while in other European glaciers are about 3 Bq kg^{-1} (Di Stefano et al., 2019).

RC1. Incidentally, Table 1 does not help here since it does not present the values measured in MPG (nor any from elsewhere in the literature) but instead has three columns: ‘Sample’, ‘Mass of ice analysed’ and ‘MDA’ (not defined in the caption – but is given in the text as ‘minimum detection activity’). Thus, there doesn’t seem to be a column for sample results (Table 2 – presenting Pb – does this (although MDA is again not defined)). I wonder whether Table 1 is missing a column; if it is not then the column labelled ‘MDA’ needs some explanation so the reader can follow the activity that was recorded.

AR Regarding this comment, we have included a new column in Table 1 to indicate the measured values of ^{137}Cs, which were all below the MDA (definition is now in the caption).

RC1. Second, the manuscript includes sufficient uncertainty (for example, in terms of ice flow, the age-distance model, the origin of englacial debris, the explanation of some higher concentrations of Pb, the exclusion of certain samples etc.) that I believe the principal interpretation that no ice is present at the glacier that formed in the last ~600 years should in all cases be presented as interpretation – and not as fact. This is only a matter of appropriate wording, and this is already done in most cases – but not all (I note one or two below).

AR We agree with this appreciation and have changed our wording to reflect more clearly which sentences are just our interpretations and which ones reflect a fact.

RC1. Third, some interpretation is still presented in the Results section. In this case, these interpretations relate to my first point above and I believe the manuscript would be clearer if these comparisons (with concentrations in modern glacier ice) were removed from Results and dealt with specifically and separately in Interpretation/Discussion.

AR The change indicated by Rev1 has been carried out.

RC1. Specific comments

AR We have corrected all the typos and carried out all changes indicated by Rev1. Only our response to the reviewer comments that require more information from our side is included.

RC1. L49 – 54. I think this could be improved. How about: "The apparent absence of ice from the past ~600 years suggests that any ice accumulated during the Little Ice Age has since ablated. This interpretation is supported by measured concentrations of anthropogenic metals, including Zn, Se, Cd, Hg and Pb, which have concentrations well below those typical of industrial-age ice measured at other glaciers *in the region*. This study strengthens the general understanding that warming the past few decades has been exceptional for the past two millennia." (*define as appropriate to the data presented*).

AR We have included the sentences indicated by Rev1 since we agree about the data presentation and comparison with other glaciers. For example, comparing with the trace element data obtained from the glacier of Mt. Ortles, it is clear that the Enrichment Factors (EFs) reported for Zn (118), Ag (135), Bi (185), Sb (401) and Cd (514) are well above the crustal value, demonstrating the predominance of non-crustal depositions and suggesting an anthropogenic origin (Gabrieli et al., 2011). On the contrary, those elements are much lower than the crustal values in MPG (Table 4).

RC1. L159: (I don't follow the argument that the glacier being frozen to its base (incidentally, no robust evidence is presented to support this claim – only that the glacier is 'small') links to the clause 'to become of substantial age'. I think this sentence needs rewriting.

AR We include as an argument that there were evidences of no movement. Then, the glacier was expected to be frozen to bedrock.

RC1. L266: (47 mm here presumably refers to the diameter of the filter; however, it is the filter's pore size that is methodologically relevant.)

AR The reviewer is right and 47 mm refers to the diameter of the filter, a data which is probably not relevant. The filters we employ - Pallflex Tissuquartz™Filters - do not have a specific pore size since they are made of quartz fibers (see the webpage of the provider - www.pall.com/lab - with detailed description: "Binder-free pure quartz offers superior chemical purity. High flow rate and filtration efficiency. Uniquely designed for air monitoring in high temperatures and aggressive atmospheres"). In fact, this type is the purest one in terms of chemistry and able to retain basically everything.

RC1. Also, see comment above – some data are needed here to demonstrate the low activities.

AR A new column is included in Table 2. References to other sites are included.

RC1. L309 and L316 and 317 are all Interpretation and not Results

AR The low values obtained have to be included here as Results. Later, those values are interpreted in the Discussion section about age model.

RC1. L311-314: These are undetectable here – fine, but when these low levels are interpreted later they need to be compared with levels in recent ice; the argument that low levels means that the ice cannot be recent needs comparison data of recent ice with higher levels...

AR We agree and values of recent ice from other European glaciers are now included.

RC1. L352-353: (This is interpretation, not Results)

AR As indicated above, we present the results here and later use them to compare with other glaciers.

RC1. L370-371: (This is a bit awkward. How about: "Our age depth-model for MPG suggests the glacier is composed of ice that is up to ~2000 years old, and that the glacier's subsequent history has involved three main …"). (Shouldn't this be 'four' main periods?)

AR We consider three periods since the last 600 years that could be period number four is not recorded in the ice, that is: we don't find any ice with that age.

References

Di Stefano, E., Clemenza, M., Baccolo, G., Delmonte, B. and Maggi, V.: ^{137}Cs contamination in the Adamello glacier: Improving the analytical method, Journal of Environmental Radioactivity, 208–209, 106039, https://doi.org/10.1016/j.jenvrad.2019.106039, 2019.

Gabrieli, J., Carturan, L., Gabrielli, P., Kehrwald, N., Turetta, C., Cozzi, G., Spolaor, A., Dinale, R., Staffler, H., Seppi, R., dalla Fontana, G., Thompson, L. and Barbante, C.: Impact of Po Valley emissions on the highest glacier of the Eastern European Alps, Atmospheric Chemistry and Physics, 11(15), 8087–8102, https://doi.org/10.5194/acp-11-8087-2011, 2011.

Gäggeler, H. W., Tobler, L., Schwikowski, M. and Jenk, T. M.: Application of the radionuclide ^{210}Pb in glaciology – an overview, Journal of Glaciology, 66(257), 447–456, https://doi.org/10.1017/jog.2020.19, 2020.

Answers to tc-2020-107 RC2 “The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods”.

Note: Reviewer 2 comments start with RC2 while author responses start with AR.

RC2 Comments by Wilfried Haeberli and Pascal Bohleber on “The case of a southern European glacier which survived Roman and Medieval warm periods but is now disappearing under recent warming” Revised paper submitted to The Cryosphere by Ana Moreno and 23 co-authors

RC2 General
The originally submitted paper is now available in a carefully revised version. The authors responded in a detailed and constructive way to the feedback and the recommendations from the side of the reviewers. The presentation of their comprehensive study about the age and composition of glacier remains at Monte Perdido (MPG) in the Pyrenees is now considerably improved and well worth publishing. A final polishing step, however, is still recommended. Besides the following general recommendations, an annotated file contains minor and rather technical comments.

AR. We appreciate very much these comments and the detailed work done in the annotated file by Rev2.

RC2. A new paper about ages of ice in an Alpine glacier was just published a few days ago:

Festi, D., Schwikowski, M., Maggi, V., Oeggl, K. and Jenk, T.M. (2020): Significant mass loss in the accumulation area of the Adamello glacier indicated by the chronology of a 46 m ice core. The Cryosphere Discussion. https://doi.org/10.5194/tc-2020-334
This study closely relates to the topic investigated at MPG. The authors may wish to read, discuss and cite this paper.

AR. Yes, we were aware of that paper and it is very good example of an ice core successfully dated by the ^{210}Pb technique. Their figure 3 shows an excellent decaying profile, which is used to date the 46 meters of that ice sequence, reaching back to around 1944 AD. However, the accumulation rate and the melting rate are certainly different from our record in MPG. We have included this reference in the revised version of our manuscript as an example to compare their ^{210}Pb concentrations with those obtained in our study.

RC2.Environmental conditions and age structure of the ice

The investigated site in a mountain permafrost environment (altitude, extreme shadow) is a perennial and quite probably cold “ice patch” or “glacieret” (most probably frozen to its bed), which developed from a considerably larger, warmer (probably polythermal) and faster moving (sliding) glacier which has been rapidly shrinking as a consequence of ongoing climate change. The internal age structure of the today remaining ice is the result of a highly complex transient development. Numerical modeling of such processes would require high-resolution spatiotemporal input parameters about changing ice geometries, mass balance or englacial temperatures, which are hardly available. In view of this difficulty and limitation, the presented results from near-surface probing together with the schematic concept of internal layering as illustrated in Figure 1 (best to be included in the paper?) of the author response file is good enough as a strongly simplified but quite reasonable first-order approximation. Such a simplified “first order approximation” should modestly be defined and treated as such. In this sense, the glacier bed in Figure 2A should be simplified and shown by a dashed line (for

uncertainty; perhaps even with question marks) if not precisely determined in situ by radar soundings. Especially the over-deepened part near the lower end of the ice patch must be dealt with in a physically sound way. If simply assumed or extrapolated from another site it would be better to eliminate it. If really and exactly documented in situ, the isochrones must be adjusted to reach the surface: ice in an overdeepening does not "flow into bedrock" as suggested now in Figure 2A but can move upslope at the ice base and reach the surface under the influence of local basal shear stresses as governed by surface slope and ice depth. This is more than a minor technical detail: With the presentation in Figure 2A the authors imply that passive and (much?) older ice is preserved in the overdeepening and overridden by younger ice along a mechanically questionable "shear zone". Even though this cannot be definitely excluded, there is no evidence visible for such conditions. Fundamental physics of glacier flow should also be more carefully considered in the interesting but extremely oversimplified Figure 5 (see comment in the annotated file).

AR. We agree with this comment and have modified the glacier bed in Figure 2A. Now it is represented by a dashed line, very simplified and without any "over-deepened parts". We think this new representation is adjusted to what we know and does not imply the presence of older ice since we don't have any evidence of it.
Figure 5 is more difficult to be modified since the schemes are smaller. Of course we agree about the fact that "layers of younger ice are not simply „put onto the surface" of already existing older ice but push older ice masses from the accumulation to the ablation area where they may ablate and disappear" and have tried to incorporate it to the figure. Additionally, we would like to note that we did not sample the upper glacier (too risky) and the colors indicating in Fig. 5 the age of the ice preserved were purely our "best guess" but not supported by any evidence. Those colors are now removed to avoid misinterpretation.

RC2. Radiometric and glacio-chemical analyses

The selection of the 14C data is now much better presented. Likewise, the presentation of the sample ID and the meaning of the depth increment used in the ice sampling has been revised and is now much clearer. However, one important point remains to be addressed: The authors use the sample ID to clearly reference the samples analyzed for 137Cs (Table 1), 210Pb (Table 2) and 14C (Table 3). The same information is still missing for the trace element and Hg datasets. In their response, the authors write "We do not have the depth information for previous Figure 3 (now figure 4) and including sample ID (from 0 to 100) appears now unnecessary." It would in fact be important to include the sample ID, for sake of completeness but even more so for the following reason: Both, the comparison with the Marboré Lake record as well as the argument for the absence of ice from the industrial period would be more convincing if the entire sample range had been measured. Since a subset of 35 samples (line 265 in the revised manuscript) has been selected for measurement, the location of the samples within the record matters. A particularly relevant question to still be answered by the authors is if the subset includes the potentially youngest portion of the record or not – corresponding to the statement that "In particular, the lack of a Pb/Al peak characterizing the Industrial Period in the upper sequence of the MPG confirms the absence of the last two centuries in MPG ice record" (line 411). One could add here "as far as it becomes evident from the analyzed subset of samples in our record" – or something similar. The sample ID could be presented in form of a table (or adding to existing tables), or quite elegantly, as an additional x-axis to Figure 4.

AR. First, we would like to note that the subset of 35 samples was selected along the whole sequence, including of course samples from the upper part. To make all this issue more clearly indicated for the readers, we have added an additional table with the Pb/Al and Hg values for

MPG samples, indicating the sample ID. We tried to add the ID labels to Fig. 4 but it was difficult to make all the numbers easy to read and we have preferred the table format.

RC2. Some minor technical comments can be found in the annotated pdf.

AR. We have revised all those technical comments and acknowledge the efforts done by the reviewers to improve our manuscript.