Reply to Anonymous Referee #1 regarding cp-2022-62

"Synchronizing ice-core and U/Th time scales in the Last Glacial Maximum using Hulu Cave 14C and new 10Be measurements from Greenland and Antarctica" by Giulia Sinnl et al., Clim. Past Discuss.,
https://doi.org/10.5194/cp-2022-62-RC1, 2022

We thank An.Ref. #1 for the feedback. We have marked our responses to each comment in blue.

>>In this study, new ^{10}Be NorthGRIP and WAIS Divide ice core measurements were compared to Hulu cave ^{14}C measurements to constrain the age scales of these records through the Last Glacial Maximum (LGM). This exercise is important for improving the understanding centennial-scale climatic events in the LGM. Radionuclide particle production changes as a result of solar activity variability. Once changes in its transport to and deposition at ice core sites are accounted for, radionuclide particle variability in proxy records is therefore independent from changes in climate. It is beneficial to use radionuclide particle records to constrain proxy age scales due to this independence. In this study, a time period characteristically similar to the Maunder Minimum identified in the LGM 10Be records was used to synchronize the Greenland (GICC05) and Antarctic (WD2014) ice core ages scales. Using this analysis, an ~125-year difference between the age scales prior to synchronization was determined. A wiggle-matching algorithm was also used to synchronize the ice core age scales to the Hulu Cave age scale. The offsets between the Hulu Cave age scale and the GICC05 and WD2014 age scales were ~375 years and ~225 years, respectively.
This study is important to publish because highly temporally resolved paleoclimate datasets can only be compared to other archives if the age scales of the datasets are accurate. An improvement in the accuracy of proxy age scales therefore leads to better understanding of the timing and progression of climate events and therefore a better understanding of the climate system.

Reply: We thank the referee for this review and for the overall encouraging words about our study. We will improve the manuscript as suggested.

>>Major comments:

>> The introduction needs to be revised. The introduction is a long description of several well-known past climate events without giving the readers any context for why they are being presented with this information. Is there something about these climate events that is unresolved that is addressed in this study? It is a nice literature review, but why is it given?

Reply: We think that the inter-disciplinarity of our study (e.g. ice cores meeting speleothems, carbon-cycle models meeting polar measurements) requires a general and complete description of the background, without giving too lengthy of an introduction. In the revised manuscript, we have improved the structure of the paragraphs, strengthening our motivations about unresolved timescale issues being problematic for climatic interpretations, while also recalling all the necessary elements that are founding for our analysis.

>>Along the same lines, in the introduction, the authors state that the “objective” of the study is a “comparison of three timescales.” This isn’t really an objective. The comparison is really the approach used to address the objective, which I believe is to improve the accuracy of the timing of climate events in the LGM, which is necessary to understand (eventually) the mechanisms behind them.

Reply: Thank you for pointing this out, we have changed the statement about our objectives accordingly. The time scale comparison is at the centre of our methodology, but we recognize that the broad scope of our efforts is more accurately explained as the deeper understanding of the LGM climate through an assessment of the event sequences that characterized this period. In particular, testing the LGM tie point found by Adolphi et al. (2018) has been an important objective as well, as the implied layer counting biases around the LGM were rather unexpected in light of a better agreement of the time scales, documented in the cited literature, both before and after the LGM.

>>The age scale development of the three proxies is then nicely summarized in the introduction, but again, the readers are not given any information about how the current study fits into any of it until ~line 155. It would be very helpful if the authors explained the flaws in the previous dating methods much earlier. Otherwise, the reader does not know why they are being given the summary. It needs to be made very clear that the benefit of using radionuclide records is that their variability is independent from (at least in the case of flux) climatic events. Therefore, the circular nature of dating proxies using climate events and then, in turn, interpreting the timing of those events, is avoided.

Reply: We have altered the structure to frontload our study’s position and relevance in relation to the cited references.

>>The uncertainties in the age scale offsets are rather large given the small magnitude of the offsets. In the conclusion, it would be helpful if the authors could suggest ways in which these uncertainties could be reduced in future studies.

Reply: Thank you for this point, in the revised manuscript we address this issue by the following arguments. We remark that the offset between bipolar ^{10}Be datasets (125±40 years) is the type of precise estimate that the carbon-modelled Δ^{14}C cannot compete with. In the future, uncertainties in the bipolar match could be reduced even more, for example, via a more accurate volcanic matching, supported by our radionuclide matching. With the guidance of an established radionuclide match, albeit with wide uncertainties, a bipolar volcanic match in the LGM will be the most precise way to link the two ice sheets.
The issue of large uncertainties in the wiggle matching lies in resolution problems of the ^{14}C data, in the low signal-to-noise ratio of both ^{14}C and ^{10}Be, and in the carbon-cycle model likely not capturing all aspects of the LGM carbon cycle. The combination of these factors leads to multiple possible fits between the two datasets.

A way to improve the matching to the speleothems would be either a higher resolution absolutely-dated tree ring ^{14}C data (with more reliable signal structures that we can match), or similarly resolved ^{14}C but from another speleothem with lower and more stable DCF than Hulu. In addition, high-resolution ^{10}Be records from other ice cores would reduce the uncertainties by limiting the (local) weather/climate noise in the NGRIP records.

>>The focus of this study is the LGM, but as the authors state that the age scales were not stretched in this study. How would the age scales before and after the LGM be affected by the offsets suggested here? Are offsets of a few hundred years too small to make much of a difference?

Reply: Thank you for this comment. In our analysis, at the common tie point in our focus, the G2B event, GICC05 is ~400 years younger than U/Th and 125 younger than WD2014. In the discussion paragraph 4.2, we argue that the missing layers of GICC05 where likely accumulated during GS 2.1a and 2.2b, i.e. between 15 and 20 ka b2k. The offset is likely at its maximum around 21 ka. Another tie point was found at 31 ka, where GICC05 and U/Th are only 150 years offset (Turney et al., 2016). Therefore, it appears the layers are over-counted somewhere before the LGM, otherwise the 400-year offset wouldn't reduce itself to 150 years, a point also made by Adolphi et al. (2018). In addition, Corrick et al. (2020) do not find large offsets in MIS3, supporting that the difference becomes smaller below the G2B event.
In the revised manuscript, in light of the recent publication by Dong et al. (2022), we also discuss a bipolar volcanic tie-point triplet, which is found at 24669 years b2k in GICC05 and 24589 years b2k in WD2014 (Svensson et al., 2020). Here, the event is 80 years older in GICC05 than in WD2014, i.e., the offset has opposite sign than at the G2B event. It therefore appears that more layers were counted in GICC05 over the interval between G2B and the triplet.
However, a uniform stretching GICC05 with respect to WD2014 is not advised: since the thinning of WDC layers is steeper than in Greenland, we cannot assume the offset would be evenly distributed. A further assessment of the time scale accuracy, via for example more high resolution ^{10}Be measurements in WDC across AIM-2, would be required.

>>The conclusion made in this study is that age scale corrections need to be made to the ice core records, and that the problem is the result of annual-layer-undercounting. Why does the problem lie with the ice cores? Is the age scale of the Hulu Cave record that much more certain?

Reply: The measured timescale offsets are relative between timescales. It is more obvious to us to investigate the issue in ice core layers, as they pose clear challenges in terms of identification, e.g. because layers are very thin during the LGM. From the published U/Th dating uncertainties we cannot conclude that U/Th could carry any absolute error, and we are not in a position to question these uncertainties. We are not aware of estimates in the LGM period showing Hulu being dated too old, but Corrick et al. (2020) do mention a possible issue of sub-optimal sample positioning of U/Th and/or $\delta^{18}O$. If one uses the argument of $\delta^{18}O$ synchroneity across Asian speleothems, considering all caveats because of climate effects, then one can observe a spread of the HE-2 onset between Hulu and the Cherrapunji speleothem (Dong et al., 2022) of about 100 years, where the Hulu record shows the oldest onset of HE2. This could indicate that dating issues in

Hulu are in fact present (given that Cherrapunji was very carefully counted over the LGM using annual lamina). If Hulu was 100 years too old in the LGM, then the offset to GICC05 and WDC would obviously be smaller. However, there is no radionuclide data for the Cherrapunji speleothem, so our methodology remains strongly dependent on the Hulu ^{14}C record. We have presented these arguments in the revised manuscript.

>>Minor comments:

>>Line 60: This sentence is confusing: "During this time, a phase of massive discharge of icebergs from the Laurentide ice sheet was inferred from the ice-rafted debris content of North Atlantic marine sediments, defining the occurrence of the Heinrich Event 2 (HE-2; Bard et al., 2000; Peck et al., 2006)." You mean that HS2 happened at the same time as the LGM, right? Simplify this sentence.

Reply: We have clarified the sentence, thank you.

>>Lines 63-66: "The term Heinrich Stadial (HS) is often used to indicate the period affected by the HE. The duration of HS-1, for example, is limited to the 14.5-17.5 ka b2k interval within GS-2.1 (Broecker and Barker, 2007), while for HS-2, a correspondence with the late 65 GS-3 is often argued for, based on speleothem water isotope records (e.g. Li et al., 2021)". It would be very useful if the timing of each Heinrich Stadial and each Greenland Stadial referenced was defined and easily referenced. Maybe a table could be added?

Reply: Thank you, we have added a table with the definitions of GS1, HS1, HE1, GS2, HS2, and HE2 to precisely refer to the nomenclature adopted in this work.

>>Even though it is commonly used, please add a sentence defining the IntCal20 curve.

Reply: We have added an explicatory sentence.

>>Line 100: "and GICC05 was extended to these ice cores." This is odd phrasing. I'm not sure what this means.

Reply: We have edited this sentence to clarify better. We mean that GICC05 was transferred from NGRIP to the other Greenland ice cores via volcanic matching.

>>Why was before 2000 (b2k) used instead of the conventional, before 1950?

Reply: That is because for Greenland time scales the convention b2k is commonly used and is endorsed for other ice core time scales as well. We will add a conversion to BP throughout the paper, where most relevant.

>>Lines 117-119: "The authors duly excluded the GI-2−AIM-2 pair from their lead-lag analysis, firstly because the GISP2 CH_4 record did not support synchronicity with the GI-2

temperature increase, and, secondly, because the older HE-4 and HE-5 were similarly associated with higher CH4 levels." What is meant by "because the older HE-4 and HE-5 were similarly associated with higher CH4 levels?" Does this mean that GI2 and the HE's can't be distinguished, and that the HE's are associated with stadials?

Reply: Thank you, we have rephrased this sentence in the revised manuscript. We intended to recall that HE-4 and 5 are also recorded in the methane data, which suggests that the methane increase during GS-3 is associated with HE-2, rather than with GI-2.
In the Matlab code provided as supplement to WAIS Project Members (2015), it is stated that the CH_4 rise in GS-3 is "not coincident with the Greenland temperature rise, as is clear from e.g. GISP2 d15N and CH_4 data. This CH4 rise is likely to reflect southern sourced CH4 during the Heinrich stadial, as is also observed during HS4 and HS5; i.e. DO 8 and DO 12 are preceded by increased CH4 concentrations also." Therefore, the WAIS synchronization excluded the AIM-2-GI-2 pair, considering the interpretation issues of the CH_4 signal.
In the Antarctic CH_4 data, within GS 9 and 13, there are double-level signals where the first level is thought to be associated with HE4 and HE5, while the second and higher level can be aligned with the following onset of GIs in the Greenland record. However, in the case of GS-3, this double-level methane structure is less clear and the matching with GI-2 is not possible. The CH_4 shapes of HS4, HS5, and HS2 are compared in Rhodes et al. (2015) at fig. 2.

>>Lines 128-130: This needs to be more prominent: "Resolving some time-scale issues, which we will delineate shortly, will clarify the distinctive timing factors of the global climate around HE-2, compared to the 'conventional' bipolar seesaw scenario."

Reply: In the restructuring of the introduction, we have given more importance to this point.

>>Lines 31-33: This point should also be more prominent: "Traces of volcanic eruptions and cosmogenic radionuclides provide synchronization tools that do not rely on the precise identification of climatic match-points and on the assumption of their synchronicity."
It is hard to see the effect of the 10Be flux calculation when the concentration and flux aren't plotted together.

Reply: In the restructuring of the introduction, we have given more importance to this point.

>>Lines 241-243: "A carbon-cycle model (here the box-diffusion model by Siegenthaler, 1983) is necessary to derive the atmospheric Δ14C signal, i.e. the decay and fractionation-corrected ratio of 14C/12C relative to a standard (Stuiver & Pollach, 1977), from the measured ice-core 10Be." Please clarify what is meant by "from the measured ice core 10Be." How was the 10Be used in the model?

Reply: We have clarified this in the revised manuscript. The ^{10}Be is normalized, amplified by 20%, and provided as an input signal to the model. This is done under the assumption that the variations of ^{10}Be, measured in ice cores, can be converted to a global ^{10}Be production rate (after correcting for a possible polar bias). The global variations of ^{10}Be are theoretically proportional to the ^{14}C global production rate variations, which is what is fed into the model.

>>Lines 258-260: “The strength of the geomagnetic field directly affects both the 10Be and 14C production rates. Although each radionuclide may be affected differently (Masarik & Beer, 2009), most studies do not find any significant difference in production rates (e.g. Kovaltsov et al., 2012; Herbst et al. 2017).”… I thought that the geomagnetic field did affect production rates? Please clarify this sentence.

Reply: We realize the two sentences might seem contradictory and we have made a clarification. We mean that recent studies suggest that the geomagnetic field affects the two radionuclides by the same proportion (i.e. a 20% change in the global ^{10}Be production rate implies also a 20% change in the global ^{14}C production rate), while only Masarik and Beer (2009), to our knowledge, find that a ratio of 1.3 is to be expected between ^{10}Be and ^{14}C production rates because of the geomagnetic field (a 10% change in ^{10}Be would go together with a 13% change in ^{14}C).

>>Lines 256-258: “To compare the measured and the modelled Δ14C, in this study we will make use of linear detrending, as this largely removes the systematic offsets associated with the unknown carbon cycle history and inventories.” Were both datasets detrended? Please clarify what was done to detrend the data and which datasets were used.

Reply: We have now added an explanation that all datasets were detrended in the same way by, first, selecting the data in a consistent timeframe for all datasets (20-25 ka b2k) and, then, using the Matlab function detrend(), which subtracts the best straight-fit line from the data.

>>What is the orange in Fig. 5?

Reply: In fig. 5 we have added that the orange indicates the intervals of missing data (like in fig. 1a)

>>Line 505-506: “The stack is shown in fig. S1, with uncertainty bands derived from the standard deviation of the 1000 simulated fluxes.” Is there a reason the stack isn’t shown in the main manuscript? Is it not particularly relevant?

Reply: The stack is later used to apply the wiggle-matching as if it constituted an additional, independent, ‘ice core dataset’. Because of the stacking method adopted, the wiggle-matching result of the stack is slightly different than simply averaging the output from the individual ice cores. We considered the stack itself not to be informative enough to dedicate a full figure in the main text, but, given your comment, we interpret that the reader might expect to see the stack directly where it is mentioned. We have added it in a panel in fig. 6 and used it to determine its own bipolar offset to Antarctica.

>>Lines 516-518: “The G2B event: a relatively abrupt increase of 30 ‰ in the modelled Δ14C from 10Be, reaching its maximum at 21,725 years b2k (GICC05 ages), about 100 years after the maximum is reached in 10Be fluxes.” This is a bit confusing because this event is called the “G2B” event, but then it is stated that happens 100 years after the 10Be. Please explain. Also, if the timing were the same as the 10Be event, wouldn’t you expect this, considering that the 10Be data are an input that is used to produce the

modelled Δ14C data?

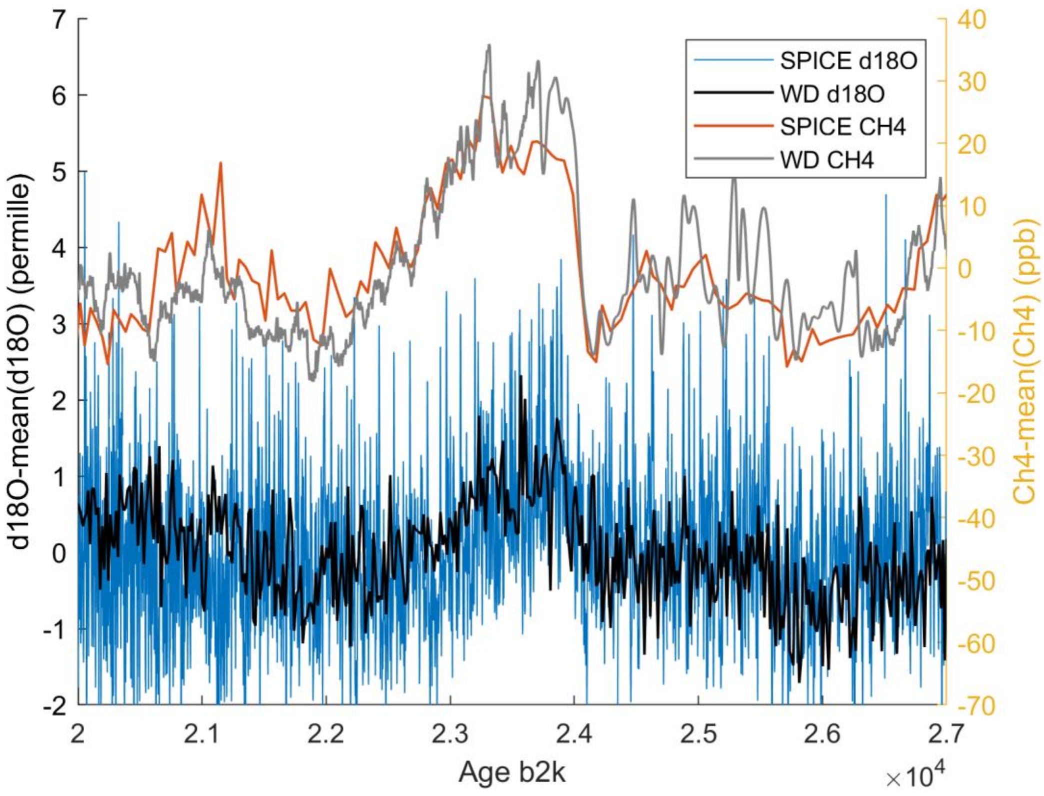
Reply: There is a dampening and a delay between changes in ^{14}C production rate (reflected in our ^{10}Be measurements) and in the atmospheric ^{14}C concentration (measured as $\Delta^{14}C$) due to the carbon cycle (due to the large active ^{14}C reservoirs) which needs to be accounted for when determining the true age of the solar minimum. Hence, the ^{10}Be-signal, which is rapidly deposited, leads the manifestation of the G2B signal in $\Delta^{14}C$. We have clarified the two ages accordingly in the text, making it clear that the event is detected in ^{10}Be and ^{14}C but for the synchronisation the about 100 years carbon cycle-related delay needs to be accounted for.

>>Table 3 is very helpful!

Reply: Thank you.

>>Lines 654-656: "We cannot provide an Antarctic comparison in this context, as the WD2014 chronology does not currently apply to other ice cores, hence an updated Antarctic synchronization across AIM-2 would be required." I don't quite understand this. Isn't WD2014 applied to the South Pole Ice core (SPICE) and to Skytrain (paper recently submitted to CP)?

Reply: We added the SPICE ice core to the Antarctic picture. We attach a preliminary figure for the revised manuscript, showing the gas data and $\delta^{18}O$ data of the WDC and Spice ice cores on their common time scale, which shows the agreement of the two ice cores regarding the shape of AIM2 and the associated CH_4 signal. The data show a broad agreement in the shape of the AIM-2 and of the CH_4increase. The Skytrain data is still under review and subject to revision, however the methane shown at fig. 5 of Mulvaney et al. (2022, in revision) appears to agree with WDC in the LGM. We have added a comment in the main text remarking the average features of the Antarctic signals.



>>Technical changes:

Reply: All the minor technical changes have been considered in the revision. We only add replies to the more complex comments.

>>Line 50: change "being debated" to "under debate"

>>Line 52: add comma after "cold period"

>>Line 54: "was established to have lasted until"…change to something like "suggest that the LGM lasted until…"

>>Line 56: "since it coincides with the age limits of our new Greenland 10Be dataset"…what does this mean?

Reply: We mean that 20-25 ka b2k was chosen as the measurement time frame for NGRIP, which is chosen as axes limits in all our figures. Since this is in broad correspondence with the LGM, which does not currently have a precise global stratigraphic definition, an informal correspondence between LGM and "measurement timeframe" is often adopted in this work.

>>Line 108: Define $\delta^{18}O_{ice}$

Reply: We have added a definition.

>>Figure 1 caption: The second “d” should be “e”
>>Sections 2.1 and 2.2: references to the 10Be methods???

Reply: We have added the relevant citations.

>>Line 323: “quantify the impact of 10Be measurements uncertainty” change to “quantify the impact of 10Be measurement uncertainty”

>>Line 275 vs. line 390: 21.7 ka event in one line and 22.7 ka event in another. Are these different events?

Reply: No, it should be 21.7 ka event throughout. Thank you for noting this.

>>Line 451: “some eruptions are better visible in the”…change to “more visible”

>>Line 461-462: “and we obtained a timescale correction, which we apply in the following to the GRIP data.” This is confusing. Please simplify this sentence.

>>Line 560: “Measured Hulu Cave used for synchronization” You should add that this is Δ14C.

>>Line 672: change “As much as the GICC05 layers are concerned,” to “As far as the GICC05 layers are concerned”

>>Line 677: change “Acknowledging the 125-years offset” to “Acknowledging the 125-year offset”

>>Line 677-678: change “the 375 years offset between GICC05” to “the 375-year offset between GICC05”

>>Lines 746-747: “However, the onset of the Greenlandic dust peak moved to be roughly synchronous with the signal in the Hulu speleothem that has been linked to the HS-2 onset.” Turn this into a sentence.

Kind regards,
Giulia Sinnl et al.

References:
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