Reviewer 1

We would like to thank Joe McConnel for reviewing our paper and for providing constructive suggestions. Please find our responses in the following:

Does the paper address relevant scientific questions within the scope of CP? Yes.
Does the paper present novel concepts, ideas, tools, or data? Yes, but the approach is not as novel as implied in the manuscript.

Corrected (see below for our answer to your specific comment 1)

Are substantial conclusions reached? Yes, although the focus of this manuscript is only on establishing a new core chronology for the Alto dell'Ortles cores. The interpretation of the new Alpine lead record is reserved for a subsequent manuscript.

Are the scientific methods and assumptions valid and clearly outlined? Yes.

Are the results sufficient to support the interpretations and conclusions? More or less. The main advance in dating is the use of a relatively new technique where a poorly dated lead record (in this case from Alto dell'Ortles) is synchronized to a well-dated lead record (in this case a previously published record from the Russian Arctic). The wiggle matching between the records is somewhat arbitrary, however, and difficult to assess objectively. Here the authors use radiocarbon dating to assess the wiggle matching but the radiocarbon dates are too few and have too large uncertainties to allow a quantitative assessment of the wiggle matching. I don't mean to be too critical since the problem of quantitatively assessing wiggle matching is not unique to this study, but the subjective nature of the tie points should be openly acknowledged.

We agree with the referee and this point is now openly acknowledged within then text. We also note that the subjective nature of the wiggle matching is already qualitatively and quantitively acknowledged within the text of the paper where a conservative uncertainty of the timescale was defined over the period of interest:

"*Wriggle-matching of records is inherently somewhat subjective….To assign a direct transfer of the dating uncertainty of the AN Pb record (±5 years) (McConnell et al., 2019) would underestimate the residual age discrepancy (204 and 288 years, see above) with the two WIOC-14C dated samples given the additional uncertainty associated with the synchronization procedure. As a consequence, an uncertainty of 10% of the matched age (expressed in years before 2012) ranging from 10 up to 200 years was assigned over this time interval. Ten years is a lower limit in the same order of the time uncertainty of the deepest sections dated by using annual layers down to 57 m depth in core #1, see below; 200 years is an upper limit in the same order of the mentioned discrepancy with the two WIOC-14C dated deeper samples*".

Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes.

Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Improvements suggested including additional citations and acknowledgement of prior similar work.

Changed accordingly (see below for our answer to your specific comment 1)

Does the title clearly reflect the contents of the paper? Yes, although it describes only one component of what was reported.

We have now revised the title to read "A multimillennial mid-latitude ice core chronology by synchronization with a polar Pb record combined with other empirical dating methods"

Does the abstract provide a concise and complete summary? Yes.

Is the overall presentation well structured and clear? Fairly clear. The text could be improved for readability and shortened.

We have now revised the readability and shortened the text by transferring some portions to two new sections of the supplementary information (see below).

Is the language fluent and precise? For the most part, yes. The text in the Supplement could be edited to be more understandable in English.

This section has been carefully revised by a native English speaker.

Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes.

Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Some of the figures are primitive by today's standards and could be improved. For example, I found the comparison of the synchronized Russian Arctic and Alto dell'Ortles lead records in the Supplement (Fig. 2 bottom) to more compelling than the same presentation in Fig. 4 (bottom).

We have now revised Figure 4, as well as Fig. 1, Fig S2, S3 and S4, accordingly to this comment.

Are the number and quality of references appropriate? Yes, but important corrections and additional references are needed.

Corrected and added (see below for our answer to your specific comment 1).

Is the amount and quality of supplementary material appropriate? Yes.

Overview

Development of well-dated historical records of human impacts and climate are important for a broad range of disciplines, including the natural, physical, and social sciences, as well as the humanities. Polar and alpine ice cores record provide direct, often highly resolved records of past atmospheric and precipitation chemistry that reflect both natural and anthropogenic emissions. The caveat is that they are most useful only if the records can be properly dated. This manuscript describes the use of standard and non-standard dating techniques to develop a new chronology for the Alto dell'Ortles cores from the Italian Alps. As is typical of cores from relatively thin alpine glaciers, annual layer counting is used in the upper section with constraints provided by known time horizons (e.g., fallout from 1950s and 1960s atmospheric thermonuclear testing, as well as fallout from volcanic eruptions or other highly unusual but well-dated events such as major forest fires or Saharan dust events). In deeper sections of such cores, annual layer counting generally is not possible because of extreme flow thinning and strain so other techniques are needed for establishing the ice age. Here the authors used measurements of lead concentrations in two of the four (or maybe three) Alto dell'Ortles cores collected in 2011 to synchronize the deeper sections to a well-dated, previously published lead record from the Russian Arctic. Additional constraints were provided by radiocarbon dates of both water insoluble organic carbon and discrete organic material from the basal section of one of the cores. The lead synchronization technique used here is relatively new and this is the first effort that I'm aware of to use annual layer counting based on seasonal pollen variations and extreme pollen events as specific time markers.z While I support publication and am especially enthusiastic about the better-dated records of climate and human impacts in Europe that will result from the improved chronology, there are number of important issues that need to be resolved first.

Specific Comments

(1) In the abstract, the authors describe as "novel" the approaches used to redate the cores. The most significant relatively new part of their approach is lead-based synchronization to a well-dated polar ice core which also is the manuscript title. In fact, exactly this lead synchronization approach has been used previously to date rapidly

thinning ice cores over the Common Era and beyond. Specifically, Osman et al., (2021) used this technique of annual layer counting in the upper section and lead synchronization in the lower section on a coastal dome core from Greenland. Similarly, Preunkert et al. (2019) used this techniques on a core from the French Alps, including additional constraints from radiocarbon dating of organic material in the deep ice corresponding to antiquity. Therefore, "novel" should be removed from the abstract and these earlier applications at least mentioned and briefly discussed to provide context for the current study. Citations to these earlier publications obviously should be added as well.

Preunkert, S., J.R. McConnell, H. Hoffmann, M. Legrand, A. Wilson, S. Eckhardt, A. Stohl, N. Chellman, M. Arienzo, & R. Friedrich (2019) Lead and antimony in basal ice from Col du Dome (French Alps) dated with radiocarbon: A record of pollution during antiquity, Geophys Res Lett, doi:10.1029/2019GL082641.

Osman, M., B.E. Smith, L.D. Trusel, S.B. Das, J.R. McConnell, N. Chellman, M. Arienzo, & H. Sodemann (2021)Abrupt Common Era hydroclimate shifts drive west Greenland ice cap change, Nature Geoscience, doi:10.1038/s41561-021-00818-w.

We have now removed the word "novel" from the abstract. Within the text we also provide additional context on the use of Pb as a tool for matching, including the two suggested references.

(2) The citation for the published Russian Arctic lead record is incorrect. It should be McConnell et al., 2019, not McConnell et al., 2018 (these are different publications and not simply the result of typos in their text).
McConnell, J.R., N.J. Chellman, A.I. Wilson, A. Stohl, M.M. Arienzo, S. Eckhardt, D. Fritzsche, S. Kipfstuhl, T. Opel, P.F. Place, & J.P. Steffensen(2019) Pervasive Arctic lead pollution suggests substantial growth in Medieval silver production modulated by plague, climate and conflict, Proc Natl Acad Sci U.S.A., doi:10.1073/pnas.1904515116.

Corrected. Thank you for spotting this.

(3) The use of SZ (the island of Severnaya Zemlya) rather than AN (the ice cap Akademii Nauk which is one of several glaciers/ice caps on SZ) as the ice core name for the Russian Arctic lead record is somewhat confusing. This may be because some earlier publications from the German/Russian team that collected and first analyzed the core referred to it both as SZ (e.g., Fritzsche et al., Annals of Glaciology, 2006) and AN (e.g., Opel et al., Journal of Glaciology, 2009; Opel et al., Climate of the Past, 2012). However, the lead record used here was published as the AN record in McConnell et al., 2019 and so the core name AN should be used here as well.

We agree. Changed from SZ to AN in the manuscript.

(4) It appears from Fig. 2 (bottom graph) that there are sometimes very large differences (nearly an order of magnitude for some periods) in the lead concentrations measured in the two Alto dell'Ortles cores. These aren't just short term differences but decadal or longer differences that I find is quite unexpected in two nearby cores. Please elaborate. Do these differences mean that the lead fluxes measured in these Alpine cores are not regionally or even locally representative?

Different Pb concentrations in cores #1 and #3 are just due to the different acid leaching time between continuous flow analyses (CFA; using online acidification; core #3) and the discrete analyses (adopting acidification of aliquots for sample preparation; core #1) as illustrated in various papers (e.g. Arienzo et al. EST 2019, Uglietti et al AG, 2014., Rhodes at al. CG 2011). Differences are larger at low Pb concentration levels probably because these are mostly characterized by crustal Pb that, unlike anthropogenic Pb, is less acid leachable (Arienzo et al. EST 2019). Nevertheless, different acidification methods do not affect trends and the Pb features (maxima, minima, fingerprint variations) used for wiggle matching. Further, when finally selecting the temporal tie points with the AN Arctic core, only features that were

reproduced in both Ortles Pb records were considered. This note has been summarized and added to the manuscript.

In addition, the tie point at ~69.5 m between the two Alto dell'Ortles lead records is incorrect – or at least not optimal. Correcting it would improve the agreement between the lead records and so make the chronologies more consistent.

This minor offset is a consequence of matching the high resolution CFA Pb record (about 0.2 cm, in Ortles core #3) with the lower resolution Pb record based on discrete samples (about 4 cm, in Ortles core #1). In general these offsets are not noticeable. In this exceptional case, a large change in Pb concentrations occurs quickly at that depth (69.5 m) where a strong thinning of the ice layers occurs. This minor discrepancy (up to 4 cm or about 5 years at this depth) is negligible as it is well within the age uncertainty adopted within this time interval (10% of the age or 100 years at this depth). We therefore consider this of negligible importance. We have added a sentence about the limitation caused by non-identical sampling resolution to the manuscript, pointing out that any potential bias is significantly smaller than the final dating uncertainty reported.

(5) The new age scale is quite different from TC2016 even in the upper 100 m where both chronologies presumably are based largely on annual layer counting (albeit with constraints). This seems quite surprising. I understand that the new chronology incorporated pollen records in the upper part of the core but what caused the annual layer counting in the original chronology to be so far off? Presumably TC2016 was based on the same δ18O and dust measurements as in the current study. Please elaborate.

The reviewer probably missed the point that the upper part of the initial TC2016 timescale was not based on any annual layer counting but was constrained by the 3H peak, Beta emissions and 210Pb dating only. The discrepancy observed is already discussed within the main text in paragraph 3.3 and also illustrated in supplementary info Fig S7.

(6) I find the use a logarithmic age axis in the flow modeling sections (Fig. 6 showing annual layer thickness vs age) rather confusing. Why did you use a logarithmic scale? The main point of the manuscript is the redating of the deeper core (below 100 m) so shouldn't that be emphasized rather than the top 100 m?

This probably relates to comment 5 above as the dating of the upper part was indeed revised and, when compared to TC2016, now also includes many more additional age constraints (e.g. pollen peaks are used to count annual layers). Log and non-log scales are adopted to provide an overall picture (panel a) and to allow visibility of details in the zoomed sections which would not be visible otherwise. We thus prefer to keep the figure as is, and believe that with the selected axis description, specifically pointing to the log-scale, any potential confusion by the reader will immediately be resolved.

(7) In the third paragraph of the introduction, you say that four cores were collected from the Alto dell'Ortles site in 2011. After that, however, I find only a discussion of three cores. Did I miss something?

Only the longest Mt. Ortles cores #1, #2 and #3 (they are all about 75 m long) were analyzed while a 4th shorter core (about 60 m; bedrock was not reached) was not analyzed and it was designated to be preserved for future analysis. We now clarify this within the text in the introduction.

(8) I don't find Fig. 1 particularly compelling or informative. Is the point to show that the water isotopes are in better agreement once the new lead-based and other improvements in the tie points between cores are made? If so, it would be much clearer to show this by overplotting the original and improved water isotope records or by using cross plots. Improvements could be quantified by showing how the correlations between different core records have improved either overall or for specific depth/time sections.

Fig. 1 has now been revised and much more information is provided including the comparison of the stable isotopes records before and after the matching. We now report the linear correlation coefficients (r) of the matched stable isotope records and their levels of significance (always $p < 0.01$) within the text in order to quantify the improvement of the alignments. In TC2016, 17 tie points between core #2 and # 1 (linear correlation $r = 0.72$) and 14 tie points between core #2 and #3 ($r = 0.67$) were used. In the revised chronology 122 tie points between core #2 and #1 ($r = 0.78$) and 87 tie points between core #2 and #3 ($r = 0.79$) were adopted. Overall, the moderate increase in r suggests that Fig 1 illustrates a subtle refinement of the depth alignments performed in the 2016TC.

Correlation of the two stable isotope records in core #2 and #3 before and after the use of Pb ties is essentially identical ($r=0.79$) because of the already highlighted low resolution of the stable isotope record in core #3. In this revised chronology, the major improvement in aligning the depths is linked to the depth intervals (Fig. 1 red tie points) linked by using the Pb ties from cores #1 and #3 where the two Pb records show a final correlation of $r = 0.91$ ($p < 0.01$). This is now mentioned within the text.