Interactive comment on *"The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years"*

Anonymous Referee #1
Received and published: 30 January 2013

1 General Comments

The paper presents a new timescale, AICC2012, and applies it to four Antarctic ice cores (Vostok, EPICA Dome C, EPICA Dronning Maud Land, Talos Dome) and one Greenland core (NGRIP) over the period 0–120 ka BP. The timescale is developed using inverse methods (the Bayseian tool 'Datice'). The Datice tool was previously used in Lemieux-Dudon et al., Quat. Sci. Rev. [2010] to revise yet earlier timescales for the Vostok, EDC and EDML cores. The major new contributions of the paper are (i) the availability of new dating tie points to synchronise the records and (ii), improved estimates of the age difference between ice and gas phase signals in the ice cores.

Previous techniques to estimate this age difference (Δage) relied on firn densification models which have recently been shown to be flawed when applied under glacial conditions to the deep Antarctic ice cores [Parrenin et al., 2012]. Here, following Parrenin et al. [2012], instead of densification models the authors make use of $\delta^{15}N$ data to estimate lock in depths and in turn Δage. Due mainly to the improved Δage estimates there is a systematic reduction in the ice ages of the Antarctic records compared to earlier chronologies, e.g. by around 500 years in the timing of the Antarctic Isotope Maxima throughout MIS 3. There authors provide some discussion of the differences between the AICC2012 timescale and previous timescales and also some very brief discussion of the implications of the timescale for our understanding of climate dynamics and the bipolar seesaw theory.

The authors have convinced this reviewer that the AICC2012 timescale is an improvement over that presented in Lemieux-Dudon et al., [2010] and that it merits publication in Climate of the Past. However, there are a number of issues, outlined below, that must be addressed prior to publication.

Answer: We thank the anonymous reviewer for his thorough review that improved our paper. A detailed point-to-point reply is provided below.

2 Specific Comments

1. The AICC2012 timescale for Vostok, EDC, EDML and Talos Dome must be made available upon publication of the manuscript. Ideally this would be as a SOM to the paper and as an entry in a publicly accessible online database e.g. NOAA's WDC for Palaeoclimatology with a link in the paper. Estimates of the uncertainly range for the timescale should also be published with the SOM/database files.

Answer: The AICC2012 timescale for each ice core record will be made available, both as SOM linked to the paper and as data files deposited on publicly accessible online database with reference to it in the paper. Estimates of the uncertainty range will also be provided, as suggested.

2. The many timescales available for Antarctic cores can be confusing. It would help

the wider palaeoclimate community if a clear statement was included (I'd suggest in the abstract) about whether the AICC2012 timescale is intended to replace all previous timescales as the state-of-the-art for these cores (including NGRIP) and/or a clear statement about what particular circumstances/applications the authors recommend using AICC2012 and in what circumstances/applications they recommend using earlier timescales.

Answer: Providing a unified chronological frame for both Greenland and Antarctic ice core records is one of the canonical targets of the ice core community. AICC2012 arises from the latest efforts of the so-called EDC4 discussion group in reaching the goal of a unified time frame for both Greenland and Antarctic ice that combines multi-record chronological information from data and glaciological modeling. Until further updates were provided - which could be expected to either improve the range and accuracy of stratigraphic linkages (new layer-counted records in the Antarctic, new absolute markers, new or refined stratigraphic tie-points, etc) or provide further methodological improvements for the Datice tool - we strongly argue that for the Antarctic ice core records analyzed in our study (ie., Vostok, EDC, TALDICE, EDML) the AICC2012 timescale is the most comprehensive dating effort available and should be employed as the preferred chronology for both ice and gas phase proxies. As for the other important Antarctic records not yet included in the Datice tool, our aim is to either have these records included progressively, or to convince the community on the advantage of adopting the Datice tool and to build site-related chronologies in direct comparison with the AICC2012 output.

Because we considered that there was no basis at present to adjust the extensively used layer counted Greenland age scale GICC05, AICC2012 has been constructed such that it is virtually identical to GICC05 for NGRIP for the last 60 ka b2k. For the Antarctic records considered, AICC2012 is now the preferred time scale for direct inter-comparison with NGRIP, as the use of AICC2012 assures the synchroneity of records within the uncertainty of the methods used. However information from GICC05modelext (ie., beyond 60.2 ka b2k) was included only via the background scenarios (and not as age markers) in the construction of AICC2012, and therefore the ages for NGRIP beyond 60.2 ka in AICC2012 are not identical to those in GICC05modelext.

Where issues of phasing between Antarctic records included in AICC2012 and NGRIP are involved, the NGRIP ages in AICC2012 should therefore be taken to avoid introducing false offsets. However for issues involving only Greenland ice cores, although AICC2012 uses more glaciological information than GICC05modelext beyond 60.2 ka b2k and thus can be regarded as more robust, there is not yet a strong basis to recommend superseding GICC05modelext as the recommended age scale for Greenland ice cores.

The following paragraphs have been introduced in the Abstract for better clarification:

'It is expected that the future contribution of both other long ice core records and other type of chronological constraints to the Datice tool will lead to further refinements in the ice core chronologies beyond the AICC2012 chronology. For the time being however, we recommend that AICC2012 should be used as the preferred chronology for the Vostok, EDC, EDML and TALDICE ice core records, both over the last glacial cycle (this study), and beyond (following Bazin et al., 2013)'. The ages for NGRIP in AICC2012 are virtually identical to those of GICC05 for the last 60.2

ka b2k, whereas the ages beyond 60.2 ka are independent of those in GICC05modelext (as in the construction of AICC2012 the GICC05modelext was included only via the background scenarios and not as age markers). As such, where issues of phasing between Antarctic records included in AICC2012 and NGRIP are involved, the NGRIP ages in AICC2012 should therefore be taken to avoid introducing false offsets. However for issues involving only Greenland ice cores, there is not yet a strong basis to recommend superseding GICC05modelext as the recommended age scale for Greenland ice cores.

3. P6014, L21–25 (abstract): This conclusion appears in the abstract with insufficient justification or discussion in the main text. As I read it, these lines are saying that the peak of the isotope maxima at EDC are synchronous with abrupt transitions at NGRIP whereas at EDML the isotope maxima have flatter tops and **'precede the transitions by several centuries'** and that these observations 'confirm the regional differences in the millennial scale variability over the last glacial period'. It would be a big result if the difference in timing was really confirmed. I don't think it is. If a point is to be made about regional differences then specific language is required about what part of MIS3/which AIMs are being referred to, how the timing of the AIMs is selected and what the relative dating errors are between the curves. More discussion is needed (see also my comment further below about P6027 L4-9).

Answer: We acknowledge that not enough details were given on the implications the AICC2012 has for the seesaw sequence of events (although we intend to dwell on these aspects at large in a subsequent work). For clarification however, we will make clear in the revised text that our conclusion is mainly valid over MIS 3, where we have the smallest uncertainty on the AICC2012 chronology thanks to the numerous new stratigraphic tie-points employed (ice-phase links, gas-phase links, the Laschamp event, etc.). It shall be noted however that we are only confident in assessing the difference between the relative behaviors of Greenland (NGRIP) versus EDML and EDC when the stadials are particularly long and well expressed, i.e. mainly over DO 8 and 12. Therefore, the main point that we wanted to make is that despite large changes in the lock-in depth (constraining the ice age – gas age difference) between the previous Datice-derived chronology using firnification modeling (i.e. LD2010) and the new approach using $\delta^{15}N$ (AICC2012), the difference in the relative timing of Antarctic (EDC and EDML as displayed in Figure 4 of the main text) and Greenland (NGRIP) water isotopic records is within the uncertainty of the chronology of 300 years (EDML and EDC) for DO 8, and 500 years (EDML and EDC) for DO 12, respectively. This is not unexpected since the uncertainty of the chronology also includes the uncertainty on the LIDIE determination (cf. discussion in SOM).

At EDML, over DO 8, the maximum $\delta^{18}O$, at the beginning of the plateau is reached at least 1000 years before the abrupt stadial-interstadial transition seen in Greenland, hence significantly more than the 300 years uncertainty. At EDC, for the same DO 8, the maximum of the AIM is synchronous within 400 years with the abrupt stadial-interstadial transition recorded in Greenland, both for LD2010 and AICC2012, respectively. For DO 12, the maximum of $\delta^{18}Oice$ at EDML is reached 1000-1400 years before the abrupt warming recorded in Greenland, which is significantly larger than the 500 years uncertainties and the difference between the LD2010 and AICC2012 chronologies. On the opposite, the maximum of $\delta^{18}Oice$ at EDC over AIM 12 is synchronous (± 300 years) with the Greenland abrupt warming. Thus, within the uncertainty of several centuries, the AICC2012 data does not modify

the general conclusion already reported in the EPICA community paper (2006) and Buiron et al. (2012) that the AIM have squared shapes at EDML and triangular shapes at EDC.

The following text has been introduced in the main text:

At EDML, over the interval corresponding to GI-8, the maximum δ^{18}Oice at the beginning of the plateau is reached at least 1000 yr – hence significantly more than the 300 yr uncertainty – prior to the abrupt stadial-interstadial transition seen in Greenland. At EDC, for the same event, the maximum of the AIM is synchronous within 400 yr with the abrupt stadial-interstadial transition recorded in Greenland, both for LD2010 and AICC2012.

For GI-12, the maximum of δ^{18}Oice at EDML is reached 1000-1400 yr before the abrupt warming recorded in Greenland, which is significantly larger than the 500 yr uncertainties and the difference between the LD2010 and AICC2012 chronologies. On the opposite, the maximum of δ^{18}Oice at EDC over AIM12 is synchronous (±300 yr) with the Greenland abrupt warming.

4. P6014, L20–22: Severinghaus et al., [1998], from which the 8-16°C figure comes, should also be cited: Severinghaus, J. P., T. Sowers, E. J. Brook, R. B. Alley, and M. L. Bender (1998): Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. Nature, 391, 141-146.

Answer: The reference has been consulted and a citation provided in the revised text.

5. P6016 L11–14: Is there any evidence to support that the convective zone at the top of the firn did not increase significantly during glacial periods? As the method for estimating the LID hinges on this assumption I think it is needed to provide some evidence or at least some additional discussion.

Answer: Apart from the data of Parrenin et al. 2012a, additional evidence for a lack of convective zone at EDC during the last deglaciation has been recently presented in detail by Parrenin et al. (2013); we now also make reference in our paper to these new data.

Reference: Parrenin et al., Synchronous change of atmospheric CO2 and Antarctic temperature during the last deglacial warming. Science, 339, 1060-1063.

6. Supplementary figure 6: This figure should be moved to the main text; it is important that the timescale uncertainties are clearly communicated. Also, please clarify whether the standard deviation in ice ages can be interpreted as a 1-sigma dating uncertainty.

Answer: In the revised version the timescale uncertainties for both the ice (Figure 1) and gas (Figure 2) proxies will be included in the figures.

7. P6019 L1–2: Were the six orbital climate links really all for T1? Briefly explain why these orbital points are removed for AICC2012. There is a note in the SOM on this but I think the reasons for excluding certain tie points (for Vostok and the other cores) should be explained in plain language in the main text.

Answer: We made general reference in that text entry to the existing Vostok timescale, but not referring exclusively to the <125 ka period, as the six orbital points mentioned were actually much older than T1: the youngest one was over T2 (at 132.4 ka) and the others at 200.6 ka, 246 ka, 293.6 ka, 336.2 ka and 373.8 ka, respectively. These orbital points do not influence the period covered in our study; reference to them and explanations are provided in the companion paper of Bazin et al. (2013), as well as in the SOM.

8. P6014 L26: I think the paper promises too much in the introduction e.g. 'we present the absolute and relative dating implications of the new chronology over the last glacial inception and for the bipolar sequence of events associated with the seesaw mechanism over middle MIS3'. I think it would be more accurate to say 'we provide some examples of absolute and relative dating implications.. etc'.
Same comment also applies to P6027 L12-13.

Answer: The final text has been adapted as suggested for both P6014 L26 and P6027 L12-13 comments.

9. P6019 L18: I don't think that it is needed to give the timescale uncertainty for the >130 ka part of EDC on the EDC3 chronology given that it is not the interval or timescale that the paper is focused on.

Answer: We referred in that specific text entry to the existing EDC3 timescale (Parrenin et al. 2007, CP) for the EDC record, but again not referring strictly only to the period <125 ka. However, the final text has been adapted as suggested.

10. P6026 L15: I'm not convinced about point (2). How can the inter-hemispheric gradient explain an offset up to a few centuries? Obviously it can't explain any part of the offset between the four Antarctic records. Please clarify.

Answer: It is not inferred from our text that the inter-hemispheric gradient contributes solely to the observed offset, but mainly as a part of cumulus of forcing factors that could eventually lead to such offsets, up to a few centuries in length.

11. P6027 L4–8: These lines read as though we are about to hear an explanation for why EDML has different shaped AIM to those observed at EDC, but none is in the end offered. Please clarify and provide additional discussion.

Answer: We did not intend to provide new explanations on the causes of different shapes of the AIM as observed in some Antarctic ice records (ie, EDML versus EDC) other than citing what was already published and well documented in the cited references. This is the reason why we simply state that with respect to the AICC2012 chronological output, the postulated difference in appearance/behavior of the climate events archived in ice records from the Atlantic sector (EDML) versus the Indian sector (EDC) of the Antarctic ice sheet is in agreement with the seesaw theory suggesting that AMOC intensity is the driving process for explaining the relative evolution of the temperature between Antarctica and Greenland on a millennial-time scale.

12. P6027 L5: TALDICE is not shown in Figure 4.

Answer: The reference to TALDICE in figure 4 has been removed from the P6027 L5 text entry.

13. P6027 L4–8: Be specific about which AIMs occur earlier at EDML compared to EDC. It is not obvious from the Fig. 4 that this is the case for AIMs 5–7 or AIMs 10–11. It may arguably be the case for AIMs 8 and 12 but it would depend on how you defined the actual AIM (which is not specified); e.g. you may get a different result if you smooth the curve to reduce what may be site-specific noise. More discussion is required here including of the relative dating errors of the EDC and EDML curves. This goes to the point made about P6014, L21-25 of the abstract.

Answer: Please see the explanations provided for comment 3. P6014, L21–25; we consider that the issues raised here have been addressed under that section.

14. P6028 L12: Are you saying here that the AICC2012 chronology is a better/more reliable chronology than GICC05modelext for this part of the NGRIP core? Can you make a statement here about under which circumstances/applications you recommend using AICC2012 and in what circumstances/applications you recommend using GICC05modelext?

Answer: An overview that relate also to this comment has been presented under the answer to Specific comment 2.

15. Table 1 and Section 4.2: Uncertainties in the event duration on the AICC2012 timescale should be included in the Table. (Quoting from the SI: 'The aim is to . . . build coherent and precise timescales with associated estimates of uncertainty range'.)

Answer: We will include the uncertainty range both in Table 1 and as specific text entries in section 4.2

16. Table 1: Regarding the pers. comm. citation to Seierstad: If Rasmussen et al [2008] has been followed then there is no need to report the details elsewhere, if there are differences then they should be noted in the main text or SOM.

Answer: The same approach as Rasmussen et al (2008) has been used, however 'reporting details elsewhere' refers to the fact that the synchronization has been extended further back in time, and these data will be presented elsewhere as Seierstad et al.

17. Figure 1: It would help the reader if labels were added to the figure denoting the AIM and GI/GIS numbers.
Done

18. P6030 L20-22: The error bars for AICC2012 (when added to Table 1) could also be referred to at this point in the text.
Done

3 Technical Corrections

1. P6014 L4: ‘best-studied in environmental science’ is a big call; suggest best studied in paleoclimatology.
Modified accordingly

2. P6014 L16: latitude records
Modified accordingly

3. P6014 L26: approximately 2°C
Modified accordingly

4. P6016 L13: ‘modulated by the bipolar seesaw mechanism’ suggest replace with ‘predicted by the bipolar seesaw hypothesis’.
Modified accordingly

5. P6015 L24: difference, called _age, reflects..
Modified accordingly

6. P6018 L16: ‘shifted -705 years’ it’s not clear if this means it was shifted 705 years younger or 705 years older, please clarify.

Answer: Reformulated, now the sentence reads: ‘*Beyond 60 ka BP we used constraints from the GICC05modelext time scale that was constructed by patching the ss09sea modeled age scale shifted to younger ages by 705 years in order to match it to the end of the annual-layer-counted time scale (Wolff et al., 2010)*’.

7. P6024 L10: Rather than be redundant wouldn’t such information help to refine and test the pairing?

Answer: The formulation was indeed misleading, as such additional information, if well-constrained could help test and eventually refine the pairings. The text has been modified accordingly.

8. P6025 L24: GICC05
Modified accordingly

9. P6028 L15–16: constraint
Modified accordingly

10. P6032–6033: The conclusion and outlook are nicely written.
Thank you

4 References

Lemieux-Dudon, B., Blayo, E., Petit, J. R., Waelbroeck, C., Svensson, A., Ritz, C., Barnola, J. M., Narcisi, B. M., and Parrenin, F.: Consistent dating for Antarctic and Greenland ice cores, Quaternary Sci. Rev., 29, 8–20, 2010.
Parrenin, F., Barker, S., Blunier, T., Chappellaz, J., Jouzel, J., Landais, A., Masson-Delmotte, V., Schwander, J., and Veres, D.: On the gas-ice depth difference (_depth) along the EPICA Dome C ice core, Clim. Past, 8, 1239–1255, doi:10.5194/cp-8-1239-2012, 2012b.
Modified accordingly