RESPONSE TO RC1

Title: **Early Holocene cold snaps and their expression in the moraine record of the Eastern European Alps**

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The authors thank Reviewer #1 (R1) very much for reviewing the manuscript and for his/her/their helpful comments. By including R1's suggestions, we believe that the quality of our manuscript has substantially improved. In this document we address in detail all of R1's comments and describe, point by point, the changes in the manuscript. R1's comments are listed in the gray boxes followed by our responses in blue. Line numbers that refer to the changes in the revised manuscript version are listed in red.

1 | MAIN COMMENTS

This manuscript reports new ^{10}Be exposure ages from Holocene moraines in the Silvretta Mountains in the Eastern European Alps and puts them into the regional and hemispheric paleoclimatic context. The data is very useful, as Holocene chronologies in the Eastern part of the Alps are still scarce, especially such robust, consistent data sets that allow for meaningful paleoclimatic interpretation. The multi-boulder ages are indeed remarkably consistent for each landform and belong thus to the most valuable data sets from the Alps, which are still relatively rare among the many existing Alpine chronologies.

The manuscript is very well written and illustrated. Also, a new and very promising method is presented that allows low-quartz or low-^{10}Be samples to be analyzed with high precision.

The manuscript is thus worth to be published in Climate of the Past. Before acceptance, a few minor issues should be addressed though.

My main comment relates to the ^{10}Be mean ages of the Early Holocene (EH) moraine sets that are reversed with regard to the stratigraphic order of the landforms. Two EH ice margins were dated in each of the studied valleys. The multiple ages from each ice margin are strikingly consistent with each other, and their mean ages are in perfect agreement between both valleys. But the ^{10}Be ages from the outer (thus older) ice margin are systematically younger, thus leading to a nominal mean age that is younger by ~500 years, in both valleys. This is not discussed nor even mentioned in the manuscript. While from a dating perspective this can be handled relatively easily (see my suggestions below), the major challenge consists in the correlation of the moraine depositions with the independent high-resolution proxies (Discussion). This is particularly notable in section 5.3.2, where the cold spells during the EH warming are discussed, and the timing of the outer moraine formation (MIF 4) is correlated with both the DCP1 (+PBO; ~11.6-11.2 ka) and DCP2 (+related cold spell; ~10.6-10.5 ka). See line 531 for the first ("…evidenced by moraines J4 and L4 dated in this study…", i.e. MIF 4), and lines 536-537 for the second ("Moraine formation…, concurrent with DCP2, is observed in the Silvretta Massif (MIF 4)"). Maybe there's a typo and the authors meant MIF 3 for the first, as the 10Be ages MIF 3 agree with DCP1. But that would of course make no sense, because a stratigraphically older moraine cannot be correlated with a younger paleoclimatic event (also see below my comment on lines 439-440, where this correlation was actually done).

I suggest that the reversed moraine mean ages should be acknowledged and possible reasons discussed. Are there any field observations that might explain a systematic age underestimation, like enhanced exhumation, erosion, cover on the outer moraines? Exhumation seems unlikely, given the big boulder sizes on the supplement pictures. Could the systematic offset just be a coincidence? It can easily be tested, e.g. by using an MSWD, if the dispersion of all MIF 3 and 4 ages is only due to analytical errors. It could be argued that the moraine formation at the two ice margins occurred within such a short interval that their ages are not distinguishable with the ^{10}Be dating method. Logically, the average of all ages from the MIF 3 and 4 ice margins would then provide the best estimate of the two glacier stabilizations. Parts of the discussion will need to adjusted to this.

We thank R1 for the positive evaluation of our manuscript. We agree with R1's main comment, namely that a discussion of the age inversion of moraines JR3/L3 and JR4/L4 – equivalent to Moraine Formation Intervals (MFI) 3 and 4 – is missing from the original version of the manuscript. The revised version includes all of R1's suggestions which address this weakness, specifically:

- adding potential explanations for age inversion of the EH moraines to the discussion ***(sections 5.2.1 and 5.2.3)***
- performing a reduced χ^2-test, also known as Mean Squared Weighted Deviation (*MSWD*) statistic ***(Supplement, section 4)***
- calculating a mean moraine formation interval based on all boulder ages featured by moraines JR3/L3 and JR4/L4 ***(section 5.2.1)***

2 | MINOR COMMENTS

Lines 20-21: *According to my above comments, better change by saying that two Early Holocene moraine formation intervals occurred around ~11 ka and that they were close both in space and time.*

We agree with R1 and modified our interpretation of the two Early Holocene (EH) moraine formation intervals according to his/her/their suggestion. We combined moraine ages from both valleys to one EH moraine formation interval, yielding an age of 11.0 ±0.7 ka.

Lines 20–21

Line 44: *revise grammar.*

Revised.

Lines 44–47

Lines 79-80: *make two sentences*

Sentence has been split.

Lines 80–81

Lines 84: *Yes, that's indeed important, also for the Late Glacial in the rest of the Alps (just a comment).*

Thank you for supporting our research objective.

Legend of Fig. 1: *For the light blue shading that's the ice extent rather than the ice margin. For the national border it might be interesting to indicate to which countries it belongs.*

Legend item "2018 ice margin" was modified to "2018 ice extent"; country labels "AUT" and "CH" were added in Figures 1c and 1d.

Legend of Fig. 1
Lines 105 and 111

Line 130: *something is wrong at the end of this line: "they form" instead of "or"*

We intended to express that moraines form along ice margins that are stable for at least a few years – or longer. We hope that the brackets have improved the semantics of the sentence.

Lines 133–134

Lines 176-179: *I recommend to at least indicate the potential impact of a possible snow pack scenario, as snow has a higher impact than erosion. The effects of erosion are tested (supplements), but one could argue here as well that it might lead to a higher age dispersion given the various geometries of the boulders. So, testing one but not the other doesn't seem straightforward*

We have included an estimate for the potential impact of a hypothetical snow cover in the revised manuscript version. If applied, boulder ages would become c. 5–6 % older (Gosse and Phillips, 2001).

Lines 188–190

Lines 192-193: *J1 is dated to the 18th, that's not the end of the LIA. Shouldn't it therefore say that J0's age falls between the LIA maximum and the turn of the 20th century? Or if you just cite Fischer et al. (2019), then phrase the sentence differently ("…is thought to fall…" or similar). The same comment applies to the first line of Fig. 2's caption.*

In our view, the deposition of J1 took not necessarily only place during the 18th century, but probably in the course of multiple glacier advances during the LIA (and potentially before). Our interpretation of the ^{10}Be exposure age cluster during the 18th century is that during this period,

Jamtalferner certainly reached its LIA maximum. However, there is strong evidence (for instance an historical map, which we refer to in the revised manuscript version) that Jamtalferner was at its maximum again around 1850 CE, which is true for many glaciers in the European Alps. Therefore, we place the age of J0 – located just inside the LIA moraine – into the period between the end of the LIA and the turn of the 20th century.

Lines 203–205

Fig. 3: *Make sure the same language is used in the text and figures (hut/Hütte)*

Homogenized throughout the manuscript.

Table 1 and 2: *The third to last column has a wrong header in each table. The blanks could be added to the tables, notably for easier comparison of the numbers of atoms ^{10}Be.*

- Column header was corrected.
- We agree with R1 that comparison of ^{10}Be atoms in samples with ^{10}Be atoms in blanks would be easier if blanks were added to Tables 1 and 2. However, in the manuscript we present our data valley-wise and based on the landforms corresponding samples were taken from. Process batches in turn were not organized by landforms, but by other criteria (e.g., availability of purified quartz). If we would add blanks to Tables 1 and 2, we would have to list each blank multiple times, which might cause confusion. A batch-wise presentation of all samples is given in the ***supplement, Table S2***.

Tables 1 and 2

Lines 308 and 345: *Given that there's just one sample, I would phrase this more cautiously: "might capture" or similar*

Corrected according to R1's suggestion.

Lines 347, 387–389

Lines 313-315: *Grouping the L3L moraine segments with the other MIF 3 moraine segments seems arbitrary, because the ages of MIF 3 and 4 are statistically the same. Unless you have more convincing arguments, I would attribute these Left-lateral ridges to both MIF 3 and 4.*

We agree with R1 and changed the name of the ridge "L3L" to "L3-4L" in all figures and the text. In our revision, we used the ages featured by L3-4L (samples LAR-19-22 and LAR-19-24) not only to calculate the landform age L3, but also included them in the calculation of L4 (sh. ***Results, section 4.2.2***).

Figure 4
Lines 348–359

Fig. 7: *According to my main comment above, it would make more sense to compare the kernel plots for MIF 3 and 4 in each valley to show that they are indistinguishable from each other, and show their mean ages and insist that they are the same in both valleys.*

Agreed and corrected. Please see also our responses regarding R1's comment to Lines 20-21 and regarding R1's main comment.

Figure 7e

Line 364: *glacier advance*

Corrected.

Line 408

Fig. 8: *It would be convenient to have one of the scales in years before present.*

Upper x-axis was changed to "yrs BP".

Figure 8

Lines 345 + 362 + 395-396 etc: *Are the earlier-LIA and pre-LIA boulders in a stratigraphically different (outer) position compared to the ~18th century boulder? And do you have field evidence that the "LIA" moraines are composite moraines? If yes, it would be good to mention this in the Results – Geomorphology section. Just to interpret this from a few isolated boulder ages is very speculative and should be handle more cautiously.*

The comment that our interpretation is based on a small number of samples, is justified. Therefore, we have formulated the sections addressed by R1 more cautiously. Also, we included the possibility of pre-exposure of the pre-LIA samples.

To the position of early- and pre-LIA boulders (please see also photo documentation in the ***supplement, section 6***):

- LAR-19-23 is positioned on the left-lateral LIA moraine (L1) in the Laraintal.
- The left-lateral J1 segment in the Jamtal, where the pre-LIA (neoglacial) boulder **JAM-18-07** was deposited, is not very pronounced, probably because much of the material was eroded due to the steepness of the terrain. The boulder itself is located on the small crest and can clearly be attributed to the J1 moraine.
- **JAM-18-16** (pre-LIA) is deposited on the right-lateral section of J1, in its upper, broader part (Figure 2 in the manuscript), shortly before a large channel. The crest is not clearly defined and hindsight, we believe that this boulder might have toppled.

Lines 387–389, 407, 439–443

Line 396: *"in the following sections…"*

Corrected.

Line 440

Lines 396-398: *This sentence probably needs to be revised, it's unclear. I guess you mean that J1 and L1 mark the MAXIMUM glacier advances and temperature minima SINCE the YD-EH transition?*

Proposed changes have been implemented.

Lines 440–442

Revise the title of section 5.2, as it's the same as for section 5.1

Fixed.

Lines 443

Line 407: *Nothing is mentioned about the fact that the nominal ages are systematically reversed, see my main comment above.*

Age inversion of moraines L3/JR3 and L4/JR4, albeit statistically non-existent, is discussed in the revised version of the manuscript. We added the following potential explanations:

- Pre-exposure of boulders featured by the inner and older moraine.
- Post-depositional displacement of boulders sampled from the outer and younger moraine.
- Surface erosion of L4/JR4 boulders due to katabatic winds along the L3/JR3 ice margin.

We note that none of the explanations is completely convincing (with more details given in the manuscript). However, the age difference is statistically not significant as highlighted by R1 in his/her/their main comments. Therefore, the age difference does not impede a plausible age interpretation.

Lines 448–462

Line 410: *Concerning the statement about the climate variability in the studied valleys, is this based on specific observations and does it refer to a specific time period? Can you provide a source?*

This part of the discussion has been moved to the end of **section 5.2.1** and has been formulated more concisely. Also, the statement is now supported with data on summer temperatures from different meteorological stations in the region.

Lines 531–536
Appendix B1

Line 411: *"Also, catchments are comparable…"?*

Corrected.

Line 531

Line 413: *It's not clear to which "variations in the timing of moraine formation" is referred here. The same applies to "age variability among moraines dated in the region". These variations have not been discussed and cited so far. I guess the statements refer to the Verwall and Ochsental chronologies, but this needs to be clarified.*

This section has been rephrased and clarified.

Lines 531–536

Line 422: *FIG. 9c-f*

Fixed.

Line 480

Line 432 and 435: *Were the ELAs in both valleys determined with the same methods? It would be good to give a few more explicit arguments that support the concept that the dated Kartell moraine is not the equivalent of the MIF 3 and 4 moraines and that the age difference is not due to dating uncertainties.*

All reported snowline depression were derived through the Accumulation Area Ratio (AAR) method (Gross et al., 1978), which is now specified in the manuscript.

The regional glacier history concept is mainly supported by numerical age data, and to a lesser extent by ELA depressions reported in previous studies. Uncertainties tied to the dating method complicate the deciphering of distinct glacier advances/stabilizations, specifically the distinction between the Kartell moraines and the MFI 3-4 moraines, and the MFI 3-4 and the Kromer moraines. This problem was briefly addressed in the first version of our manuscript (lines 414–416). In the revised version, we discuss this problem in more detail and point out that moraine ages overlap within uncertainties.

Lines 527–537

Lines 439-440: *How can MIF 4, being stratigraphically older than MIF 3, be related to a younger paleoclimatic event??? This needs to be corrected. See my main comment.*

Corrected. Please see our response to R1's main comment, and to lines 20-21.

Lines 493–502

Lines 446-337: *remove "on the one hand" and "on the other hand"*

Removed.

Lines 507–508

Lines 523 and 525: *Fig. 9 not 8*

Corrected.

Line 600–601

Line 531: *Fig. 9g-h*

Figure number added.

Line 613

Line 535: *"which in turn led…"*

Corrected.

Line 617

Line 595: *Again, a glacier stabilization that is recorded in the most external position cannot have occurred a few centuries later. Please correct this.*

We assume that R1 refers to line 559 given that line 595 does not refer to MFI 3 and/or MFI 4 in the first version of the manuscript. We removed our suggestion that MFI 4 may be linked to cooling between 10.7-10.5 ka as this interpretation is implausible.

Lines 638–639

Line 573: *this needs to be phrased more cautiously.*

In our revision, we highlight that the data, which supports a glacier advance around 500 CE, is limited in the region.

Lines 650–653

REFERENCES

Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Sci Rev 20, 1475-1560.

Gross, G., Kerschner, H., Patzelt, G., 1978. Methodische Untersuchungen über die Schneegrenze in den alpinen Gletschergebieten. Zeitschrift für Gletscherkunde und Glaziogeologie 12, 223-251.