# Final Response

Black = reviewer or editor comment / blue = author's response / "grey" = former main text / "red" = revised main text.

**Summary:**



Line numbers refer to the revised versions of Supplementary Material and Main Text.

## I. Response to anonymous Referee #1

We thank the reviewer for his/her valuable and helpful comments on the manuscript. We have implemented the following changes in a revised version.

This paper presents an improved chronology for the Antarctic EPICA Dome C ice core for the time interval 0-800 kyr. The development of this chronology involved various methods, including linking to existing Greenland and Antarctic ice cores, orbital tuning with $\delta^{18}O_{atm}$, $\delta O_2/N_2$, and total air content, and employing firn modeling. One of the significant advancements is the improvement of a section around 110 ka BP, where several previous studies have pointed out that the AICC2012 chronology is too young. Additionally, the increase of new gas data ($\delta^{15}N$, $\delta^{18}O$, $\delta O_2/N_2$, TAC) has greatly improved the precision of orbital tuning and the estimation of the Lock-in depth scenario, reducing overall chronological uncertainty significantly. While assessing whether the oldest part of the AICC2023 chronology has improved from the AICC2012 chronology is challenging, it does provide a reasonable estimate with a larger age uncertainty compare to AICC2012.

The paper is clearly written and convincingly demonstrates the method, including thorough sensitivity studies. The improved chronology for the EDC core is beneficial not only for the ice core community but also for the broader paleoclimate community. Therefore, I recommend accepting this paper for publication in *Climate of the Past* after addressing the following comments.

**General comments:**

1) I am concerned about aligning the EDC $\delta^{18}O_{atm}$ and the precession variations older than 590 ka BP, although it seems to be a better solution than the previous one. While Extier et al. (2018) suggested that

the Heinrich-like events occurring especially during deglaciations delay the response of $\delta^{18}O_{atm}$ to orbital forcing, Oyabu et al. (2022) showed that the large lags of $\delta^{18}O_{atm}$ behind 65N summer insolation (~6 kyr) are not always seen during the Heinrich-like events. For example, they showed that a large lag (>6 kyr) was found during the period of less IRD (around the penultimate glacial maximum), while the lag for HE11 during Termination II is a modest value of 4.1 kyr. Therefore, I think it would be valuable to indicate what potential errors may exist, although the authors have already given a safely large uncertainty. For example, what about applying the same approach to well-dated periods such as the last glacial period, and/or the range of time periods where $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ matching was conducted, with relatively small dating uncertainties on speleothems, and comparing each other? This might serve as a test to evaluate the reliability of the methodology, and the readers will be convinced of the reliability of the obtained chronology.

**Author's response:** Thank you for these valuable inputs.

First, we modified the Sect. 3.2.3 (L. 503 in main text). We indicated the potential errors that may exist for using this approach for the period 590-800 ka BP and referred to Oyabu et al. (2022):

"Between 810 and 590 ka BP, the $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ dating uncertainty becomes larger than 6 kyr and no East Asian speleothem $\delta^{18}O_{calcite}$ records are available before 640 ka BP. Over this time interval, we updated the following approach of Bazin et al. (2013): EDC $\delta^{18}O_{atm}$ and 5 kyr delayed climatic precession are synchronized using mid-slopes of their variations. However, from the findings of Extier et al. (2018), $\delta^{18}O_{atm}$ should rather be aligned to precession without delay when no Heinrich-like events occurs. Indeed, $\delta^{18}O_{atm}$ is sensitive to both orbital and millennial scale variations of the low latitude water cycle (Capron et al., 2012; Landais et al., 2010) and Heinrich-like events occurring during deglaciations delay the response of $\delta^{18}O_{atm}$ to orbital forcing through southward ITCZ shifts (Extier et al., 2018). We thus chose to align $\delta^{18}O_{atm}$ to precession when no Ice Rafted Debris (IRD) peak is visible on the studied period in the ODP983 record (Barker, 2021) and keep a 5 kyr delay when IRD peaks are identified. This results in shifting 12 tie points of Bazin et al. (2013) by 5,000 years towards older ages (see Fig. 6). The eight remaining tie points of Bazin et al. (2013) that coincide with peaks in the IRD record are kept (Fig. 6). To confirm the validity of our approach, we tested three methodologies to align $\delta^{18}O_{atm}$ and precession over well-dated periods when $\delta^{18}O_{atm}$- $\delta^{18}O_{calcite}$ matching was done (see Sect. 2.2.2 in the Supplementary Material). These tests support our approach but in order to account for potential errors associated with this tuning method (Oyabu et al., 2022), a 6 kyr uncertainty (1$\sigma$) is attributed to the $\delta^{18}O_{atm}$ derived tie points over the period between 810 and 590 ka BP.

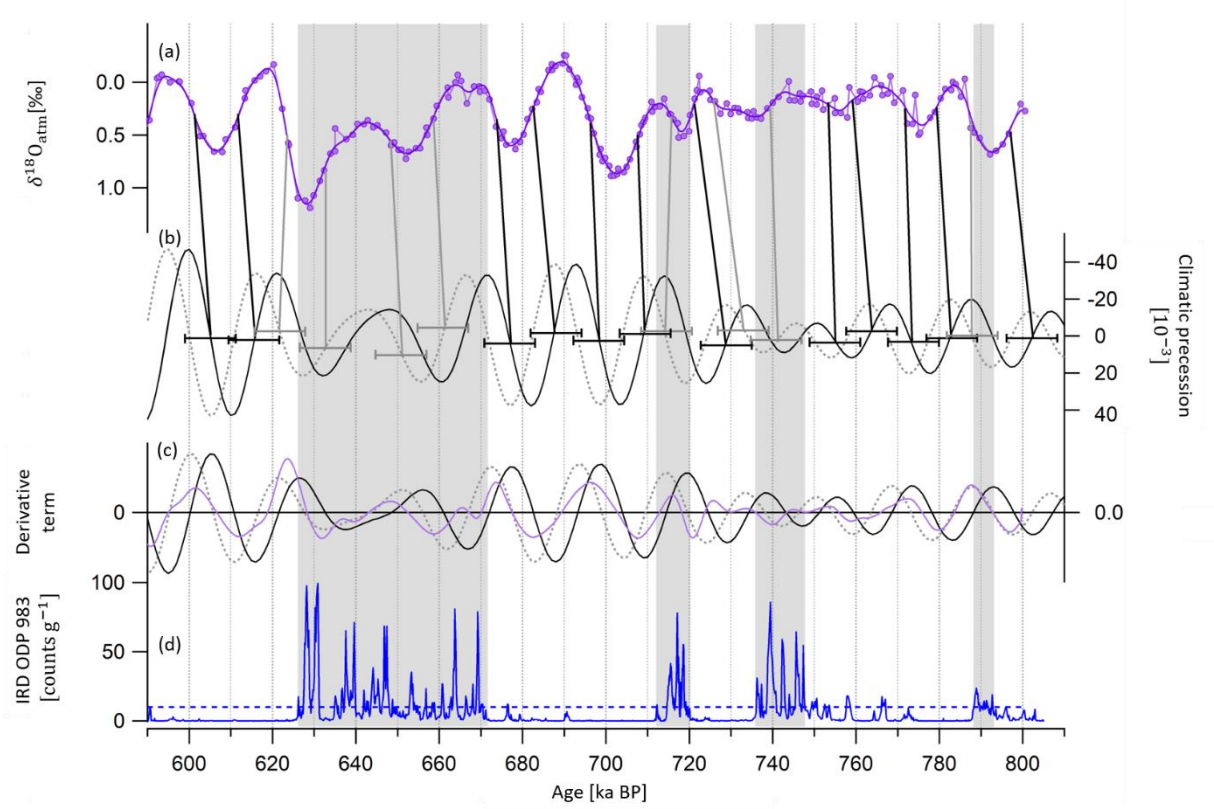



**Figure 5. Alignment of EDC $\delta^{18}O_{atm}$ and climatic precession between 810 and 590 ka BP.** (a) Compiled EDC $\delta^{18}O_{atm}$ on AICC2012 gas timescale. (b) Precession delayed by 5,000 years (grey dashed line) and not delayed (black dashed line) (Laskar et al., 2004). (c) Temporal derivative of precession (black dashed line), delayed precession (grey dotted line) and of the compiled $\delta^{18}O_{atm}$ record (purple plain line). (d) Ice-Rafted Debris at ODP983 site (North Atlantic Ocean, southwest of Iceland) by Barker (2021). The gray squares indicate periods where IRD counts are superior to the 10 counts/g threshold shown by the blue dotted horizontal line. Grey vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and delayed precession mid-slopes (i.e. derivative extrema) when IRD counts are superior to the threshold. Black vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and precession mid-slopes (i.e. derivative extrema) when no Heinrich-like events is shown by IRD record. The 12 kyr 2σ-uncertainty attached to the tie points is shown by the horizontal error-bars in panel b."

Then, we agree that applying the same approach over well-dated periods where $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ matching was conducted would be valuable in the Supplementary Material to support the use of the approach presented in the manuscript. Following your suggestion, we modified the Sect. 2.2 at L.59 in the Supplementary Material as follows:

**2.2 "Aligning EDC $\delta^{18}O_{atm}$ record and climatic precession variations**

For the construction of the new AICC2023 chronology between 800 and 590 ka BP, the EDC $\delta^{18}O_{atm}$ record is aligned with the climatic precession delayed or not by 5,000 years depending on the occurrence of Heinrich like events, reflected by peaks in the IRD record from the North Atlantic Ocean (Sect 3.2.3 in the main text). Potential errors may arise from aligning $\delta^{18}O_{atm}$ to precession (Oyabu et al., 2022). To support the use of our approach, we test three methodologies to align $\delta^{18}O_{atm}$ and precession. Four test chronologies are built:

1) The test chronology 1 is obtained by aligning $\delta^{18}O_{atm}$ to 5-kyr-delayed precession as in Bazin et al. (2013).
2) The test chronology 2 is obtained by aligning $\delta^{18}O_{atm}$ to precession as it would be expected if only precession is driving the $\delta^{18}O_{atm}$ signal.
3) The test chronology 3 is obtained by aligning $\delta^{18}O_{atm}$ to precession delayed if IRD counts are superior to 10 counts/g and to precession without delay if IRD counts are inferior to 10 counts/g.
4) The test chronology 4 is obtained by matching $\delta^{18}O_{atm}$ and $\delta^{18}O_{calcite}$ variations only.

#### 2.2.1 Between 810 and 590 ka BP

We first evaluate the impact on the chronology whether $\delta^{18}O_{atm}$ is aligned with the precession with or without delay between 810 and 590 ka BP. The age mismatch between test chronologies 1 and 2 is of 3,000 years on average, reaching its maximum value of 3,700 years at $712 \pm 2.6$ ka BP (red arrow in Fig. S4).

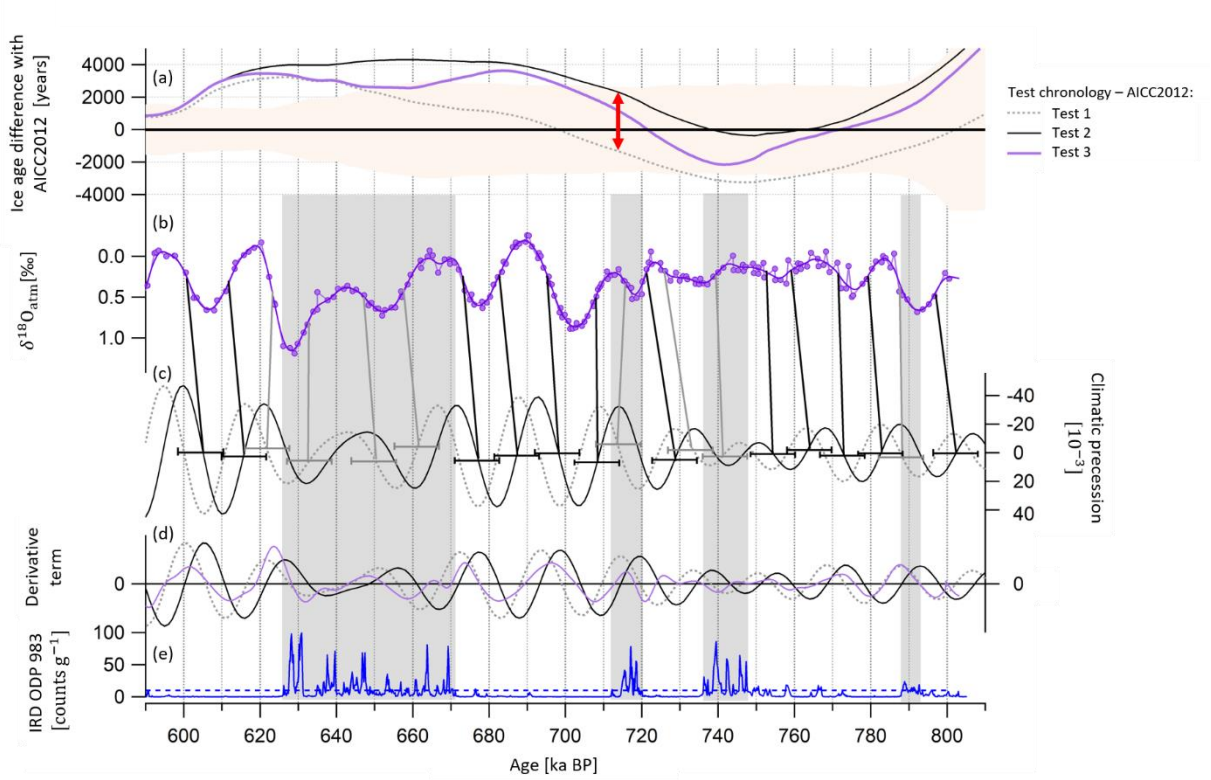



**Figure S4. Alignment of EDC $\delta^{18}O_{atm}$ and climatic precession and impact on the chronology between 810 and 590 ka BP.** (a) EDC ice age difference between AICC2012 and three test chronologies (1) test chronology 1 (grey dotted line), (2) test chronology 2 (black dashed line), (3) test chronology 3 (purple plain line). AICC2023 ice age 1σ uncertainty is shown by the red area. The largest age difference between chronology 1 and 2 is indicated by the red arrow at 712.0 ± 2.6 ka BP. (b) Compiled EDC $\delta^{18}O_{atm}$ (purple circles). (c) Precession delayed by 5 kyr (grey dotted line) and not delayed (black dashed line) (Laskar et al. 2004). (d) Temporal derivative of precession (black dashed line), delayed precession (grey dotted line) and of the compiled $\delta^{18}O_{atm}$ record (purple plain line). (e) IRD (blue by Barker et al. 2021; red by McManus et al. 1999). The gray squares indicate periods where IRD counts are superior to the 10 counts/g threshold shown by the blue dotted horizontal line. Grey vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and delayed precession mid-slopes (i.e. derivative extrema) when IRD counts are superior to the threshold. Black vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and precession mid-slopes (i.e. derivative extrema) when no Heinrich-like events is shown by IRD record. The 12 kyr 2σ-uncertainty attached to the tie points is shown by the horizontal error-bars in panel b.

### 2.2.2 Between 300 and 100 ka BP

Then, we test the three methodologies to align $\delta^{18}O_{atm}$ and precession over the 100-300 ka period, where we have high confidence in our chronology.

Over this time interval, the test chronology 3 appears to be the best compromise as it agrees well with both the AICC2023 age model and the chronology derived from $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ matching (Fig. S5). This is why we believe that it can faithfully be applied to the bottom part of the EDC ice core while keeping large uncertainties in the tie points (1σ uncertainty of 6 kyr).

This agreement is particularly satisfying over the 120-160 ka BP time interval. Over this period, Oyabu et al. (2022) identified a large peak (up to 61%) in the IRD record of McManus et al. (1999) (red plain line in panel e) corresponding to HE 11 between 131 and 125 ka BP. Yet, if we consider the IRD record of Barker et al. (2021) used in our study because it covers the last 800 kyr (blue plain line in panel e), we observe another large peak (up to 56 counts/g) at around 150-156 ka BP. Because of this presence of IRD, to establish the test chronology 3, we tuned $\delta^{18}O_{atm}$ to the 5-kyr delayed precession over the whole period stretching from 155 to 124 ka BP (gray frame), which is larger than the duration covering only HE 11.

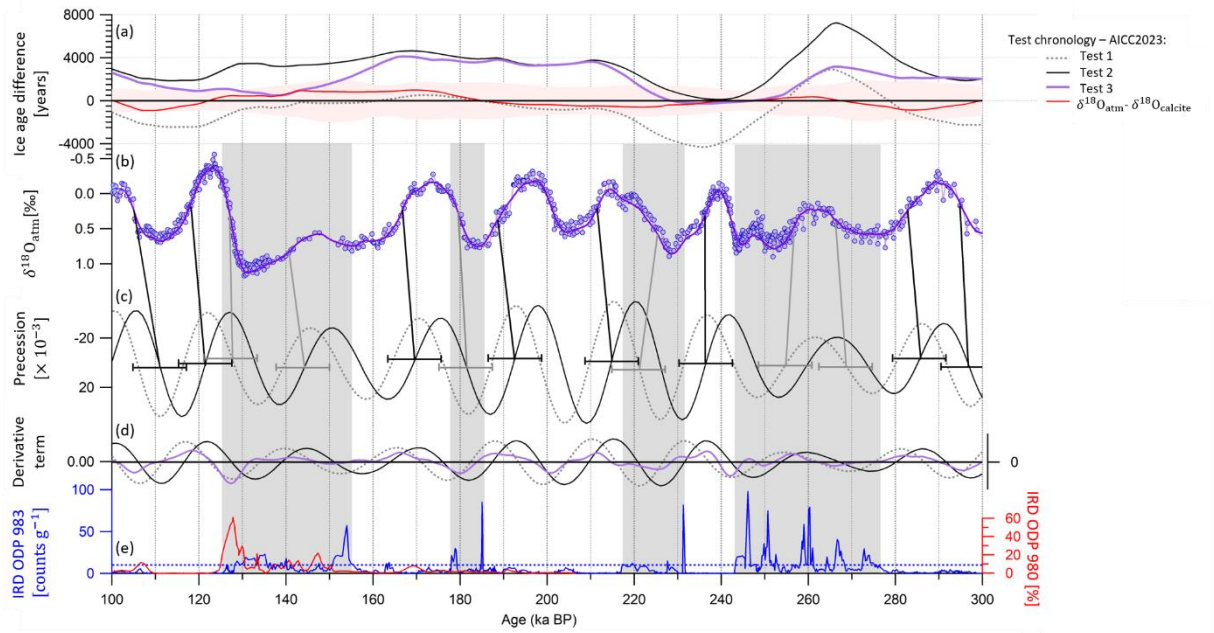



**Figure S5. EDC ice age difference between test chronology and AICC2023 between 300 and 100 ka BP. (**a) EDC ice age difference between AICC2023 and 4 tests chronologies: (1) test chronology 1 (grey dotted line), (2) test chronology 2 (black dashed line), (3) test chronology 3 (purple plain line) and (4) test chronology 4 derived using only $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ matching (red plain line). AICC2023 ice age 1σ uncertainty is shown by the red area. (b) $\delta^{18}O_{atm}$ data from EDC (purple circles) and Vostok (blue circles). (c) Precession delayed by 5 kyr (grey dotted line) and not delayed (black dashed line) (Laskar et al. 2004). (d) Temporal derivative of precession (black dashed line), delayed precession (grey dotted line) and of the compiled $\delta^{18}O_{atm}$ record (purple plain line). (e) IRD (blue by Barker et al. 2021; red by McManus et al. 1999). The gray squares indicate periods where IRD counts are superior to the 10 counts/g threshold shown by the blue dotted horizontal line. Grey vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and delayed precession when IRD counts are superior to the threshold. Black vertical bars illustrate new tie points between EDC $\delta^{18}O_{atm}$ and precession when no Heinrich-like event is shown by IRD record. The 12 kyr 2σ-uncertainty attached to the tie points is shown by the horizontal error-bars in panel b."

Regarding the gas age for the last 60 kyr, there are some age reversals in the AICC2012 chronology. I believe that the AICC2023 chronology has improved as the tie points have been updated and there have been significant progress on the construction of prior LIDs, but please make sure whether the AICC2023 chronology addressed and resolved the issue.

**Author's response:** The AICC2023 chronology resolved this issue. We believe this was due to the too important variability of the analyzed LID scenario that is transferred to the Δdepth, itself driven by the high uncertainty associated with background LID. To address this problem, we revised the background LID scenario using new data of $\delta^{15}N$ and reduced its relative uncertainty to 10-20 % (where it was evolving between 20 and 70 % in the AICC2012 chronology). Here the less variable LID scenario, along with new gas and ice stratigraphic links (Baumgartner et al., 2014; Svensson et al. 2020), result in no age inversion.

It can be seen in the figure below where EDC age difference between two adjacent depth levels is plotted as a function of EDC depth for AICC2012 (black for gas age) and AICC2023 (blue for gas age and red for ice age). If there was an age inversion, then the age difference would present negative values, as for AICC2012 (black curve). Yet, this is not the case for EDC in AICC2023 (blue and red curves). After the same verification for the four other cores, we can guarantee that there is no age inversion in the new AICC2023 age model.

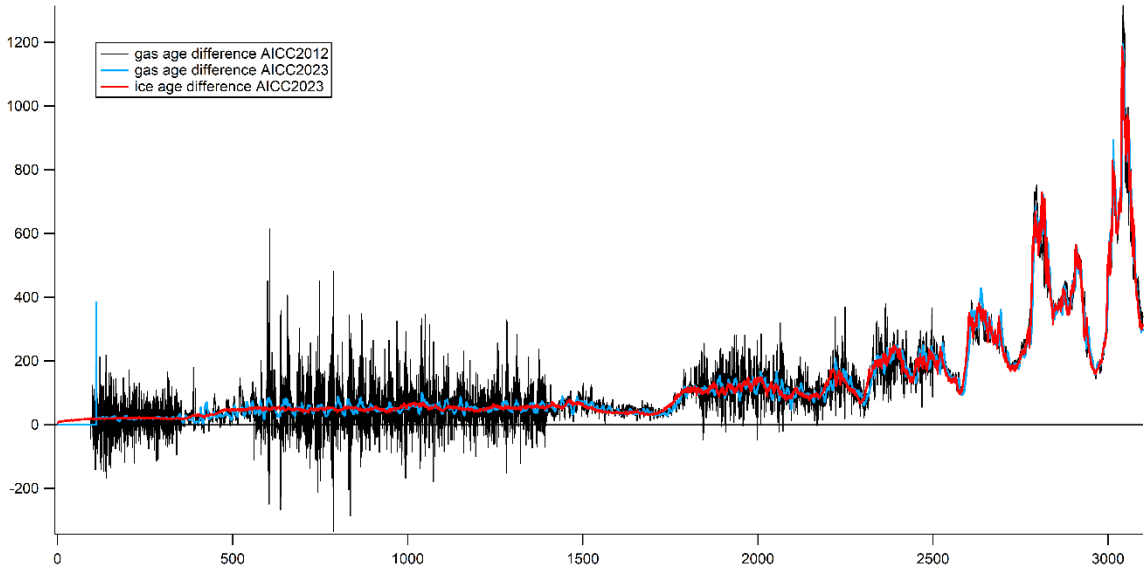



**Figure.** Age difference between two adjacent depth levels in AICC2012 (black for gas age) and AICC2023 (blue for gas age and red for ice age) as a function of EDC depth. The age difference is defined as: age (depth + 0.55 m) – age (depth).

**Specific comments:**

- The authors probably have already prepared the dataset, and please indicate data availability. New ages and their uncertainties, age markers used in this study including both updated and old ones, posterior of accumulation rate, thinning function and LID, and gas data should be included.

**Author's response:** The Code and Data availability sections of the main text have been implemented at L.847:

**"Code availability**

The input and output files of the AICC2023 Paleochrono run are available on GitHub. They contain age markers used to construct AICC2023 (including both updated and old ones).

https://github.com/parrenin/paleochrono/tree/master/AICC2023.

**Data availability**

A folder is available for each site in the PANGAEA data repository. It includes new gas and ice age scales and their uncertainties along with analyzed scenarios for accumulation rate, thinning function and LID. A correspondence between AICC2023, AICC2012 and WD2014 age models is also given.
https://doi.pangaea.de/10.1594/PANGAEA.961017
The new $\delta^{18}O_{atm}$ and $\delta O_2/N_2$ datasets for EDC are also available in the PANGAEA data repository:
https://doi.pangaea.de/10.1594/PANGAEA.961023

The folder is currently reviewed by the PANGAEA repository.

- In Paleochrono, the assignment of uncertainties to the prior scenarios (accumulation rate, thinning function and LID) has a significant impact on the final estimation of age uncertainties. Please indicate what uncertainties the authors assigned.

**Author's response:** The first version of the manuscript presented the uncertainty obtained when preserving the background uncertainties assigned by Bazin et al. (2013) (black plain line in Fig. S8 and S9). However, we agree that although there is no objective way to assign specific prior uncertainties, the values chosen by Bazin et al. (2013) seem unrealistic (i.e. 80 % of uncertainty for the LID during some glacial periods at EDC whereas firn modeling and $\delta^{15}N$ agree within a 20 %-margin at most).

That is why we believe the prior uncertainties should be reduced in AICC2023 and implemented the following changes in Sect. 3.2 of the Supplementary Material (L. 184) as follows:

**"3.2 Background uncertainties for LID, accumulation rate and thinning scenarios**

Although there is no objective way to assign specific prior uncertainties, the values chosen by Bazin et al. (2013) seem unrealistic (i.e. 80 % of uncertainty for the LID during some glacial periods at EDC whereas firn modeling and $\delta^{15}N$ agree within a 20 %-margin at most). That is why we believe the prior uncertainties should be reduced in AICC2023 and implement the following major changes (blue plain line in Fig.S8 and S9):

- The LID background relative uncertainty is reduced to values oscillating between 10 and 20 % at most, excluding values reaching 80 % used in AICC2012. The reason for this modification is that in 2012, the mismatch between firn model outputs and $\delta^{15}N$-inferred LID was not understood. In the meantime, much progresses have been made, confirming that the $\delta^{15}N$-inferred LID was correct and firn models or their forcing have been adapted (Parrenin et al., 2012; Bréant et al., 2017; Buizert et al., 2021).

- The thinning background relative uncertainty is evolving linearly, rather than exponentially as it was done in AICC2012. The linear uncertainty permits to have a significant uncertainty at intermediate depth levels while with the exponential shape, the uncertainty was essentially located at lower depth levels, which was not realistic.
- The accumulation background relative uncertainty is decreased to 20%, as opposed to 60% used in AICC2012. This choice is motivated by the study of Parrenin et al. (2007) who counted event duration in EDC and DF ice cores and found out an offset of 20% on average.

We build different test chronologies by keeping the same age constraints and background scenarios as in AICC2023 but varying the background errors (Table S4). The largest age offset is observed between the test AICC2012 and the other test chronologies at around 650 ka BP. It reaches 400 years (see red arrow in Fig. S8), which is not significant considering the uncertainty associated with the test chronologies over this period (ranging from 1,800 to 3,400 years). Since varying the background uncertainties has no significant impact on the final age model and the background uncertainties of AICC2012 seem unrealistic, we reduce the background errors with respect to AICC2012 and we use the Test 5 configuration from Table S4 to construct AICC2023.

**Table S4. The different prior relative uncertainties tested for LID, thinning and accumulation.** The LID prior relative uncertainty is set between 0.1 or 0.2 whether $\delta^{15}$N data are available or not.

| Test | Sites | LID | Thinning | Accumulation |
|---|---|---|---|---|
| Test AICC2012 | EDC | From AICC2012 (Bazin et al., Veres et al., 2013) | | |
| | EDML | | | |
| | VK | | | |
| | TALDICE | | | |
| | NGRIP | | | |
| Test 0 | EDC | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | EDML | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | From AICC2012 (between 0.2 and 0.8) |
| | VK | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |
| | TALDICE | 0.2 | From AICC2012 (exponential from 0 to 2.4) | 0.2 |
| | NGRIP | 0.2 | Linear from 0 to 0.5 | 0.2 |
| Test 1 | EDC | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | EDML | 0.1 (data) or 0.2 (no data) | Linear from 0 to 1 | From AICC2012 (between 0.2 and 0.8) |
| | VK | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |
| | TALDICE | 0.2 | From AICC2012 (exponential from 0 to 2.4) | 0.2 |
| | NGRIP | 0.2 | Linear from 0 to 0.5 | 0.2 |
| Test 2 | EDC | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | EDML | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | VK | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |

| | | | | |
|---|---|---|---|---|
| | TALDICE | 0.2 | From AICC2012 (exponential from 0 to 2.4) | 0.2 |
| | NGRIP | 0.2 | Linear from 0 to 0.5 | 0.2 |
| Test 3 | EDC | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | EDML | 0.1 (data) or 0.2 (no data) | Linear from 0 to 1 | 0.2 |
| | VK | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |
| | TALDICE | 0.2 | From AICC2012 (exponential from 0 to 2.4) | 0.2 |
| | NGRIP | 0.2 | Linear from 0 to 0.5 | 0.2 |
| Test 4 | EDC | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | 0.2 |
| | EDML | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |
| | VK | 0.1 (data) or 0.2 (no data) | Linear from 0 to 0.5 | Linear from 0.2 to 0.7 |
| | TALDICE | 0.2 | From AICC2012 (exponential from 0 to 2.4) | 0.2 |
| | NGRIP | 0.2 | Linear from 0 to 0.5 | 0.2 |
| **Test 5 (AICC2023)** | **EDC** | **0.1 (data) or 0.2 (no data)** | **Linear from 0 to 0.5** | **0.2** |
| | **EDML** | **0.1 (data) or 0.2 (no data)** | **Linear from 0 to 1** | **0.2** |
| | **VK** | **0.1 (data) or 0.2 (no data)** | **Linear from 0 to 0.5** | **Linear from 0.2 to 0.7** |
| | **TALDICE** | **0.2** | **Linear from 0 to 1** | **0.2** |
| | **NGRIP** | **0.2** | **Linear from 0 to 0.5** | **0.2** |

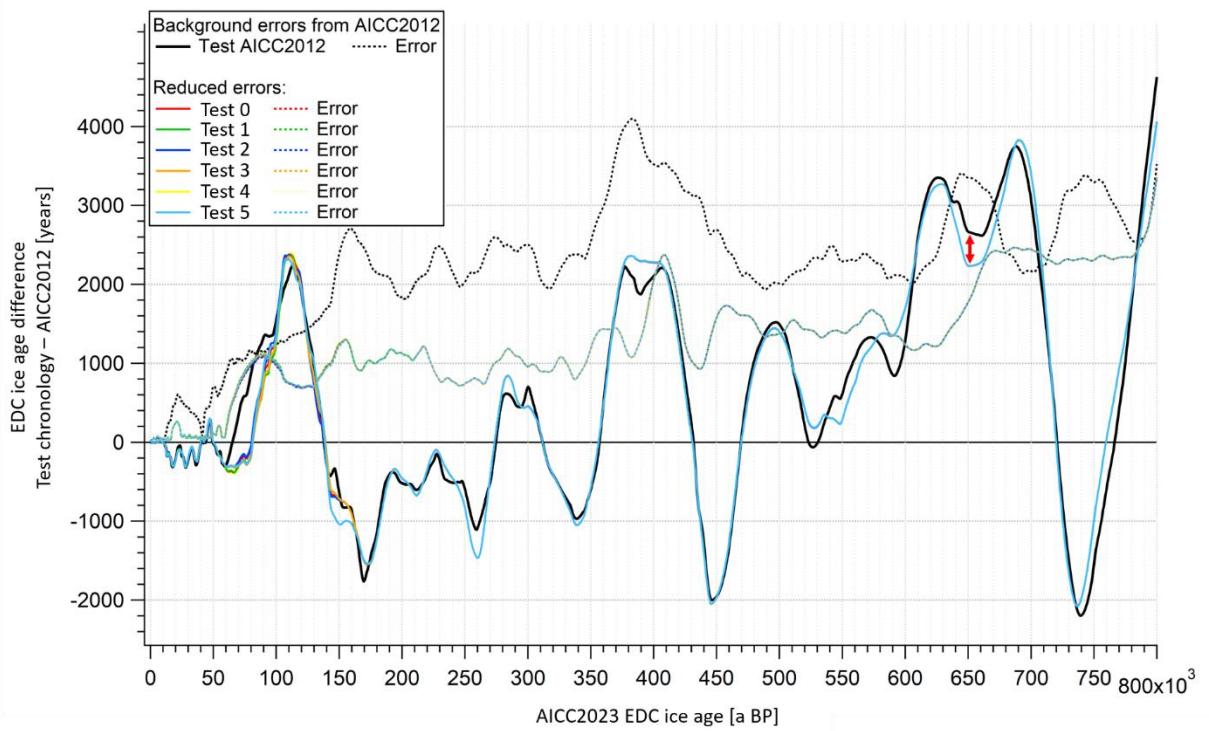



**Figure S8. EDC ice age difference between each test chronology and AICC2012 timescale between 800 and 0 ka BP.** The ice age uncertainty (1σ) obtained for each test is shown by the dotted lines. The red arrow indicates the largest age mismatch between the test chronologies.

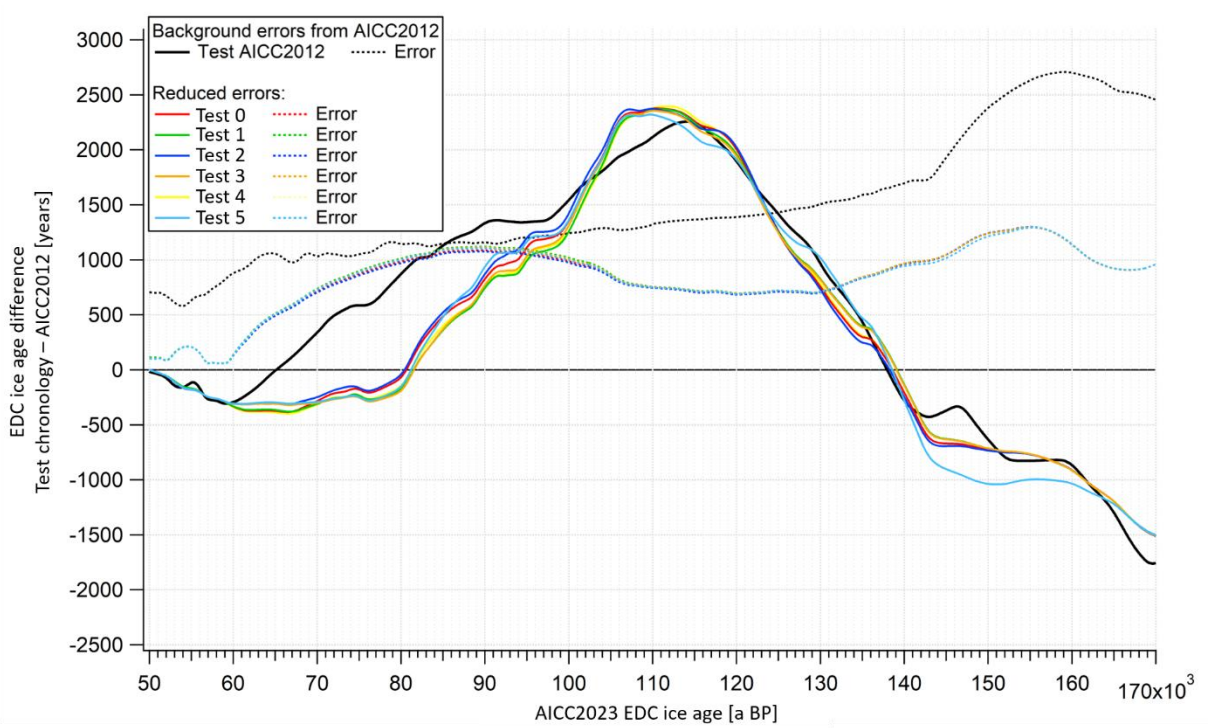



**Figure S9. EDC ice age difference between each test chronology and AICC2012 timescale between 170 and 50 ka BP.** The ice age uncertainty (1σ) obtained for each test is shown by dotted lines."

We summarized what background uncertainties are used in AICC2023 in Sect. 4.2.3 of the Supplementary Material (L.281):

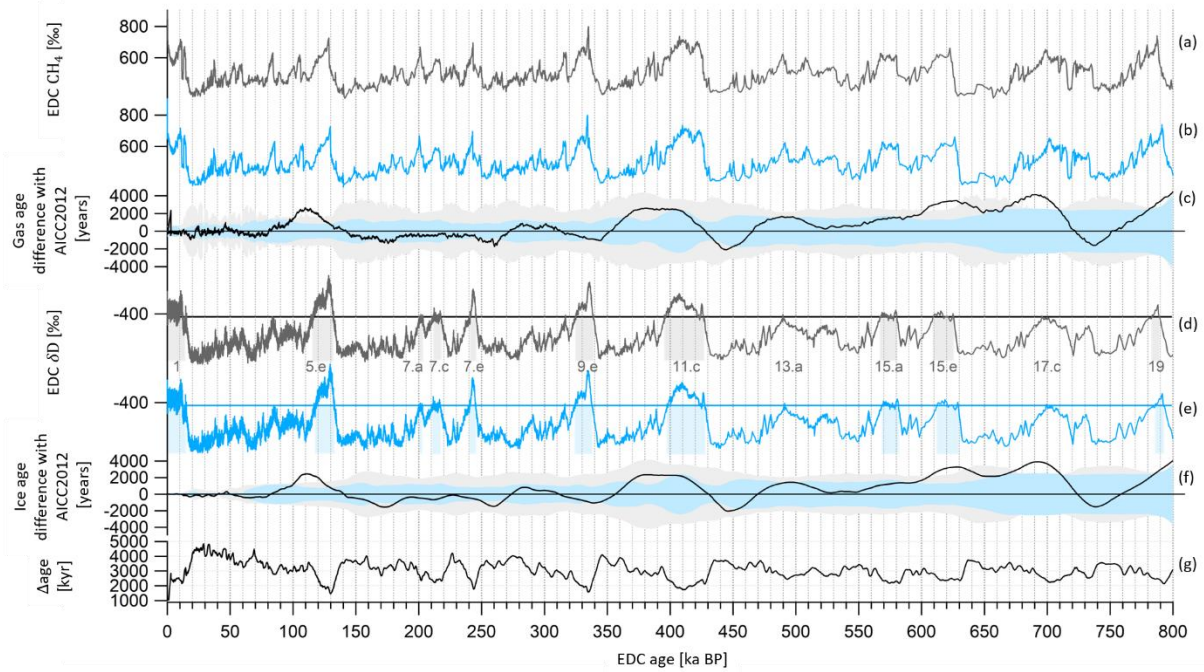
### 4.2.3 "Background scenarios and relative errors for the construction of AICC2023

With respect to the AICC2012 chronology, the background LID scenarios for EDC, Vostok, EDML and TALDICE ice cores are revised in AICC2023 (Table S8). We also reduce the background relative uncertainties associated with the LID, thinning and accumulation functions at the five sites (see Sect. 3.2 in the Supplementary Material).

**Table S8. Origin of the background scenarios of LID, thinning and accumulation for EDC, EDML, Vostok, TALDICE and NGRIP and associated relative errors used in AICC2023.** The LID prior relative uncertainty is set between 0.1 or 0.2 whether $\delta^{15}N$ data are available or not. The mention "AICC2012" means that the scenario is the same than in AICC2012 (Bazin et al., 2013)."

| | LID | | Thinning | | Accumulation | |
|---|---|---|---|---|---|---|
| | **Scenario** | **Relative error** | **Scenario** | **Relative error** | **Scenario** | **Relative error** |
| **EDC** | $\delta^{15}N$ Firn model | 0.1 (data) 0.2 (no data) | AICC2012 | Linear from 0 to 0.5 | AICC2012 | 0.2 |
| **EDML** | $\delta^{15}N$ Firn model | 0.1 (data) 0.2 (no data) | AICC2012 | Linear from 0 to 1 | AICC2012 | 0.2 |
| **Vostok** | $\delta^{15}N$, $\delta^{40}Ar$ | 0.1 (data) 0.2 (no data) | AICC2012 | Linear from 0 to 0.5 | AICC2012 | Linear from 0.2 to 0.7 |
| **TALDICE** | TALDICE-deep1 (Crotti et al., 2021) $\delta^{15}N$ | 0.2 | AICC2012 | Linear from 0 to 1 | AICC2012 | 0.2 |
| **NGRIP** | AICC2012 (Firn model) | 0.2 | AICC2012 | Linear from 0 to 0.5 | AICC2012 | 0.2 |

The reevaluation of the background uncertainties led to minor modifications of the Fig. 9 (see L. 703 in Main Text) such as smoother variations for the gas age model and associated absolute uncertainty and smaller gas and ice absolute uncertainties:



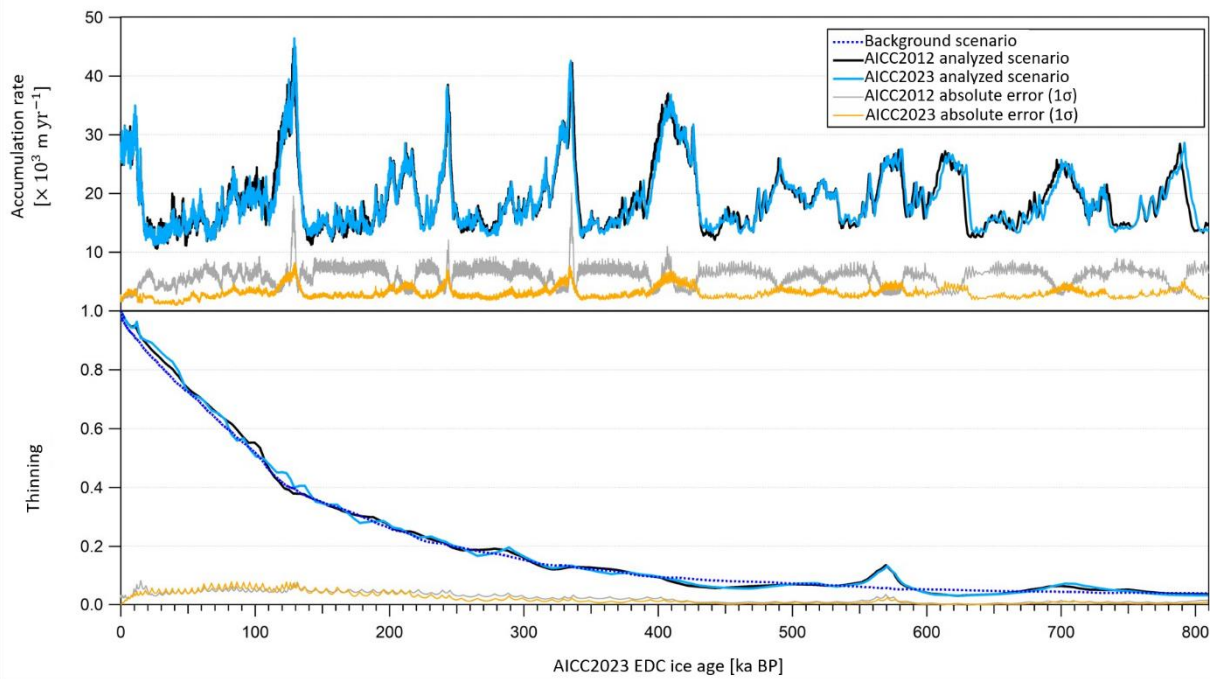

**"Figure 9. EDC gas and ice records on AICC2023 (blue) and AICC2012 (black) timescales over the last 800 kyr.** (a) EDC $CH_4$ (Loulergue et al., 2008) on AICC2012 and (b) AICC2023 gas timescales. (c) Gas age difference AICC2023 – AICC2012. Grey and blue envelops are AICC2012 and AICC2023 chronological 1σ uncertainties respectively. (d) EDC δD (Jouzel et al., 2007) on AICC2012 and (e) AICC2023 ice timescales. Grey and blue rectangles indicate interglacial periods defined when δD is superior to the threshold of - 403 ‰ (horizontal lines) (EPICA members, 2004). Interglacials are numbered from MIS 1 to 19 (Berger et al., 2016). (f) Ice age difference AICC2023 – AICC2012. (g) Age difference between ice and gas AICC2023 timescales (Δage)."

- I suggest showing not only the posterior LID but also the posterior of the accumulation rate and thinning function, either in the main text or supplement.

**Author's response:** We agree and the Sect. 4.4 has been implemented in the Supplement at L. 314:

**"4.4 The new AICC2023 age scale for EDC over the last 800 kyr**

**[…]**




243 **Figure S14**. Analyzed accumulation and thinning functions of EDC provided by AICC2012 and AICC2023 (black
244 and blue plain lines respectively) along with their absolute uncertainties (gray and yellow respectively). The
245 background thinning function is the same for AICC2012 and AICC2023 (dark blue dotted line)."

246

247 • Figure colors: Grey squares in Fig. 4, 7, 8, 9,10, 12, and S4 are too light in color to see.

248 **Author's response:** The changes have been made.

249

250 Lines 23-24: The use of three orbital markers does not necessarily reduce uncertainties.

251 **Author's response:** We agree and deleted the sentence at L. 23-24. Instead, we added this sentence at L. 30:

252 "For the first time, three orbital tools are used simultaneously. Hence, it is possible to observe that they
253 are consistent with each other and with the other age markers over most of the last 800 kyr (70 %). This, in turn,
254 gives us confidence in the new AICC2023 chronology."

255

256 Line 29: Is the uncertainty 1 sigma or 2 sigma ?

257 **Author's response:** It is 1 sigma, it is outlined in the new version.

258

Line 54: EDC -> EPICA Dome C (because it first appears here in the main text).

**Author's response:** It has been changed.

Line 59: I would specify the boundary conditions.

**Author's response:** We specified:

"poorly known parameters including boundary conditions such as bedrock topography, geothermal properties or subglacial sliding."

Line 72: Need reference(s) for 81Kr dating.

**Author's response:** We added the following reference:

Jiang, W., Hu, S-M., Lu, Z-T., Ritterbusch, F., Yang, G-M.: Latest development of radiokrypton dating – A tool to find and study paleogroundwater, Quat. Int., 547, 166-171, https://doi.org/10.1016/j.quaint.2019.04.025, 2020.

Lines 99-100: Oyabu et al. (2022) also used $\delta O_2/N_2$ for the Dome Fuji core over the last 207 kyr and they estimated uncertainties as about 250 to 600 years.

**Author's response:** This has been added in the references.

Line 115: Change to "air is trapped in enclosed bubbles and diffusivity becomes effectively zero". The gas diffuses through the ice matrix (e.g., Salamatin et al., 2001, DOI:10.1016/S0022-0248(00)01002-2), so the original description might possibly be misleading.

**Author's response:** The change has been made.

Line 145: Same as line 29.

**Author's response:** It has been changed to "AICC2012 1$\sigma$ uncertainty".

Lines 146-147: "(i) discrepancy between $\delta^{18}O_{atm}$, $\delta O_2/N_2$ and TAC series and their orbital target". Difficult to understand what the authors meant. Do the authors mention about the inherent dissimilarity in curve shape?

**Author's response:** We clarified:

"(i) some inherent dissimilarities between $\delta^{18}O_{atm}$, $\delta O_2/N_2$ and TAC series and their curve-shaped orbital target"

Line 188: Does the synchronization dating method mean orbital tuning in this context?

**Author's response:** Yes. It also refers to the method consisting in aligning $\delta^{18}O_{atm}$ to $\delta^{18}O_{calcite}$. Hence, we prefer to use the phrasing "synchronization dating method" rather than "orbital tuning".

Line 189: It seems that Δdepth constraints were not included in this study. Although Δdepth may have a small effect on reducing the age uncertainties, it should be important for constraining the ice-gas relationship. It is possible to make Δdepth constraints using δD and $CH_4$ by assuming a bipolar seesaw relationship, and I think it may help to improve dating accuracy.

**Author's response:** Many thanks for this interesting comment. Δdepth constraints are included for the NGRIP ice core as in AICC2012. Then, we prefer avoiding to assume a systematic bipolar seesaw relationship when building the chronology through alignment of $\delta$D maximum and $CH_4$ abrupt increase as suggested by the reviewer. The first reason is that this matching does not always hold (e.g. Capron et al., 2012; Landais et al., 2015; Buizert et al., 2018). However, our new chronology with more precise LID determination thanks to the new $\delta^{15}N$ data can help testing the bipolar seesaw relationship between $\delta$D and $CH_4$ over the last 800 kyr which has been suggested by Barker et al. (2011). This is beyond the scope of this study focused on the chronology.

Lines 200-204: I read the sentences as the authors did not use age intervals but used dated horizons for the last 60 kyr, and I would refer to Fig. S8 here.

**Author's response:** We preferred not to refer to Fig. S8 (Fig. S12 in the revised version) here as this figure shows the $CH_4$ matching and not the ties between AICC2023 and GICC05 mentioned in this paragraph.

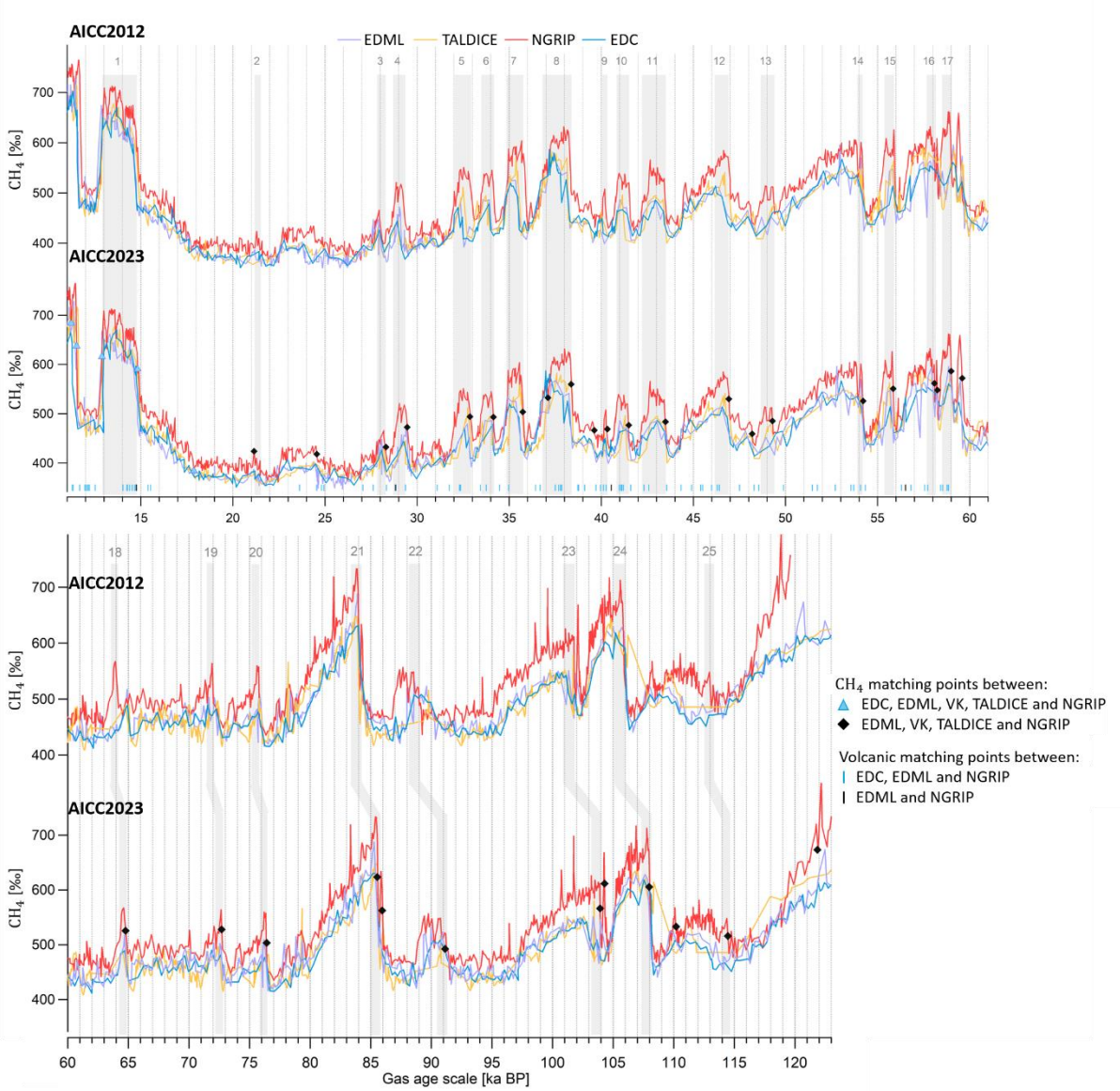
The following comments are also relevant to Section 3.4. In Fig. S8, tie points for the $CH_4$ concentrations are placed up to ~115 ka BP. Did the authors utilize tie points as dated horizons for time periods younger than 60 ka BP and as stratigraphic links between the NGRIP core and other Antarctic cores before 60 ka BP? In the AICC2012 chronology, Veres et al. (2013) employed absolute tie points placed at one-meter intervals to closely fit the

AICC2012 chronology to GICC05 over the last 60 kyr. Did the authors apply the same approach for the AICC2023 chronology? Also, where does 122 kyr (lines 162 and 594) come from?

**Author's response:** As Veres et al. (2013), we closely aligned NGRIP to the GICC05 age scale through absolute tie points placed at one-meter intervals over the last 60 kyr. In addition, over the 0-122 ka BP period, we used the $CH_4$ tie points as gas-gas stratigraphic links between NGRIP and the four Antarctic ice cores. As a result, only the age models of the four Antarctic ice cores are slightly modified so that they are better aligned with GICC05 (see Figure S12). To clarify this point, we modified the Main Text at L. 213

"In order to prevent any confusion with reference ice core timescales, the new AICC2023 chronology for NGRIP is compelled to respect exactly the layer-counted GICC05 timescale through absolute tie points placed at one-meter intervals over the last 60 kyr."

The 122 kyr refers to the oldest $CH_4$ tie point identified by Baumgartner et al. (2014) at 121.9 ka BP which was not appearing on Fig. S12. This is modified in the revised version of the Supplementary Material at L. 300.




**"Figure S12. $CH_4$ records from Antarctic and Greenland sites over the last 122 kyr.** $CH_4$ from EDML, TALDICE, NGRIP and EDC ice cores on the AICC2012 gas timescale (top panel). $CH_4$ from EDML, TALDICE, NGRIP and EDC ice cores on the AICC2023 gas timescale (bottom panel). Stratigraphic links between $CH_4$ series from EDC, EDML, Vostok, TALDICE and NGRIP ice cores (blue triangles and black squares, Baumgartner et al., 2014) and between volcanic sulfate patterns from EDC, EDML and NGRIP ice cores (vertical bars, Svensson et al., 2020) are used to constrain AICC2023 over the last 120 kyr. Abrupt D-O events are shown by grey rectangles and numbered from the youngest to the oldest (1-25) (Barbante et al., 2006)".

Lines 224-225 and line 40 of Supplementary Material: The $\delta O_2/N_2$ obtained from ice stored at -50 ˚C appears much less affected by the gas loss than those obtained from ice stored at -20 ˚C. However, I do not agree that the new data is not affected by the gas loss, because it can be clearly seen that there is offset between the values of Extier et al. (2018) and the new data (e.g., 190 – 260 ka BP in Fig. S1). This discrepancy suggests that the new data was affected by the gas loss. The 3-5 mm surface removal probably does not completely remove the ice affected by the gas loss as shown by Oyabu et al. (2021) (https://doi.org/10.5194/tc-15-5529-2021). While the

offset may not affect dating in terms of peak positions (need to check), the absolute value is still important if this data is to be used to reconstruct atmospheric oxygen concentration (e.g., Stolper et al., 2016, doi/10.1126/science.aaf5445; Extier et al., 2018). In such a case, it would be risky to state that no gas loss correction is necessary. I suggest to the authors mention about the $\delta O_2/N_2$ data that the new data is slightly affected by the gas loss, although peak positions are not affected.

**Author's response:** The authors agree and we mention at L. 243 in the Main Text: "Note that our samples were stored at -50°C since drilling to minimize gas loss effect. As a consequence, no correction for gas loss was applied (see Supplementary Material) and if gas loss may explain a slight scattering in the data, the peak positions are not affected."

We also specify at L. 335: "As these novel $\delta O_2/N_2$ measurements have been performed on ice samples stored at -50°C, there is little storage effect and they can directly be merged with the 800 kyr long record of Extier et al. (2018)"

Line 227: The reported pooled standard deviation for $\delta O_2/N$ appears to be small by one order of magnitude (Extier et al. (2018) reported it as 0.37‰).

**Author's response:** The correction has been made: "The resulting data set pooled standard deviations for the new measurements are of 0.006, 0.03 and 0.4 ‰ for $\delta^{15}N$, $\delta^{18}O_{atm}$ and $\delta O_2/N_2$ respectively."

One zero has been added by mistake.

Line 268: Need reference(s).

**Author's response:** We implemented "Herron and Langway 1980; Alley 1987; Arthern et al., 2010, Ligtenberg et al., 2011 and Kuipers Munneke et al., 2015".

Line 270: Move "Capron et al. (2013)" to the end of the sentence.

**Author's response:** This has been done.

Figure 1: I would suggest placing minor ticks between major ticks for the age scale (like fig. 9). Figure 1 and Figure 2 have duplicate items, and it would be sufficient to use only Figure 2.

**Author's response:** We kept only Fig. 2 with additional minor ticks for the age scale.

Line 302 Chapter title: This chapter mostly describes what age constraints and background LID scenarios were used. It may be better to change the chapter title (e.g., 3 Age constraints and background scenarios).

**Author's response:** The change has been made.

Lines 373-375: I would suggest having a little more explanation of how the 3 kyr was derived.

**Author's response:** We add at Line 379: "A 3-4 kyr uncertainty was evaluated by Bazin et al. (2016) on the following arguments. They examined three $\delta O_2/N_2$ records from Vostok, Dome Fuji and EDC ice cores over MIS 5 and detected some site-specific $\delta O_2/N_2$ high frequency variability that could not be explained by a timescale issue. This observation, along with the presence of a 100 kyr periodicity in the EDC $\delta O_2/N_2$ record and the difficulty of identifying $\delta O_2/N_2$ mid-slopes and maxima because of a scattering of the $\delta O_2/N_2$ signal at millennial scale, led them to recommend the use of a 3-4 kyr uncertainty. Because our higher resolution $\delta O_2/N_2$ data gives the possibility to filter the signal with more confidence and hence reduces the uncertainty in the identification of $\delta O_2/N_2$ tie points, we propose to take a 3-kyr uncertainty."

Figure 2, line 380: Change to "Extrema in the compiled filtered $\delta O_2/N_2$ dataset (blue plain line in panel a) are identified and…." . (b) in the figure should be shown a little lower (next to the insolation curve); it appears to point to the compiled $\delta O_2/N_2$.

**Author's response:** The panels were modified to a) $\delta O_2/N_2$, b) compiled and filtered $\delta O_2/N_2$, c) orbital target, d) temporal derivative.

Line 418: "All extrema are not…" should be "Not all extrema are…".

**Author's response:** This was corrected.

Figure 3, line 435: What is the bottom line? Maybe the "bottom" should be "horizontal."

**Author's response:** This was corrected.

Lines 469-470 and Figure 5: There are several cases where the vertical lines in the figure appear to point to the slope instead of the extrema of the temporal derivative. In addition, the type and number of lines connecting (b)-(c) and (d)-(e) do not match in several places—for example, around 160 ka BP and 370 ka BP.

**Author's response:** This was corrected.

Line 482: I would suggest briefly explaining the source of uncertainty for 1.1 – 7.4 kyr.

**Author's response:** We added:

"the age constraints are attached to an uncertainty varying between 1.1 and 7.4 kyr which is the sum of the uncertainties of the speleothems $^{230}$Th dating, the $\delta^{18}O_{atm}$ response to orbital forcing (1 kyr) and the $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ matching (0.5 kyr)."

Figure 5, line 484: Need a reference for the Chinese $\delta^{18}O_{calcite}$.

**Author's response:** The reference was added.

Figure 5, lines 486-487: Reconsider the descriptions. For example, "Tie points represented by blue vertical bars are determined by Extier et al. (2018) and those by black vertical bars are determined by this study. Both are used in the AICC2023 chronology."

**Author's response:** The changes were made.

Line 491: Did the author decide to use the $\delta^{18}O_{atm}$ orbital markers after 590 ka BP rather than after 640 ka BP because the age uncertainties of the speleothem become large?

**Author's response:** Yes, this is specified in the manuscript at L. 512:

"Between 810 and 590 ka BP, the $\delta^{18}O_{atm}$-$\delta^{18}O_{calcite}$ dating uncertainty becomes larger than 6 kyr and no East Asian speleothem $\delta^{18}O_{calcite}$ records are available before 640 ka BP".

Line 499: Delete the period after Bazin et al. (2013).

**Author's response:** The change was made.

Lines 508-512 and Section 4.2.3: The Matsuyama-Brunhes geomagnetic reversal has recently been dated with high precision from detailed studies of the Chiba composite section (e.g., Haneda et al., 2020; Suganuma et al., 2020), and $^{10}$Be data has also been published (Simon et al., 2019). International Union of Geological Sciences ratified the Chiba composite section as the Global Boundary Stratotype Section and Point for the Chibanian stage and middle Pleistocene subseries of the quaternary system. In addition, the age of the M-B boundary in Lake Sulmona has been suggested to be affected by remagnetization (Evans and Muxworthy, 2018). Therefore, I recommend referring to the age from the Chiba composite section. The authors possibly be able to increase the accuracy of the chronology by including $^{10}$Be matching as an absolute dated horizon (I am not a $^{10}$Be expert, and it is difficult for me to suggest an appropriate matching method between the ice core and the Chiba composite section) or to verify the final chronology with better precision with the age from the Chiba composite section.

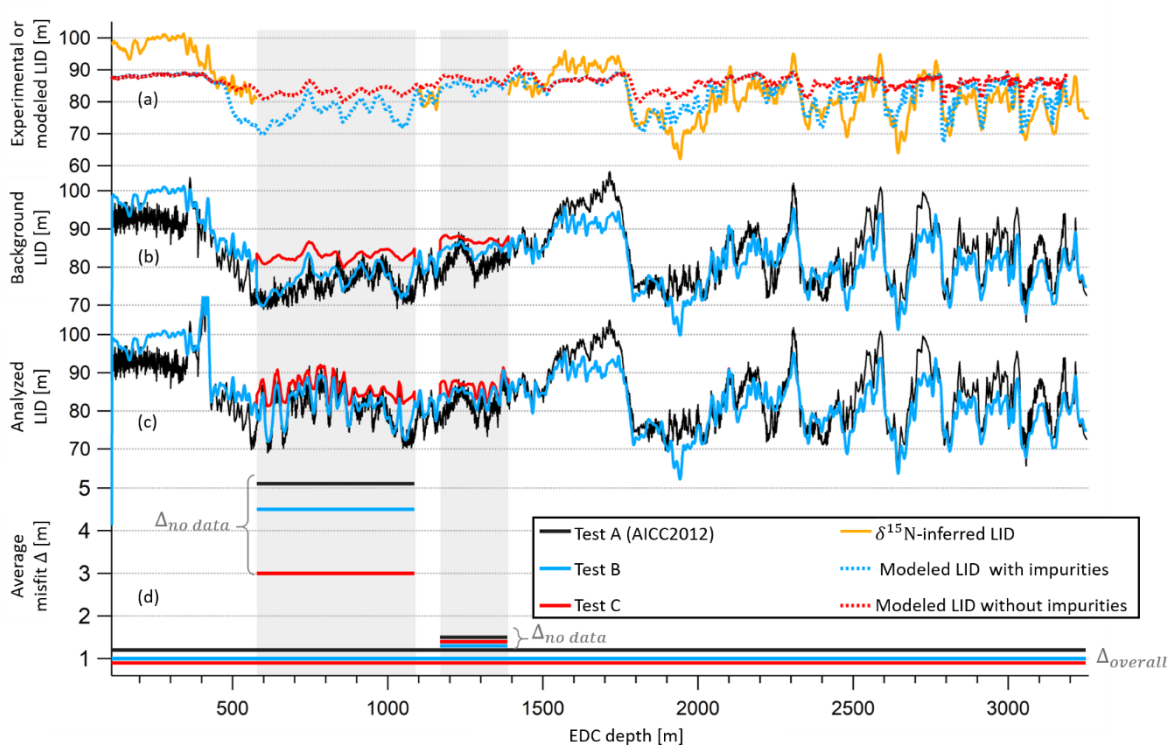
**Author's response:** We agree that the Chiba composite section also provides high-resolution $^{10}$Be record, as the Sulmona basin lacustrine succession (Giaccio et al., in prep.), the Montalbano Jonico marine section (Simon et al. 2017) and the EDC ice core do. We mention the Chiba record and specify why we only consider the Sulmona succession in the revised manuscript at L.801:

"We acknowledge that the Chiba composite section also provides high-resolution $^{10}$Be record, as the Montalbano Jonico marine section (Simon et al. 2017), the Sulmona basin succession and the EDC ice core do. Although, the $^{10}$Be flux records of Sulmona and EDC show a similar pattern and the same asymmetrical shape (i.e., slow increase followed by an abrupt $^{10}$Be peak termination), the sharp termination is less obvious in the Montalbano Jonico and Chiba records. In addition, Chiba and Montalbano Jonico records are shallow marine deposits, hence expression of paleoclimatic proxies can be amplified and/or hampered by fluvial input (Nomade et al., 2019). Finally, substantial adjustments, up to 10.2 ± 5.5 kyr (i.e., exceeding the related uncertainty) are required to fit the millennial scale variability of the Chiba record within the Sulmona radioisotopic-based chronology. Giaccio et al. (2023) point out that, despite these relatively large temporal offsets for the Chiba record, the Sulmona-based age model is more linear and describes a simpler, and likely more realistic, history of sediments accumulation. Therefore, we rather use the Sulmona succession to compare with AICC2023."

We agree that using $^{10}$Be tie points might help constrain the ice core chronology over MIS 19, though we also believe that the age models of Chiba and Sulmona also are highly questionnable between 770 and 750ka. We support the need for further work towards the synchronization of such paleoclimatic archives, but this is beyond the scope of this study.

Section 3.3 and Figure S4: I am curious to see how well the Bréant model reproduced the $\delta^{15}$N based LID. It is difficult to see a similarity from Fig. 7(b) and 7(c), and I would like to see a figure that both LIDs are plotted on the same panel (either in the main text or supplement).

**Author's response:** We agree and superimposed modeled and experimental LID scenarios in Fig S6 in Sect. 3.1 of the Supplementary Material at L. 144:




**"Figure S6. Mismatch Δ between background and analyzed LID for EDC over the 100-3200 m depth interval**. (a) Experimental LID (orange) and modeled LID scenarios as per configuration 1 (with impurities, blue dots) and configuration 2 (without impurities, red dots). (b) Composite background LID as per tests A (black), B (blue) and C (red). (c) Analyzed LID scenarios given by Paleochrono. (d) Three values of the misfit Δ are calculated for the three composite LID: $\Delta_{no\ data}$, averaged over the two depth intervals where $\delta^{15}$N data are not available (either between 578 and 1086 m or between 1169 and 1386 m, see intervals shown by grey rectangles), and $\Delta_{overall}$, averaged over the whole 3200 m."

Figure 7, line 535: The data of Bréant et al (2019) is not mentioned.

**Author's response:** The reference was added.

Section3.4: I recommend uploading the file containing all tie points used in this study, together with the chronology and its uncertainty, to a data repository.

**Author's response:** The file containing the chronologies and their uncertainties at the five sites is under review in the PANGAEA repository. The files containing the tie points are available on GitHub. Both PANGAEA and GitHub links are given in Data and Code Availability sections at L. 847 of the revised main text:

**"Code availability**

The input and output files of the AICC2023 Paleochrono run are available on GitHub. They contain age markers used to construct AICC2023 (including both updated and old ones).

https://github.com/parrenin/paleochrono/tree/master/AICC2023.

**Data availability**

A folder is available for each site in the PANGAEA data repository. It includes new gas and ice age scales and their uncertainties along with analyzed scenarios for accumulation rate, thinning function and LID. A correspondence between AICC2023, AICC2012 and WD2014 age models is also given.
https://doi.pangaea.de/10.1594/PANGAEA.961017
The new $\delta^{18}O_{atm}$ and $\delta O_2/N_2$ datasets for EDC are also available in the PANGAEA data repository:
https://doi.pangaea.de/10.1594/PANGAEA.961023

Figure 8: Grey squares, vertical and horizontal ticks and MIS numbers are too light in color to see.

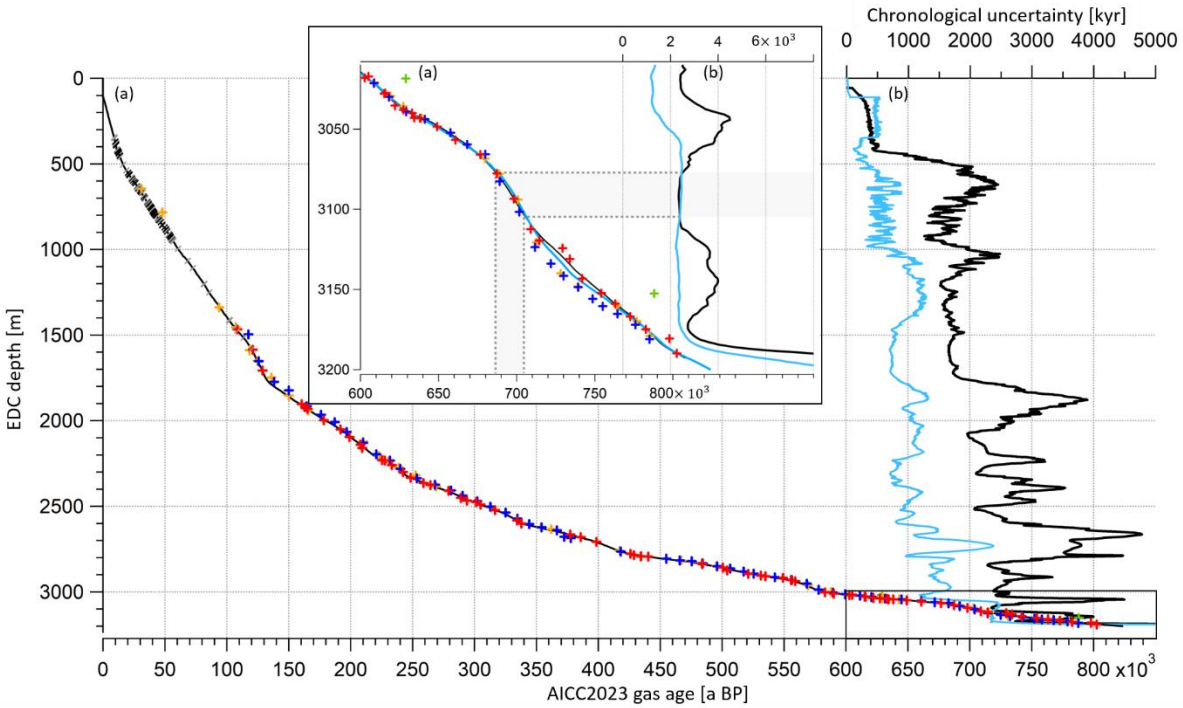
**Author's response:** The changes were made.

Line 673: Insert "and" between $\delta O_2/N_2$ and $\delta^{18}O_{atm}$.

**Author's response:** The changes were made.

Figure 9: Is the uncertainty shown in the figure 1σ? I suggest adding a figure of gas age similar to Fig 9.

**Author's response:** Yes, it is now mentioned in the caption. Such a figure would be quite similar to Fig. 9, hence we added it in the Supplement at L. 311.




496 **"Figure S13. EDC gas age and uncertainty as a function of the depth.** (a) EDC gas age (AICC2012 in black,
497 AICC2023 in blue). (b) 1σ uncertainty (AICC2012 in black, AICC2023 in blue). Crosses and slashes represent
498 new age constraints (ice stratigraphic links in black, gas stratigraphic links in grey, $\delta^{18}O_{atm}$ in red, $\delta O_2/N_2$ in blue,
499 TAC in orange, $^{81}Kr$ in green). Inset is a zoom in between 800 and 600 ka BP. Grey rectangles frame periods
500 where the new AICC2023 uncertainty is larger than AICC2012 uncertainty."

501

502 Figure 10, line 699~: References for the $CH_4$ and δD data are necessary.

503 **Author's response:** The references were added.

504

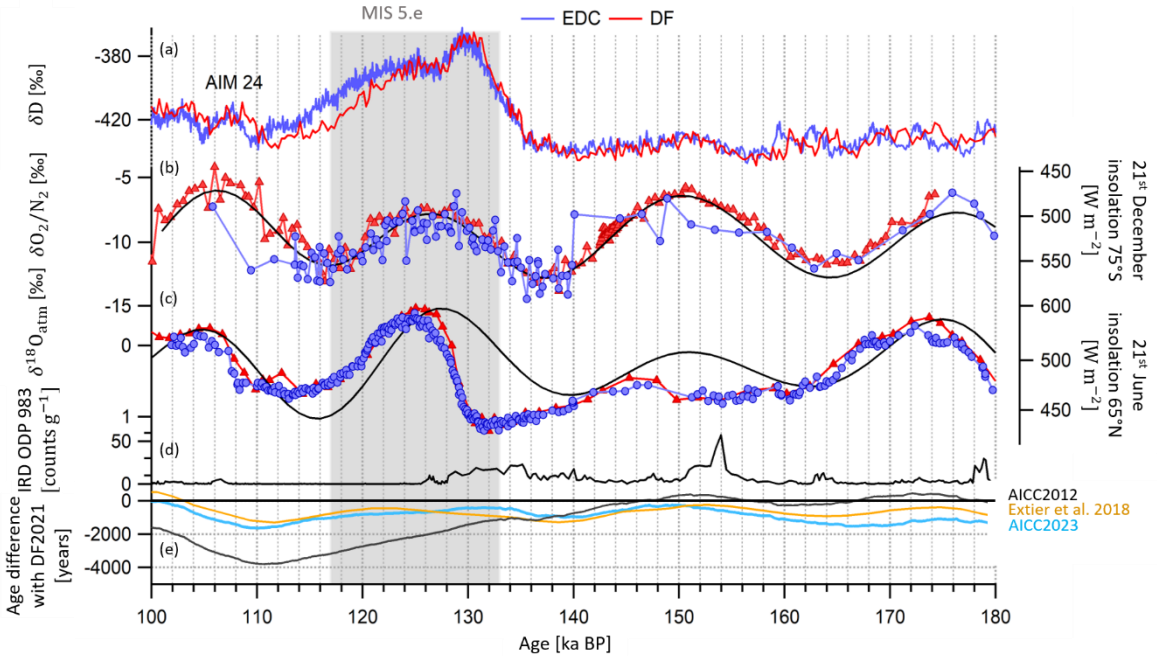
505 Lines 749-750: I agree that a smaller sample size generally increases the noise in data. In addition, I suspect that
506 the EDC samples were slightly affected by gas loss, producing some scatters.

507 **Author's response:** Yes, the gas loss effect on EDC $\delta O_2/N_2$ data is discussed in Sect. 1 of the Supplementary
508 Material at L19: "The bubbly ice analyzed here has been stored at -20°C. The associated mean level of $\delta O_2/N_2$ is
509 not significantly different from the one measured for samples stored at -50°C but the scattering is much larger as
510 already observed on other series from bubbly ice (e.g. Oyabu et al., 2021)"

511

512 Figure 12: The $\delta O_2/N_2$ data from Oyabu et al. (2022) is extended to 207 kyr BP. The gray rectangle in the figure
513 is drawn slightly younger from MIS5e.

**Author's response:** The changes were made in the revised version:




**"Figure 11. Evolution of EDC and DF records on AICC2023 and DF2021 chronologies between 180 and 100 ka BP.** (a) $\delta$D records from DF (red, Uemura et al., 2018) and EDC (blue, Jouzel et al., 2007). (b) $\delta O_2/N_2$ records from DF (red triangles, Oyabu et al., 2022) and EDC (blue circles, this work). (c) $\delta^{18}O_{atm}$ records from DF (red triangles, Kawamura et al., 2007) and EDC (blue circles, this work). DF and EDC records are represented on DF2021 and AICC2023 timescales. (d) IRD from ODP 983 (Barker et al., 2021). (e) Ice age difference between DF2021 and (i) AICC2023 (blue), (ii) Extier et al. (2018a) chronology (orange) and (iii) AICC2012 (black). The age difference is calculated as per EDC age – DF2021 age. DF2021 age is transferred onto EDC ice core via the volcanic synchronization of Fujita et al. (2015). Grey rectangle indicates MIS 5e."

Figure S4: Modify the label of panel (b) (Backgroun"d").

**Author's response:** The change was made.

Figure S8: Hard to distinguish between blue and black markers for the volcanic matching points. Also, see the comments for lines 200-204.

**Author's response:** The changes were made.

## II. Response to Anonymous Referee #2

We thank the reviewer for his/her valuable and helpful comments on the manuscript. We have implemented the following changes in a revised version.

Review of Bouchet et al., 2023 – AICC2023

Bouchet et al., 2023 present an update to the AICC ten years after the first AICC. The update is focused on the EDC ice core and the older portion of the timescale that is based on orbital tuning. The increased density of measurements of d18Oatm, TAC, dO2/N2 and d15N are welcome and represent a significant improvement.

This manuscript describes a useful update the AICC. I remain confused by the exclusion of all(?) US, British, New Zealand, and Australian ice cores from the AICC. This is of relatively minor importance to this manuscript given that the different age ranges and the focus here on ages older than 100 ka and almost exclusively on EDC. I will urge that this chronology is names the EAICC – the East Antarctic Ice Core Chronology – given that there are more West Antarctic cores excluded from this chronology than East Antarctic cores that are included.

**Author's response:** Many thanks for this comment. We acknowledge that the aim of this study was perhaps not made very clear. The objective was indeed to focus on the long timescale (before 60 ka BP) to present the numerous new data available on the EDC ice core and using them to update AICC2012 with a special focus on deep time scales.

Adding the ice cores not yet included in the Paleochrono tool and mainly covering the last 60 kyr would be a different study which requests a lot of resources for the implementation of the ice cores in the Paleochrono tool. It was thus not possible to include everything in this study and we decided to focus more on the deep timescales with a particular focus on EDC. This is clarified in the revised manuscript at L. 219:

"We acknowledge the exclusion of the WAIS (West Antarctic Ice Sheet) Divide ice core (WDC) from the construction of the AICC2023 age scale as for AICC2012 age scale. Over the last 60 kyr, though, we recommend the use of timescales tied to the WAIS Divide 2014 age model (WD2014, Buizert et al., 2015; Sigl et al., 2016). A correspondence between AICC2012, AICC2023 and WD2014 age models based on the volcanic synchronization of WDC and EDC using sulfate data (Buizert et al., 2018) is provided over the 0-58 ka BP period (that is to say for the section above the depth of 915 m for the EDC ice core, see Data Availability section)."

As for the name of the chronology, after discussion with co-authors, we acknowledge that the name EAICC could have been a more suitable choice in the first place.

However, we would prefer to keep the name AICC for several reasons. It is less confusing and allows to show that AICC2023 is an update with respect to AICC2012 and that it should replace it. AICC provides an age model mainly for multiple glacial cycles where only the East Antarctic cores provide information. AICC uses age constraints from a set of cores (including NGRIP, so not just East Antarctic) and can be used as a template for West Antarctic cores as well (as for the Skytrain Ice Rise, Mulvaney et al. 2023). Finally, as mentioned above, one important future development would indeed be to include the high-resolution information from WAIS Divide and other cores.

The authors describe a large range of atmospheric gas measurements. The improvement in resolution of the many records is impressive. The orbital tuning of these records remains quite challenging and thus requires a myriad of subjective choices to develop both the timescale and the uncertainty. The orbital tuning, and the tuning to speleothem calcite, suffer from a lack of understanding in either cause of the variations in the measured parameter, the orbital parameter to tune to, or both. In particular, both O2/N2 and TAC have no process-driven explanation for why they vary based on the orbit characteristics and the variations are not produced by firn models. While this highlights the need for better understanding, particularly as great effort is going to extracting multiple >1Ma ice cores that reach the 40 ka world, it should not prevent doing the best that can be done with current understanding. And Bouchet et al. do this. They have produced a thoughtful chronology and while the manuscript is dense, it is also clearly written.

There are a couple of areas that stand out as areas of concern:

1) The firn modeling

This sentence is particularly confusing: "To obtain a coherent scenario, the firn modeling estimates have been adjusted, by standard normalization, to the scale of LID values derived from $\delta$15N data (later referred to as experimental LID)."

This seems to hiding a major limitation in the methodology. If I understand correctly, the authors cannot get the firn model to match the d15N-inferred firn thicknesses, so they just give up on the actual values and instead seek to match the variations. Whether this is due to an inappropriate firn model (Breant) or outdated forcing (the forcing isn't shown but I suspect the authors are using the classical isotope-temperature scaling that Buizert et al. 2021 showed to be too cold at the LGM). The firn modeling should really be done with multiple models – which is actually relatively easy to do thanks to the Community Firn Model – and with a range of climate forcings. I think the authors efforts would be better served employing other firn models and forcings rather than the impurity scenarios which the author reject.

**Author's response:** Thank you for raising this contradiction. The idea behind this proposition of fitting the modeled LID (orange curve on Fig. S7) to experimental LID values was to avoid any discontinuity when switching from experimental to modeled values when no data are available (grey rectangles on Fig. S7).

Following this comment and for more coherence, we prefer to use the raw firn thickness predicted by the firn model, rather than fitting it to experimental LID values. This modification is considered in the revised manuscript and we modified the Sect. 3.1 in the Supplement at L.168:

**"3. Sensitivity tests on background scenarios and associated relative uncertainties**

**3.1 Background lock-in-depth (LID) scenario at Dome C**

**[…]**

Discontinuities are visible when switching from experimental to modeled values when no data are available (grey rectangles on Fig. S7). To avoid these discontinuities, we test a LID scenario where the modeled LID is fitted to experimental LID values (orange curve in Fig. S7). In other words, the firn modeling estimates are adjusted, by standard normalization, to the scale of LID values derived from $\delta^{15}$N data. Adjusting the modeled LID to experimental LID values induces a modification of 4.7 m at most (see red arrow) which remains within the background relative uncertainty (20%).

On the depth interval from 578 to 1086 m, the modeled scenario without any fitting to $\delta^{15}$N inferred LID (blue curve, Fig. S7) is almost as effective as the one that was fitted (orange curve, Fig. S7) (i.e., close Δ values). On the second depth interval of interest, from 1169 to 1386 m, both scenarios show equal Δ values.

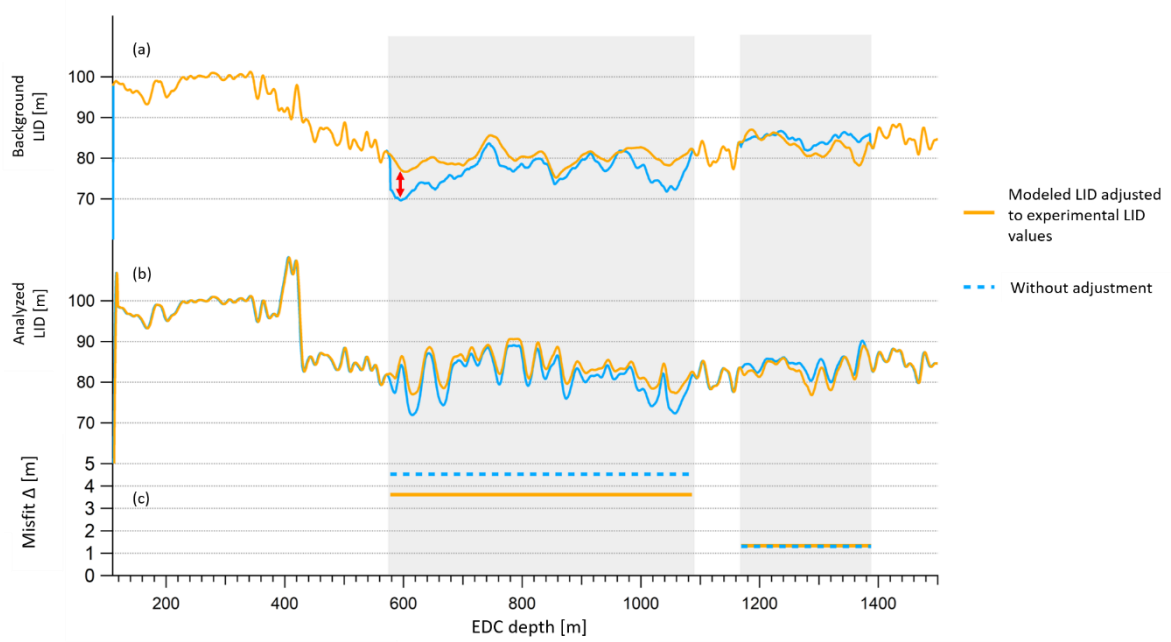



**Figure S7. Mismatch Δ between background and analyzed LID for EDC over the 100-1500 m depth interval.** (a) Background LID with and without adjusting the modeled LID to experimental LID values (orange and blue curves respectively). (b) Analyzed LID. (c) The averaged value of the misfit, Δ, is calculated for the two LID over the two depth intervals where $\delta^{15}$N data are not available (either between 578 and 1086 m or between 1169 and 1386 m, see intervals shown by grey rectangles).

We thus conclude that we can keep the scenario combining $\delta^{15}$N-inferred LID and modeled LID in the construction of AICC2023."

We also noted the comment on the use of other firn models. Actually, we tested other firn models in a first instance (in particular the simple Herron and Langway model used also by Buizert et al., 2021) but we chose to keep the firn model outputs giving the best agreement with the $\delta^{15}$N data over the last 800 kyr at EDC to fill the few gaps existing in the data series. The reason why we did not use the Buizert et al. (2021) approach is that it would require (i) a new EDC temperature scenario over the last 800 kyr while Buizert et al. (2021) only provided the temperature scenario over the last Termination as well as (ii) a new adapted temperature scenario for Vostok (which would be confusing for the readers since our goal is not to revise the Antarctic temperature reconstructions over the last

climatic cycle). Indeed, to use the Buizert approach, we would have needed to adjust the temperature scenario so that the Herron and Langway model reproduces best the $\delta^{15}$N data. We thus do think that testing the Breant model with different parameterizations (all of them published) and keeping the outputs resembling the most the $\delta^{15}$N-inferred LID was the simplest approach (and less confusing) to fill the few gaps in our $\delta^{15}$N-inferred LID.

2) I would like to see an analyses of the thinning function. The EDC AICC2012 thinning function does not decrease monotonically as expected from ice flow modeling (i.e. the input background scenario). If AICC2023 results in a smoother thinning function, this would provide significant support for the methodology.

**Author's response:** We added the Sect. 4.4 in the Supplement at L. 320:

**"4.4 The new AICC2023 age scale for EDC over the last 800 kyr**

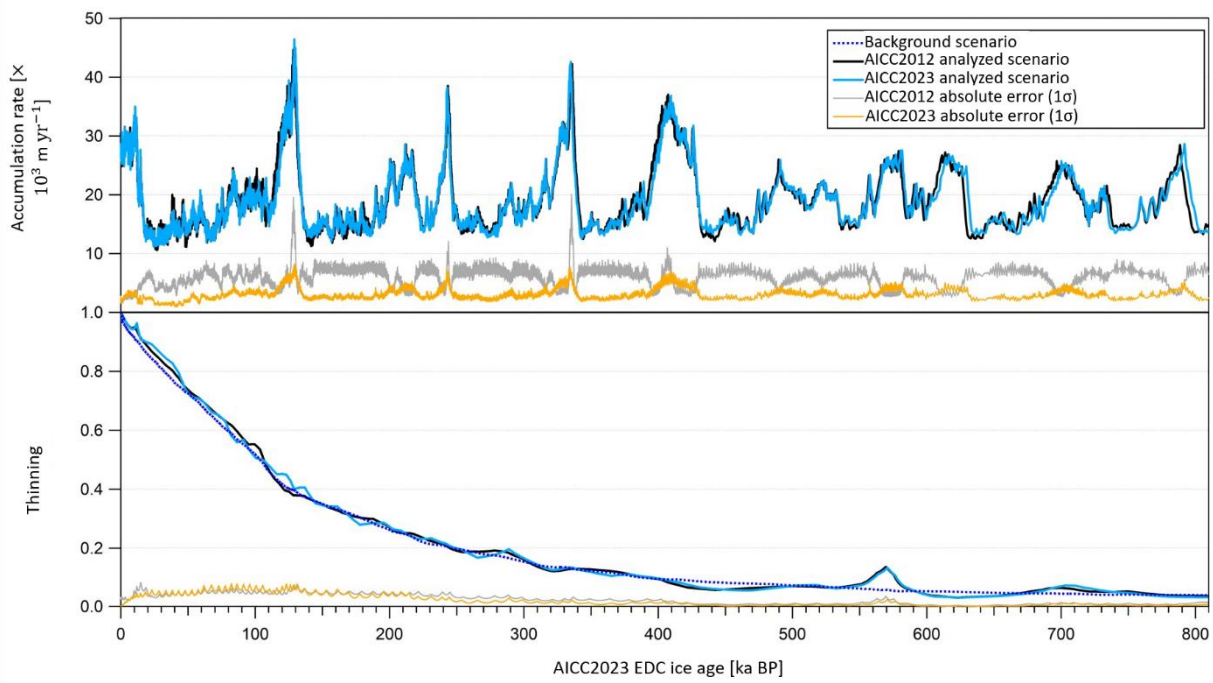



**Figure S14. Analyzed accumulation and thinning functions for EDC over the last 800 kyr.** They are provided by AICC2012 and AICC2023 (black and blue plain lines respectively) along with their absolute uncertainties (gray and yellow respectively). The background thinning function is the same for AICC2012 and AICC2023 (dark blue dotted line)."

Although the new AICC2023 chronology reduces the absolute uncertainty of the thinning function compared to AICC2012, it does not provide a smoother and strictly monotonous scenario (see Fig. S14). However, we believe that this is not a problem for the following reasons:

(i) In a tube flow model, like Vostok's (Parrenin et al., 2004), the thinning function is not monotonous since ice thickness variations are reflected in the thinning function. If the location of the dome at Dome C shifted over the past 800 kyr, the same effect could have affected the thinning function.

(ii) There may also be non-laminar flow effects such as deformation due to more or less hard ice layers.

For instance, Dreyfus et al. (2007) described such a particularly complex thinning scenario at Dome C over the MIS 15 (~580-560 ka BP).

General comments on Figure

For all figures, the timescale that each parameters is plotted on should be stated explicitly. It gets really confusing when match points are connected with lines which are not vertical but the two parameters are plotted on the same age x-axis.

**Author's response:** The changes were made.

Vertical lines corresponding the major axes ticks would be really helpful in assessing the alignment of features

**Author's response:** The changes were made.

It would be really helpful to see the uncertainty assigned to each tie point. Presumably this could be done with a horizontal bar on the match (on the EDC record)

**Author's response:** The changes were made for Fig. 1, 2, 4 and 5 (see revised manuscript).

Specific comments

L36 – The introduction could really use subheadings.

**Author's response:** We agree and use the following subheadings in the revised manuscript:

1.1 Building age scales for deep polar ice cores
1.1.1 Motivation
1.1.2 Glaciological modeling
1.1.3 Chronological constraints derived from measurements
1.1.4 Bayesian dating tools
1.2 The AICC2012 chronology
1.3 The new AICC2023 chronology

669

670 L43 – "zipped" I don't think this is the right translation to English. I'm not sure what you are going for. I think
671 you are trying to say that a large amount of time is stored in a thin amount of ice.

672 **Author's response:** "zipped" was changed to "stored".

673

674 L44 – need to make community possessive > community's

675 **Author's response:** The change was made.

676

677 L44 – "core" not "cores"

678 **Author's response:** The change was be made.

679

680 L46 – add "the" before surface

681 **Author's response:** The changes was made.

682

683 L53 – what about Nye?

684 **Author's response:** We suggest to change to: "chronologies of ice cores at low-accumulation sites are commonly
685 established using ice flow and accumulation models (Nye, 1959; Schwander et al., 2001), later on tied up with
686 chronological and glaciological constraints (Bazin and Veres et al., 2013; Parrenin et al., 2017)."

687

688 L95 – I think it's worth emphasizing that Bender found no causal link between dO2/N2 and insolation and was
689 quite forthright about that.

690 **Author's response:** We believe that the quote from Bender (2002): "We assert that insolation influences snow
691 metamorphism and grain properties in shallow firn. The insolation signature in these properties is retained
692 throughout the firn, and influences $O_2/N_2$ fractionation during bubble closeoff" is coherent with what we wrote in
693 the introduction: "observations led Bender (2002) to assert that local summer solstice insolation affects near-
694 surface snow metamorphism and that this imprint is preserved as snow densifies in the firn and, later on, affects
695 the ratio $\delta O_2/N_2$ measured in air bubbles formed at the lock-in-zone."

I don't expect that the authors will agree to incorporate WAIS Divide, but the introduction should have a paragraph that acknowledges the exclusion and points readers to the timescales for these cores that are tied to WAIS Divide as the best ones to use for past ~60 ka.

**Author's response:** We agree to designate the WD2014 chronology as the best candidate for the past 60 kyr. For greater coherence within the manuscript, we added a paragraph at the end of sect. 2.1 at L.219: "We acknowledge the exclusion of the WAIS (West Antarctic Ice Sheet) Divide ice core (WDC) from the construction of the AICC2023 age scale as for AICC2012 age scale. Over the last 60 kyr, though, we recommend the use of timescales tied to the WAIS Divide 2014 age model (WD2014, Buizert et al., 2015; Sigl et al., 2016). A correspondence between AICC2012, AICC2023 and WD2014 age models based on the volcanic synchronization of WDC and EDC using sulfate data (Buizert et al., 2018) is provided over the 0-58 ka BP period (that is to say for the section above the depth of 915 m for the EDC ice core, see Data Availability section)."

L118 – "peculiar" I think you mean "particular"

**Author's response:** We changed "peculiar" to "singular" as "particular" is not exactly what we meant.

L308 – shouldn't you reference Tison et al. 2015 here?

**Author's response:** The reference was added.

More general comments

L349 – "superior" in English implies "better". I think "greater than" is better phrasing

**Author's response:** The change was made.

L372 – the discarding of "tie points" worries me. Doesn't this imply that you don't understand the underlying mechanisms that link the measurements parameter on the target tuning parameter? If you are discarding tie points all together, should the uncertainty for the tie points you keep be increased to respect that the relationship the ties are based on are not stationary?

**Author's response:** I think the word "discarding" was poorly chosen. Over the period of MIS 11 (gray frame in the Figure below), it is impossible to match $\delta O_2/N_2$ and insolation variations as they do not resemble each other. For instance, two peaks in the insolation curve (dashed black line) only correspond to one peak in the $\delta O_2/N_2$ data (blue circles). Hence, there is no tie point in the first place to be discarded. We did the following modifications at lines 375-386: "In such cases, the uncertainty (1σ) associated with each tie point is ranging from 6 to 10 kyr (precession half period) and some extrema in the target are not used to tune the $\delta O_2/N_2$ record (5 extrema over MIS 11 out of 63 over the last 800 kyr). Otherwise, $\delta O_2/N_2$ seems to evolve in phase with the inverse summer solstice insolation variations and the tie points uncertainty (1σ) is set at 3 kyr. A 3-4 kyr uncertainty was evaluated by Bazin et al. (2016) on the following arguments. They examined three $\delta O_2/N_2$ records from Vostok, Dome Fuji and EDC ice cores over MIS 5 and detected some site-specific $\delta O_2/N_2$ high frequency variability that could not be explained by a timescale issue. This observation, along with the presence of a 100 kyr periodicity in the EDC $\delta O_2/N_2$ record and the difficulty of identifying $\delta O_2/N_2$ mid-slopes and maxima because of a scattering of the $\delta O_2/N_2$ signal at millennial scale, led them to recommend the use of a 3-4 kyr uncertainty. Because our higher resolution $\delta O_2/N_2$ data gives the possibility to filter the signal with more confidence and hence reduces the uncertainty in the identification of $\delta O_2/N_2$ tie points, we propose to take a 3-kyr uncertainty."

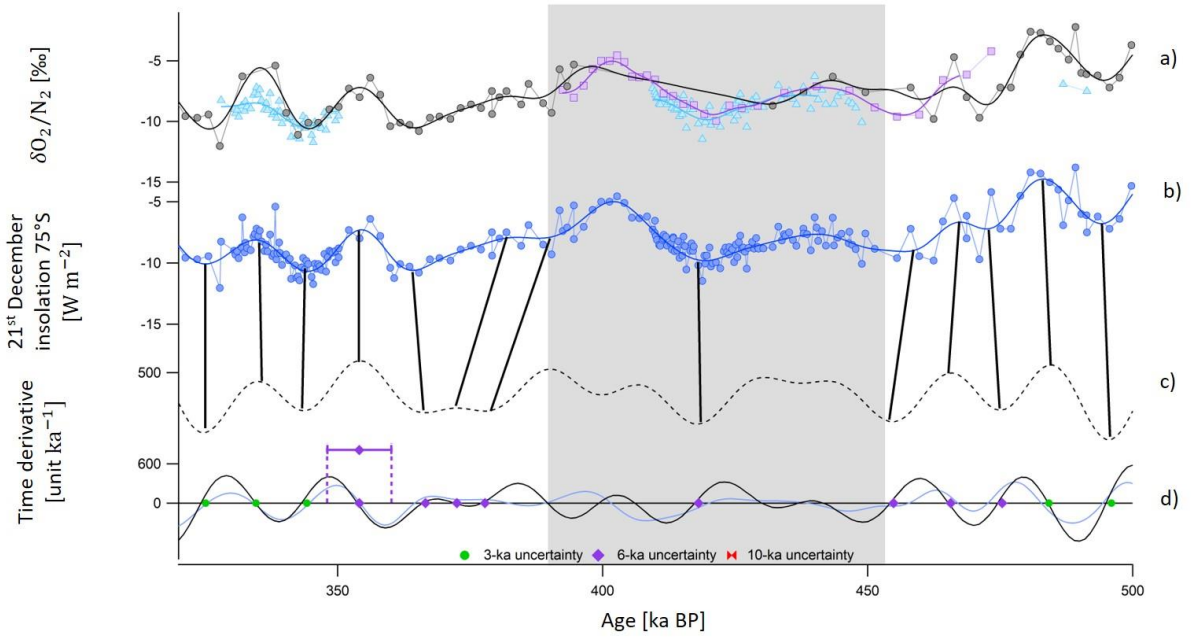



**Figure**. Alignment of $\delta O_2/N_2$ and insolation between 500 and 300 ka BP. (a) EDC raw $\delta O_2/N_2$ old data (black circles for data of Extier et al. 2018) and purple squares for data of Landais et al. 2012), outliers (grey crosses) and filtered signal (black and purple lines). EDC raw $\delta O_2/N_2$ new data (blue triangles, this study) and filtered signals (blue line). The $\delta O_2/N_2$ data are plotted on AICC2012 ice timescale. (b) Extrema in the compiled filtered $\delta O_2/N_2$ dataset (blue plain line) are identified and matched to extrema in the (c) 21st December insolation at 75° South plotted on a reversed y-axis and on the age scale given by Laskar et al. (2004) (dash line). The matching peaks are linked by black vertical bars. (d) The 0 value in the time derivative of insolation (black line) and of the filtered $\delta O_2/N_2$ dataset (blue line) corresponds to extreme values in the signals. The determined tie points between $\delta O_2/N_2$ and insolation are depicted by markers on the horizontal line. Green circles are attached to a 3 kyr uncertainty and purples squares are associated with a 6 kyr uncertainty (purple horizontal error-bar represented at 354.1 ka BP).

748 Between 390 and 475 ka BP, all extrema are not tuned to the target due to the poor resemblance between the signal
749 and insolation (see gray frame).

750

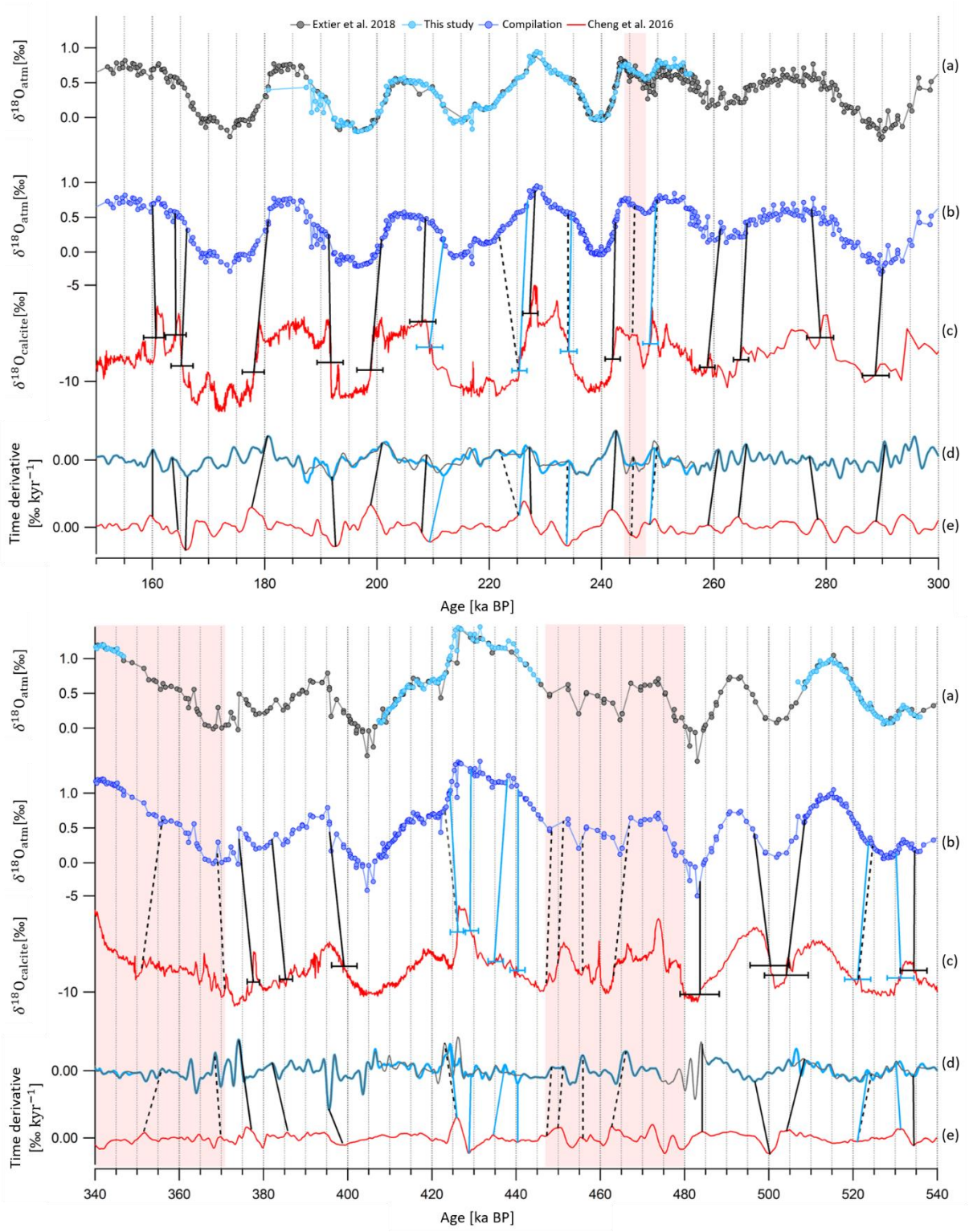
751 L396 – The authors should not use "continuous" to describe the discrete gas measurements. These samples are
752 still quite sparse. Instead, the authors should emphasize increase in sample resolution and the reduction in the
753 largest gaps.

754 **Author's response:** We agree and several changes were made to remove the adjectives "continuous" or
755 "discontinuous" when designating the gas records.

756

757 Figure 5 – I find the match points between d18O-O2 and speleothem d18O to be unconvincing. What features are
758 being matched and what features aren't seems arbitrary. Maybe this would be improved by showing the uncertainty

759 **Author's response:** This point was also raised by the Referee 1 and we modified the figure so that the uncertainty
760 is shown:




761 **"Figure 4. Alignment of EDC $\delta^{18}O_{atm}$ and Chinese $\delta^{18}O_{calcite}$ records over time periods where new tie points**
762 **are defined.** (a) EDC $\delta^{18}O_{atm}$ new and old datasets on AICC2012 gas age scale. (b) Compiled EDC $\delta^{18}O_{atm}$. (c)
763 Chinese $\delta^{18}O_{calcite}$ on U-Th age scale (Cheng et al., 2016). (d) Temporal derivatives of compiled EDC $\delta^{18}O_{atm}$ (blue
764 curve) and of the old $\delta^{18}O_{atm}$ dataset (black curve). (e) Temporal derivative of Chinese $\delta^{18}O_{calcite}$ (red curve).
765 Extrema in temporal derivatives are matched. Tie points represented by black vertical bars are determined by
766 Extier et al. (2018) and those by blue vertical bars are determined by this study. Both are used in the AICC2023
767 chronology. Dashed vertical bars show tie points identified by Extier et al. (2018) that are not used in AICC2023.

2σ uncertainties attached to the tie points are shown by the horizontal error-bars in panel c). Red vertical areas frame periods of lacking resemblance between $\delta^{18}O_{atm}$ and $\delta^{18}O_{calcite}$ variations."

Please note that we also corrected some mistakes that were present within this figure in the first version of the manuscript (example at 280 and 290 ka BP where two matching points were missing).

L500 – I'm concerned the 6ka uncertainty is way to small. 6ka seems reasonable for the actual matches, but shifting the tie points based by 5ka based on whether there is a Heinrich-like event is not well founded. This really needs process modeling for support. Since that is outside the scope of the study, I recommend increasing the uncertainty at least 10 ka (5ka since you don't know what to tune to and 5ka for the murky matches themselves).

**Author's response:** Jouzel et al. (2002) presented the drawbacks of assuming a constant phase between $\delta^{18}O_{atm}$ and insolation which is a key assumption of the orbital tuning approach. To evaluate the uncertainty of the phasing between $\delta^{18}O_{atm}$ and insolation, Parrenin et al. (2001) assumed that the number of precessional cycles can be counted in the $\delta^{18}O_{atm}$ record. For them, this assumption "is straightforward considering how clearly this cycle is imprinted in the $\delta^{18}O_{atm}$ series" and implies that "ice and gas chronologies are assigned to pass through a succession of large doors with a width of 6 kyr (1/4 of a precession cycle)". The authors estimated this width by combining glaciological modeling and orbital tuning.
We chose to stick with the recommendation of Jouzel et al (2002) and to use a 6-kyr uncertainty (1σ), which also allows to remain coherent with previous orbital dating studies already conducted (Bazin et al., 2013; Dreyfus et al., 2007).

L576 – As mentioned above, I don't really understand what you are doing to get a coherent scenario. Are there other firn models which get better agreement? And what are the climate forcings?

**Author's response:** We agree that the adjustment of modeled LID values to experimental LID values is not necessary and we used the raw modeled LID values in the revised study (see L. 574-610 of this document).

L588 – Why are you not using the tie points to WAIS Divide directly? These ties are well established in Buizert et al. 2018. The WAIS Divide timescale is more accurate than GICC05 as demonstrated by Svensson et al. 2020 who had to shift the dates of GICC05 more than WDC14 for the bipolar matches.

**Author's response:** Although we agree, we would prefer to remain coherent with the AICC2012 study, that is to say to update the timescale AICC between 60 and 800 ka BP while keeping GICC05 between 60 and 0 ka BP. However, we understand fully this comment and we have implemented a correspondence between AICC2012, AICC2023 and WD2014 age models using Buizert et al. (2018) tie points in the dataset submitted to PANGAEA.

In the new version of the manuscript at L.219 we insist that for now, we focus mostly on the 60-800 ka BP age interval and stipulate that the WD2014 age model is more accurate over the last 60 kyr:

"We acknowledge the exclusion of the WAIS (West Antarctic Ice Sheet) Divide ice core (WDC) from the construction of the AICC2023 age scale as for AICC2012 age scale. Over the last 60 kyr, though, we recommend the use of timescales tied to the WAIS Divide 2014 age model (WD2014, Buizert et al., 2015; Sigl et al., 2016). A correspondence between AICC2012, AICC2023 and WD2014 age models based on the volcanic synchronization of WDC and EDC using sulfate data (Buizert et al., 2018) is provided over the 0-58 ka BP period (that is to say for the section above the depth of 915 m for the EDC ice core, see Data Availability section)."

Ideally, one possible future development would indeed be to include the high-resolution information from WAIS Divide (and other cores). To do so, the WAIS Divide ice core should be added to the Paleochrono experiment along with the ties established by Buizert et al. (2018) and background glaciological scenarios that need to be determined. This development is beyond the scope of this study.

## III. Response to Editor

We thank the editor for his valuable input and helpful comments on the manuscript. We have implemented the following changes in a revised version.

Dear authors,

Thank you for uploading your response to the reviewer comments. Based on your responses, I hereby invite you to submit a revised manuscript along the lines of the your responses. Based on the reviewer comments, a minor revision is necessary.

With your revised document, also please provide a detailed response to the reviewer comments. For their main comments, please provide more specific details than you have done so far on the changes you made.

In preparing your response, please consider my additional comments below. All line numbers refer to the line numbers in your Author comments.

Good luck in preparing your revision, and please reach out if you have questions.

Best,

Christo Buizert (CP editor)

Reviewer 1 Author Comments:

Line 82: "The less variable LID scenario results in less gas age inversion": besides providing a plot, can you ensure/guarantee that there are no age inversions in this version? We know these to be unrealistic.

**Author's response:** We slightly modified our answer to the referee 1 and guarantee that there is no age inversion in AICC2023: "The AICC2023 chronology resolved this issue. We believe this was due to the too important variability of the analyzed LID scenario that is transferred to the Δdepth, itself driven by the high uncertainty associated with background LID. To address this problem, we revised the background LID scenario using new data of $\delta^{15}N$ and reduced its relative uncertainty to 10-20 % (where it was evolving between 20 and 70 % in the AICC2012 chronology). Here the less variable LID scenario, along with new gas and ice stratigraphic links (Baumgartner et al., 2014; Svensson et al. 2020), result in no age inversion.

It can be seen in the figure below where EDC age difference between two adjacent depth levels is plotted as a function of EDC depth for AICC2012 (black for gas age) and AICC2023 (blue for gas age and red for ice age). If there was an age inversion, then the age difference would present negative values, as for AICC2012 (black curve). Yet, this is not the case for EDC in AICC2023 (blue and red curves). After the same verification for the four other cores, we can guarantee that **there is no age inversion in the new AICC2023 age model.**

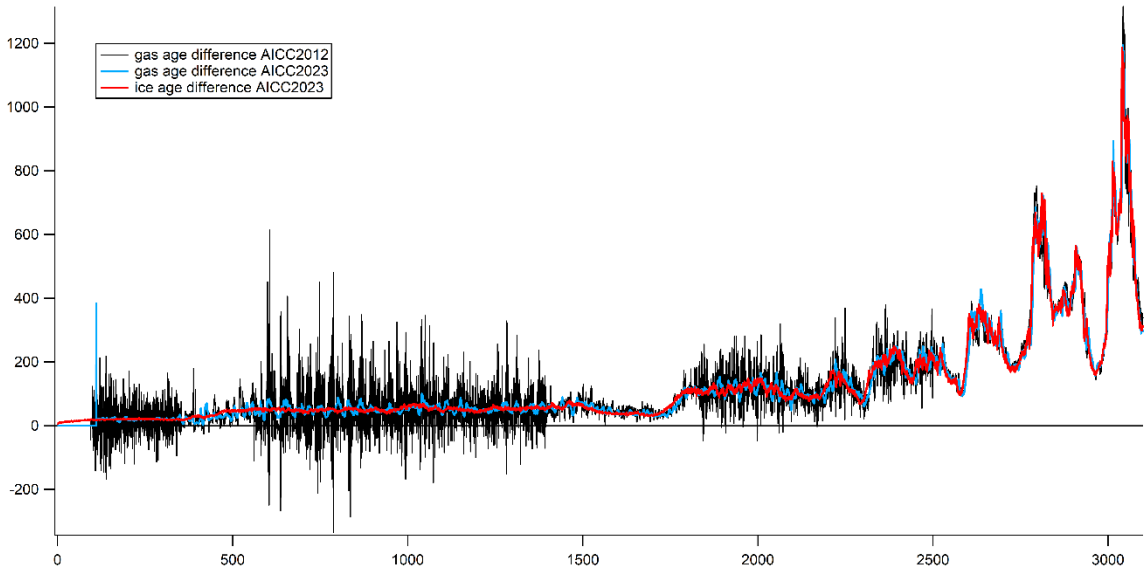
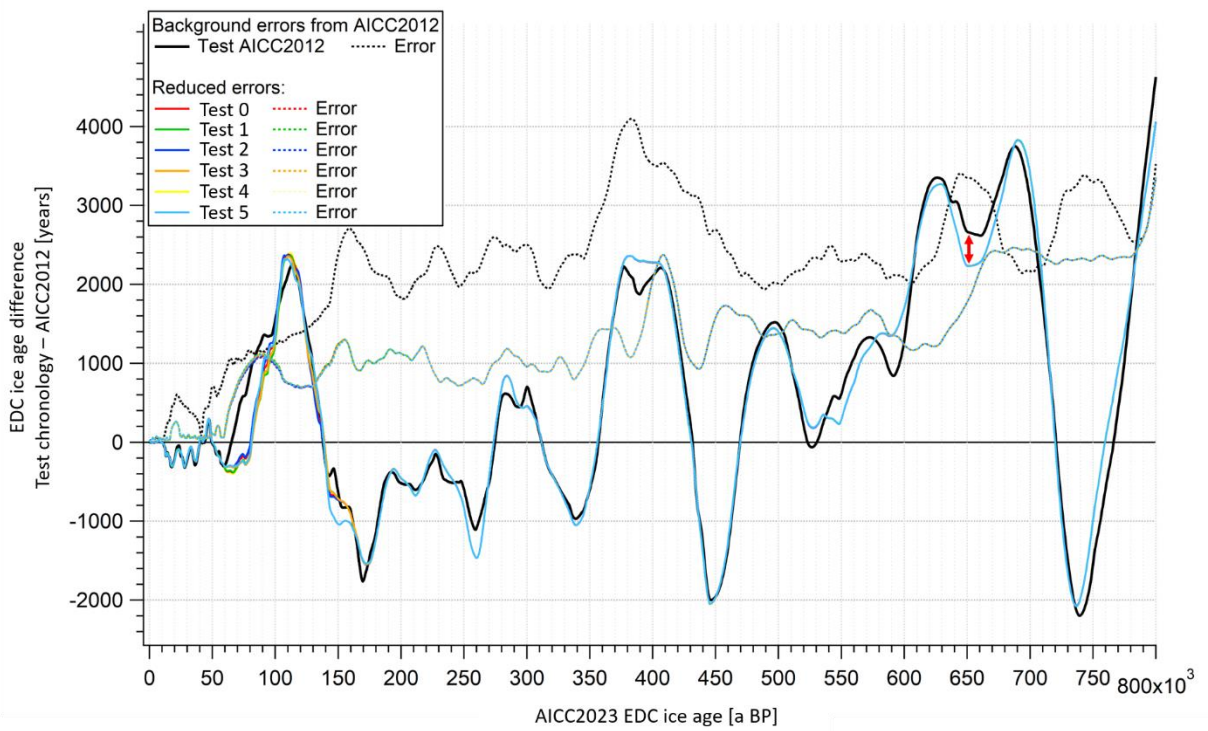


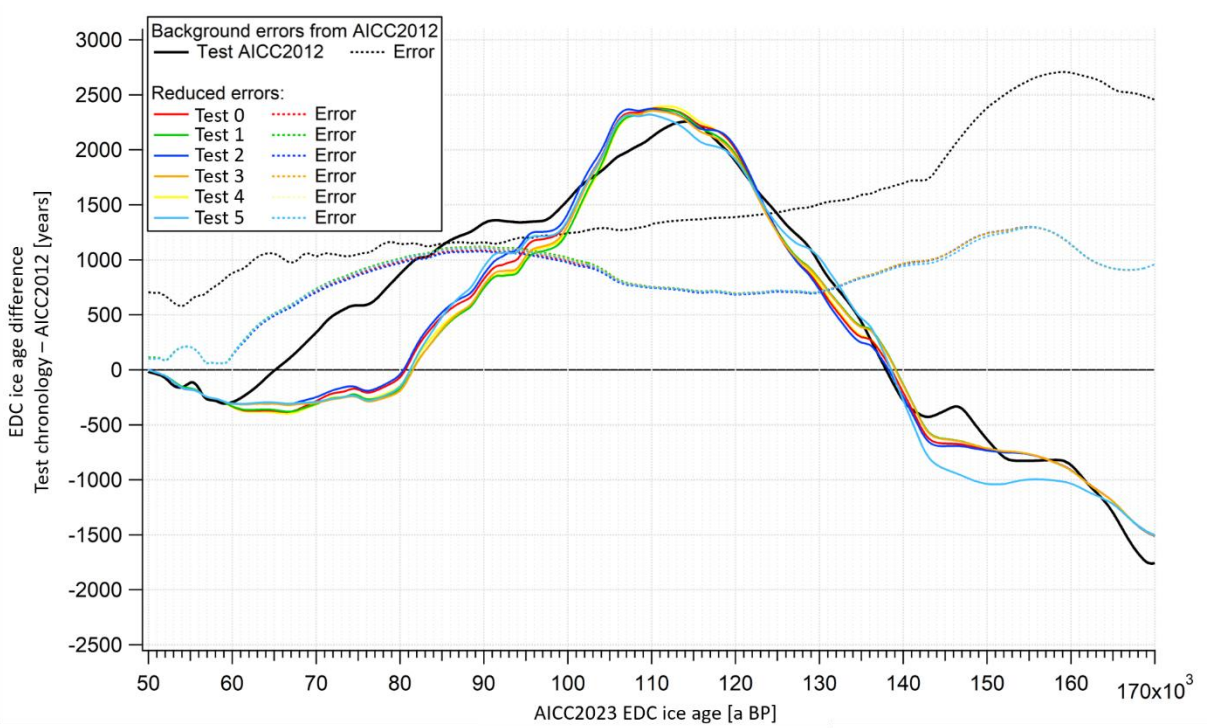

**Figure.** Age difference between two adjacent depth levels in AICC2012 (black for gas age) and AICC2023 (blue for gas age and red for ice age) as a function of EDC depth. The age difference is defined as: age (depth + 0.55 m) – age (depth)."

Line 131 + 134 Figures: What are the two dashed lines?

**Author's response:** They represent absolute chronological uncertainties for each test. We added the legend that was missing:




852 **Figure S8. EDC ice age difference between each test chronology and AICC2012 timescale between 800 and**
853 **0 ka BP.** The ice age uncertainty (1σ) obtained for each test is shown by the dotted lines. The red arrow indicates
854 the largest age mismatch between the test chronologies.




855 **Figure S9. EDC ice age difference between each test chronology and AICC2012 timescale between 170 and**
856 **50 ka BP.** The ice age uncertainty (1σ) obtained for each test is shown by dotted lines."

857

At line 181: I think this misses the point of the reviewer, who suggests that the D-depth constraints improve the chronology itself – which I think is true because the accumulation rate, thinning function, LID and D-depth are closely linked. We know that the EDML AIM d18O peak always leads the peak in other cores, so we can use that knowledge to make the Ddepth estimates more accurate.

**Author's response:** In the Paleochrono tool, each ice core is attached to a folder in which there are different files for each type of constraints.

For example, the NGRIP ice core folder contains the following input files:

- LID
- Thinning
- Accumulation
- Δdepth
- Ice age horizons
- Gas age horizons

The Δdepth file is filled with depth offsets observed when aligning $\delta^{15}N$ and $\delta^{18}O_{ice}$ abrupt variations in gas and ice phases. Δdepth is believed to be the depth offset between two phases of same age. So, the NGRIP Δdepth constraints are included in AICC2023.

We understood that Referee 1 suggested to add Δdepth constraints on Antarctic ice cores assuming that $\delta D$ maximum and $CH_4$ abrupt increase are synchronous (see Barker et al., 2011) to determine Δdepth. We answered to this suggestion by saying that we would prefer not to base our chronology on this bipolar seesaw hypothesis but would rather use our new chronology to test this hypothesis. This was not clear in our first answer which has been revised.

As far as I understand, you suggest that we deduce Δdepth constraints from comparing several ice cores. This strategy is not compatible with the Paleochrono model which implies that the folder of each ice core is built independently from the other cores and should be self-sufficient. What we will do, instead, is to study the outputs of the Paleochrono model to evaluate lags between the same or different proxies recorded in different ice cores as it was done for example in Landais et al. (2015).

Line 252, 253, 330 and 332 no response is provided. I assume these are answered all together, but still please make sure these are addressed.

**Author's response:** Yes, these were addressed. We revised our answer to the Referees so that is is clearer.

Reviewer 2 author comments:

Line 16: While the reviewer has a good point that AICC is somewhat of a misnomer, I agree that you should keep the name AICC for consistency. In your revision, please elaborate on the changes you made to "better explain"

(line 23) the rationale. Besides West Antarctic cores, the really well-dated Dome F ice core is also not included while that cores would certainly improve the deep chronology.

**Author's response:** Indeed, Dome Fuji chronology has recently been revised by Oyabu et al. (2022) over the last 207 kyr. Improving the chronology over older periods would require to use $\delta O_2/N_2$ data that is not published yet.

As mentioned above, adding the ice cores not yet included in the Paleochrono tool requests a lot of resources for the implementation in the tool and would be a different study. It was thus not possible to include everything in this work and we decided to focus more on the deep timescales with a particular focus on EDC. As mentioned in the manuscript at L.844, one important future development would indeed be to include information from other cores such as WAIS Divide and Dome Fuji:

"A final important aspect would be to further extend the Paleochrono dating experiment by implementing other ice cores such as Dome Fuji, WAIS Divide and NEEM (North Greenland Eemian), for which a large amount of chronological and glaciological information is now available."

Line 234: I don't understand this response. Please elaborate, and specify the changes made in response.

**Author's response:** We believe this comment of Referee 2 was referring to his/her first major comment about firn modeling (L. 567 of this document). Therefore, we answered both comments in the same response:

**"Referee's comment:** This sentence is particularly confusing: "To obtain a coherent scenario, the firn modeling estimates have been adjusted, by standard normalization, to the scale of LID values derived from $\delta$15N data (later referred to as experimental LID)."

This seems to hiding a major limitation in the methodology. If I understand correctly, the authors cannot get the firn model to match the d15N-inferred firn thicknesses, so they just give up on the actual values and instead seek to match the variations. Whether this is due to an inappropriate firn model (Breant) or outdated forcing (the forcing isn't shown but I suspect the authors are using the classical isotope-temperature scaling that Buizert et al. 2021 showed to be too cold at the LGM). The firn modeling should really be done with multiple models – which is actually relatively easy to do thanks to the Community Firn Model – and with a range of climate forcings. I think the authors efforts would be better served employing other firn models and forcings rather than the impurity scenarios which the author reject.

**Author's response to Referee's comment:** Thank you for raising this contradiction. The idea behind this proposition of fitting the modeled LID (orange curve on Fig. S7) to experimental LID values was to avoid any discontinuity when switching from experimental to modeled values when no data are available (grey rectangles on Fig. S7).

Following this comment and for more coherence, we prefer to use the raw firn thickness predicted by the firn model, rather than fitting it to experimental LID values. This modification is considered in the revised manuscript and we modified the Sect. 3.1 in the Supplement at L.168:

"3. Sensitivity tests on background scenarios and associated relative uncertainties

3.2 Background lock-in-depth (LID) scenario at Dome C

[…]

Discontinuities are visible when switching from experimental to modeled values when no data are available (grey rectangles on Fig. S7). To avoid these discontinuities, we test a LID scenario where the modeled LID is fitted to experimental LID values (orange curve in Fig. S7). In other words, the firn modeling estimates are adjusted, by standard normalization, to the scale of LID values derived from $\delta^{15}$N data. Adjusting the modeled LID to experimental LID values induces a modification of 4.7 m at most (see red arrow) which remains within the background relative uncertainty (20%).

On the depth interval from 578 to 1086 m, the modeled scenario without any fitting to $\delta^{15}$N inferred LID (blue curve, Fig. S7) is almost as effective as the one that was fitted (orange curve, Fig. S7) (i.e., close Δ values). On the second depth interval of interest, from 1169 to 1386 m, both scenarios show equal Δ values.

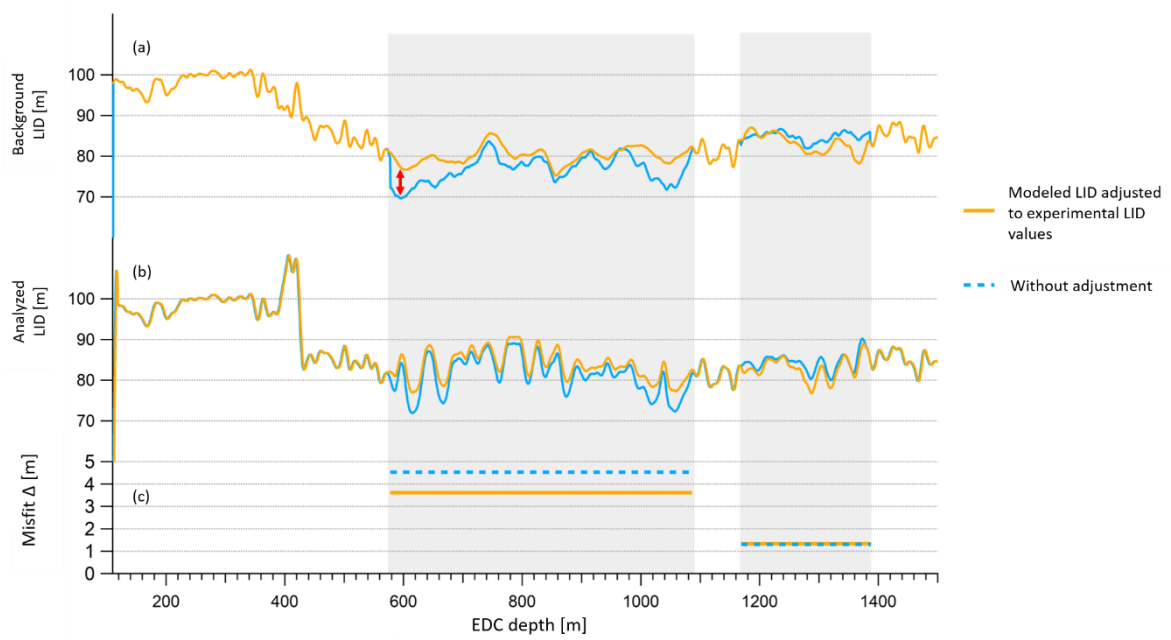



**Figure S7. Mismatch Δ between background and analyzed LID for EDC over the 100-1500 m depth interval.** (a) Background LID with and without adjusting the modeled LID to experimental LID values (orange and blue curves respectively). (b) Analyzed LID. (c) The averaged value of the misfit, Δ, is calculated for the two LID over the two depth intervals where $\delta^{15}$N data are not available (either between 578 and 1086 m or between 1169 and 1386 m, see intervals shown by grey rectangles).

We thus conclude that we can keep the scenario combining $\delta^{15}$N-inferred LID and modeled LID in the construction of AICC2023.""

## IV. Additional author comments

948 **Average absolute 1σ-uncertainty**

949 In the revised manuscript we say that the average chronological uncertainty of AICC2023 over the last 800 kyr is
950 900 years. It is the average of the varying 1σ error given by Paleochrono as a function of EDC depth over the 0-
951 3192.75 m depth interval, corresponding to the depth interval on which the AICC2012 age model was provided
952 (Bazin et al., Veres et al., 2013). In the first version of the manuscript, this uncertainty was larger as we considered
953 the 0-3260 m depth interval. However, we would prefer to stay coherent with what was done for AICC2012, that
954 is why we provide the new AICC2023 age model and associated error over the 0-3192.75 m depth interval.

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